CANoe - Simulink
Integration of Vehicle Model in
Existing Test Environment

Nils Espfors

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

CANoe – Simulink
Integration Of Vehicle Model In Existing
Test Environment

PowerDrive Systems

Location: Landskrona

Author: Nils Espfors

Faculty of Engineering (LTH), Lund University

Division of Industrial Electrical Engineering and Automation

Abstract

This master's thesis investigates the possibility to integrate an existing vehicle model from Simulink into the main testing software, CANoe. The purpose of integrating this was to achieve autonomous testing of real driving scenarios in an electronic control unit. This would in turn simplify and thus improve the test environment and test procedure at BorgWarner. By utilizing a vehicle model similar to the vehicle in testing, the test process is more akin to the real world thus ensuring the quality and safety of the product. The thesis is mainly focused on the software side of the development at BorgWarner, but it also shares some information about the hardware used at BorgWarner. This master's thesis took place at BorgWarners facility in Landskrona, Sweden.

Sammanfattning

Detta examensarbete utforskar möjligheterna att integrera en existerande fordonsmodell konstruerad i Simulink in i BorgWarners existerande testningsmiljö som är konstruerad i CANoe. Syftet med att integrera detta är för att uppnå större autonom testning för verkliga körscenarion. Detta hade i sin tur förenklat och således förbättrat testningsmiljön och testningsprocessen på BorgWarner. Genom att utnyttja en fordonsmodell liknande den bil som produkten är ämnad för kan man göra testningen mer lik verkligheten. Detta har i sin tur effekten att produktens kvalité- och säkerhetskrav som ställts utav BorgWarner och fordonstillverkaren verifieras. Examensarbetet är huvudsakligen relaterat till mjukvaruutvecklingen hos BorgWarner men arbetet berör även information om hårdvaran som används hos BorgWarner. Detta examensarbete utfördes i Landskrona på BorgWarner Power Drive Systems.

Acknowledgements

This master's thesis took place at the software testing department, TVR-SW, at BorgWarner Power Drive Systems in Landskrona. The work took place from May 2018 to November 2018 with a break during June and July to do summer work at the same department. The purpose of this work was to provide deeper knowledge and experience with integration between CANoe and Simulink. Furthermore, its purpose was to develop an existing vehicle model further and investigate the possible benefits this vehicle model could provide in CANoe and to the software testing department in whole.

I would like to thank Richard Pendrill and Måns Andersson for always answering my questions and pointing me in the correct direction. This work explored parts that were unknown to some extent and it was therefore crucial that Måns, Richard and I discussed continuously on how the work should progress. I would also like to thank Pierre Pettersson for helping me develop some of the vehicle dynamic features in the vehicle model further to accomplish a more realistic vehicle model. I would also like to thank Gunnar Lindstedt who always answered quickly and provided me with feedback and solutions to many different problems that arose around the work. Lastly, I would like to thank Anton Karlsson for being my supervisor despite working on his PhD thesis.

Table Of Contents

Innehåll

Abbreviations

ABS – Anti-lock Brakes

AWD – All Wheel Drive

AYC – Active Yaw Control

BEV – Battery Electric Vehicle

BSW – Base Software

BW - BorgWarner

CAN - Controller Area Network

CANoe - Controller Area Network open environment

CAPL - Communication Access Programming Language

CPU – Central Processing Unit

CSW – Control Software

dll – dynamic link library

DTC – Diagnostic Trouble Code

ECU - Electronic Control Unit

eLSD – electrically activated limited slip differential

ESP – Electronic stability program

FWD – Front Wheel Drive

FXD – Front Cross Differential

GCC – GNU Compiler Collection

GNU – A UNIX-based software environment.

HIL – Hardware-in-the-loop

IDE - Integrated Development Environment

MEX – MATLAB executable

MinGW – Minimalist GNU for Windows

MQB - Modularer QuerBaukasten (VW vehicle platform)

My (μ) – friction coefficient between tire and road surface

PDS – PowerDrive Systems

RWD – Rear Wheel Drive

SPA – Scalable Product Architecture (Volvo vehicle platform)

TVR-SW – Test, validation and reliability software Testing

1. Introduction

1.1 BorgWarner European Tech Center

BorgWarner PowerDrive Systems (PDS) in Landskrona is part of the larger BorgWarner incorporation. BorgWarner is a worldwide automotive industry incorporation and parts supplier and exists in 62 locations in 17 different countries. The BorgWarner corporation include several divisions that develops and manufactures different products for vehicles such as manual and automatic transmissions, turbochargers, engine valve timing components and all-wheel drive system components. The focus in Landskrona at BorgWarner PDS is torque transfer components and electrical/hybrid solutions for vehicles. The torque transfer components designed and developed in Landskrona are of the "on-demand" type where torque is applied to the either front wheels or rear wheels depending on the driving situation and vehicle configuration. The applied torque is controlled by a centrifugal electro-hydraulic coupling. The electronic control unit (ECU) that is responsible for controlling the hydraulic pump is located on the coupling itself. The coupling is then mounted on different positions throughout the vehicle depending on the vehicle configuration. This will be further explained in Chapter 2. Background. By having an AWD system of the "on-demand" type, there can be savings in fuel consumption and the overall friction in the drive train is reduced during normal driving. This is due to the increase in drag and parasitic losses when supplying torque to all four wheels in a vehicle compared to two wheels.

Figure 1 Generation 5 of the electro-hydraulic AWD-coupling [1].

Figure 1 above is a generation V (5) AWD-coupling designed for a vehicle manufactured by Volkswagen. The torque control is achieved by the ECU through a multitude of the vehicle sensors. The inputs; for instance, actual speed of the different wheels, lateral acceleration, yaw rate, steering angle and so forth provide the ECU with a plethora of information. The ECU controls the coupling in real time and strives to achieve a safe, reliable and fun driving experience for the driver. A safe driving experience is for instance achieved through the vehicle having full grip, which is achieved through having almost identical wheel speed when driving in a straight line or by each wheel having

near zero slip. The goal for the torque control is to be completely seamless for the driver so that the driver can maintain control of the vehicle despite demanding conditions.

The electro-hydraulic coupling can be utilized in several different ways. Its position in the vehicle drivetrain determines what type of function it will enable. Below is a short description and overview of how the coupling can be positioned in a vehicle and its corresponding function.

1.1.1 FWD with AWD-capabilities.

This is the most used implementation and the most manufactured coupling at PDS. The engine is positioned at the front in a transversal configuration and drives the front wheels primarily. The rear wheels are disengaged during normal driving. The rear wheels are engaged in a fraction of a second when a situation arises where torque is needed at the rear wheels to maintain stability. Figure 2 below showcases a Volkswagen Golf with the AWD-coupling from Figure 1 integrated in the rear axle.

Figure 2 VW Golf AWD System [2].

1.1.2 RWD with AWD-capabilities

This setup is mainly found in high performance vehicles such as the Audi R8 in Figure 3 below and the Lamborghini Huracán. The engine is positioned in the center of the vehicle and the torque is mainly transferred to the rear wheels, when additional traction is needed, torque is sent to the front wheels.
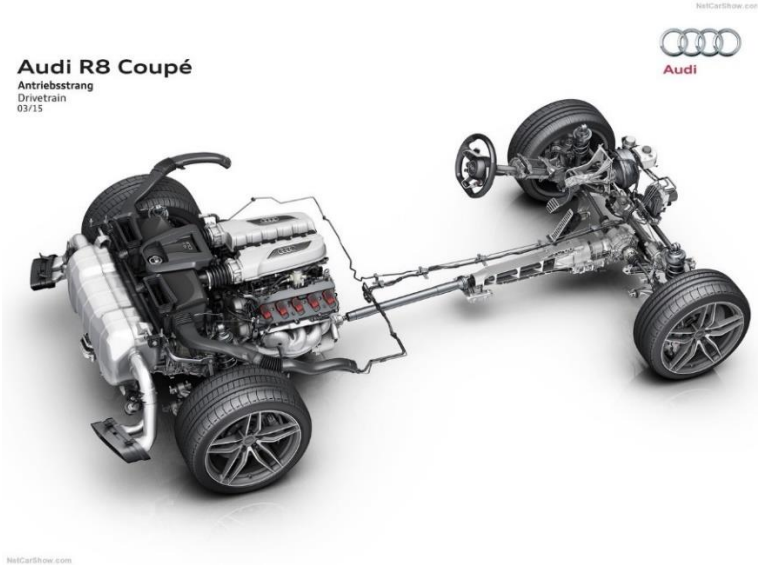
Figure 3 Audi R8 AWD [3].

1.1.3 RWD with transfer case

This solution is mostly found in SUV- type vehicles and other vehicles more capable in off-road environments. These vehicles have the engine positioned at the front in a longitudinal form which powers the rear wheels mainly. When additional traction is needed, a transfer case in conjunction with a transfer case coupling enables AWD by sending torque to the front wheels. This can in some cases also be controlled manually from the driver's position. This can be observed in Figure 4 below.
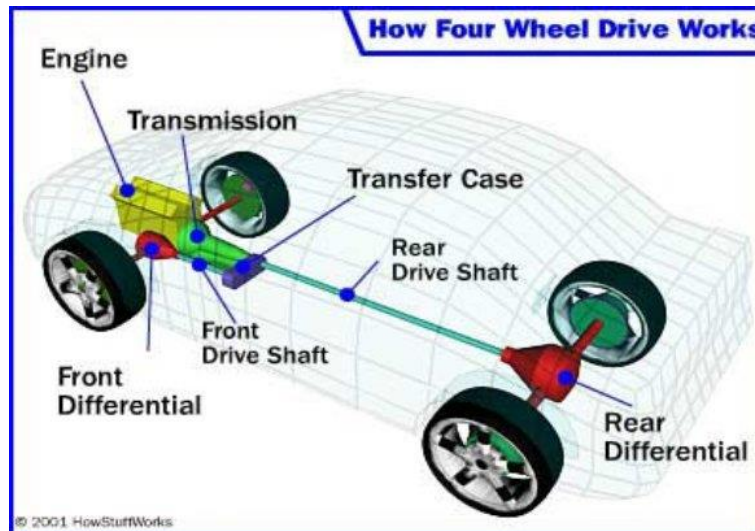
Figure 4 Transfer case in longitude engine configuration [4].

1.1.4 Front cross differential layout

A front cross differential (FXD) is placed after the gearbox in a vehicle with an engine mounted in the front of the vehicle in a transversal configuration. A FXD distributes the engine torque across the front wheels through an electrically activated limited slip differential (eLSD). A common issue with front wheel drive vehicles is that during hard acceleration the driving wheels' experience different levels of grip. This has the effect of wheel slip between the front wheels and the vehicle will change direction towards the part of the lowest grip. The FXD combats this by providing up to 100% of the torque to either wheel. By doing this it can achieve superior traction when accelerating and cornering compared to a vehicle without a FXD, achieving greater stability when driving. Below is Figure 5 which provide an overview of the FXD's location in the vehicle.

Figure 5 FXD-layout [5].

1.2 Test and validation at BorgWarner PDS

The parts in the AWD/FXD-coupling is tested thoroughly to ensure that it meets the safety requirements and performs as expected. This ensures that the product remains functional despite being exposed to a large number of different operating conditions. There are two different departments at BorgWarner PDS in Landskrona which are responsible for testing the product. One of these is the TVR-SW department which is responsible for testing of the different software versions and together with the software developers finalize the software for the product. It is at the software test department, TVR-SW, that this work has been completed, and the following sections mostly concern TVR-SW.

1.2.1 Software testing

The software test department handles the majority of software testing at BorgWarner in Landskrona, which includes having the ECU with the test rig in a "Hardware-in-the-loop" environment to provide a complete environment similar to the actual vehicle. It is a growing team of 12 people performing systematic testing of the different ECUs configurations. Each car manufacturer has different solutions on how the software communicates with the other parts in the vehicle, thus making it unique and it must therefore be tested separately.

BorgWarner have developed an environment for automatic testing of the software used in the ECU controlling the AWD/FXD-systems. This is done in CANoe, a software test development tool developed and sold by Vector Informatik GmbH [6]. CANoe is explained further in chapter 2. The testing of the ECUs is today separated into base software and control software testing. There is also live testing performed at two different tracks in Sweden to analyse and complement the CSW testing.

1.2.1.1 BSW Testing

Base software testing consists of testing the underlying functions in the ECU. These tests mainly consist of testing that diagnostics are working correctly, that the communication between different ECUs in the vehicle is working and that the ECU respond in a logical manner to changes in other parts of the vehicle. It is BSW that takes up the majority of the time for TVR-SW when testing a new software release. Proper communication to the other nodes in the vehicle is essential to maintaining the security and integrity of the vehicle. This work did not involve any major work related to BSW and as such this is the only section mentioning this part of the software development.

1.2.1.2 CSW Testing

Control software testing consists of testing how the software behaves when subjected to different driving parameters such as having different wheel speeds, lateral acceleration or if the ABS-system is engaged. This testing is done with either a control panel changing one parameter at a time or with an automated test that cycles through different parameters. These tests do not change significantly between models using the same AWD-layout. These tests are then compared to a specifications sheet where, for instance, supplied torque is compared to wanted torque. It is in these tests that this work is mainly focused.

These tests are separated into four different sections. These are; input tests, error handling tests, tuning tests and customer specific tests. Input tests correlate how the ECU interprets and handles different inputs such as the ones mentioned earlier. Discrepancies between how the input is interpreted by the ECU and the database could cause severe issues that would otherwise go unnoticed.

The continuation of these tests are the error handling tests. These test how the ECU handles invalid signals and what the failsafe for these variables are. Invalid signals could for instance be a wheel speed that is considered bad due to severe fluctuations or a value which is out of range. It is very important to handle these erroneous signals when they occur to maintain a safe vehicle.

The tuning section of the CSW test suite contains all tests that relate to the AWD control algorithm. These tests are each divided into six different subsections. The first one is the mode selector tests which investigate how the ECU responds to the different vehicle drive modes. The next sections contain all the drive tests that relate to how the AWD behaves during normal driving. The following section is the AYC section, these tests focus on how the ECU maintains stability when the vehicle is changing direction rapidly. A classic example of AYC testing that was invented in Sweden is the moose test which puts big requirements on the ESP and AWD systems in the car.

The following section contains pre-lock tests. Since the AWD system is of the on-demand type, there can be a noticeable feeling in the vehicle when the AWD system engages. This can especially be felt during very slippery conditions. The pre-lock algorithm attempts to prevent this feeling during take-off by engaging the AWD system before the vehicle has set off. This also ensures that the vehicle has a stable take-off. The algorithm determines the appropriate action through several different signals and these tests verify that the control algorithm behaves correctly.

A continuation of the pre-lock algorithm is the slip controller algorithm and its specific tests. The slip controller is activated when the individual wheel speeds have a difference greater than the tolerated limit. This difference could occur during several different scenarios. A typical scenario is hard acceleration during slippery conditions or for example when the accelerator pedal is completely released and the engine decelerates the driving wheels.

The final section of the CSW test suite contains the customer specific test cases. There is a need for customer specific tests since BW-PDS develops for several different driveline configurations and for several different manufacturers where each manufacturer has different ways of determining the behaviour and overall safety of the vehicle.

1.2.2 Real & dynamic testing

The product is tested on an actual track to finalize the development cycle and fully determine that the product delivers per its specifications. This is the only chance to see how the product reacts to a dynamic driving environment. BorgWarner PDS has different tracks for testing the vehicle with the product. They are located in the south and northern part of Sweden. The northern track is in Arjeplog and enables full dynamic testing on ice tracks. Figure 6 on the next page showcases some of the ice tracks located outside of Arjeplog, Sweden.

Figure 6 Ice tracks located outside of the northern town of Arjeplog [7].

The cold snowy climate of northern Sweden provides a harsh testing environment for the vehicle. The manufacturers get a chance to test the dynamic driving capabilities of their product as well as test how it behaves in the colder climate. There are currently several different manufacturers testing their products in Arjeplog.

Figure 7 Ljungbyhed test track and runway [8].

The track in Ljungbyhed is located about 47 km from the PDS facility in Landskrona. It provides testing on asphalt. Figure 7 above showcases an overview of the Ljungbyhed facility.

These tracks are only some of the tracks used for testing the products. The car manufacturers also have private tracks across the world where there is also extensive testing of the different products. The private tracks are often used since shipping a vehicle to the northern part of Sweden from e.g. China is a very expensive and time-consuming process. Vehicle manufacturers that are testing on such tracks test how the entire vehicle performs and are not necessarily focused on specifically the AWD performance.

1.3 Main assignment

The current CSW testing at the test department is performed either via a panel in CANoe where input values sent to the ECU are set static or through test cases that set variables static. The output from the ECU is then monitored and evaluated to determine if the driving characteristics of the vehicle are as expected. The main focus of the current CSW tests are to test that the product satisfies the requirements set by the development team; these requirements are then cross-referenced with the test results by the test team. Using static input values for vehicle signals can cause some discrepancies between the requirements and how the products would behave when doing live testing. An integrated vehicle model could give a larger insight into how the torque control manifests in a vehicle and thus preventing products passing CSW tests despite not working correctly. The live testing provides a lot of information on how the vehicle actually performs with the product. These tests provide a larger variety of events that can happen such as snow hitting the product which cools it. These tests are unfortunately very time consuming and require extensive analysis before conclusions can be drawn. By integrating a vehicle model into CANoe and extending the testing environment a greater number of events can be tested and repeated in the exact same way thus providing a more stable test environment than driving in the real world. This would then later be confirmed by live testing thus reducing overall cost if faults are found before live testing.

The purpose of this work was also to provide deeper knowledge and experience with integration between CANoe and Simulink. Furthermore, its purpose was to try and develop and integrate an existing vehicle model further into CANoe. Adding a vehicle model to current testing environment could provide the testing process with more extensive knowledge about how dynamic driving scenarios are controlled and how the vehicle responds to different scenarios. This in turn could give the test department greater flexibility and a more powerful testing environment. Some of the questions that this work could provide answers for are:

- Can you integrate the vehicle model from Simulink into CANoe?
- If yes, can you perform more extensive testing?
- If yes, can you configure the vehicle model to be an independent testing module that can be integrated into any CANoe configuration supplied by a vehicle manufacturer?
- How does the vehicle model perform in a CANoe environment?
- What improvements can be made to the existing model?
- How does the implementation benefit the overall testing procedure and environment?

There was not a clear idea of the final product when the work was started. The purpose was instead to continuously evaluate and determine how far the work could progress during the time period of 20 weeks. There was also an uncertainty on how far this work could progress with respect to integration into the existing testing environment.

1.4 Related work

The documentation for integration between Simulink and CANoe is extensive and similar work has been performed by other researchers [9]. There has not been any similar research performed at BorgWarner but there is however a department that has several different vehicle models created in Simulink which they use to analyse dynamic vehicle behaviour. The vehicle model used in this work was created in 2014 and has been used for some simulations but as of 2018, it is not used in any major work and there has not been a vehicle model used in the testing process at the software testing department.

1.5 Outline of the report

This report consists of 8 chapters and are as follows: Chapter 1 handles the introduction with generic information about BW-PDS and how the testing is constructed and performed. Chapter 1 also explains the main assignment. Chapter 2 explains the fundamental information about the work from both a hardware and software perspective. Furthermore, Chapter 3 explains the equipment that was used to accomplish the assignment and what function it has in the testing procedure. Chapter 4 describes how some parts of the main assignment were achieved and how the work progressed.

Chapter 5 states how the implementation of the vehicle model went and what it resulted in during this work and how the vehicle model and test suite compare to the previous testing procedure. Chapter 6 interprets the results from the new tests that were created and discusses how they were useful in progressing further. And then finally Chapter 7 aims to tie the work together with a conclusion of the entire work. Chapter 8 discusses different areas of the vehicle model and this work that could be progressed further. Chapter 9 contains the bibliography and four appendixes are located at the end of the report.

2. Background

This chapter aims to provide the background of the work and to add context to how this work was performed and what it is based around. This chapter is divided into two main sub-chapters, chapter 2.1 about software and chapter 2.2 about hardware. The hardware used in the work is described and briefly discussed with the different possibilities it provided for the testing process. The hardware used in this work has no major deviation from a standard testing environment to ensure that this work could adapt to another project. In chapter 2.1 there is an extensive explanation of the underlying software that enables the communication between the software and hardware and thus enables the development of this work. Chapter 2.2 handles how the test hardware is set up and how it communicates.

2.1 Software

2.1.1 CAN

CAN is a communication protocol for microcontrollers that was developed and released by Robert Bosch GmbH in 1986 with the purpose of simplifying and improving communication for automotive applications [11]. Today, CAN is not only used in the automotive industry but in several other industries such as medicine and industrial automation. This design made it possible to reduce wiring in vehicle to just two wires for communication between different ECU's in the vehicle namely, CAN Hi and CAN lo. This was a crucial step since there can be upwards of 100 or more different ECUs in a modern vehicle. There has been further development by Bosch and in 2012, CAN with flexible data-rate, CAN FD, was released. This enables faster and more robust communication when compared to the older version.
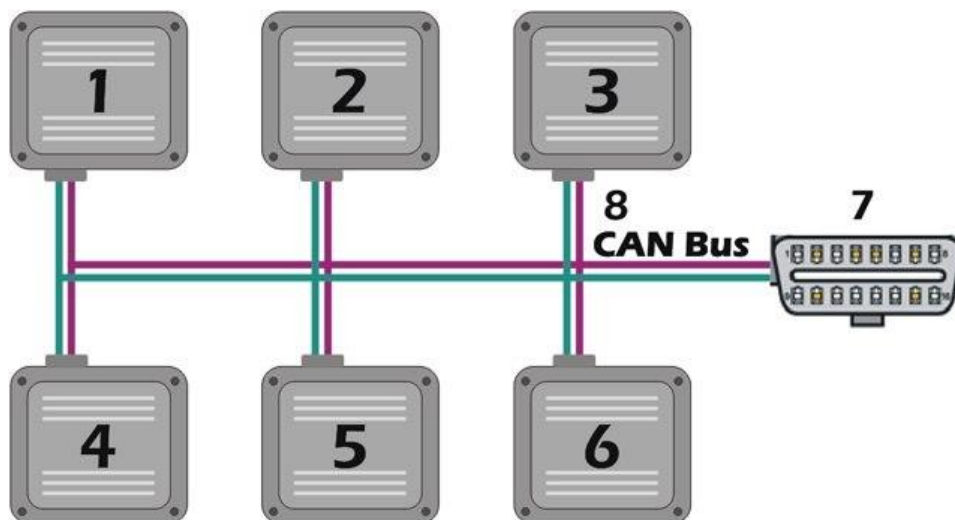
Figure 8 CANBUS Topology [11].

The physical connection between different nodes in the system as shown in Figure 8 has as described before just two wires, CAN High and CAN Low. The nodes on the system are connected to these wires in a bus network and each end is terminated by a 120 Ω resistor. Each node can consist of an ECU controlling the engine, gearbox or traction control. The signals transmitted through these wires are differential where the signal is transferred in two separate wires (CAN H / CAN L) and is compared by the receiving node. There is a transceiver on each CAN-node in the network which compares the transmitted signal to a reference ground. The maximum transmission speed is approximately 1 Mbit/s when the cable length is less than about 40 meters. A reduction in transmission speed will

occur when exceeding this length as well as a risk of faulty transmissions. There is a possibility to extend the cable length by reducing the speed but this is not often possible which is why an alternative type of communication protocol would be preferable in these scenarios.

2.1.2 CANoe by Vector

CANoe is a software test development tool developed and sold by Vector Informatik GmbH. CANoe was first released in 1996 and has since become one of the biggest pieces of software used in automotive testing. Vector provides both hardware and software and the license to execute the software is coupled together with hardware components. The software can be used on all types of vehicles and is also used in machines in medicine and aeroplanes. CANoe has support for several different communication protocols such as CAN, LIN, FlexRay and Ethernet. Vector has developed a programming language which is used in both the hardware and software. This language is called CAPL and has similarities with Java, C and Python [12]. CAPL is used for several functions and a more extensive explanation can be found below.

CANoe has adopted a matching design language as used in other Microsoft applications such as Microsoft Word and Excel, which gives a uniform design language across several applications and thus a simple and intuitive interface even for new users.

2.1. 3 Vector CAPL Browser and the CAPL language

The Vector CAPL Browser is a tool supplied together with CANoe. It is used to write code which is then used by CANoe in the testing process. The code written in the browser can for instance be used to output a report of the activities from the test case or control some parts of the testing in CANoe. The browser has many similarities with other integrated development environments (IDE) and compiles the CAPL code before CANoe can use it. It was the primary tool for constructing tests before vTESTStudio was created. It was used in this work to adapt and configure older parts of the CANoe configuration that was created when the configuration was used in development.

CAPL is easy to use if one is familiar with the mentioned programming languages but provides additional features that are useful when working toward an ECU and communicating over CAN.

2.1.4 vTESTStudio

vTESTStudio is the newer work environment for developing test for CANoe configurations. The software development part of this thesis has been constructed in vTESTStudio, MATLAB/Simulink and CAPL Browser. vTESTStudio provides a complete environment for creating and structuring tests and the main advantage over CAPL Browser is a better way of displaying the test sequence structure. vTESTStudio creates a test unit executable that can be easily imported into a new project.

The test environment is structured by a. vtt file which contains the tree structure displayed in Figure 9 below. This gives an overview of what test cases are active in the test module and which functions it implements. This is where the current CSW together with new cases were structured in the test module that was created in this work.
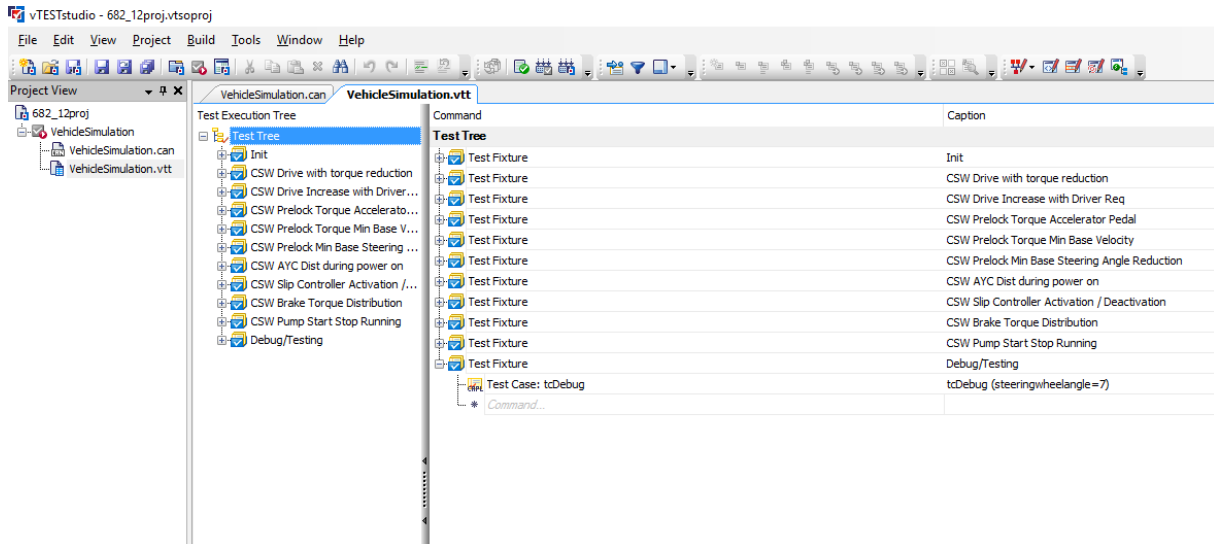
Figure 9 vTESTStudio Test Structure.

Tests in vTESTStudio are also written in CAPL and the IDE part of vTESTStudio is very comparable to the CAPL Browser. There are however greater possibilities in vTESTStudio. The "VehicleModel" test unit in Figure 9 above contains the structure file .vtt and the .can file contains all the test cases. The user is however able to include other files in the project. The files could consist of parameter files where test cases retrieve parameters to use or other files that define how the tests should be configured.

2.1.5 MATLAB/Simulink

MATLAB is a software program and programming language developed and sold by Mathworks. The first edition of MATLAB was released 1984. It has since then been updated heavily and is today used by a large number of companies and universities. MATLAB can calculate advanced numerical problems and is used for several different purposes and has a large number of add-on programs. These add-ons provide additional features which are often specialized in a certain area. One of the add-on programs sold with MATLAB is Simulink.

Simulink is a graphical programming tool sold as an add-on to MATLAB. Simulink is a model-based design add-on and is often used in control theory and digital signal processing. By using model-based design in conjunction with the computing power of MATLAB, a powerful system can be created that retains the ability to easily overview different parts of it. Simulink can communicate with several different external software and programming languages.

CANoe has since version 7.5 had support for Simulink models. For this support to work MATLAB/Simulink must generate code which is then used by CANoe. This support is achieved using MEX-files. MEX file contains a wrapper function which is created to allow MATLAB data types to be passed and returned between different programming languages.
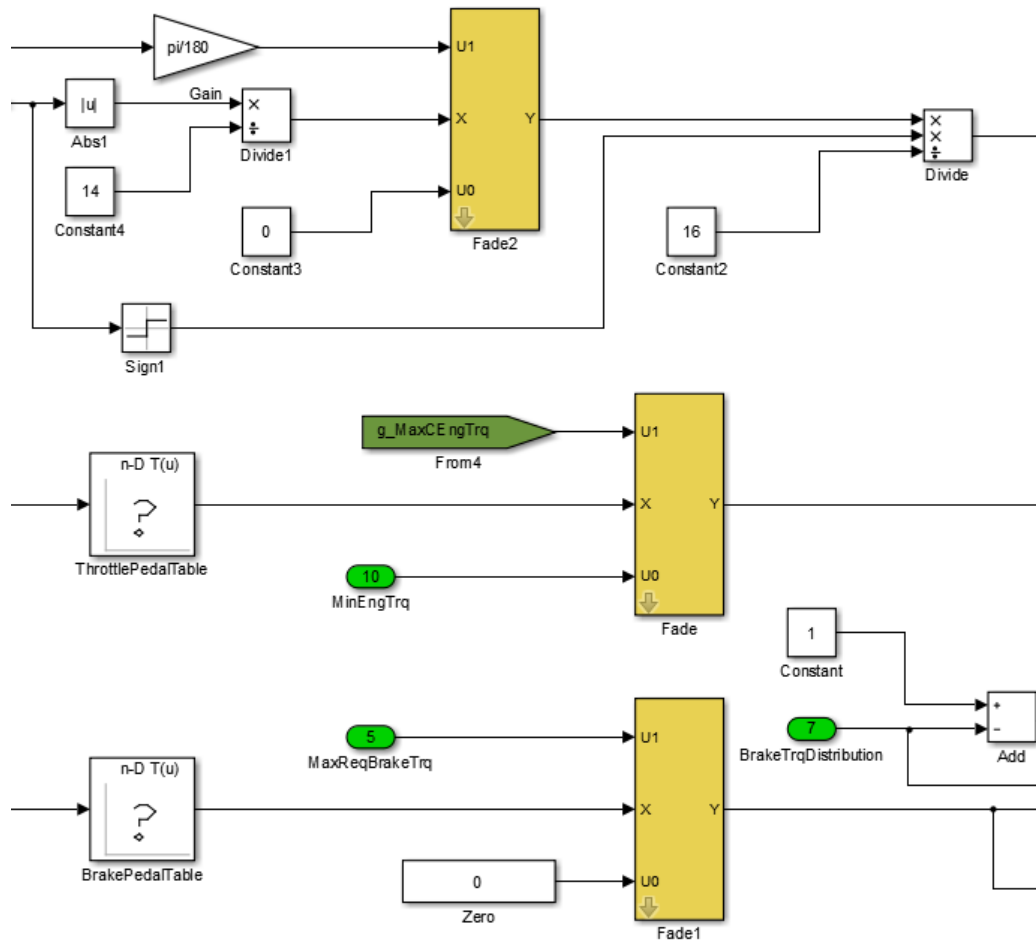
Figure 10 Model Based Design. Driver interface from the vehicle model.

Figure 10 above is an example of the driver interface from the vehicle model implemented in MATLAB/Simulink using model-based design. This section translates the different driver inputs such as accelerator and brake pedal position to required engine torque and required brake torque. The main advantage in Simulink is the ability to create complex controllers and models but still retain a simplistic overview and keep the understanding of what is happening during the execution. By using subsystems and keeping each subsystem simple, good knowledge can be retained about the overall system. The model is separated into several sub-systems corresponding to the different parts of the vehicle such as tires, engine and AWD-system. These subsystems are modelled in the tree diagram in Appendix C.

The tree diagram in Appendix C gives a simple overview of how the vehicle model is connected in Simulink. It does not contain how each input and output is connected and was mainly used to give understanding to how the different vehicle model blocks are related. This in turn simplified the development process and integration into CANoe.

2.1.6 Vehicle model

The vehicle model used in this work was developed in house at BorgWarner for software development. Development began in 2014 and the model has been used for a variety of reasons. The vehicle model consists of both static and dynamic inputs and outputs. The static inputs are

21

comprised of information about the vehicle and surrounding area such as vehicle mass, friction coefficients and wheelbase length. The dynamic input consists of driver inputs such as throttle position, steering angle and brake pedal position. The model then proceeds to calculate the required torque to either the front or rear wheels to retain stability. This in turn gives a resulting wheel speed and acceleration of the vehicle. The vehicle model has currently support for one of the products developed at BW-PDS, the rear hang on limited slip coupling. This is the "FWD with AWD-capabilities" configuration explained in 1.1.1 FWD with AWD-capabilities. This is the most produced coupling and this configuration has existed the longest in Landskrona. Each variable is then fed through output blocks specific for Simulink models before it is processed by CANoe and lastly sent to the connected ECU over CAN or the other supported communication protocols.
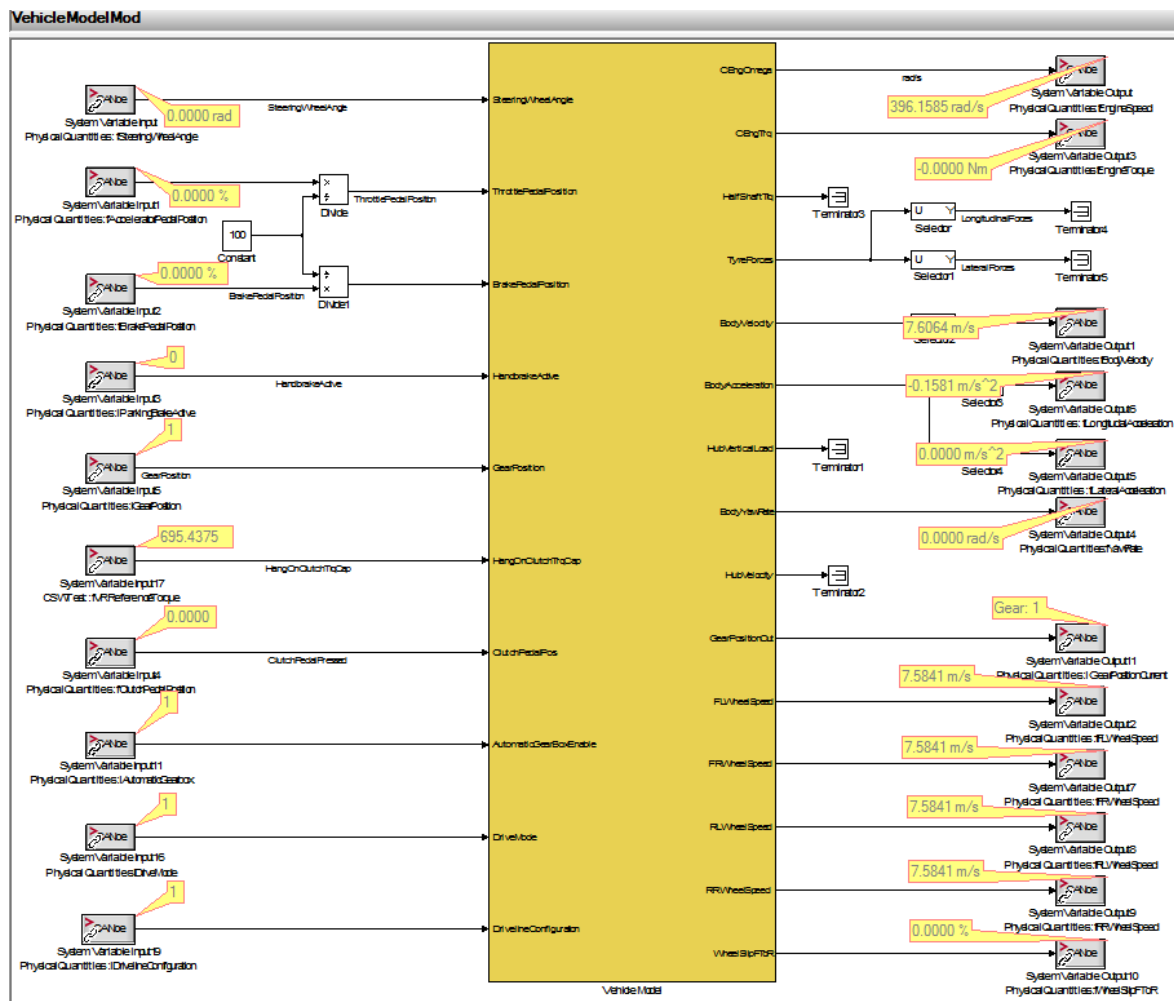
Figure 11 Vehicle model overview in CANoe with Simulink implemented.

Figure 11 above is the main page for the vehicle model and it is the page one observes when it is used in CANoe in conjunction with the vehicle control panel explained in 5.2.1 CANoe Vehicle Control. It contains all the necessary inputs and outputs which change dynamically.

2.1.7 MinGW Add-on for MATLAB

MinGW is a free and open source software tool created for constructing Microsoft Windows applications. MinGW contains several different core components such as GCC and ports of the GNU toolchain. Its main functionality is to port Unix software to Windows. The add-on to MATLAB enables

MATLAB/Simulink to communicate with software outside of the MATLAB environment. MinGW is essential for this work since it enables a communication layer between MATLAB/Simulink and CANoe and gives the user the possibility to access CANoe signals and variables as well as MATLAB/Simulink variables in CANoe.

2.2.8 MQB CANoe

The first vehicle test environments that was used in this work was a Volkswagen based configuration for the Volkswagen MQB platform. The MQB platform is a platform developed and used by Volkswagen for over 20 different models. The models range from the smaller Volkswagen Polo Mk6 and Audi TT Mk3 up to the larger Volkswagen Tiguan Mk2 and the Volkswagen Atlas/Teramont. There is consequently a very wide array of vehicles for where the vehicle model is applicable from just the MQB configuration. The MQB project has been in development for several years and was at the start of the project considered a legacy project. This ensured that the software on the ECU was responding correctly to the different inputs.

2.2.9 Volvo generation VI for the scalable product architecture platform

The second vehicle test environment used in this work was the gen VI (6) ECU for the SPA platform that is currently in development at BorgWarner. This is a platform developed by Volvo for their larger models. The SPA platform is currently used for the following models: XC90, S90, V90, V90 XC, XC60, S60, V60 and the Polestar 1. This test environment provided additional reference and evaluation to the vehicle model and was used to verify that the vehicle model works on different ECUs and different test environments.

2.2 Hardware

A test setup at TVR-SW consists of several different components. These subsections give an explanation to each one that can be or was used at TVR-SW.

2.2.1 Electronic control unit

The ECU or Electronic Control Unit is an embedded computer system which consists of several inputs and outputs. Its main purpose is to control parts of the electrical system in a vehicle. The control is achieved through gathering information from the multitude of sensors and setting the appropriate outputs.

2.2.2 Test rig

The ECU is connected to a test rig supplied by Vector Informatik GmbH. Their products come in different shapes and sizes depending on the testing requirements and one of the latest versions of the smaller testing rigs is the VN8914 which was used in this project. It is based on Windows 7 embedded.

Figure 12 VN-systems used in testing [10].

Figure 12 on the previous page is a VN-system which is a compact version of the different hardware products supplied by Vector. Both the VN and the VT system is used at TVR-SW. The VN-system focuses on testing software related error and software communication. It lacks some of the hardware for testing hardware related faults and is better suited for software diagnostics

Figure 13 VT-system used in testing.

The VT system in Figure 13 is a high-performance modular test system for ECU testing. It is a physically much larger hardware configuration than the VN-system. The VT enables added functionality such as a complete on-board Windows 7 based OS. The user can connect to the desktop to investigate errors related to the CANoe configuration. It also has the ability to run tests such as testing hardware related errors that draw a high amount of current and require more precision since it is equipped with a more capable power supply. This system is more suited for testing these different hardware related errors such as short circuits and open circuits in the different components. These tests draw a high amount of current and it is therefore essential with a more capable power supply.

2.2.3 Test setup
The VN/VT system is connected to the ECU via CANBUS or FlexRay. The VN/VT system communicates with the PC over either USB or Ethernet and provides the PC with information about the different signals and variables that the ECU is processing. These VN/VT systems emulate a complete vehicle communications network and can be configured to contain exactly the same nodes as in the vehicle. These nodes can for instance be the engine ECU, gearbox ECU, ABS/ESP ECU and so forth. This ensures that the ECU behaves as close as possible to the behaviour in the actual vehicle. A more extensive explanation about the communication is given in 4. Software Implementation.

3. Hardware Equipment

This chapter aims to provide a detailed explanation of the hardware tools that were used in the performed work. The hardware in this work was used to provide testing with a real product to evaluate and diagnose the implementation.

The standard MATLAB license at BorgWarner does not support the modules described in chapter 2.2 and thus access to a remote computer with another type of license was given. This computer was used to generate the code that would later be imported into the CANoe environment. This combined with the HIL-mode enabled the work to progress since no MATLAB-license was required on the local computer for running tests with the vehicle model.

The hardware used in the work at TVR-SW is very comparable to the hardware used for regular testing in the department. The hardware used by the department is mostly unchanged regardless of the ECU that is being tested. The software products provided by Vector are coupled via licenses to different types of hardware products.

3.1 Testing rig

The testing rig used in the work consisted of a Vector VN8914 paired to a power supply from Delta Elektronika. The power supply communicates with an analogue input/output board to the Vector module whereas the Vector module communicates via Ethernet to the PC. The test rig used in this work is showcased in Figure 14.
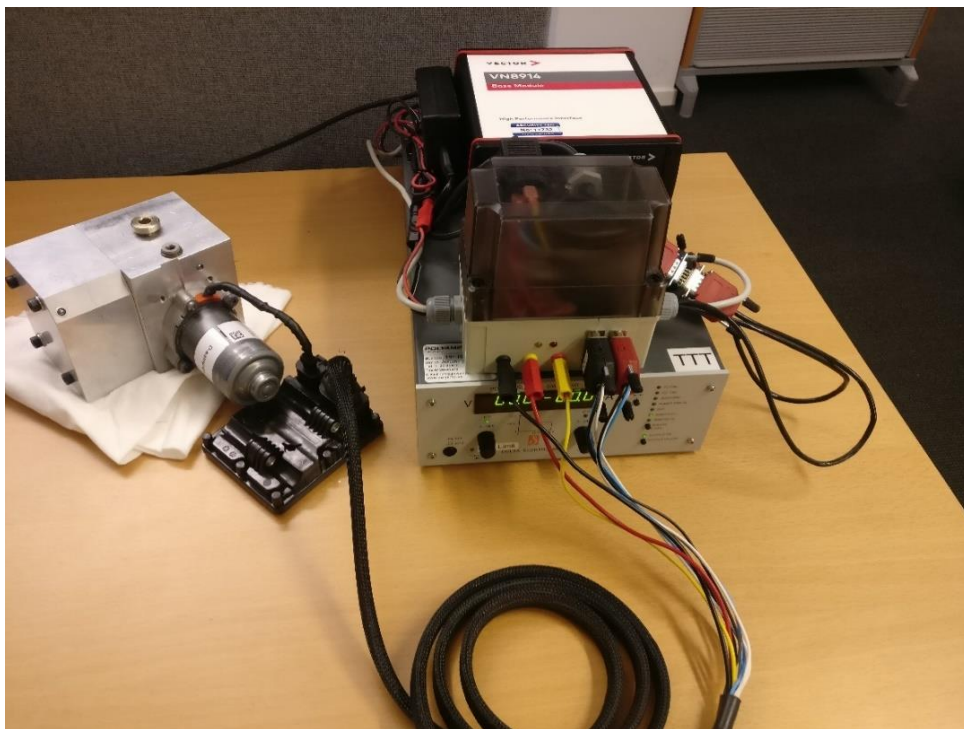
Figure 14 Testing rig at TVR-SW. To the left is the pump block for circulating oil with the pump connected which is in turn connected to ECU.

The Vector hardware was connected to a generation 5 MQB ECU that was connected to the hydraulic actuator which in turn was mounted to a pump block. The purpose of the pump block is to let the hydraulic actuator pump oil in the block and build pressure similarly to a real AWD/FXD-product, this can then be monitored with a pressure sensor which is often used during testing to ensure that the

coupling is behaving correctly. This sensor is not included in the final product and consequently there is no way of measuring the pressure in the coupling in a production vehicle.

The setup used in this work is very comparable to the test setup used in the test process and it enabled a complete hardware testing environment where both hardware and software feedback from the ECU could be interpreted. The hardware feedback consisted of the audible noise the pump makes when running. The software feedback consisted of the signals and variables set by the ECU and provided by the VN-system.

3.2 Gen V & Gen VI ECU – Electronic Control Unit

The ECU's used in this work consisted of both a generation V and VI ECU used in the AWD-coupling. The generation V ECU was based for VW MQB development and thus the ECU was used together with an MQB CANoe configuration. The generation VI ECU was based on a Volvo SPA Gen VI ECU and was used together with a Volvo configuration. The ECU that is used is independent of the integrated vehicle model and it is up to the tester which ECU and testing environment that is to be used with the vehicle model.

Figure 15 Generation 5.

Figure 15 above is the generation V ECU that was used in the work. It is mounted on the side of the AWD-coupling with a larger connector which supplies the ECU with power and communication and a smaller connector for driving the electro hydraulic actuator. The development of the ECU used at BorgWarner PDS is currently in its sixth generation. Each generation enables new functionality and benefits as BW continues to improve its products. The current development and soon to be released generation VI will greatly reduce the overall size of the ECU as well as implementing a new and improved actuator. This will in turn enable easier implementation into newer projects and better portability between different vehicle manufacturers.

Figure 16 Left: Gen VI ECU. Right: Generation 5 ECU.

The gen VI ECU is as Figure 16 shows a lot smaller than its predecessor. This enables the ECU to be mounted in a more convenient location where it is physically mounted on the hydraulic actuator itself thus reducing the need for a cable to the hydraulic actuator and eliminating cable related errors. The ECU has therefore only one large connector which supplies the ECU with power and communication to the other nodes in the vehicle. This generation is currently being rolled out to new projects and will soon take over as the primary development platform for torque transfer applications at BorgWarner PDS.

4. Software Implementation

4.1 Integration between CANoe and Simulink

The integration between CANoe and Simulink requires some steps before it can perform as intended.

There are some requirements from CANoe for the integration to work, it requires the following product versions or newer:

- CANoe 7.5
- MATLAB R2012b
- Visual C++ 8.0

MATLAB requires the following modules to enable communication:

- CANoe Integration Package
- MinGW for MATLAB
- Simulink Coder

The CANoe Integration package provides all the additional Simulink blocks that are needed to implement CANoe signals into the existing Simulink model. MinGW and the Simulink coder are both fundamental for MATLAB/Simulink to be able to compile the model and create the necessary C/C++ files that CANoe then loads into the testing environment.

The CANoe – Simulink integration has three different execution modes:

1. Offline Mode, Running a simulation in MATLAB/Simulink.

In this mode, MATLAB/Simulink is the simulation master and CANoe is the slave and this mode is best suited for non-real-time simulation. The simulation is entirely controlled by MATLAB/Simulink environment and is useful for early design stages. Communication between MATLAB/Simulink and CANoe takes place over Microsoft DCOM.

2. Synchronized mode.

This mode shares several features with offline mode with the exception that MATLAB/Simulink and CANoe now have a synchronized time base. This simulation runs almost in real-time and typical resolution is about 1 millisecond if the model is not too complex. This mode depends on that MATLAB/Simulink computes the model faster than the real-time resolution. This mode is best suited for testing on real CAN hardware devices but still retain the debugging features of MATLAB/Simulink.

3. Hardware-In-The-Loop (HIL), running a simulation in the CANoe execution environment.
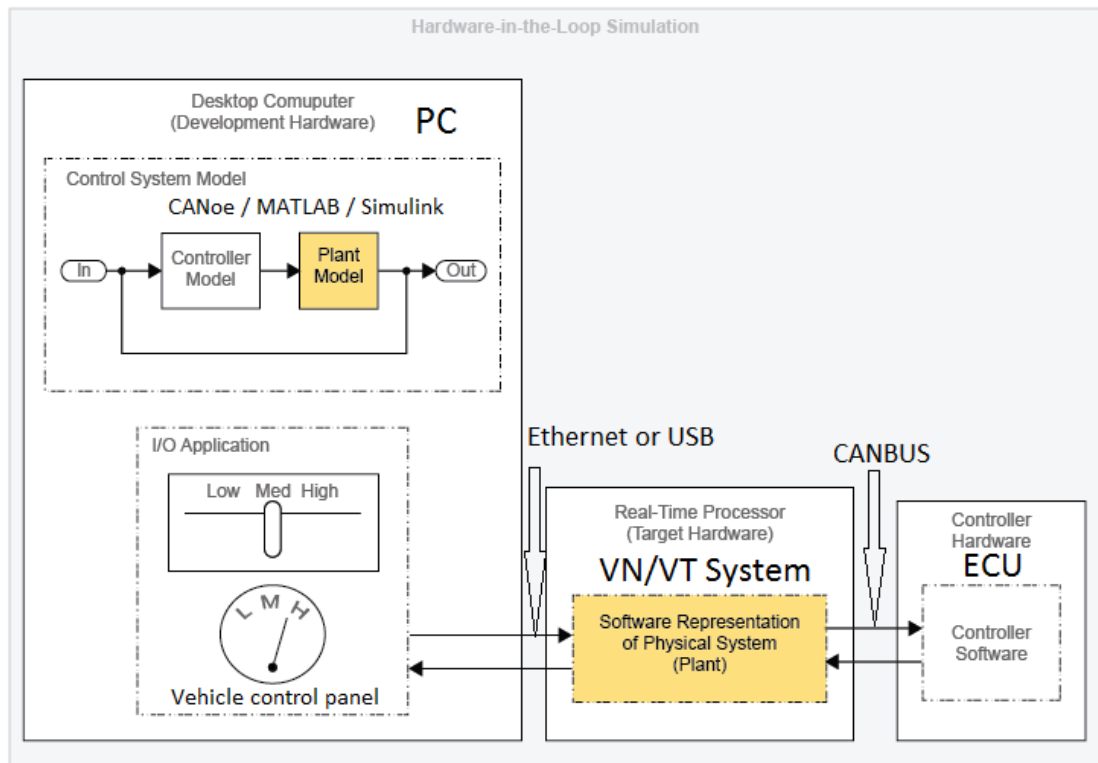

Figure 17 HIL mode [13].

Figure 17 above is how the real-time simulation mode was configured in this work. It provides real hardware access and optimized runtime behaviour. In this mode MATLAB/Simulink is fully integrated into the CANoe environment on the PC which in turn loads the environment into the VN/VT system to perform simulations. The software representation on the VN/VT System is in this case an entire CAN-BUS network which consists of the different nodes in the vehicle.

The MATLAB/Simulink model can be run in its entirety in CANoe on the VN/VT System and Figure 17 is how CANoe communicates with the VN/VT System and subsequently the ECU. The I/O application in this work is explained in 5.2.1 CANoe Vehicle Control. CANoe imports C-code generated by MATLAB/Simulink to be able to run the model independently of MATLAB/Simulink. This is done through the MATLAB/Simulink integration package and Simulink Real-Time Workshop which were explained earlier in this chapter.

The HIL-mode is the mode used in this work since it provides the best real-time performance and is required since MATLAB/Simulink is not a part of the testing procedure and as such there is no possibility to integrate it in another way. Another reason is the possibility to test on real hardware in real-time which is only supported in the HIL-mode. This mode also supports several ECUs to be run simultaneously.

When communication between CANoe and Simulink was established, a smaller test model was created in Simulink. Soon after verifying that it communicated as it should, the work progressed into integration of the existing vehicle model.

4.2 Integration of the vehicle model

For this work, HIL-mode was chosen for integrating the vehicle model since this mode only requires a single CANoe license for running the model once code has been generated by MATLAB. When CANoe has been configured to accept Simulink models, the integration of the vehicle model is achieved by adding a network node into the CANoe CAN-network. Once added, a Simulink model can be configured and the implementation in CANoe is completed.

This simple process enables the vehicle model to be integrated into a large complex existing CANoe configuration without having to go through complex instructions which would delay the overall testing time line.

The process in MATLAB is also simplified to reduce overall implementation time. The code generation takes approximately 0.5-2 minutes depending on size of the model and the speed of the CPU. It is important to have a consistent model with respect to sample time and definitions to reduce Simulink model-introduced errors into CANoe. When the model is configured correctly it is a simple process to update the model with changes and generate the required code. The vehicle model is configured to be easily integrated into CANoe with respect to data types and simulation parameters. This is further explained in Chapter 5.

4.3 Test suite

A test suite was needed to handle all the tests that are related to the vehicle model. The test suite was mainly created in vTESTStudio with some configuration needed with the help of the CAPL Browser. The test suite provides the new tests that are coupled with the vehicle model and the CAPL Browser is needed to handle the small adjustments that are needed in a new configuration.

4.4 Assessment of development

The work was evaluated each week. This evaluation consisted of a meeting to ensure that the work was progressing in the desired direction. The vehicle model implementation was continuously compared to known test results and to the results when running in Simulink to ensure that no errors were introduced or kept when developing further. There were also meetings with other departments to distinguish if the vehicle model was behaving correctly.

There was also a short written summary of the work conducted each week which was sent to the tutor and examiner at LTH to keep them updated on what was happening and how the work was progressing.

4.5 Version control

The vehicle model and the associated files were integrated into the version control program that TVR-SW utilizes to provide access for the whole department and to provide easy access for new users that want to use the vehicle model in their project. The time spent to upgrade and correct the model for all users was therefore reduced greatly.

5. Results Of Implementation

The result of this work has met and answered the questions of the main assignment. But it did also discover new areas and features which were not originally thought of and was not written down in the main assignment that were stated in 1.3 Main assignment. This caused the work to expand into new sections that is explained in the following sections.

5.1 Primary assignment

These were the questions asked in Chapter 1. This section provides the answers for each question.

- Can you integrate the vehicle model from Simulink into CANoe?

Yes, the entire vehicle model was integrated into CANoe. It did not require any major design change. There were however quite extensive modifications to how the model inputs and outputs its values as well as new additional features.

- If yes, can you perform more extensive testing?

The vehicle model enables dynamic testing which is close to real world testing. There are many possibilities for the vehicle model. An example is comparing a vehicle model log to a real-world driving log during testing in Arjeplog. This is further explained in chapter 6.

- If yes, can you configure the vehicle model to be an independent testing module that can be integrated into any CANoe configuration supplied by a vehicle manufacturer?

Yes, an extensive testing module was created in vTESTStudio and implemented alongside the vehicle model in CANoe. This model uses two separate files. The larger one contains the majority of the functionality and test cases. The smaller one is unique to each project and contains all the project specific functions. By doing this, implementation time and configuration setup is kept to a minimum. The vehicle model contains two parameter files which is used in a project. It is separated into variables that are specific to the project and to the vehicle model itself, by separating the parameters the initial setup time is reduced as the project specific parameters are already gathered.

- How does the vehicle model perform in a CANoe environment?

The vehicle model runs without problem on the VN8914 hardware but there is a possibility that it will cause measurement overruns and test abortions when running on a slower test rig. This would occur if the test rig is unable to process the amount of incoming information and subsequently loses timing between the test rig and the ECU. One can observe the performance in the simulation performance tab of the vehicle control panel and determine if the step time of the CANoe configuration is exceeding normal behaviour. It is therefore suggested that the vehicle model is run on high performance testing rigs.

- What improvements can be made to the existing model?

There were several improvements and extensions to the vehicle model. They are explained later in this chapter. There were some features that were not implemented during this work, they are discussed in 8.1 Future work.

- How does the implementation benefit the overall testing procedure and environment?

It provides an additional reference point for CSW related testing. It also created new possibilities for testing how the ECU and coupling would behave in a real vehicle. This is further discussed in Chapter 6.

5.2 CANoe Implementation

5.2.1 CANoe Vehicle Control

An input panel was created in CANoe to be able to control the vehicle model manually as well as have direct feedback when running the vehicle model. This panel also enabled parametrization of both the dynamic and static variables used by the vehicle model. Appendix D contains the entire main page for the vehicle control panel. The following sections explain the different parts of the vehicle control panel.

The AWD Vehicle control panel in CANoe consists of the different inputs and outputs that are relevant to the user during testing. Each subsection below describes different parts of the panel. A complete overview of the vehicle model control panel can be observed in Appendix D.
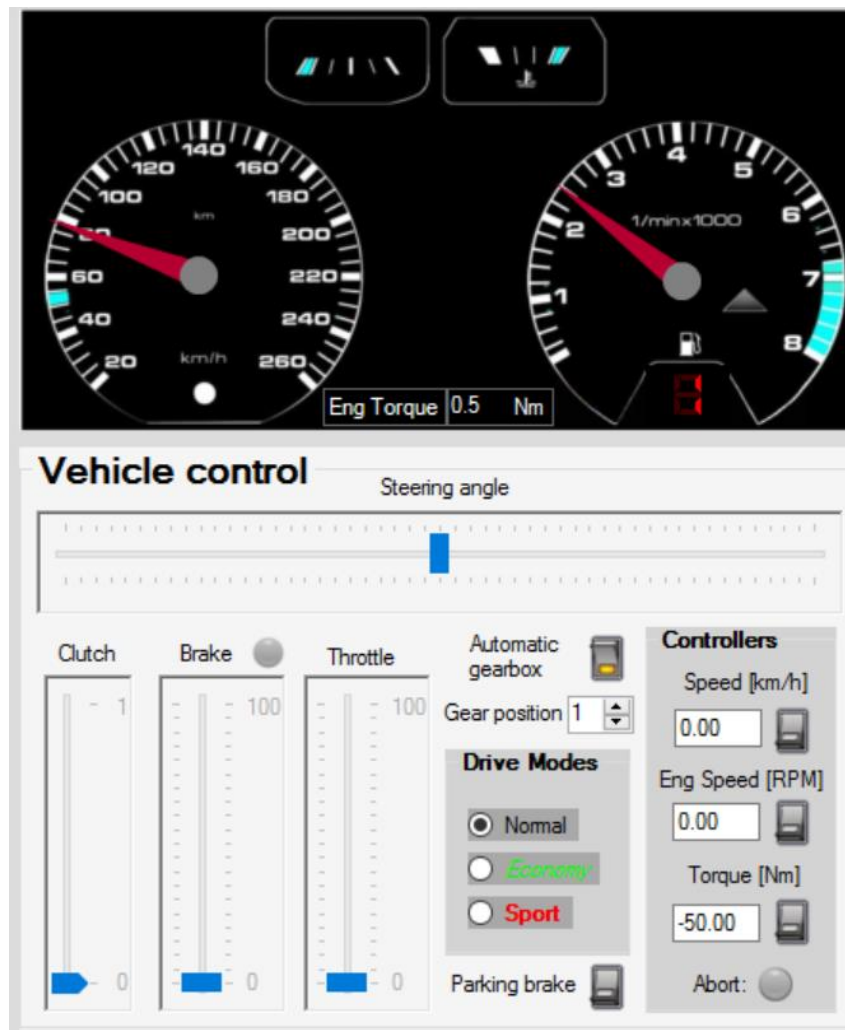

Figure 18 Vehicle control panel part 1.

5.2.1.1 Driver input

The driver inputs in Figure 18 consist of the same inputs as in a regular vehicle. Bottom left is sliders for the clutch, brake and throttle pedal position. Bottom left also contains a slider for the steering wheel angle. Together with these are switches for the automatic gearbox and parking brake as well as 3 different automatic gearbox drive modes for the user to choose from. These modes change when the gearbox switches gear during accelerating.

5.2.1.2 Controllers

There are also three different controllers together with the driver inputs in Figure 18. These can be used when the user wants to put the vehicle in a specific scenario. The controllers are enabled by inputting a value in the desired controller and activating the switch. By pressing abort at the bottom, control is regained by the user. These are useful when running the vehicle model in manual mode but the user needs to observe parameters other than vehicle speed, engine rpm or engine torque.
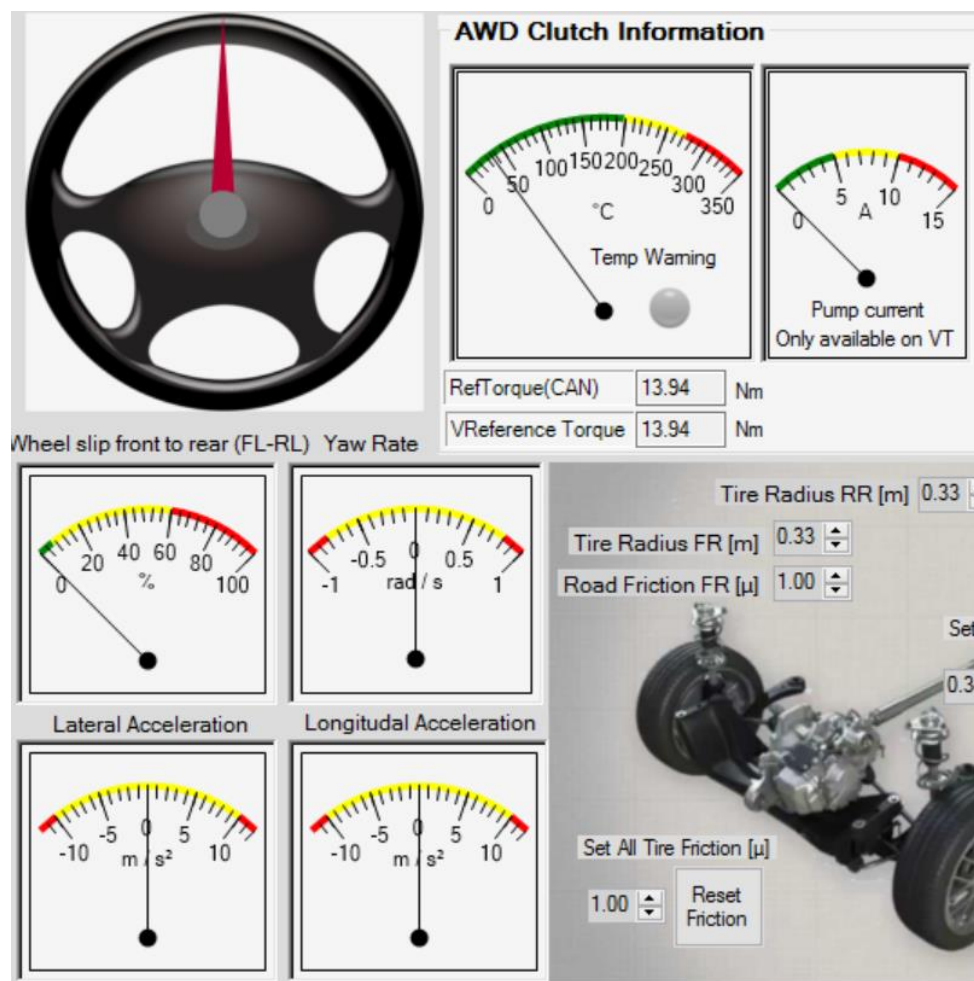

Figure 19 Vehicle control panel part 2.

5.2.1.3 Vehicle dynamic output

In the top left corner of the panel in Figure 18 is the dashboard, which is used for feedback from the vehicle model. It displays the vehicle speed, engine speed, current gear, current engine torque and will also tell you when it is time to shift up. In Figure 19 is a steering wheel which shows the current steering wheel angle. Below the steering wheel are four different meters for displaying wheel slip front to rear, yaw rate, lateral acceleration and longitudinal acceleration. They can be observed to

see if the vehicle simulation is doing something that is not expected by the tester. This could for instance be if the vehicle is supposed to be accelerating forwards but the longitudinal acceleration meter shows a negative value hence the vehicle is accelerating backwards. To the right of the steering wheel is a temperature meter which is connected to the ECUs internal temperature estimation of the friction discs. Since temperature is critical for the longevity of the product it is coupled with a warning light and when exceeding the limit the ECU will automatically turn off.

This window also displays the *RefTorque* and *VReference Torque.* These display the amount of torque the coupling is transferring and what the ECUs control software requests to transfer respectively. They are identical during normal operation but differ when the ECU wants to run a sequence such as venting the air out of the coupling or when it is put into manual control overriding the control software. Next to the temperature display is a display for the maximum current the hydraulic actuator and ECU is using at any given moment. This current measurement is only available on the VT-systems. This can easily be cross referenced to another signal in this area to ensure that the coupling is behaving correctly.
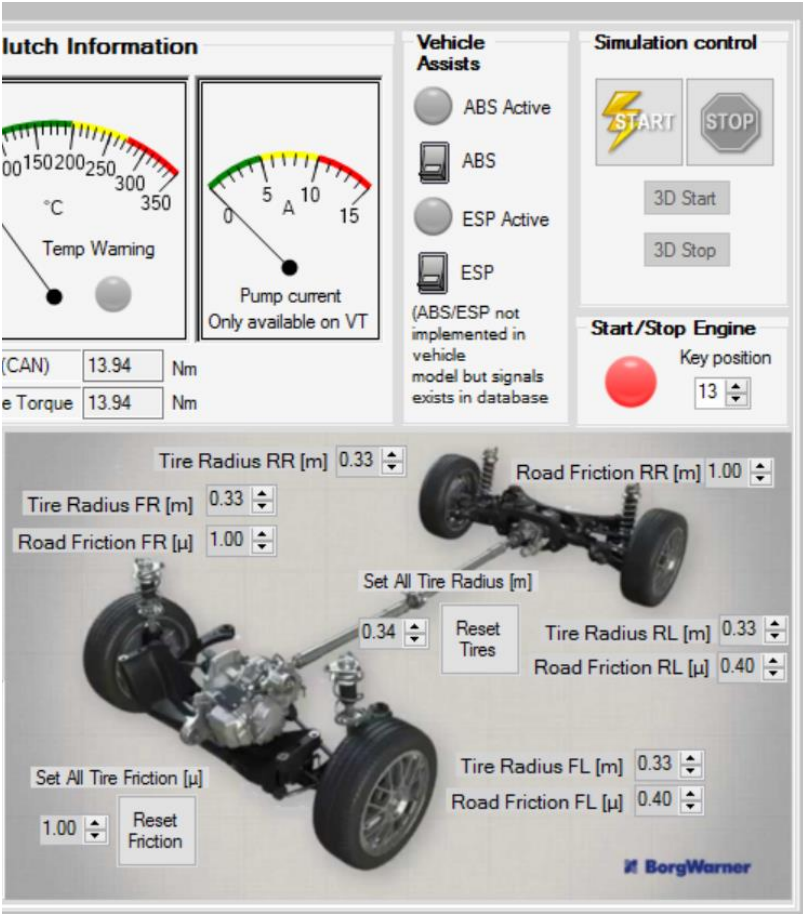

Figure 20 Vehicle control panel part 3.

5.2.1.4 Road/Tire control

In Figure 20 is the display for the different wheel radiuses and tyre frictions. This is placed at the same panel as the driver inputs instead of the vehicle parameters tab to enable the user the possibility to quickly change the tyre radius and/or the road friction and observe how the vehicle model and the ECU responds. Additionally, there are two input areas that can set all four wheels at

the same time, one for friction and one for tire radius. Next to these are two reset buttons to give the user the possibility to quickly reset the parameters to the ones given by the initialization.

5.2.1.5 Vehicle Assists and Simulation control

The vehicle model does not support the use of ABS or ESP control. There are however often signals present in the databases provided from the manufacturer that correspond to the outputs from the ABS and ESP ECU. This panel can manually activate these signals when needed. These signals can also be used during an automated test and observed on this panel when they are expected to activate. The tester must however be fully aware that these signals are not handled by the vehicle model. At the top right is the buttons for starting and stopping the simulation as well as starting and stopping the engine. It is also prepared for a 3D visualization but it was not implemented.

5.2.2 CANoe Vehicle Parameters

There are several important vehicle specific parameters implemented in the vehicle model. Some of these have the possibility to be changed easily by inputting a different value in the vehicle parameters tab. Some of these values are received from the parameter import, explained in section 4.3.9. The other parameters are defined by following a generic vehicle model. Each project is different with respect to what parameters can be imported into the vehicle model. It is required of the user to adapt this part to the current testing configuration.
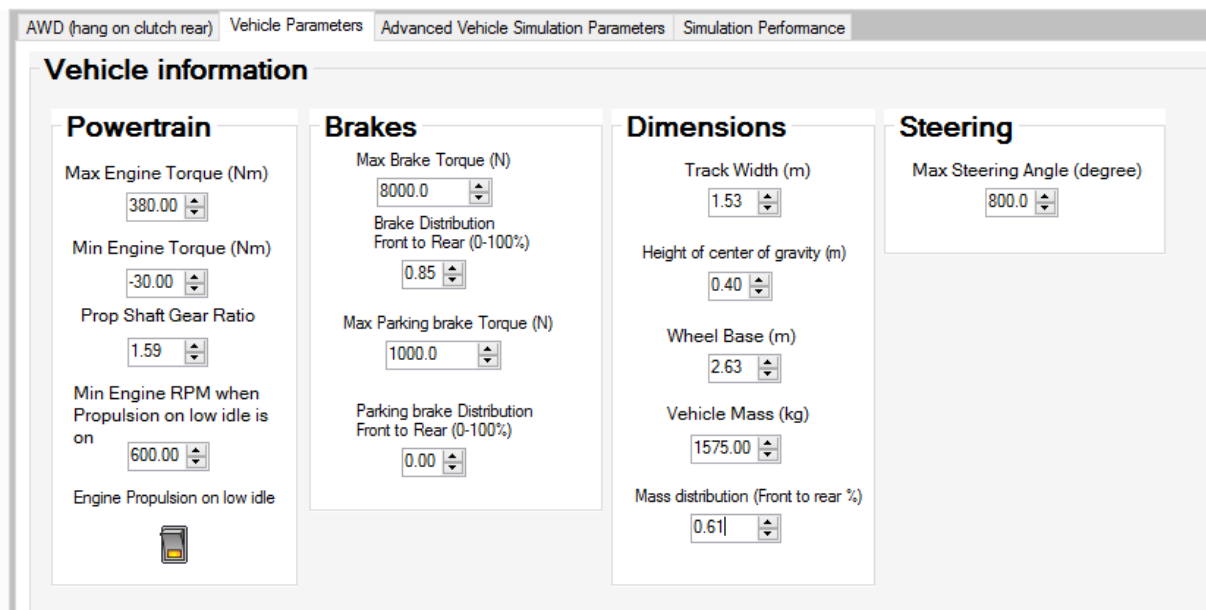

Figure 21 Vehicle Parameters.

Figure 21 above showcases how the vehicle parameter section of the vehicle control panel in CANoe is configured. The values correspond to a Volkswagen Golf R Mk 7 and are automatically adjusted when running the vehicle model test suite.

5.2.3 CANoe Vehicle Model Performance

There are several different ways of ensuring that the online simulation is behaving correctly and not executing too slowly. A fast way of checking that the vehicle model is consistent is by clicking the Simulation Performance tab and observing how fast the Simulink model is processed by CANoe. Figure 22 below contains the performance measurement that the user can observe in the simulation performance tab of the vehicle control panel.
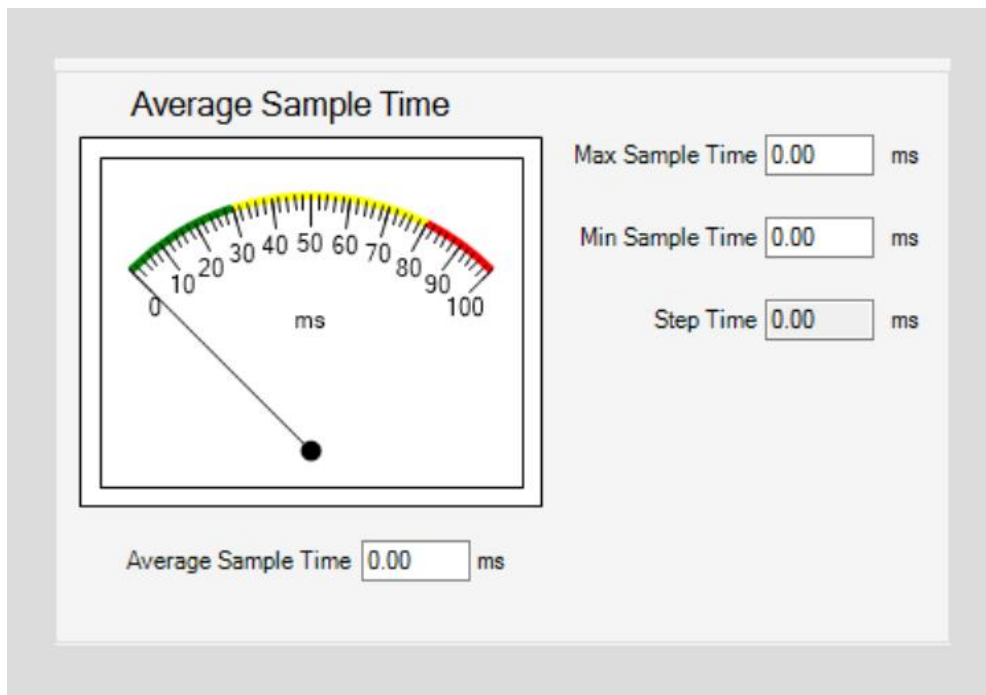
Figure 22 Simulation Performance.

5.3 Development of the vehicle model in vTESTStudio

One of the main assignments was to create an independent test module that could be attached to any generic testing environment be added as an extension to the present CSW tests. This part of the assignment took place in vTESTStudio where a test suite was created. The tests that were implemented from the present CSW tests required several new important functions for controlling the vehicle model. These are explained in the subsections below.

5.3.1 Vehicle speed controller

A vehicle speed controller was added to the vehicle model to be able to achieve the vehicle speeds that were requested by the tests. A PI-controller was chosen for the controller since the acceleration of a vehicle is a slow responding system and the PI-controller provides a short setup time. The controller parameters were estimated by user experience and adjusted more precisely after some testing. There was no constraint given to how quickly or slowly the controllers should reach their target and it would provide no additional information or feature to the tester if the controllers were remarkably quick to their target. Some additional properties were added such as different proportional and integral gains as a function of the desired speed. This ensures that the desired speed is reached in a consistent way. The controller controls the speed by adjusting the accelerator pedal position. To ensure that the controller is maintaining a stable speed when the test progresses to another step, a timer parameter was added to the controller design. When the controller is within 1 km/h of the desired speed, a timer starts and when it reaches the time supplied in the time parameter, the CPU stops running the controller and continues with the test.

The vehicle model has an idle speed of about 7 km/h in first gear which is due to the gear ratio in the gearbox of most vehicles and that the vehicle model utilizes an idle speed controller similar to an actual vehicle engine. A real combustion engine needs to maintain a certain engine speed to run continuously and the vehicle model has replicated this with the idle speed controller. Observe that

36

this function can be turned off with the button "Engine Propulsion on low idle" in Figure 21 Vehicle Parameters..

By turning the idle speed controller off the lowest engine speed is 0 and the vehicle can stop completely even though the engine is on. The idle speed controller puts a constraint on the control strategy used for speeds below idle speed. The controller will instead utilize the brakes to keep the vehicle model from accelerating. This enables the vehicle model to be used in tests where the vehicle needs to move very slowly forward. This also enables a way of testing how the vehicle model and ECU react when the car is being loaded because it is travelling at lower speed than the engine is trying to maintain. There is also a possibility to adjust the torque output of the engine which effectively removes the idle speed of the vehicle. If this is used, the vehicle speed controller uses the accelerator pedal as well during speed below the standard idle speed.

5.3.2 Engine speed controller

Similarly, to the speed controller, the engine speed controller controls the accelerator pedal position to maintain a specified engine speed. This controller is also a PI-controller but is much easier to setup since the engine responds very quickly to changes in the accelerator pedal position. The function is used for tests that respond to changes in the engine speed.

5.3.3 Engine torque controller

This controller is also similar to previous sections. This controller tries to achieve a desired engine torque in the current gear position by changing the accelerator pedal position. If the automatic gearbox is engaged, it will shift gear to try to fulfil the desired torque. This can be used in conjunction with the different test cases to setup the car in the desired scenario. There are several restrictions to this controller, the biggest one is there is a risk that the desired engine torque is impossible to fulfil There is also the possibility that the desired engine torque puts the vehicle into an entirely different scenario since the vehicle is accelerating/deaccelerating depending on conditions.

5.3.4 Steering angle ramp

This function takes a desired steering wheel angle as input and ramps the steering wheel angle in a smooth way to replicate real driving. The tester can also observe steering wheel angle at any given moment in the vehicle control panel.

5.3.5 Resetting the car

Since a lot of tests have a test start from a standstill a function was implemented to bring the car to a stop to be able to conduct another type of test in succession. This function puts the car in the same state as when the vehicle model is started by stopping the car, putting the gearbox into neutral and releasing all pedals once completed.

5.3.6 Wheel slip measurement

A new measurement was added to correlate with how the torque is transferred between the front and rear wheels. This measurement compares the front left wheel speed with the rear left wheel speed and outputs a ratio between 0 and 1 where 1 corresponds to having near zero rear wheel speed and normal front wheel speed or having near zero front wheel speed and normal rear wheel speed. A value of 0 corresponds to no slip between the front and rear wheel. This function is difficult to observe during the test but can be used for cross-reference if logged together graphically with other appropriate variables.

5.3.7 Driving surface

Real world vehicles travel across all types of surfaces. A function that can simulate different surfaces was therefore created. The function can set four different surface conditions: dry asphalt, wet asphalt, snow and ice. It achieves this by changing the friction of each individual wheel. There is also the option to set a low friction, such as ice, for each individual wheel.

5.3.8 Set wheel slip

This function was implemented to test how the ECU responds to different tyre size and accidents that can happen to the tyres when driving. The function requires two inputs, the specific wheel and the change for its radius. This was based on older tests that often change one wheel individually.

5.3.9 Vehicle model differentials

Originally the vehicle model distributed the torque evenly on the front wheels and the transferred torque to the rear wheels was also distributed evenly. This does not resemble a real vehicle and consequently differentials were implemented in the vehicle model. The front differential distributes the engine torque across the front wheels depending on the individual front wheel speeds. A wheel that is rotating faster than its counterpart transfers less torque to the ground which in turn increases the torque on the other wheel. A similar solution was implemented on the rear axle with the exception that the distributed torque was based on how much torque the AWD coupling was transferring from the gearbox to the rear wheels. Figure 23 below show the different adjustments that can be made.
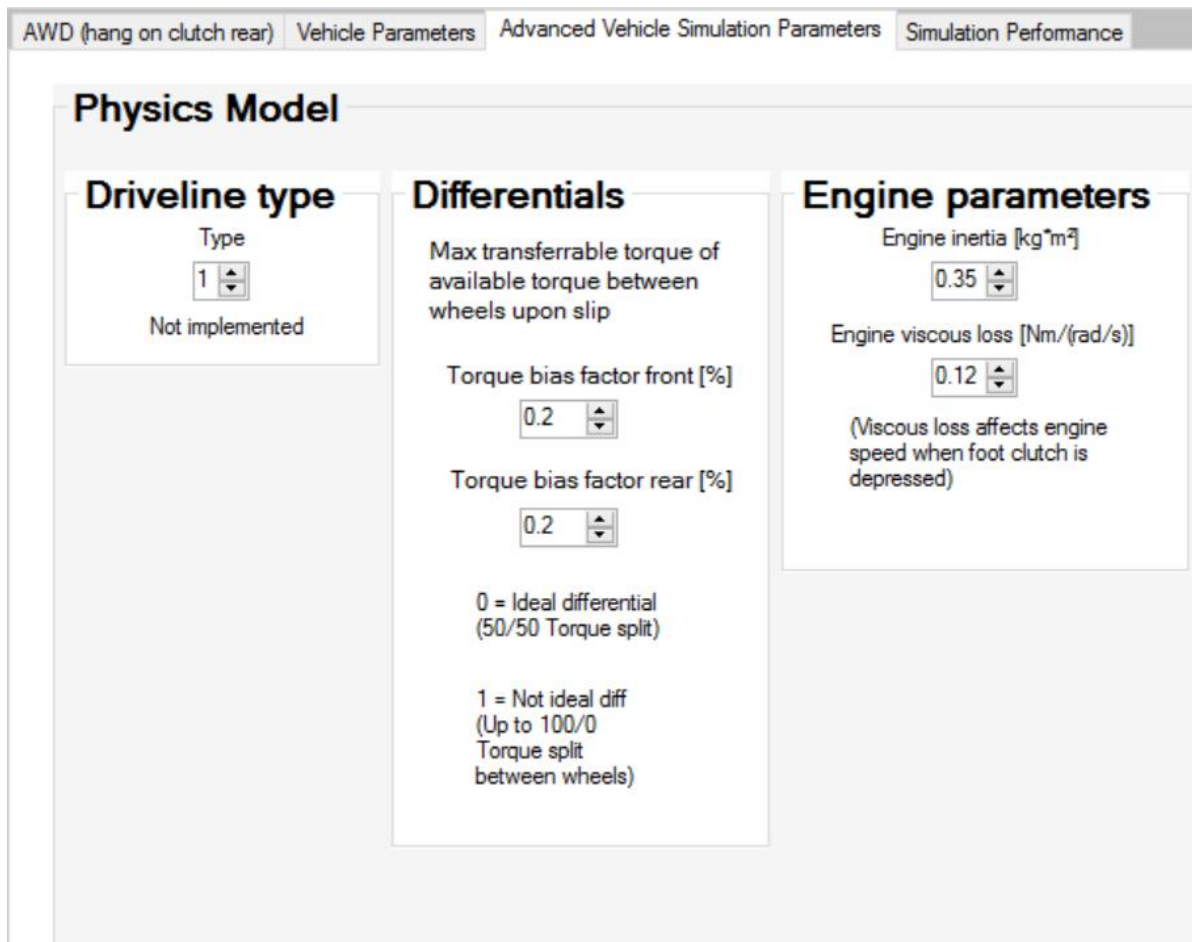

Figure 23 Advanced Vehicle Parameters.

The transferrable torque between the wheels is configurable in the *Advanced Vehicle Simulation Parameters* tab in the vehicle control panel.

5.3.10 Parameter import and vehicle configuration

When initiating the test suite, the ECU is put into an online state and the chosen test cases are run. The test suite configures the vehicle model at the end of the initiation part. The initiation imports all the available parameters from the same file that the ECU uses for its vehicle specific parameters. This ensures that the simulated environment is behaving as similar as possible to the actual vehicle that the product is destined for. The parameters are specific to each project and can often have different names or be used differently. A typical scenario is a vehicle which uses several different engine configurations. An engine with a higher torque output could use more parameters which transfers torque more aggressively to the rear wheels to complement the higher engine torque output.

5.3.11 Vehicle model integrity

This test was created to debug the vehicle model when implementing it into a new project. The variables it observes are output variables from the ECU. By comparing these variables to the input variables in the vehicle model the test ensures that each variable is interpreted correctly throughout the entire testing hardware. Each new project has a slightly different way of using the inputs and outputs of the CANoe configuration. By running these tests, the tester can be assured that the inputs and outputs of the vehicle model are interpreted correctly by the ECU. These tests and the "Parameter import vehicle configuration" need to be observed and possibly adjusted when implementing the vehicle model in a new configuration.

5.3.12 Test Cases

There were several different test cases implemented together with the vehicle model in the test suite. They were adapted to work with the vehicle model. This was achieved by using the different features and functions of the vehicle model to achieve the desired speed, torque or steering angle that was required in the different tests. This was done for the purpose of comparing some results to the existing results in the CSW test suite.

5.3.12.1 CSW drive torque Reduction with velocity

This test aims to test how the requested torque transferred from primary axle to secondary axle is reduced with increasing vehicle velocity. The test looks at 3 different velocities: 15, 35 and 55 m/s. This is a feature to reduce stress on the drivetrain since high vehicle velocity causes more rotational wear and stress on the drivetrain components.

5.3.12.2 CSW drive torque increase with driver requested torque

This test aims to test how the requested torque transfer from primary axle to secondary axle is increased when the driver requests a higher torque output from the engine. The test looks at different accelerator pedal position when travelling at a moderate speed and then compares them to how the ECU changes torque transfer to the secondary axle.

5.3.12.3 CSW pre-lock steering angle torque reduction

This test looks at how the pre-lock function works in the ECU while turning the steering wheel at different distinct steering wheel angles and observing the pre-lock torque requested by the ECU. The pre-lock is the amount of torque transferred to the secondary axle when the vehicle is in a scenario where it is about to take off. This could for instance be when the vehicle is stationary at a red light

and as the light turns green the vehicle transfers some additional torque to the secondary axle to minimize wheel slip during take-off. The accelerator pedal position is set at a value where pre-lock is enabled.

5.3.12.4 CSW AYC

This test puts the vehicle in a scenario where the active yaw control algorithm in the ECU is active. The test achieves this by turning the wheel, accelerating to 70 km/h and then testing different amount of engine torque output resulting in the vehicle driving in circles with bigger and smaller radiuses depending on the engine torque output. The torque output requests ranges from 30 to 300 Nm which the test achieves by using the torque controller in the vehicle model.

5.3.12.5 CSW brake torque distribution

This test looks at how the brake torque is distributed across the four wheels when applying engine braking during a moderate velocity. This is achieved through accelerating the vehicle up to 55 km/h and then releasing the accelerator pedal through which the engine applies braking torque.

5.3.12.6 CSW sanity tests safe driving steps

These tests are the new test cases that were created to evaluate the vehicle model and how it behaves when compared to real driving. It is based on the driving test instruction referred to "Safe Driving" for actual vehicle testing but adapted to work with vehicle model in CANoe. These tests were based around the safe drive instruction created for AWD/XWD. This test consists of 17 separate parts which all focus on that the coupling is to react in a safe way when subjected to different driving scenarios. These scenarios include several different speeds and steering inputs as well as braking and turning in different radiuses to investigate how the vehicle behaves.

5.3.13 Vehicle model manual

A manual for the vehicle model implementation was created to give new users of the vehicle model the ability to integrate the vehicle model into their current testing configuration. The process to integrate the vehicle model in CANoe is short but it is important to be able to understand each piece to fully utilize and to quickly find errors when running tests. The vehicle model is difficult to troubleshoot for new users since they are not familiar with its layout. It is therefore crucial that all steps in the manual are followed precisely.

An explanation was also given to the vehicle control panel in CANoe and the project in vTESTStudio since the control panel in CANoe is required for controlling the vehicle model and the testing process manually. This ensured that the vehicle model was made applicable to many kinds of projects with minimum start up time required.

6. Results of comparison between vehicle model and actual vehicle

The main assignment was concentrated around implementing the vehicle model and developing functions for it in CANoe but as a means of evaluation the vehicle model test results were compared to older test results and to the newer safe driving tests. One of the biggest issues with the implemented tests was that they were not correctly received by the ECU. The communication between CANoe-Simulink-ECU must be configured correctly with respect to how the signals are interpreted. Big errors could occur when sending a signal in m/s when it is expected to be in km/h. There is a possibility that some of the CSW test results are different since there are a lot of variables that are automatically set in the vehicle model which they are not in these tests.

6.1 CSW tests

The conclusion that can be drawn from the CSW tests is that the vehicle model behaves similar to the expected values in the tests. There are however several confidental values in these tests that can not be included in this report. Table 1 showcases a test result example that was achieved from the CSW Test "Pre-lock Steering angle torque reduction".

Table 1. CSW Pre-lock Steering Angle Torque Reduction

CSW Test	Requested Torque	Vehicle Model Torque	Grade
Steering angle 1	>704 Nm	>704 Nm	Pass
Steering angle 2	>663 Nm	>663 Nm	Pass
Steering angle 3	>594 Nm	>594 Nm	Pass
Steering angle 4	>437 Nm	413 Nm	Fail
Steering angle 5	>268 Nm	214 Nm	Fail

The results from the remaining CSW tests did not provide any additional information about the vehicle model which is why they are not included in this report.

6.2 Safe Driving

A better way of evaluating the vehicle model is to compare it to an actual vehicle. There is currently only one safe driving test instruction at BorgWarner PDS but an older version was also used to provide additional information on how the vehicle model behaves. The newer version replaced its predecessor to provide a more objective test instruction since the old version included several instructions which were based upon the driver's subjective feelings. The following figures are comparing the vehicle model to actual vehicle results. The instructions for each test case are described in Appendix A and B at the end of this report. Each step consists of the actual vehicle graph, the vehicle model graph and a text to describe similarities and differences. These results are mainly for observing similar behaviour from the ECU. Observe that no further scientific comparison can be made because of differences in ECU software during the work that could not be reversed.

6.2.1 Old Safe Driving Instructions

Test step 3, 4 and 9 in the old safe driving test. The other tests were not applicable for the vehicle model or provided no additional information. Test step 3 tests that the ECU shuts off when the engine is off. Note that the vehicle model converges to a static idle speed. Below is Figure 24 which displays engine speed and the current drawn by the ECU. Following Figure 24 is Figure 25 which showcases the equivalent parameters in the vehicle model.
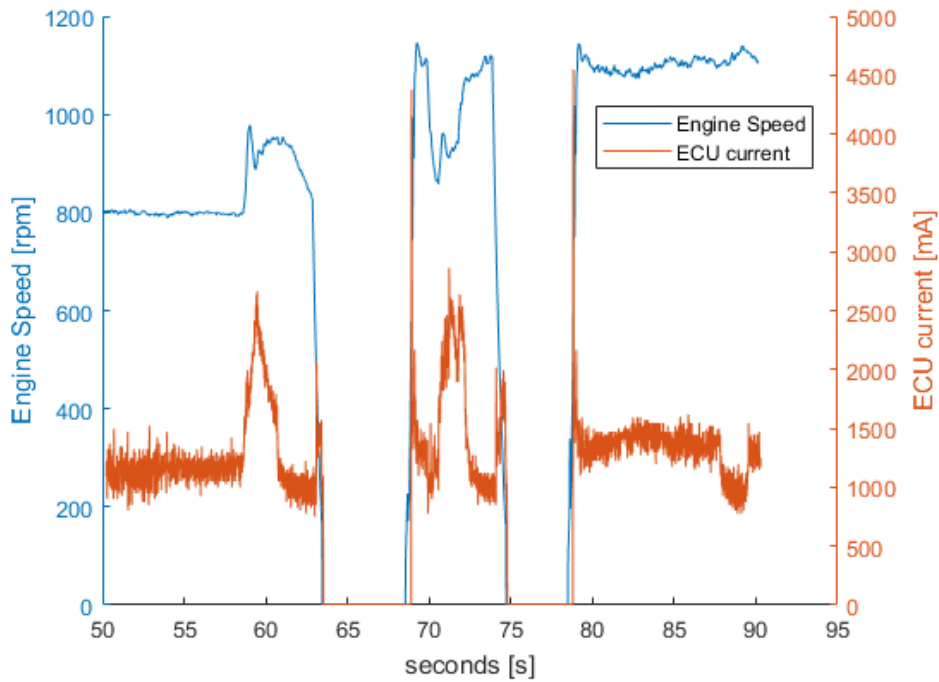

Figure 24 Safe driving step 3 from a real vehicle.
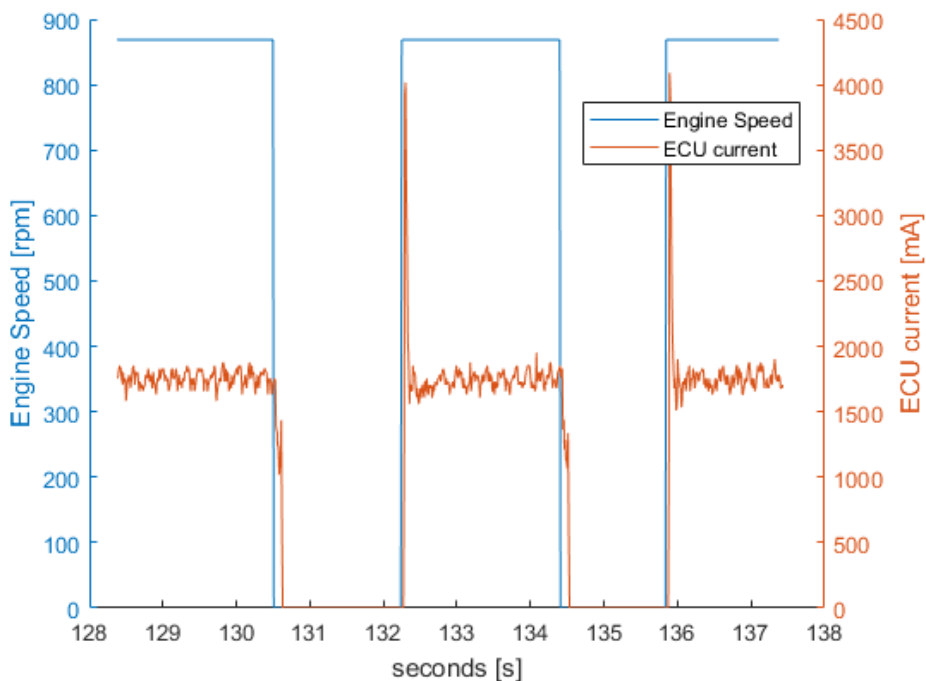
Figure 25 Safe driving step 3 from vehicle model.
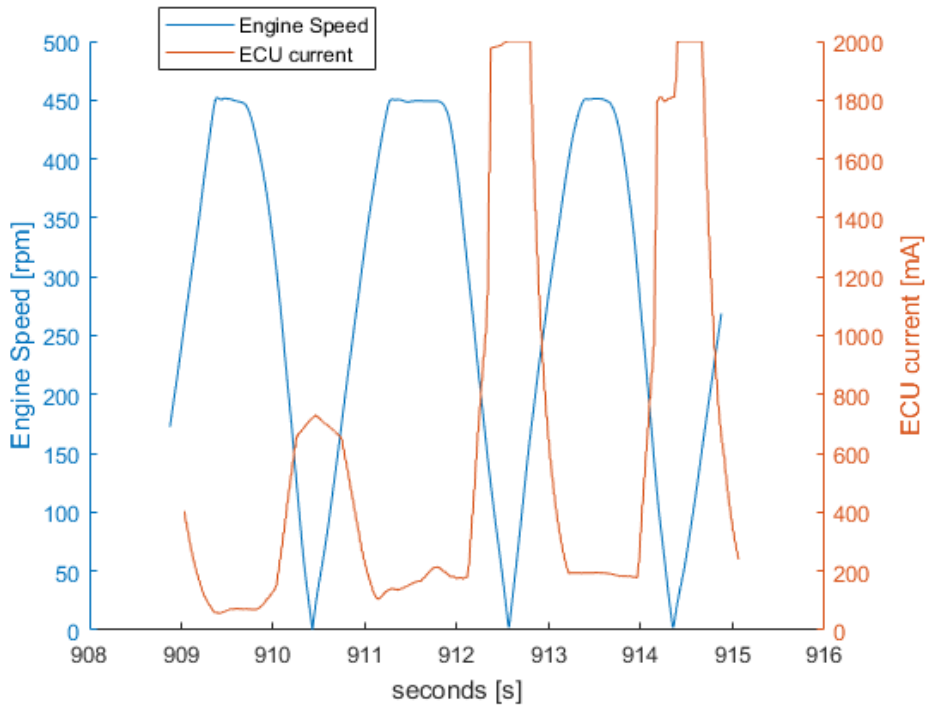
Figure 26 Safe driving step 4 from a real vehicle.
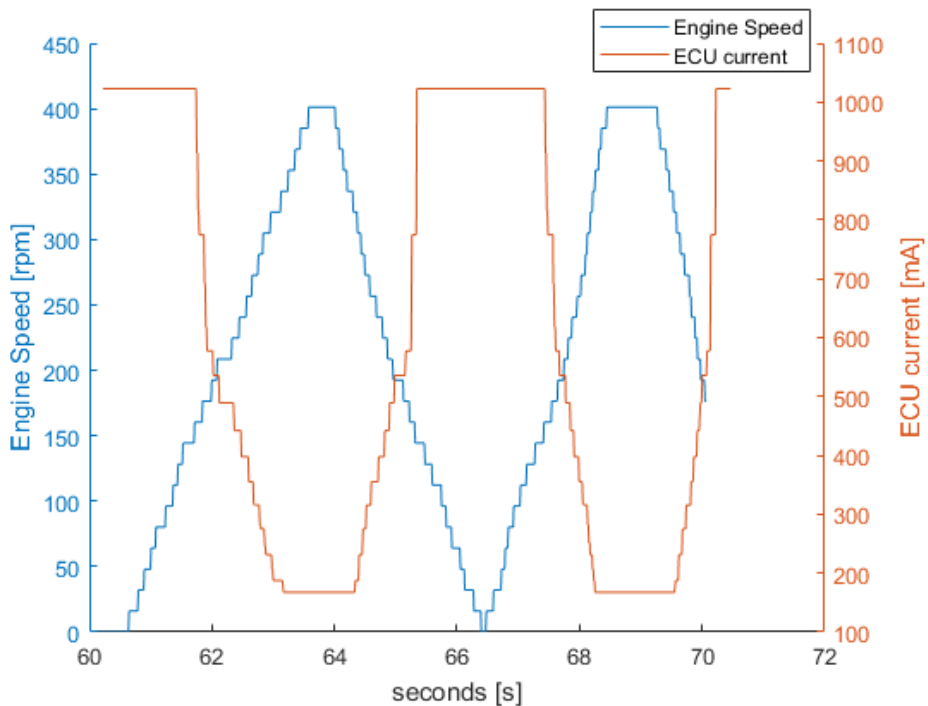
Figure 27 Safe driving step 4 from vehicle model.

We can see in Figure 26 that the torque request is lowered when turning the steering wheel. We see the same behaviour in Figure 27 where the torque request is lowered in correspondence with an increasing steering angle. The jagged edges in the steering wheel angle in Figure 27 is caused by the slider in the vehicle control panel. An automated test would ramp the steering wheel angle smoothly.
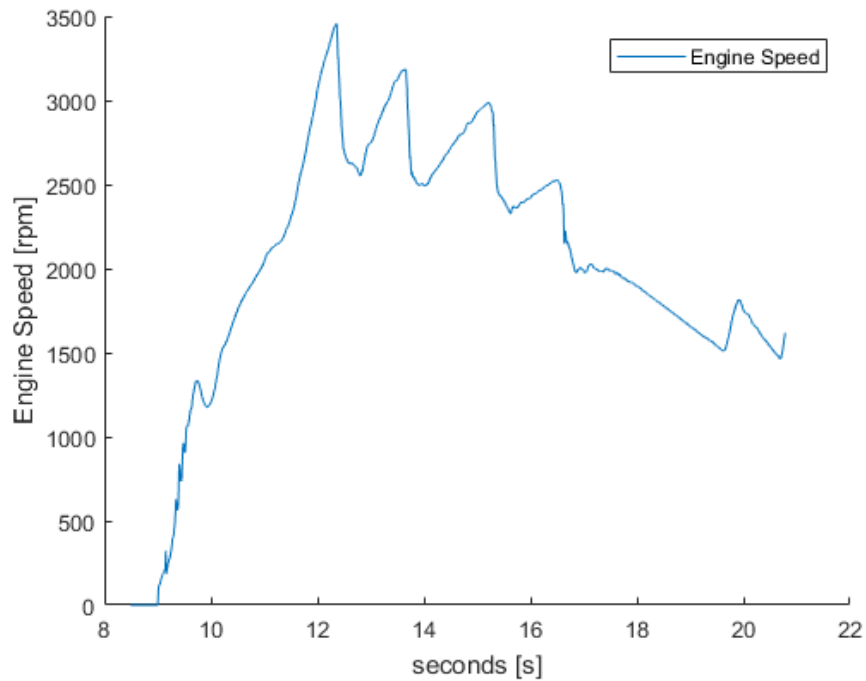
Figure 28 Safe driving step 8 from a real vehicle.
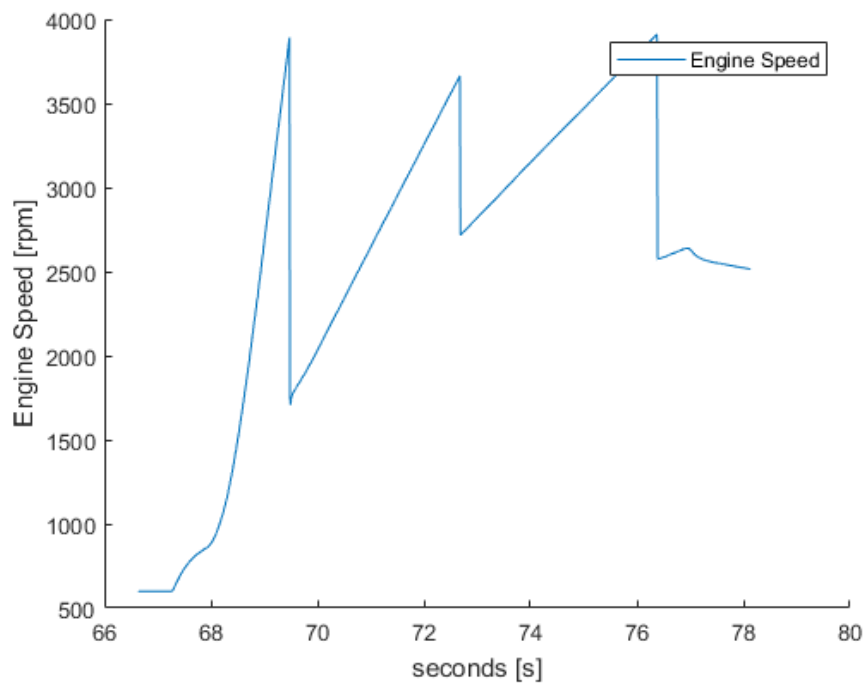
Figure 29 Safe driving step 8 from vehicle model.

Test step 8 consists of an acceleration from gear 1 to 3. We observe in Figure 28 that the gearbox in the actual vehicle is shifting gears in short succession. Figure 29 show how the vehicle model accelerates. Observe the difference in engine speed between the gears in the vehicle model compared to the actual vehicle, possibly pointing to a difference in gear ratios in the gearbox between the vehicle model and the actual vehicle.

6.2.2 New Safe Driving Instructions

Test step 4: the test looks at changes in accelerator pedal position and corresponding changes in the requested torque. The vehicle model and the actual vehicle behave similarly. The difference in the amount of torque requested between the vehicle model and the actual vehicle was not determined during this work and is most likely because of differences in the ECU software. Observe that accelerator pedal position timeline in Figure 31 Safe driving step 4 from vehicle model. is offset to the left because of a logging fault in CANoe. In reality, the rear axle torque in Figure 31 reacted very similar to the actual vehicle in Figure 30.
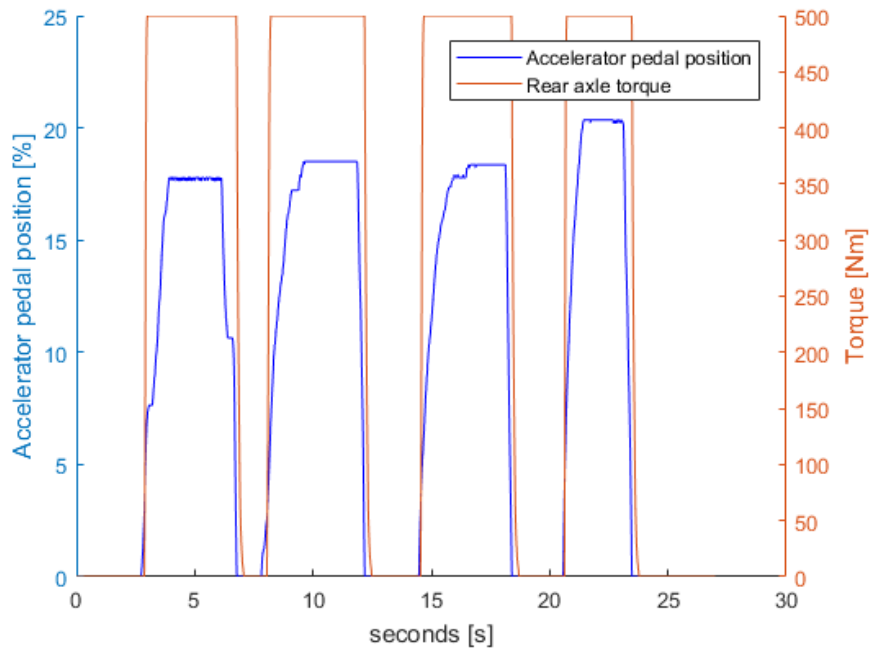
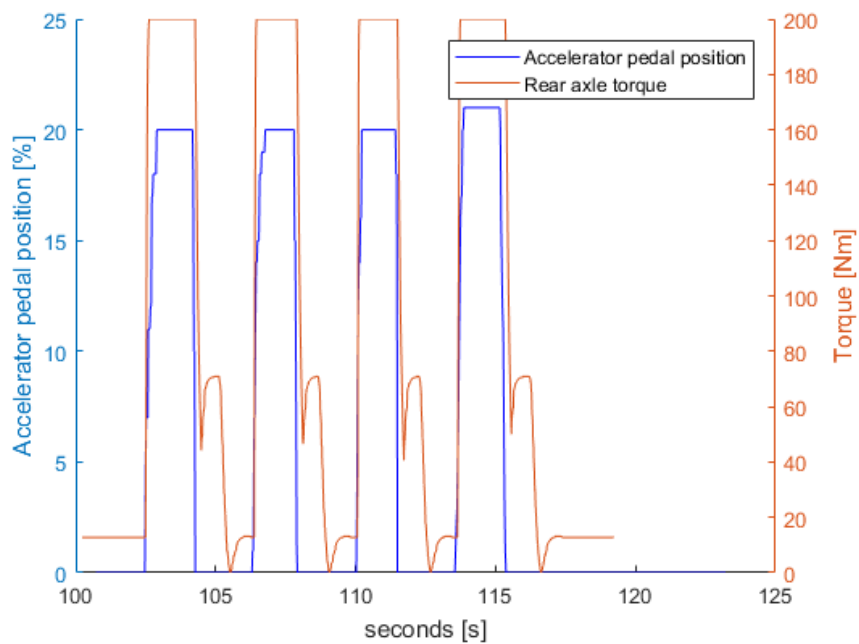

Figure 30 Safe driving step 4 from a real vehicle.

Figure 31 Safe driving step 4 from vehicle model.

Test step 14: This test is very similar to step 8 in the old safe driving tests. It accelerates the vehicle on ($\mu = 1$) and observes that the torque request responds to changes in vehicle velocity and engine rpm. The vehicle model and the actual vehicle behave similar in this aspect. This can be observed in Figure 32 and Figure 33 where the front left (FL), front right (FR), real left (RL) and rear right (RR) wheel speed for both the vehicle model and the actual vehicle is plotted.
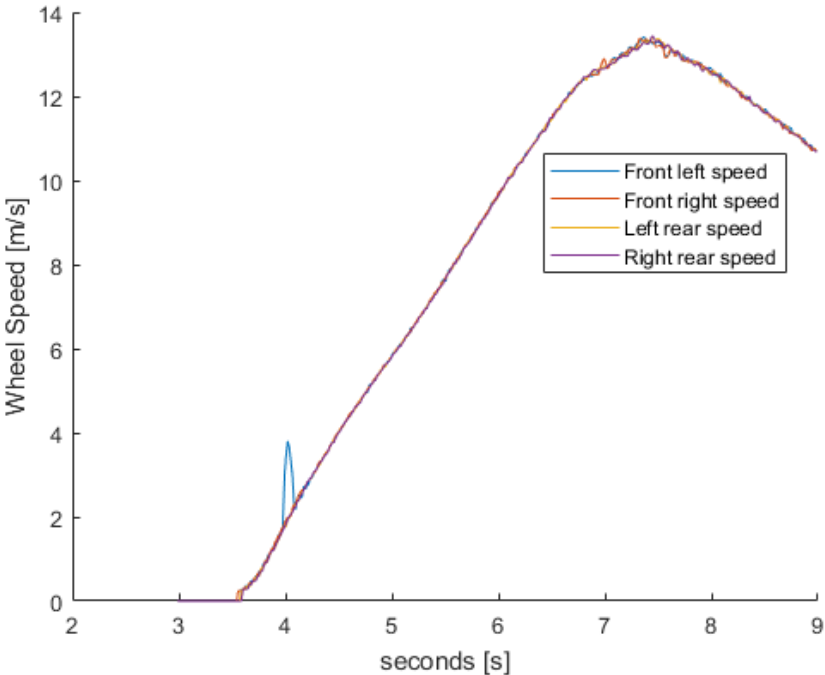

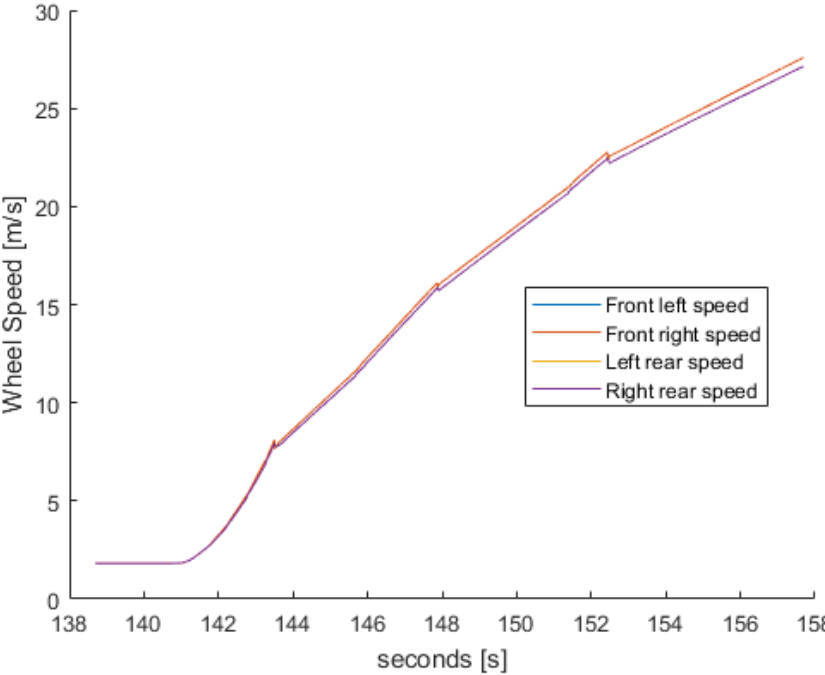*Figure 32 Safe driving step 14 from a real vehicle.*

Figure 33 Safe driving step 14 from vehicle model.

7. Discussion

7.1 Benefits and improvements

The main advantage of this work is that there can be a greater understanding of how an actual vehicle will respond when subjected to different driver inputs and when it is put into different scenarios. This could during a longer time period simplify and shorten the testing process whilst retaining the quality that is needed when releasing a new product. There is now a possibility to record and compare actual vehicle data to a recording from the vehicle model in CANoe. Future work will ensure that the vehicle model is developed to be more akin to the actual vehicle.

The future will tell what benefit this vehicle model had on the software verification process but the main assignment has been successfully achieved and the conclusions in the results answered the questions in the main assignment. This work was not a straight line to the finish but instead changed direction during the work to better suit the department and the scope of the work. It was a new area that was explored and as such there was no option to fully determine how the work should progress but the work would have come to a very similar conclusion should it be repeated. It has been of great contribution that there was a summarization and discussion each week of each weeks work. Communication is of the essence in these types of work and everyone that is planning to do their master's thesis should try and maintain proper communication during the work.

7.2 Disadvantages

There are some differences in some of the CSW tests (that I couldn't share) that are difficult to explain. Since the CSW tests are more of a static test and as such they are perhaps not suited for the vehicle model. They can provide additional knowledge to the tester but there is a risk that they confuse the tester.

The physical differences between the vehicle model and the actual vehicle will always be a disadvantage. The future will tell if some of the differences could prove to cause differences that is not negligible. It is very important that the user is vigilant towards differences in the results provided by the vehicle model when compared to an actual vehicle and ensures that they are the source of a difference in the expected result and not in the physical model of the vehicle model.

This implementation will not replace or remove any existing testing procedure. It is purely built to provide an additional reference point for doing different types of dynamic testing. The safe driving test that is done in a vehicle will continue to be run in an actual vehicle to ensure that each product behaves correctly. But there is still the possibility that the implemented safe driving tests with the vehicle model discovers some flaws with the control software before it is tested in the actual vehicle thus reducing overall cost and time spent on testing. There are still some features that are not implemented in the vehicle model that could make a difference when comparing it to the actual vehicle. They are explained later in this chapter.

8 Conclusion & future work

All in all, this work has provided the test department with a stronger testing environment and it has fulfilled everything in the main assignment on which it was set out to achieve. I feel that this work has retained its original idea and assignment and I think I would come to the same conclusion if I were to do this work again. The vehicle model has proved to be an important tool in the continuation of the development that the test department does to improve its results and BorgWarners products in general. Future work will solidify the vehicle model as an additional reference point in the software verification process.

8.1 Future work

Not all the features were implemented due to the time and size constraint of the work. The following sections discuss different additional features that could be implemented in the future by a master's thesis worker or through the departments' own development. The vehicle model will receive frequent updates from employees but bigger changes might require a master's thesis worker or a summer worker.

8.1.2 Parameter verification

The vehicle dynamics department is often the department that decides how the coupling should behave with respect to driving dynamics. In some cases, this tuning is done by a third party recruited by the vehicle manufacturer. There is a need in both cases to verify that the parameters that are set are reasonable for the application. The consequences for a parameter being configured incorrectly might be severe.

These errors are often not detected until the vehicle is tested on a track since the TVR-SW department verifies that the coupling is behaving according to its parameters and not that the parameters themselves are correct. In this case, there is a benefit to comparing the newer parameter files with an older verified parameter file. The vehicle model is the perfect platform for doing these types of tests and this test will hopefully be implemented in the near future.

8.1.2 Driveline configurations

As of finishing this report, the vehicle model has support for the rear hang on clutch. This is however just one of all the products that are produced and developed at BW-PDS.

Future work could investigate the possibility of adding different driveline configurations such as the ones described in the Introduction. All of these configurations are currently developed and produced at BW-PDS thus there is benefit to having a more capable vehicle model. The model is prepared for additional driveline configurations with support both in the Simulink model as well as in the *Advanced Vehicle Simulation Parameters* tab in the Vehicle Control Panel in CANoe.

8.1.3 Electric Drivetrain

All the bigger vehicle manufacturers have interest in implementing some sort of electric propulsion and battery technology into their model line-up. BorgWarner is constantly trying to innovate and look for new solutions and an electric drivetrain could be one of them. Therefore, it could be of interest to implement a hybrid as well as BEV-type vehicle into the vehicle model. This would widen the testing platform greatly and prepare it for future projects.

8.1.4 3D Visualization

There is a sample CANoe configuration provided by Vector that utilizes a vehicle model 3D-visualization for feedback when running the model. The model communicates via UDP and is written specifically for this sample configuration. The model used by CANoe was not possible to use in this work since it was specifically built for the sample configuration. There are however several benefits by using a 3D-visualization as feedback to ensure that the vehicle model is behaving correctly and as such this could be part of future work.

8.1.5 ESP and ABS

These signals are not implemented in the vehicle model and the signals are required to be set manually or in an automated test. Future work could investigate the possibility to implement ESP and ABS controllers in the vehicle model so that the vehicle model would behave more comparable to an actual vehicle and how the ECU control software would react to these simulated signals. This implies that the vehicle model is outputting the ESP signal during aggressive turning and the ABS signal during hard braking. ESP outputs and handles several different signals which is dependent on what vehicle configuration is used which would cause the ESP integration to be greater than just implementing a stability controller. An implementation of ESP and ABS controllers would benefit the vehicle model as a whole but since different manufactures use different ESP and ABS controllers this could be part of a master's thesis or summer work.

9. Bibliography

[1] "Generation V," 16 May 2018. [Online]. Available:
http://www2.borgwarner.com/en/powerdrive/products/PAges/GeneraionV.aspx.

[2] "Motor Authority," 29 August 2018. [Online]. Available:
https://www.motorauthority.com/news/1031262_vw-adds-4motion-awd-to-mark-vi-golf. [Använd
29 August 2018].

[3] "NetCarShow," 27 August 2018. [Online]. Available: https://www.netcarshow.com/audi/2016-
r8_v10/. [Använd 27 August 2018].

[4] "AutoKrusers," 18 September 2018. [Online]. Available:
http://autokrusers.com/YAKFourWheelDriveRepair.html. [Använd 18 September 2018].

[5] "FXD Product Sheet," BorgWarner, 21 May 2018. [Online]. Available:
https://www2.borgwarner.com/en/powerdrive/products/Literature/BW%20TTS%20FXD%20EU.pdf.

[6] "Vector CANoe," [Online]. Available: https://vector.com/vi_canoe_en.html. [Accessed 31 May
2018].

[7] "Arjeplog test track," Arjeplog, 21 May 2018. [Online]. Available: http://www.arjeplog.se/naringsliv-
-utveckling/fordons---komponenttest/is--och-landbanor.html.

[8] "Japtuning," 12 2013. [Online]. Available: http://www.japtuning.se/wp-
content/uploads/2013/12/Ljungbyhed-1.jpg. [Accessed 25 May 2018].

[9] J. W. Y. W. C. L. Linlin Yao, "Research on vehicle integrated control algorithm based on MATLAB and
CANoe co-simulation," in *IEEE Conference and Expo Transportation Electrification Asia-Pacific*,
Beijing, China, 2014.

[10] "CAN CIA," [Online]. Available: https://www.can-cia.org/can-knowledge/can/can-history/.
[Accessed 2018 May 31].

[11] "Quora," 23 September 2017. [Online]. Available: https://www.quora.com/What-is-a-CAN-bus.
[Accessed 31 October 2018].

[12] "Vector CAPL," Vector, 23 May 2018. [Online]. Available: https://kb.vector.com/entry/48/.

[13] "Vector Module," Vector, 16 May 2018. [Online]. Available: https://vector.com/vi_vn8900_en.html.

[14] "Mathworks," 24 October 2018. [Online]. Available:
https://se.mathworks.com/help/physmod/simscape/ug/what-is-hardware-in-the-loop-
simulation.html. [Accessed 24 October 2018].

Appendix A New test cases safe driving

Table 2. New test instructions

| No	Sequence Description
1	Switch on ignition, but not engine for 20sec
2	Start Engine, wait for stable engine idle speed.
3	While car standing still, let engine idle for 20 sec. No brakes or handbrake activated
4	While car standing still, gently perform one accelerator pedal step: 0%…25%…0%, gearbox in neutral.
5	If electric parking brake While driving at 15 km/h engage handbrake. While driving at 50 km/h engage handbrake. While driving at 90 km/h engage handbrake.
6	Drive straight forward at 50km/h, brake hard to engage ABS function.
7	If possible, perform an ABS-brake, as in step 7, on split my (μ). For example, one wheel on grass and one on asphalt
8	Intentionally left blank
9	Accelerate to 20km/h perform a minimized radius right curve with accelerator pedal at 0 %
10	Accelerate to 20km/h perform a minimized radius left curve with accelerator pedal at 0 %
11	Accelerate to 20km/h perform a minimized radius right curve with continuous vehicle speed. Accelerator pedal <=10%
12	Accelerate to 20km/h perform a minimized radius left curve with continuous vehicle speed. Accelerator pedal <=10%
13	Acceleration on split my (μ). Right side on high Left side on low
14	Acceleration on high my (μ).

15	Drive in a curve with medium acceleration, release accelerator pedal in the curve. The coupling will apply torque to stabilize the vehicle. This may require a sporty right foot to be able to trig.
	Right hand curve
	Left hand curve
	Repeat a) with ESP off and gearbox S
	Repeat b) with ESP off and gearbox S
16	Simulate an evasive manoeuvre like the famous moose test.
17	While the car is standing still, let engine run at 2000 rpm for 3 seconds. Keep the engine revs and turn steering wheel to the maximum steering angle and release it

Appendix B Old test cases safe driving

Table 3. Old test instructions

No	Sequence Description
1	Make sure car is standing still with steering wheel centred and ignition switched off.
2	Switch on ignition but not engine.
3	Start engine. Let the engine run on idle speed
4	While the car is standing still, let the engine run at 2000 rpm for 3 seconds. Keep the engine revs and turn the steering wheel to the maximum steering angle and release it.
5	Drive off and accelerate gently up to 75km/h and drive in constant speed for a few minutes.
6	Put the car with the front wheels on the test rollers. Stand with 1st gear engaged and no accelerator pedal for 5 seconds and then drive the car over the test rollers.
7	Drive straight ahead on first gear and at engine speed 1500 rpm. Turn into a min radius circle.
	After 5 seconds release the accelerator pedal and press the clutch pedal (if existing).
	After 3 seconds' brake to a standstill.
8	From standstill, accelerate from 1st to3^{rd} gear with around 50% accelerator pedal position
9	Drive straight forward at constant car speed 50 km/h, release the gas pedal and engage brakes so that ABS is activated. Perform a minimized radius left curve with accelerator pedal at 0 %
10	Drive straight forward at constant car speed 90 km/h, release the gas pedal and engage brakes very light.
11	Drive straight forward at constant car speed 90 km/h, release the gas pedal and engage brakes so that ABS is activated.
13	Optional test, **only to be performed if it can be done in a safe manner**:
	Drive straight ahead in 50-70 km/h. Make a step in the steering wheel input and then back in order to trigger the ESP system.

Appendix C Vehicle Model Overview
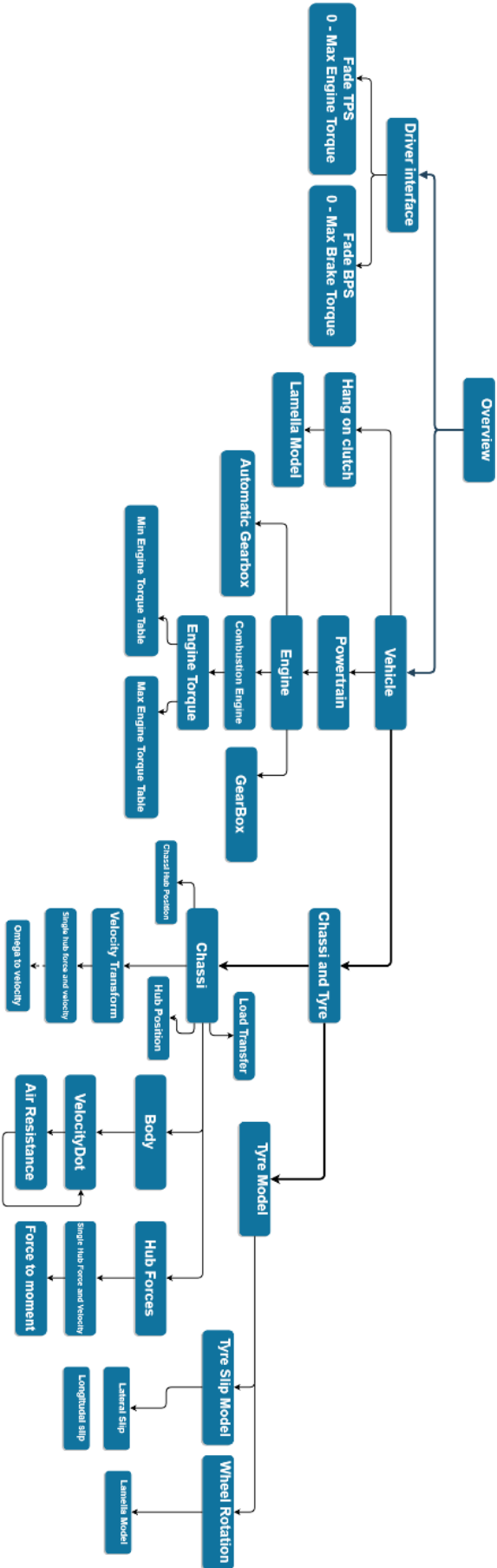
Appendix D Vehicle Control Panel