Virtual Verification Framework for Vehicle Motion Systems

Master's thesis in Mobility Engineering

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Cover: Picture of Zeekr Tech EU's innovative vehicle M-vision Concept designed for future mobility solutions.

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Abstract

The automotive industry continually strives to enhance vehicle development processes to be faster, more cost-effective, and of higher quality. This thesis presents the development of a Virtual Verification Framework (VVF) to improve the Computer Aided Engineering (CAE) verification process for vehicle motion systems. The focus is on the initial stages of vehicle development, specifically replacing traditional Vehicle-in-the-loop (ViL) testing with more efficient Software-in-the-loop (SiL) methods.

The framework is developed using IPG CarMaker, a widely adopted simulation software, and Simulink, allowing detailed subsystem simulations such as braking systems. The objective is to create a correlated CAE environment that can perform high-fidelity simulations and provide reliable data for system verification. This involves implementing accurate simulation models, selecting relevant verification scenarios, and analyzing both simulations' and real-world data's performance and accuracy.

Key research questions addressed include the analysis of output data reliability for correlation studies between SiL and ViL and the potential expansion of the SiL stage to replace some aspects of ViL in system verification. The thesis demonstrates that while a complete VVF is not yet realized, significant progress has been made, particularly in implementing system-specific models and functional testing within CarMaker for Simulink (CM4SL).

Challenges identified include simulated and real-world data discrepancies, particularly with tire modeling and sensor frequency differences. Despite these, the framework shows promise for future scalability and application, aiming to reduce reliance on physical prototypes, enhance safety in early-stage testing, and streamline the vehicle development process. The work concludes that a more robust and trustworthy virtual verification environment can be established, significantly benefiting the automotive industry's development cycles.

Keywords: Virtual Verification Framework, vehicle motion systems, Computer Aided Engineering, CarMaker, MATLAB, Simulink, brake system, vehicle dynamics verification, Software-in-the-Loop, Vehicle-in-the-Loop

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Albijon Blakqori and Mille Kotur
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List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ABS Anti-lock Braking System
ADAS Advanced Driver Assistance System
BCM Brake Control Module
CAE Computer Aided Engineering
CM4SL CarMaker for Simulink
COS Completion of steer
DAE Differential-Algebraic system of Equation
DLC Double lane-change
ECM Engine Control Module
ESC Electronic Stability Control
FFT Fast Fourier Transform
HiL Hardware in the Loop
ISO International Organization for Standardization
KPI Key Performance Indicators
NHTSA National Highway Traffic Safety Administration
PSCM Power Steering Control Module
SAE Society of Automotive Engineers
SiL Software in the Loop
SIS Swedish Institute for Standards
TC Traction Control
TCS Traction Control System
ViL Vehicle in the Loop

Nomenclature

Below is the nomenclature of parameters, and variables that have been used throughout this thesis.

Parameters

μ	Road surface friction coefficient

Variables

S_x	Calculated longitudinal (x-direction) slip ratio
V_w	Is the wheel longitudinal velocity
R_w	Is the effective tire radius
ω	Is the wheel angular velocity
a_x	Calculated decelerations
v_1	Is the initial velocity
v_2	Is the ending velocity of the measurements
d_x	Is the measured braking distance
$-\bar{a}_X$	Is the mean longitudinal accelerations $[m/s^2]$
d_{eff}	Is the actual stopping distance $[m]$
v_{eff}	Is the actual initial velocity $[m/s]$
Y	Steering-wheel angle
t	time in seconds

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Introduction

Feature verification activities are used to verify systems within the area of Motion Systems (brakes, steering, and propulsion) in the vehicle development at Zeekr Technology Europe. The work is performed and coordinated with the Vehicle Dynamics team. The constantly modernized requirements, such as stakeholder, attribute, legal, function, and functional safety requirements, have to be scrutinized, verified, and validated. In the work towards faster, cheaper, and higher-quality development, simulations are more important than ever.

1.1 Background

The verification of vehicles is performed in different stages. The first and earliest stage is SiL [3], where the testing is done in simulation software. The next stage is Hardware in the Loop (HiL), where the vehicle's hardware is physically mocked up on racks and connected to test their functions. Lastly, there is ViL, where the complete vehicle is built and real-life tests are done. All these stages sum up to a long lead time from idea to physical vehicle. The complexity of changing a vehicle's specifications and characteristics increases with the level of maturity of the vehicle development. Therefore, increasing the usage of Computer Aided Engineering (CAE) [4] for verification and validation is highly beneficial in terms of time and cost. CAE is already used to a high extent but with limitations in credibility. To be able to rely on the vehicle models provided by the vehicle dynamics team and the suppliers, a virtual verification framework needs to be developed.

The software already used at Zeekr Tech EU for the simulation of the vehicle models is CarMaker [5] from the company IPG Automotive. IPG CarMaker is widely used at Zeekr Tech EU, and the existing HiL-rigs use the same software to assess the open-loop control systems.

The vehicle model in CarMaker can be derived from the vehicle's sub-systems developed at each sub-team at Zeekr Tech EU. The corresponding vehicle dynamics characteristics are generated from simulations made in the associated simulation software, where, for example, Adams Car is used for vehicle dynamic properties.

1.2 Purpose

This thesis work aims to develop a correlated CAE framework to replace as much as possible of the time-consuming evaluation of the vehicle features testing within HiL and ViL. This will streamline the process of verification of vehicles towards various requirements. The result of this work will lead to faster, cheaper, and higher quality development of vehicles. The following research questions will be answered.

1.2.1 Research question 1

To be able to perform a correlation study between SiL and HiL/ViL, it is crucial to analyze output data that is as reliable as possible. This study evaluates the appropriate resultant data for use in simulating vehicle performance. This will also affect which parameters are used in the HiL and ViL and which instruments are used.

The inputs that impact the simulation outcomes also have to be addressed [6]; hence, the quality of the output will never be better than the input data. An empirical investigation will be conducted to analyze the experiment's properties, relationships, and specific factors. The result from the investigation has to be quantified according to an agreed conformity index [7], which can be used to evaluate the simulation.

Therefore, this project is highly important in addressing what is crucial in a high-fidelity simulation model and which input and output data should be used. The quality assurance of the model should also be considered together with how it is implemented, considering the input and output data and which signals are implemented.

How can a correlation study between SiL and ViL be conducted to ensure the reliability of output data for simulating vehicle performance?

1.2.2 Research question 2

Labeling a system or function not verified as early as possible is important in vehicle development. Hence, the complexity of making changes increases the further the project has developed. Due to modernized requirements, such as stakeholder, attribute, legal, function, and functional safety requirements, it is crucial for vehicle development to rely on the verification process in the CAE stage.

Therefore, it is of great interest to evaluate the possibilities to expand the SiL stage further and also replace both HiL and ViL in some system verification. This could be beneficial in areas where the HiL cannot correctly simulate parts of the hardware with the SiL, but a complete and trustworthy virtual simulation can. For example, a wheel speed sensor in the HiL-rig can be faulty, and thus, the whole simulation can be compromised. Or to verify a system's function requirements rather than evaluating the performance.

What are the possibilities and benefits of expanding the SiL stage to replace some *aspects of ViL in the system verification process for vehicle development?*

1.3 Objectives of the issue being investigated

An important first step in the thesis project is to narrow down the scope due to the vast amount of, for instance, functions and requirements. The development process at the company has been well-defined since before, however, the main objective of the thesis project is to develop a better virtual verification framework.

In more detail, the main objective can be specified according to:

- Implement the appropriate simulation models in the simulation setup.
- Select and implement a chosen set of verification scenarios with pass/fail criteria.
- Analyse the performance and accuracy of both the simulation results and the models used with either driver models or with test drivers at all stages.
- Suggest a way of working to empower virtual verification in the future.

1.4 Boundaries

The work will mainly focus on the vehicle development's SiL part. The simulation models will be modified, evaluated, and correlated to real vehicle data.

Zeekr Tech EU will provide the vehicle models with all the parameters, such as tires, suspension, brakes, steering, etc. Thus, these will not be researched in this report.

Due to the vast number of requirements available, all vehicle requirements will not be evaluated. With the short time limit, this is not feasible, and thus, the work will be focused on one or two systems with only a handful of chosen requirements.

The test results from HiL or vehicle testing may also not be derived in this report and are solely taken from tests done by Zeekr Tech EU already. This is also due to the time limit that is faced in the project.

1.5 Ethics assessment

If the project leads to a positive outcome, the benefits will be many. One of these is the safety aspect of vehicle testing. When testing new vehicles, parts, or functions, there is always a risk of something going wrong. A good example is the test of Anti-lock Braking System (ABS) or the test of Electronic Stability Control (ESC) on a high-speed maneuver. With a virtual verification method these risky tests will not be needed to be done in the early stage of the development where the uncertainty is high. With well-performing and reliable simulation tools, these systems can be developed, tested, and also verified long before a physical model is created. This leads to the second point. The need for physical models will decrease; thus, there is much to save in terms of time, money, and, most importantly, energy. This is very positive in terms of the sustainability of our earth since the energy usage during development can decrease.

As with every leap forward in innovation, there are prone to be some things that are not affected as positively as the first points. One of these aspects is that when the need to build physical models and carry out a vast amount of real tests decreases, the need for manpower will also decrease. This can lead to fewer jobs being available, and, in the worst case, people already working with physical models and real-life testing losing their jobs. Another point is when the milestone is reached that the development of vehicles will be solely done with virtual verification methods, there are prone to be bugs in the program or cases that a simulation cannot predict. Thus, the reliability of these virtual verification methods can be discussed.

2

Theory

The following chapter describes the theory regarding vehicle modeling, software, standardized test scenarios, and the associated Key Performance Indicators (KPI). The focus will be on implementing the brake model in Simulink that is currently used in the vehicle platform being developed at Zeekr Tech EU and how it can be assessed according to standardized test scenarios in IPG CarMaker. Because of confidentiality, the models of the sub-systems can only be described to an extent where no classified information is revealed.

Given the focus of this project, understanding the modeling of motion systems (e.g., brakes, steering, and propulsion) and their functionality in vehicles is significant. To effectively analyze data from SiL, HiL, and ViL, it is necessary to have prior knowledge of vehicle and sub-system models, vehicle motion systems, CAE simulation tools, and the test scenarios employed in the verification of these motion systems.

2.1 Vehicle model

The parameterization of the vehicle comes from modeling and the estimated performance from simulations made during the development of each sub-system's design parameters (e.g., brake rotor size, steering ratio, wheel diameter, etc.). Each subgroup in the vehicle development contributes with parameters for their specific area. E.g., Adams Car [8] can be used to analyze the suspension and model the characteristics, which then can be used in IPG CarMaker; see chapter 2.4.1 below. With dynamical equilibrium for the complete vehicle, with as many considered forces as necessary, a complete mathematical model can deliver realistic estimations of the vehicle dynamics behavior. For the types of simulations that will be made in this project, it is essential to use mathematical models [2], specifically Differential-Algebraic system of Equation (DAE), that consider the time history and add the variations over time according to the previous state.

Since some functions will be tested independently, it is important to manipulate the non-modeled sub-systems according to the estimated characteristics. Additionally, isolating the tested sub-system from other factors might be necessary to address this issue.

2.2 Tire model

Tire modeling is one of the most complex and essential parts of vehicle modeling. Regardless of how well the systems (e.g., brakes, steering, or propulsion) of the vehicle are parameterized and modeled in CAE, the overall performance of the simulations will never be better than the tire model. Since the tires have an extensive impact on vehicle characteristics, even though they have a small contact point to the ground, the smallest deformation or structural behavior is important to consider. Differences in the simulated results from the CAE and the vehicle testing will be solved by applying calibration coefficients [9] to the tire model.

2.2.1 Tire slip

The tire slip ratio [10] is an important expression when evaluating tires. The expression allows an understanding of the relationship between the tire deformation and the longitudinal forces. It is also essential when designing an effective anti-lock braking system. The standard Society of Automotive Engineers (SAE) definition of wheel slip is:

$$S_x = -\frac{V_w - R_w \omega}{V_w} \tag{2.1}$$

where

S_x is the calculated longitudinal slip ratio;

V_w is the wheel longitudinal velocity;

R_w is the effective tire radius;

ω is the wheel angular velocity;

The slip ratio directly influences the braking forces acting on the tire. As the slip ratio increases, the braking force also increases up to a certain point, beyond which it starts to decrease due to tire lock-up. Understanding and controlling the slip ratio is crucial for optimizing braking performance and preventing loss of vehicle control during braking maneuvers.

2.3 Vehicle motion systems

Understanding the different motion systems of a vehicle is crucial for correctly conducting the project. A deeper understanding of these models enables their accurate integration into simulations, facilitating a clear interpretation of the obtained results.

2.3.1 Brakes

A modern brake system for a passenger vehicle consists of three main parts. Firstly, there is the brain of the brake system, the Brake Control Module (BCM). This part of the modern brake system is one of the most critical parts of the safety system of a modern vehicle. The main function of the BCM is to monitor the individual wheel speeds and correct the brakes. Inside the BCM, there are systems such as ABS and Traction Control System (TCS).

The main functions of the ABS pump and valves [11] regulate the pressure that goes to the brakes. When a wheel locks up, the BCM detects this through a wheel speed sensor and thus can tell the ABS valve to drop the pressure on that wheel until it has gained traction again. In the same way the ABS pump [12] is used for stability control, individual wheels can be braked to gain stability.

At last, there are the brakes on each wheel. The brake system [13] consists of a disc attached to the wheel, a piston that is actuated by the brake pressure, and brake pads in between, which create friction and, thus, stopping force. The friction generated between the brake pads and the disc results in a braking moment transmitted to the wheel, causing it to decelerate.

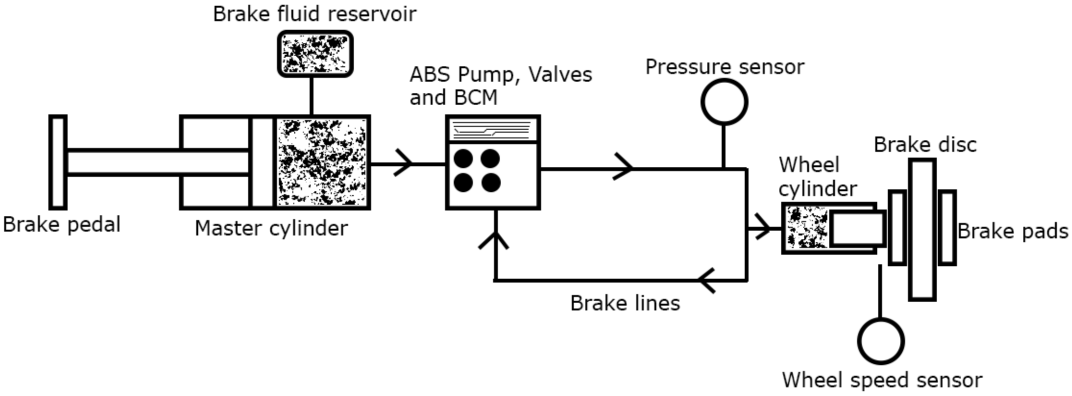


Figure 2.1: Sketch of a simple brake system.

2.3.2 Steering

A vehicle's steering [14] comprises the steering wheel, which is attached to the steering column and steering rack, which transfers the motion of the steering wheel to the wheels. When the steering wheel is turned it also turns the attached steering column. Consecutively the steering column moves the steering rack left and right. The steering rack is connected to the wheels with a leverage arm, which makes the wheels steer. There is also usually a power steering system, which can be electrical or hydraulic, that lowers the required steering wheel torque for the driver.

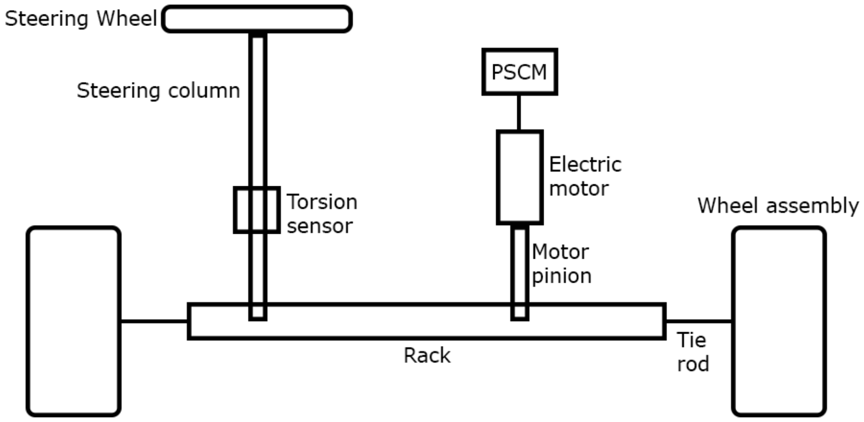


Figure 2.2: Sketch of a simple steering system.

The power steering system and the traditional steering can, in the future, be replaced [15] by the steer-by-wire technology. In this system, the steering wheel and the steering rack are physically disconnected. Instead, a steering wheel angle sensor steers electric motors on the steering rack, which successively steers the wheels. Steer-by-wire is becoming popular with the increased implementation of ADAS systems and mainly autonomous driving. It makes it possible for the car to steer without any input from the passengers or movement in the steering wheel. It also has other benefits, such as completely customizing the steering feel and varying steering gear ratio. The steering system has become more complex, and as a result, a Power Steering Control Module (PSCM) has been added. The module controls the relation between the steering wheel angle and the output force to the electrical motor on the steering rack.

2.3.3 Propulsion

The primary function of a car is to transport occupants and items from one location to another, making the propulsion system essential to the vehicle. For the propulsion we have three main parts. The first one is the engine, which traditionally consists of an Otto engine [16] driven by some liquid fuel. For a long time, this was the norm until electrical motors started becoming popular.

The electrical motor [17] offers high efficiency and zero tailpipe emissions. Connected to the engine is the second part of the propulsion system, which is the transmission and the differential. It consists of different gears and ancillary ratios. Gear reduction lowers or increases the output speed [18] from the motor out to the wheels. Another benefit is that a traditional multi-speed transmission is no longer needed; thus, the propulsion system can consist of the electrical motor alone with a differential.

Added to the electric vehicle is a large battery that supplies the electrical motor with power. Since the battery consists of DC power and the electrical motor is driven by AC power, an inverter is used in between these to convert the power. The Engine

Control Module (ECM) is responsible for regulating the torque output in response to torque requests.

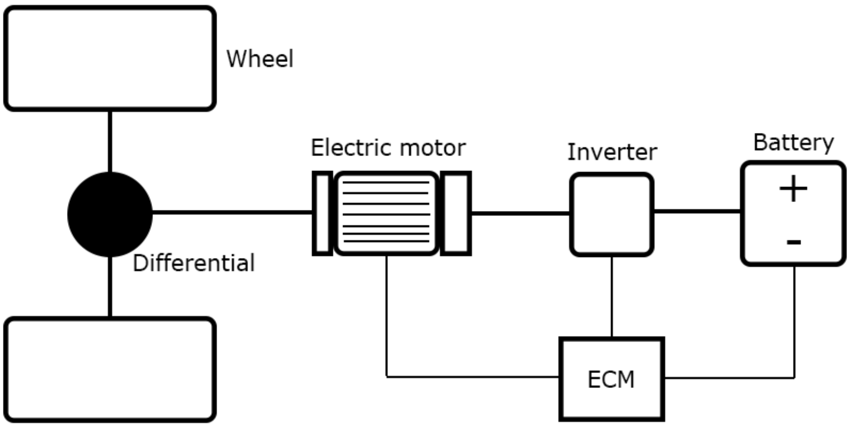


Figure 2.3: Sketch of a simple propulsion system.

2.4 Simulation tools

To be able to simulate the different systems and vehicles, the use of CAE tools is necessary. Therefore, selecting appropriate tools for the job and getting well acquainted with them is essential. In this project, IPG CarMaker is mainly used along with MATLAB and Simulink. This is due to the vehicle model at Zeekr Tech EU already exist as a IPG CarMaker model, and the motion system models already exist as Simulink models. The wide simulation functionality of IPG CarMaker and how well it can be integrated into Simulink through MATLAB make these tools powerful. In this section, the three main simulation tools will be described further.

2.4.1 IPG CarMaker

IPG CarMaker is a CAE tool developed by IPG Automotive to be a simulation solution for the development and virtual testing of cars. The tool offers a virtual vehicle environment to model a complete vehicle's motions, kinematics, and compliance characteristics. Implementing physics equations in these areas brings the virtual vehicle's behavior closer to real-life behavior. The differences between simulated and real-life vehicles can be neglected with parameterization.

2.4.2 Simulink CM4SL

For further utilization of IPG CarMaker, a CarMaker for Simulink (CM4SL) extension is integrated. This allows models to be built inside of Simulink, which are then simulated in real-time from IPG CarMaker. This leads to high flexibility and customization of models. For instance, a complete motion system can be implemented. New motion system versions and the corresponding Simulink model can be implemented with the old inputs and outputs. Most often, the inputs to the model will follow a standard designation and, therefore, be straightforward to implement.

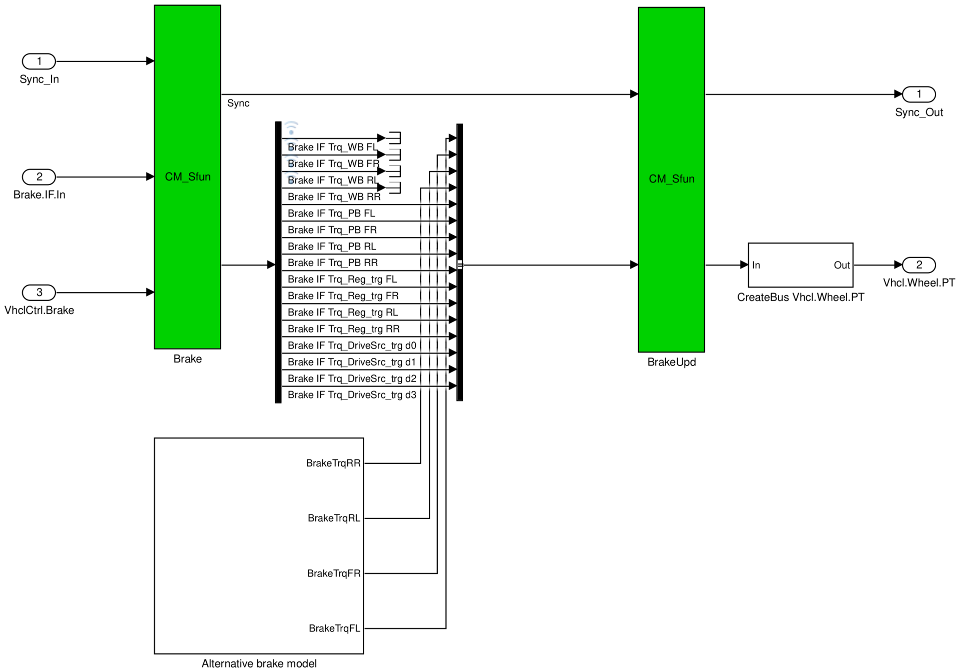


Figure 2.4: Example of an external brake model overriding the IPG CarMaker signals. This is how a Simulink model of a subsystem is implemented in IPG CarMaker for Simulink.

2.4.3 MATLAB

MATLAB is a desktop environment used for, among other things, iterative analysis. It uses a programming language that asserts matrix mathematics directly. MATLAB is also the environment on which Simulink is based, allowing for easy communication between them. Thus, MATLAB can be used to send parameters to Simulink and post-processing the data from Simulink.

Further with IPG CarMaker and Simulink configured and working together, MATLAB can be utilized to run and control the whole framework. The compatibility makes it possible for MATLAB to send ScriptControl commands to IPG CarMaker. The commands enable full IPG CarMaker control from MATLAB, just like using them inside of IPG CarMaker. From here, a code can be scripted to load the correct maneuver, send in the correct parameters (speed, μ, etc.), run the simulation, and extract the result from the simulation. At last the MATLAB code can also be scripted to directly plot, evaluate, and correlate the results.

2.5 Data analogy

To evaluate the relationship between the simulated data from SiL, HiL, and real data from ViL, there are different approaches. This thesis will mainly focus on functional requirements and not the non-functional requirements. Thus, performance requirements will not be studied, including brake distance, brake pressure, etc. In the early stage of vehicle development, gaining knowledge about the intervention strategies that work in critical situations is more important than the actual performance. However, it is worth noting that tuning the motion system's aspects becomes essential in the later stages of vehicle development to follow the requirements.

2.5.1 Correlation study

A correlation study is one way to measure the quality of the implemented vehicle models for the simulations. Pearson's product moment of the correlation coefficient [6], a statistical measure to evaluate the linear relationship between two sets of data, will be used in this project.

The correlation coefficient range is between -1 and 1, where 0 indicates no relationship at all between the two datasets. The closer the correlation coefficient is to ±1, the closer the similarity between the test results. As aiming for a positive correlation coefficient close to +1, negative proportionate relationships are undesirable in the analysis. The correlation study will be performed with certain KPIs, depending on the evaluated test scenario and sub-system. Eventually, it will be used to rank the implemented subsystem models and visualize the validity of the verification process.

2.5.2 Fast Fourier transform

As an addition to the correlation study, the comparison between the SiL and the measured data from ViL can be made through a FFT. This method of analysis [19] is used to convert the time domain of the measured data to a representation of the frequency domain. This approach allows for determining potential similarities between the simulated and measured data based on their respective characteristics. This can be especially valuable when evaluating the ABS function of the vehicle. Since the ABS valves work in a certain frequency domain during ABS intervention.

2.5.3 Intervention strategy

The study of the intervention strategy from ABS and ESC can verify whether the functions meet the requirements by evaluating and comparing simulated data with measured data from real-life testing. Since many factors affect performance in physical testing, it can be challenging to compare the level of performance in the simulated environment. Therefore, it is valuable to evaluate the intervention strategy to determine whether the functional requirement is met.

Data, such as wheel speed, yaw rate, steering angle, and brake pressure, offer valuable analysis and pattern recognition insights. Understanding the intervention strategy through data analysis can help recognize patterns and ensure proper functioning. This assessment includes measuring non-functional requirements to verify similarities in the safety systems' effectiveness, such as stopping distance, lateral and longitudinal accelerations, and the understeer gradient, ensuring the system's attributes.

2.6 Requirements and test scenarios

There are standardized test procedures for evaluation of the vehicle dynamics performance and to control whether the active safety systems (e.g., ABS and ESC) intervene or not. The test scenarios that will be used in this work and that are mentioned in this chapter come from the International Organization for Standardization (ISO), the National Highway Traffic Safety Administration (NHTSA), and SAE.

The braking system is a key contributor to the vehicle's longitudinal and lateral stability, which means that the braking system and its extensive functions must be evaluated with several test scenarios. The test scenarios can be, for example, braking maneuvers on various surfaces with varying coefficients of friction surfaces to test the intervention of ABS or even more complex, such as double lane change where the active yaw control is tested. The following chapter will describe the safety systems, the related test scenarios, and corresponding KPIs.

2.6.1 Braking system requirements

The braking performance is an important safety feature for the vehicle. One KPI [20] of the braking system is the braking distance, which can be heavily influenced by the vehicle characterization and the test environment, including the surface friction. The driver, or the performance of the Advanced Driver Assistance System (ADAS), also contributes to the performance of the vehicle's braking performance.

2.6.1.1 ISO 21994 - Straight-line braking with ABS

According to ISO 21994 [20], the braking system's performance is tested on the stopping distance and the mean deceleration with enough braking force to trigger the ABS intervention. The test conditions and test procedures are based on standardized principles, as stated in ISO 21994. Test methods determine the build-up phase of the braking and where the vehicle comes to a standstill from an initial velocity of 100 km/h on a high friction road surface. The normalized braking distance is the traveled distance from the initial brake pedal contact until the vehicle comes to a standstill. The test can be divided into two parts. The first, where the first velocity decrease of 10 km/h is seen as a normalized build-up phase. The second is the normalized distance under full ABS-controlled deceleration from 90 km/h to a complete standstill. The tolerance of the initial longitudinal velocity is 100 km/h $\pm$ 2 km/h at the time of brake application.

Determination of the normalized braking distance is calculated in the velocity range between 100 to 5 km/h due to the higher measuring accuracy in the specific domain of the used measuring equipment. The calculated mean deceleration shall be calculated according to formula 2.2.

$$a_x = \frac{v_1^2 - v_2^2}{2 \cdot d_x} \tag{2.2}$$

where

a_x is the calculated decelerations;

v_1 is the initial velocity;

v_2 is the ending velocity of the measurement;

d_x is the measured distance of the braking procedure.

2.6.1.2 ISO 14512 - Straight-ahead braking on split-μ

In addition to the previously stated test scenario in 2.6.1.1, the directional behavior of the braking system will be determined in ISO 14512 [21] under the influence of split friction road surfaces. The directional behavior of the vehicle should be considered since the course-holding capabilities for the driver or the ADAS will be highly affected in any braking scenario. As stated in ISO 14512 [21], the friction coefficients of the road surface will have a high impact on the course-holding ability of the vehicle. Ensuring vehicle safety involves maintaining stable course control during braking on all surfaces, regardless of road irregularities.

Braking on a split-coefficient road surface implies driving with the left and right wheelsets on one low-μ and high-μ surface characteristics, e.g., one wheelset being in contact with ice, roughness, or oil spills on the road and the other in contact with dry asphalt. Braking on a split friction surface could lead the vehicle to oversteer since the wheels on the low-friction part would lock up and, therefore, lose traction, causing the vehicle to rotate toward the side with higher friction.

The test track should be divided into low-μ and high-μ with at least a difference of 0.5. The brake test is then performed with one wheelset on each friction surface. Applying the brakes should occur as earliest as both applicable wheels are in contact with the low-μ surface. To ensure the validity of the test, it is important that the lateral deviation of the vehicle remains such that the vehicle does not cross the border between the two road surfaces. It is also essential that the steering wheel and accelerator are kept constant for the initial condition and remain held until the vehicle reaches a standstill. For the initial velocity for subsequent tests, it is recommended to obtain a constant velocity of 80 km/h ± 2 km/h, with increments of 10 km/h or 20 km/h. The steering wheel can move ± 3° during the observed period.

The characteristic values linked to braking on split coefficient surfaces determine its performance regarding yaw stability and yaw rate, °/s, and the vehicle's stopping distance. Measuring the achieved longitudinal deceleration against the yaw rate can be of great value.

2.6.2 Yaw and side slip control

Another important safety system of a vehicle is the control of yaw and side slip. This will help when a driver turns and brakes hard, e.g., with induced yaw disturbances.

The KPI for this function is mainly the lateral acceleration and yaw velocity. Similar to the braking system requirements, see chapter 2.6.1 above, the indicators can be heavily influenced by the same parameters, such as vehicle characteristics, test environment, the driver, etc. Therefore, these must be taken into consideration when the correlation is performed.

2.6.2.1 ISO 7975 - Braking in a turn

The braking performance regarding yaw and side slip control is, according to ISO 7975 [22], determined and evaluated by the mean longitudinal acceleration and yaw velocity with a set steering angle and enough braking force to trigger ESC. The test is carried out using a standardized procedure according to ISO 7975. A test is initialized with steady-state cornering at a fixed speed of 100 km/h. The vehicle is then decelerated down to 20 km/h with deceleration rates of 2 m/s^2, 3 m/s^2 and 5 m/s^2. The performance indicators are then calculated, correlated, and evaluated.

Determination of the mean longitudinal acceleration is calculated from the average value of longitudinal acceleration during each test. The value is calculated according to the formula 2.3.

$$-\bar{a}_X = \frac{v_{eff}^2}{2 \cdot d_{eff}} \tag{2.3}$$

where

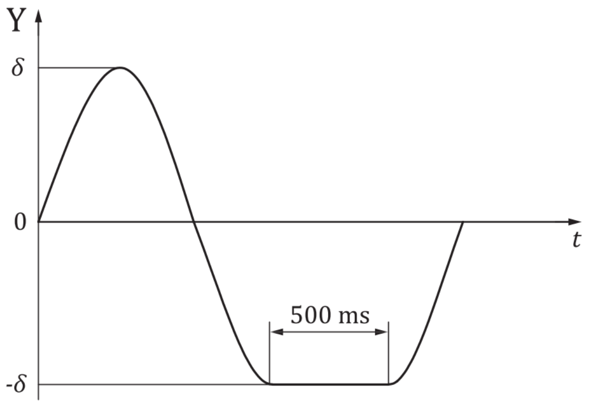
$-\bar{a}_X$ is the mean longitudinal acceleration in m/s^2;

d_{eff} is the actual braking distance, in meters;

v_{eff} is the actual initial velocity, in m/s;

2.6.2.2 ISO 19365 - Sine with dwell stability control testing

According to ISO 19365 [1], a specific steering maneuver is done at (80 ± 3) km/h to evaluate the stability of traction control. From this maneuver, the steering-wheel angle can be evaluated against yaw rate and lateral acceleration. The maneuver is standardized according to ISO 19365 with a specific steering input. A steering pattern of a sine wave with a frequency of 0.7 Hz and a delay of 500 ms at the second peak amplitude. Multiple tests are done with the steering pattern increasing by $13.5\deg/s$ until a lateral acceleration of 0.5 g is achieved. The test is performed once with clockwise steering and once with counterclockwise steering.



Key

Y	steering-wheel angle
t	time

Figure 2.5: Steering-wheel input for a sine with dwell test [1].

The stability criteria are evaluated according to the ISO 19365 by:

a. "The value of yaw rate measured 1 second after the Completion of steer (COS) time shall not exceed 35% of the value of the first peak value of yaw rate recorded after the steering-wheel angle changes sign."

b. "The value of yaw rate measured 1,75 seconds after the COS time shall not exceed 20% of the value of the first peak value of yaw rate recorded after the steering-wheel angle changes sign."

If these criteria are fulfilled the stability traction control is considered stable according to ISO 19365.

2.6.2.3 ISO 3888-1 - Double lane-change

According to ISO 3888-1 [23], the stability traction control's performance is determined and evaluated by the steering input over time and the entry speed while keeping the vehicle inside the track. The test is standardized according to ISO 3888-1. The test course is divided into sections with dimensions set according to the standard based on the vehicle geometry. The testing can be done using two different methods. The first test is conducted at an entry speed of (80 ± 3) km/h, while the second test is performed at the maximum speed possible to complete the course. The throttle is held stable in both cases, and the steering inputs, driver control strategies, and vehicle performance are evaluated. Thus, certain aspects of the road-holding ability of a vehicle can be evaluated.

3

Methods

To acquire a way of working for the Virtual Verification Framework, a method needs to be established to study the implementation, verification, and analysis of a vehicle motion system. The main steps of the method are presented in figure 3.1.

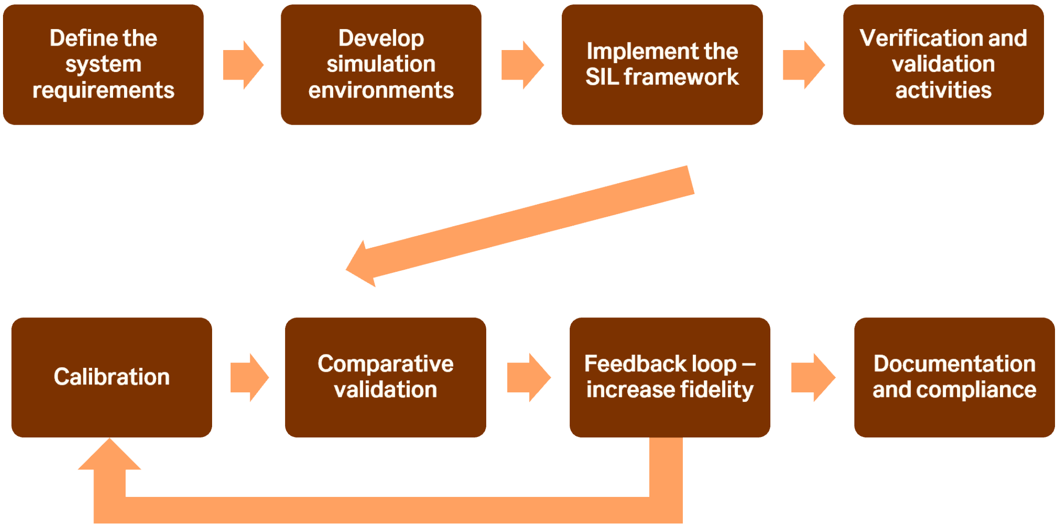


Figure 3.1: Overview of the methodology for the study of a virtual verification process.

3.1 Define the system requirements

The specified requirements are set by the product and function owners at Zeekr Technology Europe. These come from stakeholders, attributes, legal, function, and functional safety requirements, which are constantly evolving with markets and the customer's interest. Requirements on the ABS, ESC, and the TCS are key functions in the development of vehicle motion sub-systems such as braking, steering, and propulsion. The stated sub-systems all work cooperatively in scenarios where ABS, ESC, and the TCS are activated. To be able to verify the tested simulation model, it is necessary to gain knowledge of the verification process and its key performance indicators.

In the development of these systems, there are both functional and non-functional performance indicators to verify the requirements. Since this thesis is narrowed down to test specific sub-systems, the focus will mainly be the characterization of the sub-system's behavior and not the overall performance of the vehicle. Therefore, implementing one sub-system at a time will be the way of working. The key in the early stage of the systems development is to be able to decide that the functional requirements are met rather than verifying the performance, hence the difficulties in predicting that the complete vehicle model is true to the future reality.

3.1.1 Straight-line braking

The ABS should intervene in straight-line braking, whether it is a driver or an autonomous system that applies a hard brake request. In most cases the wheels will lock up regardless of whether the surface is icy, wet, covered in gravel, or even in perfect weather conditions with dry asphalt. The ABS will intervene as soon as the braking forces are at the limit of adhesion between the tires and the road surface. The ABS function should also adapt to the shifting road conditions in terms of varying road friction and vertical forces, meaning that it should be able to function at low mue as well as high mue. It is crucial for the braking performance that the ABS is tuned to intervene fast enough but without excessive wheel slip in the initial braking phase. The ABS function should also be able to compensate for the tires and loading conditions on the vehicle, and still perform well.

One key performance indicator in straight-line braking, where the ABS function should intervene, is yaw torque. Depending on variation over the contact patches between the four wheels, split-μ can be detected. Split road surface coefficient is common in icy and snowy conditions or with puddles of water, which can lead to aquaplaning and, consequently, lead to yaw torque build-up. It can also be concluded that the slip on the front axle should be less than that on the rear axle, resulting in increased yaw stability.

3.1.2 Braking in a turn

In addition to the straight-line braking, the ESC function must also consider the steering wheel angle. Braking heavily while cornering increases the risk of oversteering due to the forces acting on the vehicle. The forces acting on the vehicle while braking will move the grip distribution towards the front outer wheel. Hence, it would imply an unstable rear of the vehicle and increase the risk of oversteering. The main effect of the ESC is to create an understeering yaw torque with lateral brake force distribution between the inner and outer wheels.

Potential oversteering is detected by monitoring yaw rate and the slip on the inner and outer wheels and comparing the slip on the rear and front axles. An increasing yaw rate can be seen as an unwanted reaction from the vehicle while braking, and the increased difference in yaw rate versus steering wheel angle should trigger the ESC to intervene. A higher slip on the rear wheels would signify a dangerous situation where the vehicle will most likely oversteer. The available grip on the inner and outer wheels shall also decide what strategy the function should use to reduce the oversteer, thus a varying brake pressure distribution between the wheels. An oversteer situation can be counteracted by braking both or one of the outer wheels, depending on the slip level at that specific time and the intervention strategy.

3.1.3 Double lane-change

With its highly dynamic steering wheel inputs, the double lane change is a verification method that tests the vehicle's safety systems where over- and understeering occurs. The lateral stability is tested in the double lane change to test the vehicle's maneuverability. The test is performed to verify the ESC and vehicle dynamics characteristics. When performing the double lane change, the ESC is designed such that it should cease the over- and understeer situation and maintain a stable course and assist the driver to control the vehicle. This can be done by reducing propulsion to a specific wheel at a certain critical point. The main objective with the ESC is to stabilize the vehicle regarding lateral stability.

the ESC and vehicle dynamics characteristics

The ESC shall intervene when there is undesirable yaw torque build-up, thus helping control the vehicle in the desired direction. The function shall also help the driver turn in the vehicle when understeering occurs. As in the previously mentioned test scenarios, the ESC depends on the steering wheel angle, torque from the propulsion system, already applied brake pressure, and the understeer gradient. One crucial part of the ESC is that it will, dependent on the intervention strategy and the scenario, brake on either wheel to keep the vehicle on the desired path. The ESC does not only control the vehicle with its braking system, but also with added or reduced torque from the propulsion system.

3.2 Develop simulation environments

The core of a virtual verification framework are the simulation tools which are used to simulate reality. Thus, choosing the right software for the verification process is very important. At Zeekr Tech EU, the vehicle simulation software IPG CarMaker is widely used. More specifically, the HiL team uses the software with an existing vehicle model, making the choice of IPG CarMaker very clear. This facilitates sharing maneuvers between teams and easily running the same tests in both HiL and SiL environments. IPG CarMaker allows for specific system implementation, for example an specific brake model, but the compatibility of extending IPG CarMaker to be used with Simulink is more powerful. This allows for straightforward signal manipulation and implementation of a specific motion system. Zeekr Tech EU possesses a Simulink model of their brake model, making the use of Simulink and IPG CarMaker very fitting. Thus, the wheel brake torque signals to the individual wheels from the supplied brake model can be implemented.

3.2.1 Straight-line braking including split-μ conditions

The straight-line braking is tested according to ISO 21994. The test environment is set up in IPG CarMaker with a wide and long road for the ability to test without the vehicle ending up outside of the road. Inputs such as road surface friction will be changed according to the built-in function "Bump Friction". The road surface friction will vary depending on the received test data from ViL testing and can also be parametrized according to a split road surface friction condition. The vehicle velocity, road surface friction, and applied braking ratio are set from the MATLAB script. The split-μ surface is visualized in figure 3.2.

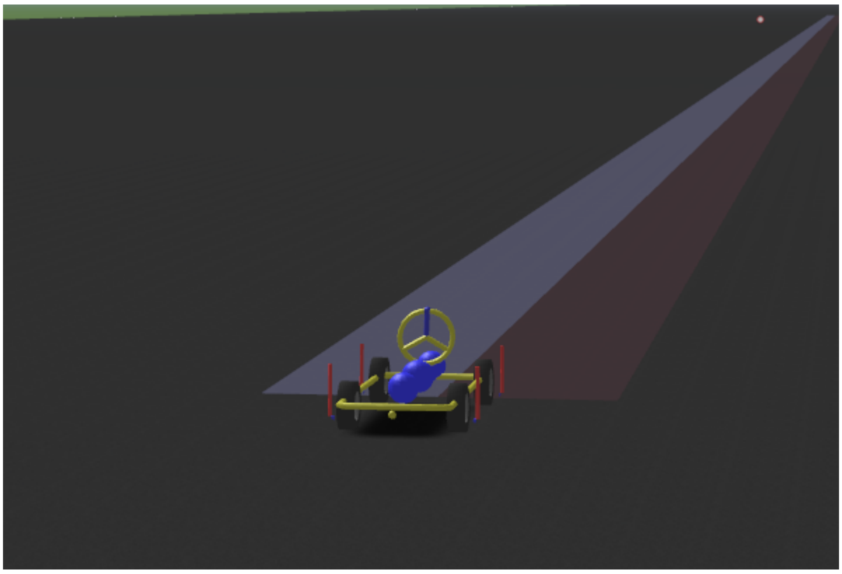
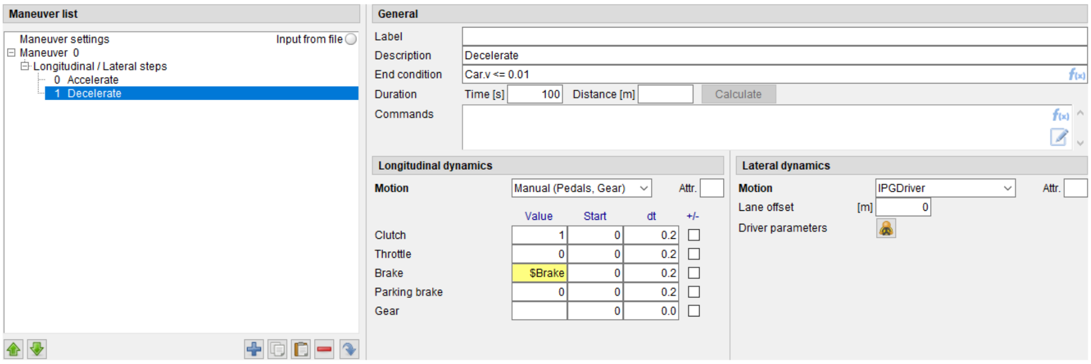


Figure 3.2: A visualization of the test track used for the straight-line braking and the bump friction pads.

The IPG driver model parameters are set such that the driver is accelerating longitudinally at a maximum of 3 m/s^2 and braking according to the brake pedal position when the test track start is reached according to the set braking ratio. The IPG driver model is used in the test since a need for a steering intervention will emerge in a braking scenario on split road friction coefficients. Hence, it can be seen as a closed-loop control. The maneuvers are set according to figure 3.3.



Maneuver settings
Input from file ○
Maneuver 0
Longitudinal / Lateral steps
0 Accelerate
1 Decelerate

Label:
Description: Decelerate
End condition: Car.v <= 0.01
Duration: Time [s] 100 Distance [m]
Commands:

Motion: Manual (Pedals, Gear) Attr.

	Value	Start	dt	+/-
Clutch	1	0	0.2	☐
Throttle	0	0	0.2	☐
Brake	$Brake	0	0.2	☐
Parking brake	0	0	0.2	☐
Gear		0	0.0	☐

Motion: IPGDriver Attr.
Lane offset [m] 0
Driver parameters

Figure 3.3: The maneuver list for the straight-line braking test where the brake ratio is imported from MATLAB, and IPG Driver stands for the lateral motions.

3.2.2 Brake in turn

The test case of the corner braking is performed as explained in ISO 7975:2019. The test track is initially designed according to the standard, with a 100 m radius circle, and holds a split friction pad to further evaluate the ESC. Since the vehicle testing will be performed according to the ViL test engineers' preferences, the test track will vary in radius, longitudinal velocity, and even lateral acceleration to some extent. According to ISO 7975:2019, the initial longitudinal velocity is set with respect to max lateral acceleration of 5 m/s^2. Further, there is the possibility of additional test runs with increasing steps of 1 m/s^2. The test track can be seen in figure 3.4.

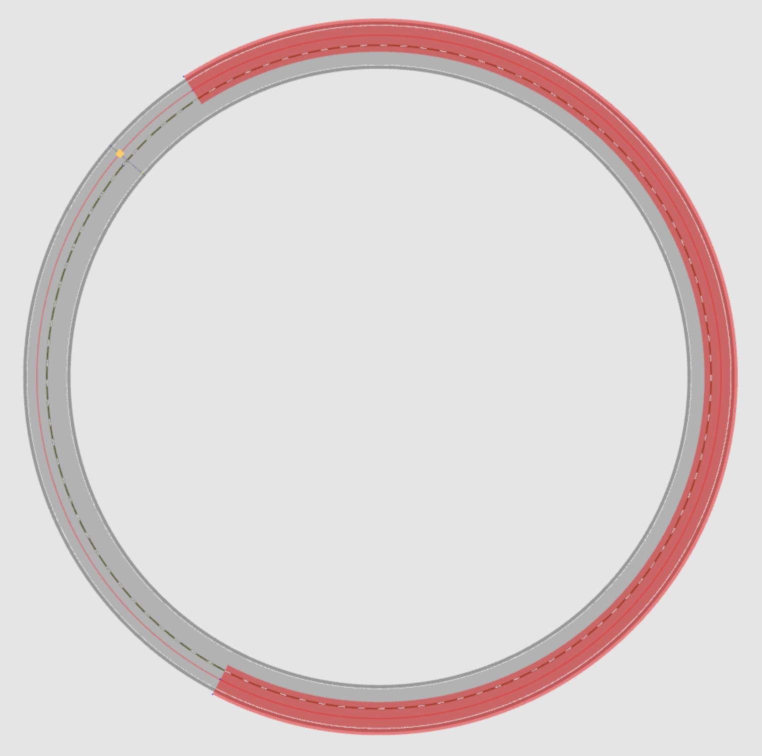


Figure 3.4: A visualization of the test track used for the corner braking scenario with its friction surfaces.

As in straight-line braking, bump friction is used to effectively perform a split road surface friction condition. Since this test will be performed as a closed-loop control, the IPG Driver will control the vehicle laterally in the corner braking scenario. The longitudinal controls are performed in straight-line braking, with initial conditions, the applied brake pedal ratio set from MATLAB, and a closed-loop steering controller by the IPG driver.

3.2.3 Double lane-change

The DLC is performed according to an open-loop input from the driver or test robot made in a previously performed test at a test track. The steering input is recorded from the real-life driving and implemented in the Simulink model. The IPG Driver will control the vehicle until the initial conditions are reached. Thereafter, the measured steering wheel inputs are used to replicate the scenario. With the same initial conditions and steering wheel inputs, the resulting lateral forces should be equal.

3.3 Integration of SiL framework

After the high-fidelity models are received and the suitable simulation software is selected, they need to be integrated into a unitary system.

3.3.1 Implementing the model

The received Simulink model of the brake system is integrated into the CM4SL template of a new IPG CarMaker project. This is done according to model specifications. The output of the model is brake torques to the different wheels of the vehicle. The standard signals in the Simulink environment are overridden with the signals from the model, as seen in figure 2.4.

Further, the model must also be implemented with the correct inputs from the simulated vehicle to work properly. It is important to collaborate with both the model source and stakeholders involved with the model development to find the correct signals. A set of signals needs to be time-variable signals from the simulated vehicle, for example, the actual steering wheel angle. Another set of signals is a constant value signal that the BCM needs to be in the correct state. One core signal-value is, for example, drive mode, which needs to be set to the correct value for the BCM to know the car is in driving mode. Another one is as simple as the correct battery voltage input. The list of desired signal-values is long which makes it important to implement sufficient and correct signals carefully.

3.3.2 Maneuvers in IPG CarMaker

With the model implemented, IPG CarMaker can now utilize it to run simulations. A vehicle model for IPG CarMaker is received from Zeekr Tech EU. With the complete vehicle and the appurtenant parameters in IPG CarMaker, the signals from the received brake system can be integrated into Simulink.

With the vehicle configured, the rest of the environment inside IPG CarMaker can be built. The maneuvers are set up according to the different ISO standards explained in chapter 2.6. For each maneuver, a fitting road is created. For the straight hard brake a long road is needed, for the curve brake a road with the correct radius and for the ESC a long and wide road is needed.

3.4 Verification and validation activities

At this stage in the Virtual Verification Framework, the process is automated. The input parameters and test cases are set up from MATLAB according to the ISO standards and company requirements. Multiple tests are performed back-to-back to compare the fulfillment of different functions. From these tests, signals of interest can be plotted to see the system's behavior.

3.4.1 ABS verification

The already mentioned test scenarios, straight-line braking and straight-ahead braking on the split coefficient of friction surfaces, are used to evaluate the ABS function. To verify the ABS system, there are multiple signals of interest. The first one is the individual wheel speed. It is interesting to see if there is a sudden drop in wheel speed when the brake is applied and if it decelerates according to company requirements. It is interesting to study the wheel slip along with the wheel speed. If the simulation experiences full wheel slip, the ABS is not working, and if there is low wheel slip or none, the ABS is working poorly. Further, the brake pressure is of interest to be studied. Firstly, check that it is building up pressure according to requirements, and secondly, see that it rapidly cuts off pressure, as an ABS should do when in use. An example of the measured and estimated slip, with the applied brake pressure, can be seen in figure 3.5 below.

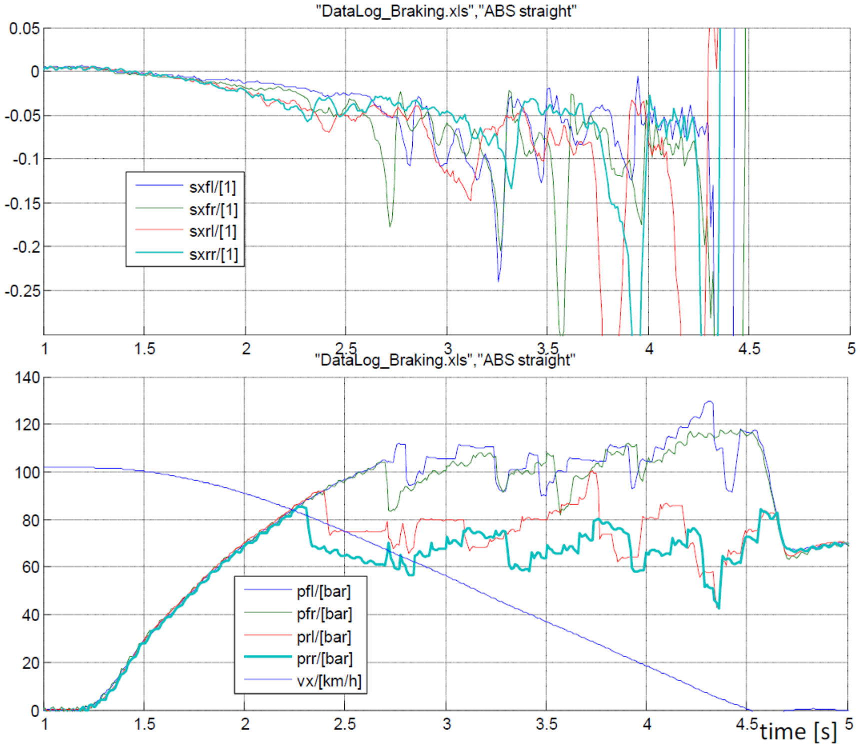


Figure 3.5: The slip on each wheel is represented in the top graph, while the brake pressure is seen in the below graph from an ABS intervention. [2]

From the logged data, which is represented in figure 3.5, it can be seen that when brake pressure is built up, it increases the slip ratio. Eventually, the brake pressure will increase to a point where the system detects an extensive slip ratio on a certain wheel. This should result in a pressure drop, since the ABS valve reduces the pressure on the specific wheel. It can also be seen in the represented curves of the four wheels, that the pressure is adjusted frequently to adapt to the surface friction and the slip ratio. A good example of how it should work can be seen at approximately 2.7 seconds, where the front right wheel slip ratio has decreased to a exalted level. The brake pressure can be seen dropping in the same moment, which is the intervention to reduce the amount of slip.

3.4.2 ESC verification

The earlier described test scenarios brake in turn (ISO 7975), DLC (ISO 3888-1), and sine with dwell (ISO 19365) can be used to evaluate the ESC and vehicle dynamics characteristics. The ESC is a broader system than the ABS and thus not as straightforward. The same signals can however be used to verify that it works as it should. As in the evaluation of the ABS function, it is also required to gather data from the wheel speed sensors, leading to the estimation of wheel slip. Additionally, the steering wheel angle is required to be monitored since it provides information about the desired path of the vehicle. In addition to the mentioned sensor signal, brake pressure, torque request of the propulsion system, and the lateral and longitudinal accelerations are monitored.

Depending on the situation with varying slip ratio on each wheel, the steering wheel input, and other forces acting on the vehicle, various ways of ESC and Traction Control (TC) interventions will exist. When performing a test of the ESC system, the brake pressure is studied to see if it is intervening as intended. A normal behavior is that when oversteering, the rear inner or front outer wheel must brake to straighten the car. During DLC several interventions occur, as seen in figure 3.6 where the brake pressures are elevated.

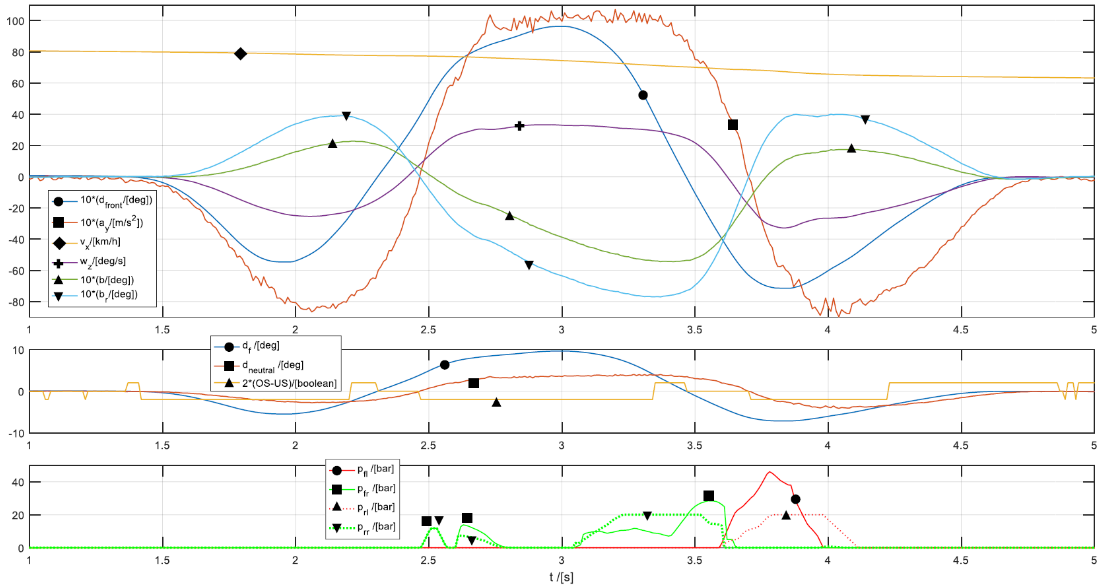


Figure 3.6: The upper graph represents the vehicle's motion, the middle represents the under- and oversteer coefficient defined from the neutral steer, and the lower visualizes the applied brake pressure on each wheel. [2]

Figure 3.6 shows that stability interventions are required for a DLC maneuver. According to the yellow curve in the middle graph, the vehicle will oscillate between under and oversteering behavior, depending on which inputs are made and how the lateral forces affect the vehicle. The driver has, at approximately 1.5 seconds, initiated a left turn. This creates a negative lateral acceleration, and the vehicle understeeres until 2.2 seconds. When the driver makes a rapid directional change, the vehicle starts to oversteer slightly, and the ESC helps redirect the vehicle in the desired path. It can be seen from the applied brake pressure on the front outer wheel and the rear wheel. To help reduce the oversteering of the vehicle, there is an increased brake pressure on the outer front wheel. This behavior from the ESC is expected to help the vehicle turn and reduce the risk of oversteering. It can be deducted from the figure above that the ESC intervenes, and a pattern recognition can be made.

3.4.3 Validation in MATLAB

MATLAB is further utilized to postprocess the data from the IPG CarMaker simulation. This allows for the plotting of the signals of interest. The signal values are plotted against time and can thus be visualized. With engineering judgment, it is possible to see straight from a brake pressure plot if the ABS works.

3.4.4 Future-proof

When the framework is up and running, it is easy to implement new deliveries of future models. All the input and output signals already found and determined are transferred to the new model. If signals are changed, the old signals are replaced with new signals. The parts around the actual model stay the same. The project in IPG CarMaker does not need to be changed, and the MATLAB script can stay the same.

3.5 Calibration of the SiL

When the model is fully implemented, calibration is needed to compare it against data for real-world testing. The problem when evaluating simulations is that they are perfectly executed under ideal conditions. This is not the case in real-life testing, which makes the simulation data less relevant. To achieve more realistic data, it is essential to ensure that the simulations are run under conditions that closely replicate real-world scenarios. This includes accounting for the same road friction and environmental conditions present during physical testing. However, this process is not about calibrating the model or the simulation environment but ensuring consistency across different testing scenarios. It is important to simulate all levels of road friction to validate the model thoroughly. Calibrating models based solely on measured signals can be problematic, as it may not account for all influencing factors, potentially leading to inaccurate representations.

3.5.1 Calibration of the model

The model could be correctly implemented but still not give reality-like results. Thus, something corrupt with the logic created inside the model could exist. There could also be losses that are not accountable for or incorrectly modeled, like friction or inertial losses. Reality can thus be very complex to model, which can lead to incorrect models.

3.5.2 Calibration of the simulation environment

The next step in the framework is to correct the simulation environment. One important value to consider is the road friction value, μ. In real life, the μ could fluctuate from patch to patch on the road surface. Further, the tire and road temperature can vary, making it hard to replicate in simulation. Therefore, it is important to calibrate the friction surface correctly to the desired driving case.

When the road friction and tire parameters are calibrated, the focus can shift to the next area needing adjustment. It is hard to maintain a fixed speed when entering a maneuver, and it is also hard to maintain a correct steering angle or fix brake pedal pressure. Therefore, it is also important to calibrate for human error in the simulation environment. This can be done by inducing noise in the different human-affected values. This will account for small discrepancies created by the driver.

3.5.3 Choosing a level of fidelity

When calibrating the SiL environment, there can be large amounts of man-hours and funds to make it perfect. What is important is that there needs to be a clear line on when to stop calibrating. The main purpose of the virtual verification framework is to verify functions. To be able to do this, there is no need for a perfect correlation between simulation and reality. It may be sufficient that the trends and behavior are alike rather than that the performance is perfectly the same. This will be enough to verify that various functions are doing their job. Therefore, it is important to consider that the model and the simulation environment do not need to be calibrated to the point that it correlates perfectly with reality but enough that the same behavior is experienced.

Another important aspect to consider is that a company is profit-driven. Higher fidelity means more expensive development and expensive simulation runs. If the functions can be verified at a lower fidelity, there is no need to invest further in reaching higher fidelity. It is also important to consider the lead times. A vehicle company needs to deliver new products fast to keep up with the market, thus the investment of time needs to be considered. Further, it is important to consider what higher fidelity gives us. If the simulation only has a small difference in stopping distance from reality, there is probably no need to perfect the simulation.

3.6 Documentation and compliance

Finally, thorough documentation is essential. To ensure the faithfulness of the simulation model results, all the test data and appurtenant inputs must be saved systematically and securely. This information is essential when the models are evaluated for their trustworthiness in a future review. It will also facilitate future revisions of the models and aid future attempts at improvements.

Within the automotive industry, regulatory compliance with the different industry standards is significant for the development of vehicles. Following these standards and adapting when new guidelines are released is highly important. This assures that simulation results are future-proof and continuously meet strict industry standards.

Following documentation principles and regulatory compliance will lay a solid foundation for continued innovation and refinement of the virtual verification process. By assuring that all the test data and corresponding inputs are saved in the correct manner and that all relevant regulatory requirements and industry standards are fulfilled, the framework can guarantee the integrity and fidelity of the SiL system.

4

Results

The results from the thesis are presented in this chapter. The results include a way of working according to the Virtual Verification Framework for Vehicle Motion Systems and the performed tests for the specific motion system. Each test is evaluated according to the general requirements. Additionally, discussions are included of the interpretation of the results. The results from straight-line braking, braking in turn, and DLC are evaluated. The extent to which the models can be trusted and how they should be used are included.

4.1 Way of working

When receiving a new model, the model should be implemented in a certain and trusted way. Also considered is how to interpret the data from the results. The performed work in this project is described in chapter 3, whilst this section briefly describes the implementation process and the do's and don'ts according to figure 4.1, seen below.

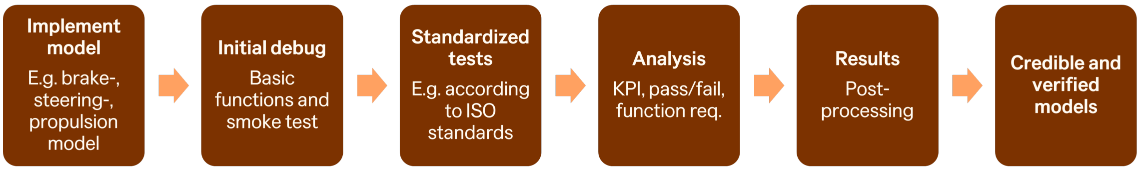


Figure 4.1: The resulting flowchart of the Virtual Verification Framework for Motion Systems.

The results from the verification process will be described in the next part of the report. They will be interpreted and discussed according to the general requirements that are mentioned earlier. It will also be evaluated whether the desired KPI's can be used or not. Because of confidentiality, the used software versions, the graphs, and their sensitively associated values will be undisclosed.

4.1.1 Implement model

With the delivery of the model and the included documentation, implementing the motion system model is expected to be straightforward. When implementing the model, errors can occur in both Simulink and IPG CarMaker. The model source is anticipated to support the implementers in this stage. The following bullets can be seen as a standard procedure in the Virtual Verification Framework:

- Setup a IPG CarMaker project with the relevant vehicle model and the parameters gained from kinematics and compliance.
- Implement model according to instructions regarding input parameters and variables, such as virtual sensors and initial conditions for the correct functioning of the vehicle modules.
- Implement CM4SL, which overrides the standard IPG CarMaker signals. It is important to change the parametrization settings of IPG CarMaker.

4.1.2 Initial debug

This section can be seen as a smoke test of the implemented model. After the implementation, it is crucial to see whether the simulation even starts and if it is deterministic. If not, the sub-system model could be faulty.

- Initialization of simple maneuvers in IPG CarMaker.
- Perform multiple repeated tests to see if the model is deterministic.
- Check several output parameters, such as ABS and ESC on/off, brake pressure, accelerations, applied brake pedal ratio, steering wheel input, yaw rate, etc.

4.1.3 Standardized tests

Several crucial functional requirements must be tested according to the implemented sub-system. Gather information regarding the requirements and the expected behavior of the system. Depending on the tested sub-system, there will be different standardized test scenarios. The way of working and some general testing of the brakes, steering, and propulsion can be:

- Gathered function requirements from function and attribute owners. These should have the best knowledge of the desired behavior of the systems.
- Test according to commonly used scenarios by test engineers and ISO/ SAE verification methods, such as:
  - Straight-line braking
  - Braking in a turn
  - Double lane change

  - Obstacle avoidance
  - Sine with dwell
  - J-turn

4.1.4 Analysis

The tests are analyzed according to the already mentioned standardized tests. With gained knowledge of the requirements and the performed tests, the results will be interpreted regarding the following data:

- Key Performance Indicators
  - Front and rear slip
  - Yaw rate
  - Systems activation
  - Brake pressure
- Fast Fourier Transform or Power Spectral Density
- Correlation study
- Pattern recognition of the system's intervention

4.1.5 Results

It is necessary to save all test results for the tested versions. Updated versions must be regression tested and checked against the present requirements. Hence, the input data and performed tests must also be saved to repeat the exact scenario.

4.1.6 Credible and verified models

Since this framework is mainly focused on the early stage of vehicle development, the vehicle model's level of maturity is sufficient to only be good enough to represent a plausible simulation. With the information gained about the system requirements, correlation study, and expected behavior, it can be deducted if the model performs well.

4.2 Verification

One of the crucial parts of this project is to use valuable and interpretable KPI's. The results will be evaluated according to correlation studies, FFT and to study the intervention strategies. As mentioned, the intention is to use this framework in an early stage to gain knowledge about the sub-system by itself and thereby be able to verify the functional requirements.

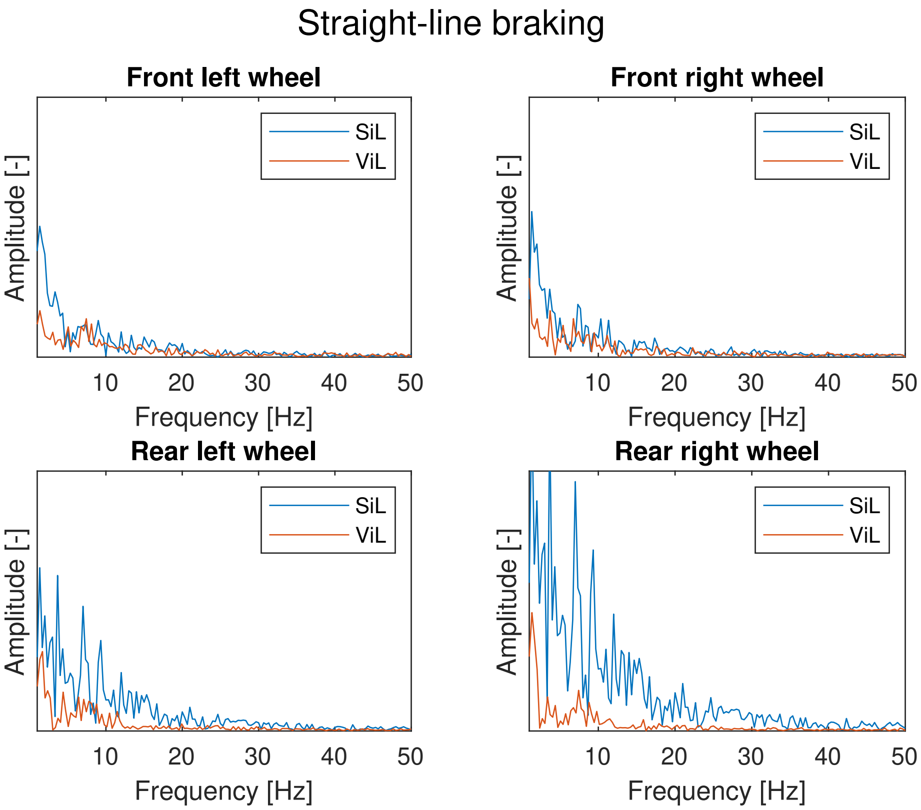


Figure 4.2: These graphs represents each wheel's FFT on the brake pressure from SiL and ViL.

What can be seen in figure 4.2 is that the frequency information is not focused on a specific frequency domain. A higher amplitude at approximately 5 – 15 Hz would imply an ABS intervention from the brake scenario due to the frequency of the ABS valve. Since the data is spread and varied across the domain with no specific amplitude at a certain frequency, the FFT will not be used as an analysis tool for the results.

4.2.1 Straight-line braking

Straight-line braking results include brake pressure, slip ratio, and wheel speed. The tests in SiL and ViL are performed on high-coefficient-of-friction surfaces with summer tires in a full-brake scenario from 100 to 0 km/h.

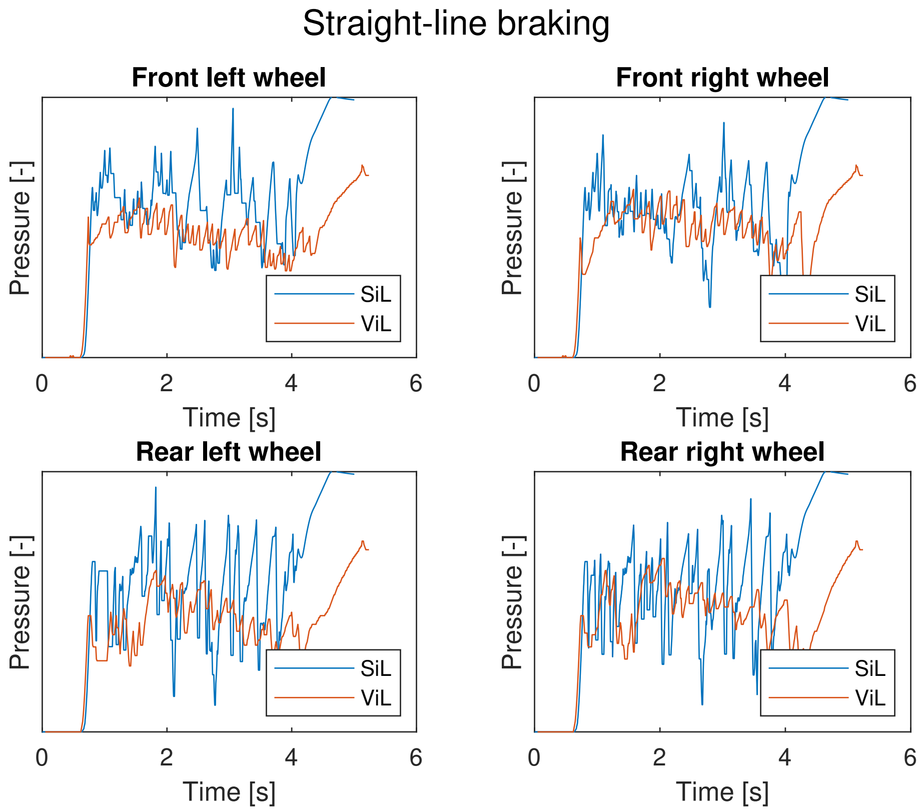


Figure 4.3: These graphs represent the brake pressure on each wheel from both SiL and ViL.

What can be seen in figure 4.3, is that the hard brake event triggers the ABS function in the vehicle, due to the fluctuating graphs of the brake pressure. It should neither be at constant pressure nor drop to an extent where the braking efficiency decreases. With the noticeable fluctuations on both SiL and ViL, it can be interpreted that the dropping of brake pressure is performed when there is a large slip increase, as seen in figure 4.4.

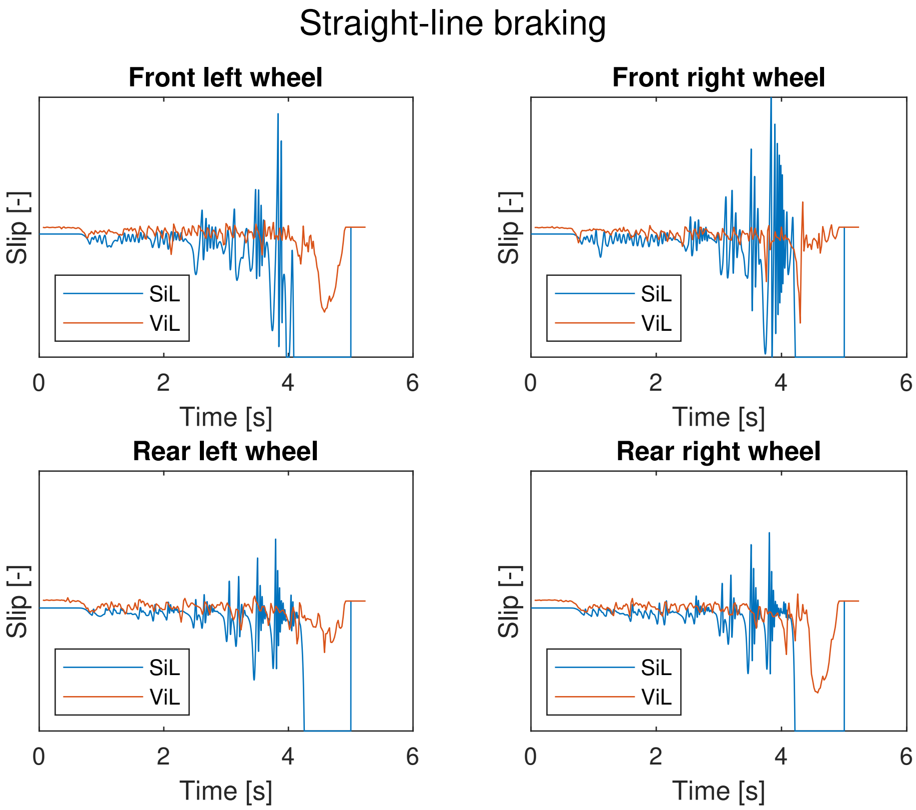


Figure 4.4: These graphs represent the wheel slip plotted over time for each wheel from both SiL and ViL.

As seen in figure 4.4, is that the slip ratio does not reach full slip in the hard brake scenario. Hence, the ABS function is working as intended. With fully applied brake-pedal and the function of regulating the brake pressure on each wheel, dependent on wheel slip, result from a working ABS.

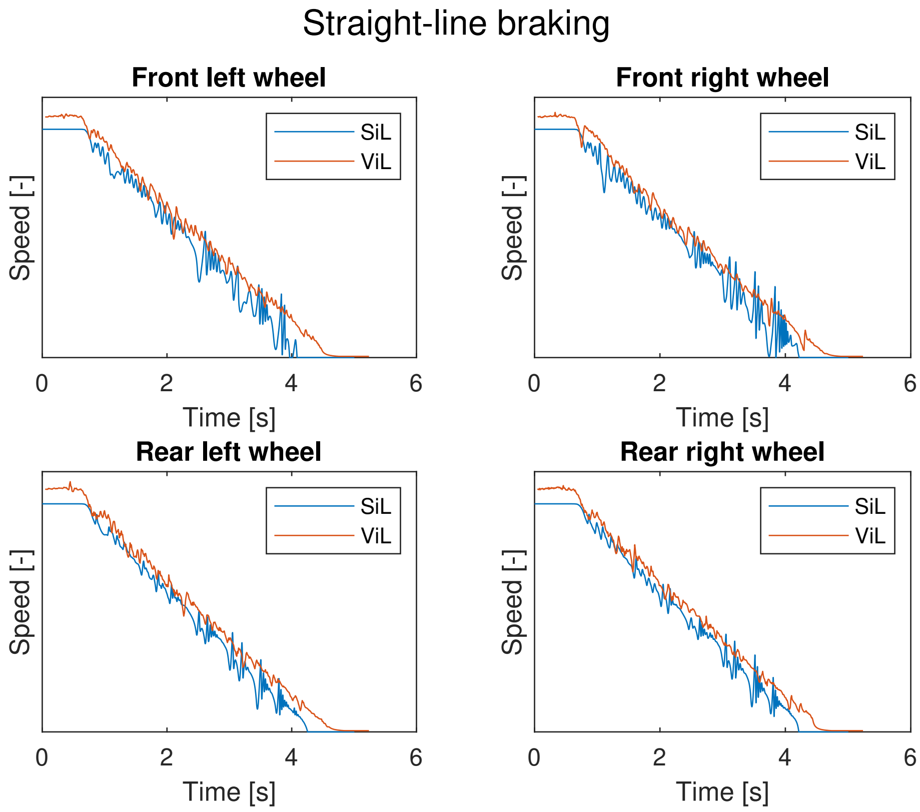


Figure 4.5: The four graphs represent the wheel speed on each wheel from both SiL and ViL.

The fluctuating decrease in wheel speed is caused by the ABS valve adjusting the brake pressure on each wheel. It can be seen that the wheel speed stays out of the full-wheel lock-up and adjusts the brake pressure to maintain the slip ratio. Even though the peaks and valleys of the SiL do not match ViL, it can be interpreted that the function is working as intended due to the evenly decreasing wheel speed.

4.2.2 Braking in a turn

The ESC is evaluated using brake pressure, slip ratio, and wheel speed information. The full brake will be made in a left turn. Here, it can be found that the results will vary due to the simulation model being equipped with summer tires, whilst the vehicle testing is performed on a low coefficient of friction surfaces. Even though the different conditions in SiL and ViL, it is of great value to see how the tire model affects the results.

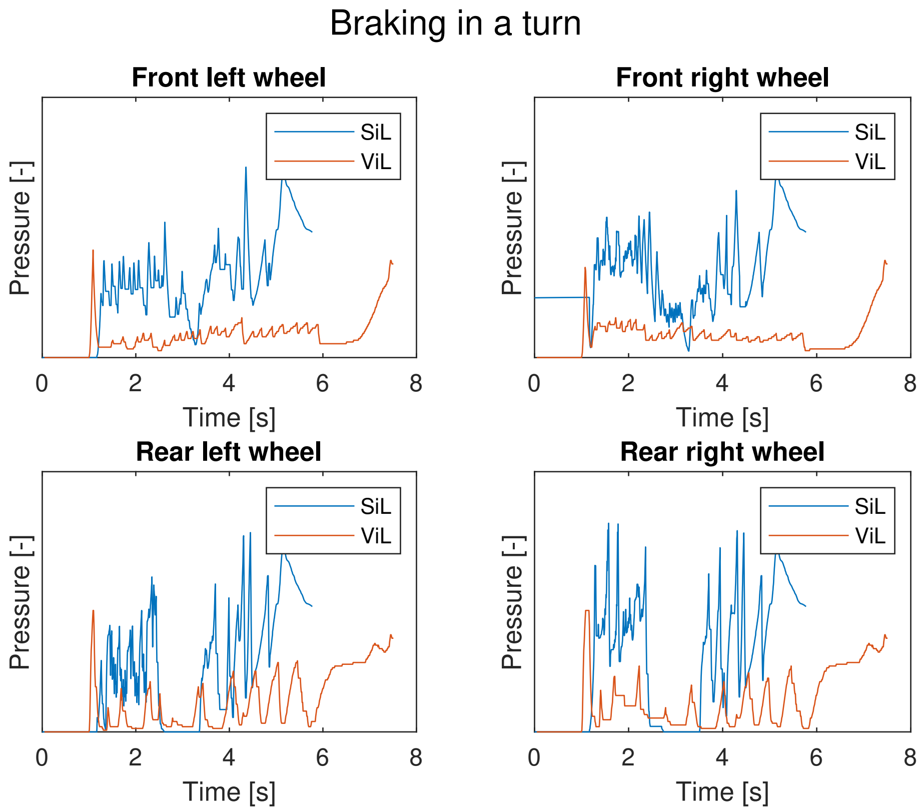


Figure 4.6: This figure visualizes the brake pressure from the braking in a turning scenario, where the blue curve represents the simulated, and the orange curve represents the vehicle tested results.

The results from the simulated brake pressure in figure 4.6 show that the initial conditions with a different tire setup and coefficient of friction surfaces affect the results immensely. An expected outcome is that the brake pressure in the SiL will reach a higher amplitude due to the higher coefficient of friction surfaces. It can be seen before the braking action that the front right wheel has an increase in brake pressure. The ESC has detected a yaw stability error and, therefore, applies brake pressure on one of the wheels even though the brake pedal is not applied by the driver. This is because the stability intervention is applied on the front right wheel to counter the oversteer.

The driver applies the brake pedal at approximately one second into the test. At that moment, it can be seen that both outer wheels' pressure reaches a higher amplitude; hence, the ESC intervenes in the resulting oversteer situation. The ESC can also be seen correcting from an over- to understeer situation at the valleys of the applied braking pressure on the outer wheel approximately 2.5 seconds into the scenario. The results will be seen to vary between SiL and ViL, but on the other hand, the pattern can be recognized as an ESC intervention in both. This ensures that the brake system functions as intended, thereby making the model credible and verified regarding yaw stability.

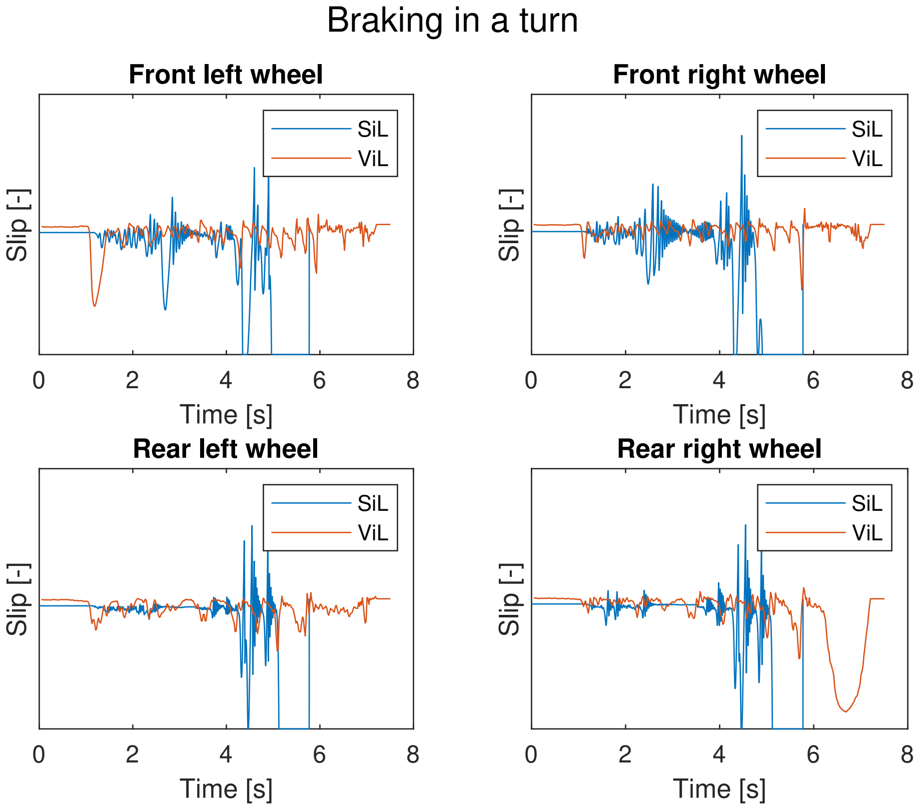


Figure 4.7: These graphs represent the wheel slip on each wheel from both SiL and ViL in the braking in a turning scenario.

What can be seen in figure 4.7 is that the brake pressure distribution is adjusted by the ABS and the ESC according to the slip ratio. The front wheels can be seen locking up at 2.5 seconds, which correlates to the pressure drop in figure 4.6.

By looking at the vehicle test results, it can be stated that the lower coefficient of friction surfaces impacts the slip ratio when applying the brake pedal. The inner wheels' brake pressure drops as expected to counter the decrease in wheel slip. Compared to the simulated results, the slip ratio stays stable until it reaches a certain low speed. The reason for the fluctuating slip ratio of the simulated results could be that summer tires are used on relatively low coefficient of friction surfaces. The real-life test is performed with winter tires in snowy conditions, whereas the simulation is performed with summer tires on 0.5 μ.

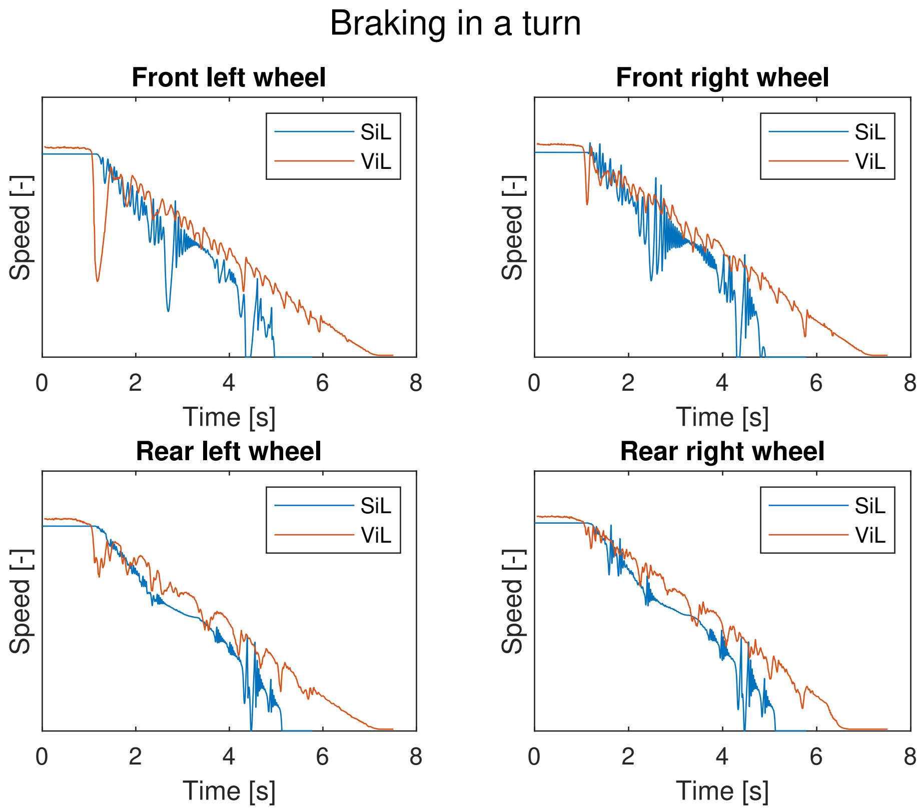


Figure 4.8: The four graphs represent the wheel speed on each wheel from both SiL and ViL in the braking in turn scenario.

Even though the decrease in wheel speed differs substantially, comparing SiL and ViL, it can be stated that the ESC works. It can be seen in figure 4.8 that ESC regulates the brake pressure, addressing the yaw stability criteria with an uneven wheel speed decrease on each wheel. The system's performance cannot be deducted from the simulations since significant factors vary, e.g., the complete vehicle is not modeled, the specific motion system is not fine-tuned, etc.

4.2.3 Double lane-change

The DLC also contributes to the verification activities of the ESC system. Compared to the braking in a turn scenario, the driver does not activate the brakes. The brakes are applied by the ESC to intervene under and oversteering situations. Additionally, the steering wheel input in ViL is used as the input also in the SiL to replicate the driving path.

taken from the ViL test to replicate the driving path as equally as possible.

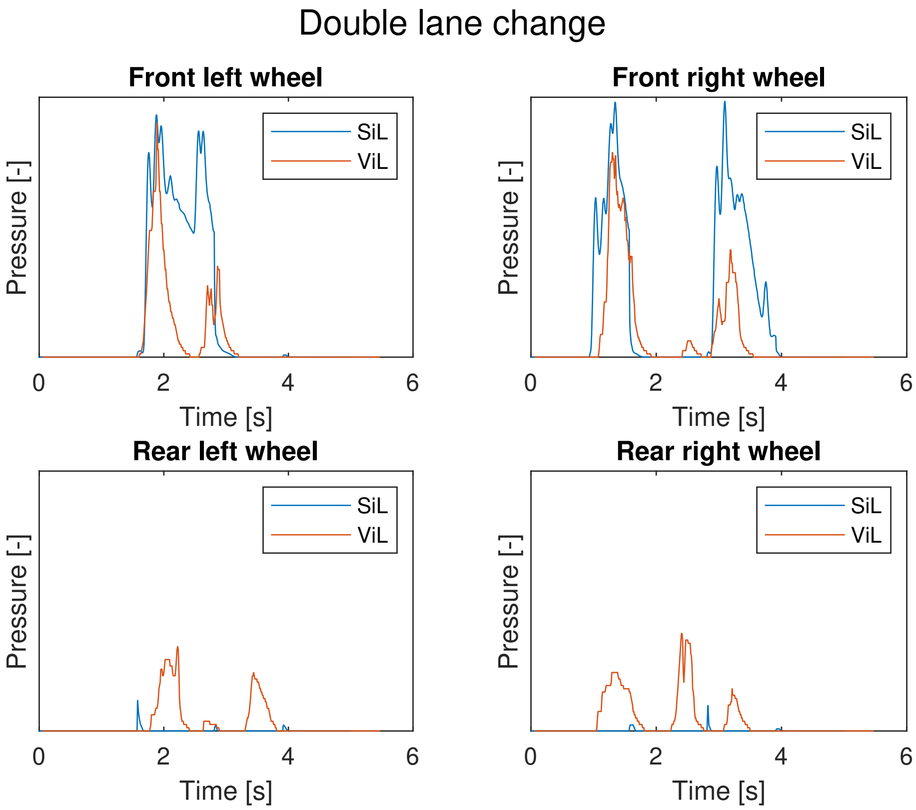


Figure 4.9: The four graphs represent the brake pressure on each wheel from both SiL and ViL in the DLC scenario.

The brake pressure distribution from the SiL and ViL results are represented in figure 4.9. It can be seen that the brake pressure amplitudes and distributions differ between SiL and ViL. Nonetheless, similarities in the ESC intervention can be seen between them both.

The ESC can be seen making large corrections on the vehicle to improve the cornering ability and prevent dangerous oversteering situations. At approximately one second in the scenario, the front right wheel brakes hard to counter an oversteering situation in the left turn. It also applies to the rear outer wheel in a later stage, and to a lower extent, to counter the understeering situation. The brakes in SiL and ViL can be seen intervening similarly, which is the key in the verification process.

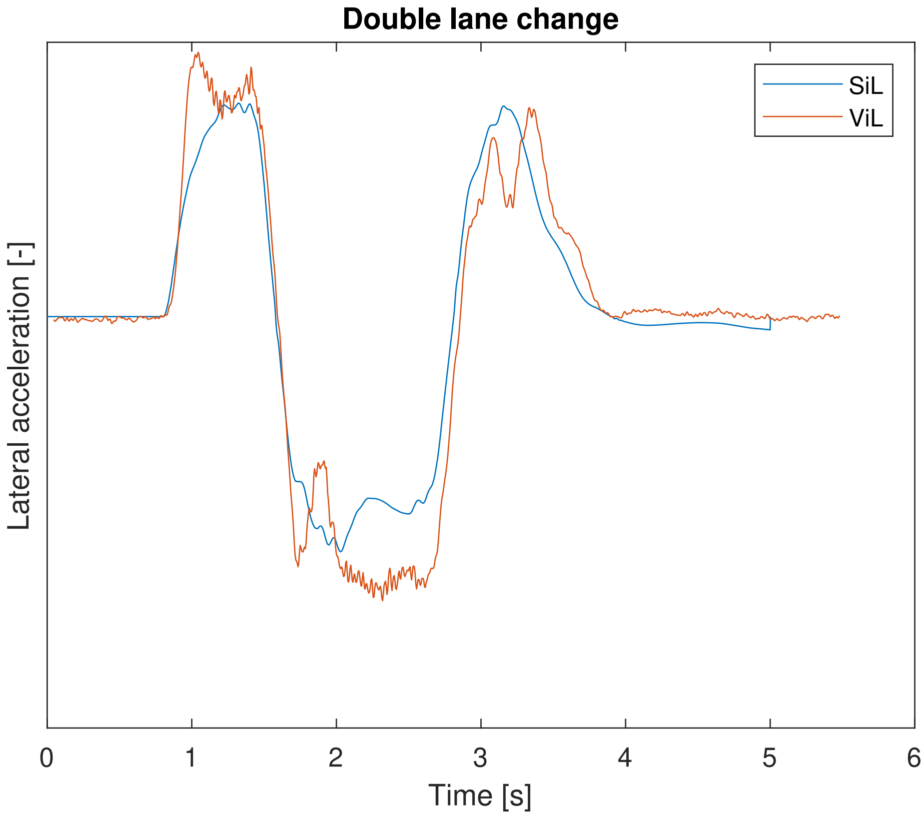


Figure 4.10: The graph represents the vehicle lateral acceleration from both SiL and ViL in the DLC scenario.

The plot of the lateral acceleration, in figure 4.10, is key in the DLC maneuver. It shows that the lateral forces are achieved, and a comparative analysis can be made. The reason for the deviation amplitudes in SiL can be connected to the fidelity of the simulation model, where the real-world environment (e.g., varying road surface friction, tuning of the motion model, tire models, overall vehicle performance, etc.) could differ.

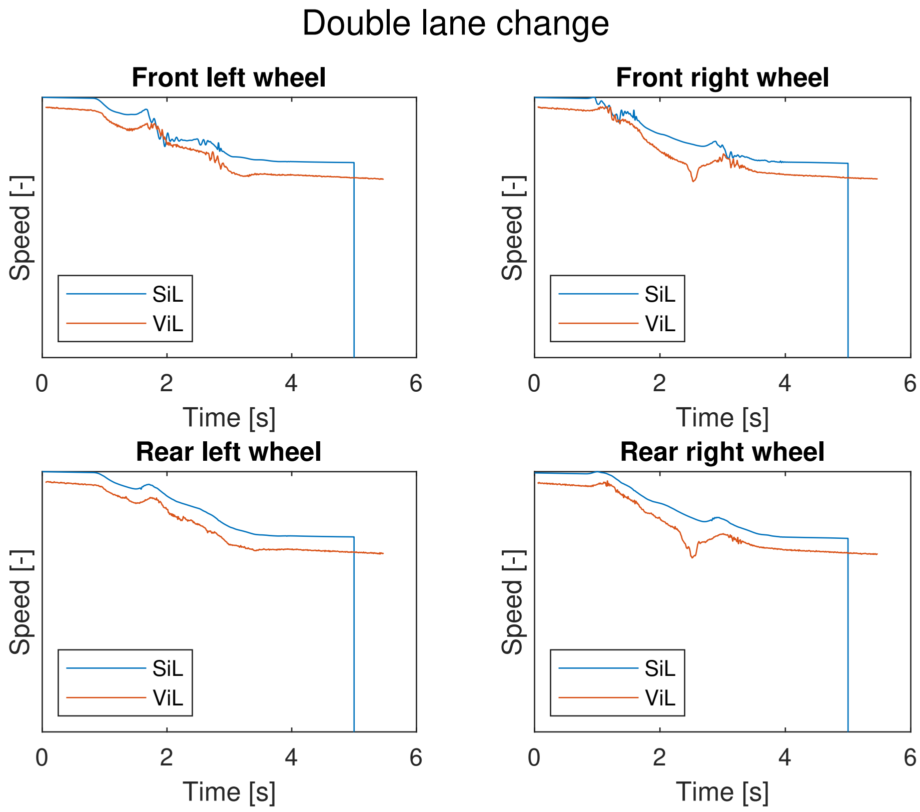


Figure 4.11: The four graphs represent the wheel speed on each wheel from both SiL and ViL in the DLC scenario.

The similarities in the wheel speed from the scenario can be seen in figure 4.11. The sudden wheel speed changes imply a working ESC model. It can be seen to regulate the wheel speed by slowing down an individual wheel at a time, depending on the yaw stability.

The logic behind the ESC interventions remains consistent despite discrepancies between simulated results and real-world testing. During the DLC test, the ESC system shows similar regulatory behavior for the front and rear left tires, adjusting their speeds to maintain vehicle stability and control.

5

Discussion

The finished master thesis is an initial study on how to build a framework for CAE verification within Motion Control. The work has been done around a brake system as a pilot project to research how functional verification can be carried out in future work and increase the results relative to seat time in the vehicle. This is done in a way so that the Virtual Verification Framework can later be generalized for other vehicle motion systems. Much of the work has been to find boundaries and initialize a road for future work in the same area. The work has also given an approximation for the possibility of doing more functional verification virtually with CAE. Thus, a finished framework is not created in this project.

Even though the work is considered initial for a Virtual Verification Framework, much has been achieved during the project. Implementing a system-specific model has been done to the extent where full functionality has been reached. Even though all signals were not implemented, the model was fully functional and could perform testing, search for bugs, and perform smoke tests. Therefore, it was also found that the framework applied in Simulink was very futureproof. The implementation of new models was quick and took only a few minutes. The process was to copy and paste the found signals into the new model. Worth mentioning is that this could not be the case for all future updates. If signal names are to be changed, the copied signals must also be renamed to suit these. Thus, more work could be needed in the future if a larger update is done. The positive side is that with the old signals, the new ones are easy to find since there is information on what to search for.

The tire model is the recurrent topic when comparing simulated vehicles with real ones. Tires are hard to model properly, and simulations will give different results than reality. This means that fully correlating simulations with reality is not feasible, at least in a low-cost project like this thesis. Another aspect is that it was impossible to receive real test data with the same tire that was available as a model in CarMaker. This leads, of course, to different results in simulations and real life. Some tests were also done with winter tires, which are very different from the summer tires available in CarMaker. Resources are thus a limitation in the representation of reality. Therefore, it is important when correlating to consider that there is a difference in tires between simulations and reality.

When studying data and correlating simulations with real-world measurements, a significant challenge arises from the difference in how data is captured in SiL and ViL testing. In SiL, all aspects of the system are simulated, leading to high-frequency data collection. Conversely, in ViL, most data is obtained through physical sensors, which often operate at lower frequencies compared to simulations. This discrepancy can cause important data points, such as peaks observed in simulations, to be missed in real-world measurements. The lower sampling rate of physical sensors might overlook transient events that are critical for accurate analysis and correlation.

Additional challenges arise when comparing simulated data with measured data due to the absence of certain transfer functions in simulations. For instance, the hydraulic losses within the brake lines are difficult to model accurately and require substantial computational power, often leading to approximations. It is difficult to model the hydraulic system and computationally heavy to simulate. These estimations can result in significant discrepancies that are not reflected in the simulations. Conversely, real-world measurements also involve estimations where direct measurement is not feasible. A notable example is wheel slip. In practical scenarios, accurately measuring the nominal wheel radius and vehicle speed when all wheels have slip is challenging, leading to estimations of wheel slip. In contrast, simulations can consistently measure the wheel radius, resulting in potential differences in data accuracy.

In calibrating models and simulations against reality, it is important to balance fidelity with practicality. Perfect alignment with real-world conditions is often unachievable and unnecessary; the primary aim should be replicating general trends and behaviors to ensure functional verification. Real-world conditions, such as road friction and environmental variability, pose significant challenges, making exact modeling difficult. Therefore, introducing variability and continuous validation of models is essential. By focusing on achieving sufficient fidelity for functional verification and continuously updating models with new data, simulations can effectively mirror real-world behaviors while remaining cost-efficient and practical.

5.1 Conclusion and RQ discussion

How can a correlation study between SiL and ViL be conducted to ensure the reliability of output data for simulating vehicle performance?

The research demonstrated that empirical investigations and pattern recognition can effectively conduct a correlation study between SiL and ViL. By carefully selecting and analyzing output data from both simulation and real-world testing, the study was able to identify KPI such as wheel speed, brake pressure, and yaw rate, which are critical for evaluating vehicle performance. The results indicated a high degree of correlation according to the intervention strategies between SiL and ViL data, which underscores the reliability of SiL simulations in predicting real-world vehicle behavior. Furthermore, the use of FFT analysis provided results that were hard to interpret and could therefore not be used together with these KPI's.

What are the possibilities and benefits of expanding the SiL stage to replace some aspects of ViL in the system verification process for vehicle development?

Expanding the SiL stage to replace some aspects of ViL offers significant possibilities and benefits, including cost reduction, increased safety, and faster development cycles. Hence, software issues can be observed in an earlier stage. The study found that SiL can be particularly beneficial in scenarios where ViL systems fail to measure certain KPI accurately. For instance, SiL effectively simulates the wheel slip, while it is estimated in ViL-testing, thereby ensuring more reliable system verification. Additionally, the ability to perform extensive virtual testing reduces the dependency on physical prototypes, leading to substantial savings in time and resources. This also minimizes the risks associated with early-stage testing of new vehicle features, enhancing overall safety and vehicle development reliability and increasing the focus on fine-tuning the motion systems.

5.2 Future work

Addressing these following areas, future research can build on this study's findings to further streamline and improve the vehicle development process through advanced virtual verification techniques.

5.2.1 Enhancing model fidelity

Future work should focus on enhancing the fidelity of simulation models, especially for complex components like tires. Improved tire models that closely replicate real-world conditions could significantly enhance the accuracy of SiL simulations, further reducing the need for physical testing.

5.2.2 Integration with machine learning

Incorporating machine learning techniques to analyze simulation data as a pattern recognition could provide deeper insights into system behavior and performance. Machine learning models could be trained to predict potential issues and optimize various parameters, thereby improving the efficiency and reliability of the virtual verification process.

5.2.3 Expansion to other vehicle systems

While this study focused on the brake system, future research should expand the virtual verification framework to include other vehicle systems, such as steering, propulsion, and suspension. This would help create a more comprehensive and robust verification process.

5.2.4 Continuous verification and validation

Implementing a continuous validation and verification approach, where SiL and ViL simulations are regularly updated and validated against real-world data, would ensure that the simulation models remain accurate and reliable over time. This could involve setting up automated MATLAB script that continuously collect data from real-world tests and use it to refine and validate the simulation models.

Bibliography

[1] ISO – International Organization for Standardization, “ISO 19365:2016: Passenger cars – Validation of vehicle dynamic simulation – Sine with dwell stability control testing,” 2016. [Online]. Available: https://www.sis.se/produkter/fordonsteknik/personbilar-husvagnar-och-latta-slapvagnar/ssiso193652016/ [Accessed: 2024-02-13]

[2] B. J. et al, *"Compendium in Vehicle Motion Engineering"*. Vehicle Dynamics Group, Divison Vehicle and Autonomous Systems, Department of Mechanics and Maritime Sciences, Chalmers University of Technology, 2023.

[3] APTIV, “What is software-in-the-loop testing?” https://www.aptiv.com/en/insights/article/what-is-software-in-the-loop-testing, accessed: 2024-01-30.

[4] Dassault Systemes, “The advantages of computer-aided engineering,” https://www.3ds.com/store/cad/computer-aided-engineering, accessed: 2024-01-30.

[5] IPG Automotive, “Carmaker,” https://ipg-automotive.com/en/products-solutions/software/carmaker/, accessed: 2024-01-30.

[6] M. Denscombe, *The Good Research Guide: For small-scale social research projects.* Open University Press, 2010.

[7] Dr. -Ing. J. Weber, *Automotive Development Processes: Processes for Successful Customer Oriented Vehicle Development.* Springer-Verlag Berlin Heidelberg, 2009.

[8] Katzourakis, Diomidis and Angelis, Stavros and Johnsson, Albin and Klomp, Matthijs and Hansson, Robert, *Virtual Brake Software Release*, 2015. ISBN 978-1-138-02885-2

[9] J. Svendenius, B. Wittenmark, *Brush Tire Model with increased Flexibility.* IEEE - Institute of Electrical and Electronics Engineers Inc., 2003.

[10] Shannon L. Miller, Brett Youngberg, Alex Millie, Patrick Schweizer, J. Christian Gerdes, “Calculating Longitudinal Wheel Slip and Tire Parameters Using GPS Velocity,” 2001. [Online]. Available: http://www-cdr.stanford.edu/dynamic/WheelSlip/SlmillerGerdesACC.pdf [Accessed: 2024-02-24]

[11] ATP Electronics, “What is electronic brake control module (EBCM)?” 2024. [Online]. Available: https://atpelectronics.co.uk/what-is-electronic-brake-control-module-ebcm/ [Accessed: 2024-02-26]

[12] SINSPEED, “What Is An ABS Pump + How Does It Work?” 2019. [Online]. Available: https://www.sinspeed.co.uk/blog/what-is-an-abs-pump-how-does-it-work/ [Accessed: 2024-02-26]

[13] Universal Technical Institute, “HOW DO CAR BRAKING SYSTEMS WORK?” 2021. [Online]. Available: https://www.uti.edu/blog/automotive/braking-systems [Accessed: 2024-02-26]

[14] GoMechanic, “How Does A Car Steering System Work? | Explained,” 2020. [Online]. Available: https://gomechanic.in/blog/car-steering-system-explained/ [Accessed: 2024-02-27]

[15] MakeUseOf, “What Is Steer-by-Wire Technology?” 2022. [Online]. Available: https://www.makeuseof.com/what-is-steer-by-wire-technology/ [Accessed: 2024-02-27]

[16] Universal Technical Institute, “TYPES OF CAR ENGINES,” 2024. [Online]. Available: https://www.uti.edu/blog/automotive/engine-types [Accessed: 2024-02-27]

[17] U.S. Department of Energy, “How Do All-Electric Cars Work?” 2024. [Online]. Available: https://afdc.energy.gov/vehicles/how-do-all-electric-cars-work [Accessed: 2024-02-27]

[18] Universal Technical Institute, “WHAT IS A TRANSMISSION AND HOW DOES IT WORK?” 2024. [Online]. Available: https://www.uti.edu/blog/automotive/transmission [Accessed: 2024-02-27]

[19] C. V. Loan, *Computational Frameworks for the Fast Fourier Transform.* Society for Industrial and Applied Mathematics, 1992. ISBN 9780898712858

[20] ISO – International Organization for Standardization, “ISO 21994:2022: Passenger cars - Stopping distance at straight-line braking with ABS - Open-loop test method,” 2022. [Online]. Available: https://www.sis.se/produkter/fordonsteknik/fordonssystem/bromssystem/iso-219942022/ [Accessed: 2024-02-13]

[21] ——, “ISO 14512:1999: Passenger cars – Straight-ahead braking on split coefficient of friction surfaces – Open-loop test procedure,” 1999. [Online]. Available: https://www.sis.se/produkter/fordonsteknik/allmant/iso14512/ [Accessed: 2024-02-13]

[22] ——, “ISO 7975:2019: Passenger cars - Braking in a turn – Open-loop test method,” 2019. [Online]. Available: https://www.sis.se/produkter/fordonsteknik/personbilar-husvagnar-och-latta-slapvagnar/ss-iso-79752019/ [Accessed: 2024-

02-13]

[23] ——, “ISO 3888-1:2019: Passenger cars – Test track for a severe lane change manoeuvre – Part 1: Double lane-change,” 2019. [Online]. Available: https://www.sis.se/produkter/fordonsteknik/allmant/ss-iso-3888-12019/ [Accessed: 2024-02-13]

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