CHALMERS
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Vehicle Dynamics Development Process With Offline and Driver-in-the-loop (DIL) Simulation

Master's Thesis in Master's Programme System, Control, and Mechatronics

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Abstract

In this thesis, tools and methods are developed for the vehicle dynamics development process that includes offline simulation tools and Driver-in-the-Loop testing for the first development phases in automotive projects. The development process will allow for the first stage of vehicle development by using simulation tools and when there is a working vehicle model in place, transfer the vehicle model to the driving simulator for further development. The process aims at reducing the time and cost of the whole vehicle dynamics development process. A simulation system has been developed based on IPG CarMaker as the simulation tool connecting with the motion driving simulator CASTER at Chalmers. The thesis has practically proved the effectiveness of the new development process in Case Studies and estimated its benefits and improvements of the development process in the early development phases.

Keywords: simulations, vehicle dynamics, DIL simulation, motion driving simulator, development process

Contents

Notation

Clarifications

1. Gas/Accelerator
   Both words in this thesis refer specifically to the accelerator pedal.
   The mixed-use of these two words is due to that IPG in their CarMaker software using *Gas* instead of Accelerator or Throttle which are more commonly used in both academy and industry.

2. Upgrade of software in CASTER
   The control software of the motion driving simulator, named Panthera, has been upgraded during this project. This project mainly used on the old Panthera software, but the updated version will be mentioned in the report as the change of software has affected the work in the project and it will be important for the future use of the driving simulator.

Abbreviations

ABS	Anti-lock Brake System
ARB	Anti-Roll Bar
CASTER	Abbreviation of Chalmers Automotive Simulator Technology Education Research, a student team running the motion simulator at Chalmers
CFD	Computational Fluid Dynamics
CM	IPG CarMaker
DIL	Driver-in-the-Loop
DLC	Double Lane Change
DOF	Degree of Freedom
EBD	Electronic Brakeforce Distribution
ESC	Electronic Stability Control
FMI/FMU	Functional Mock-up Interface/Unit
HID	Human Interface Device
ISO	International Organization for Standardization
MIL	Model-In-Loop
NHTSA	National Highway Traffic Safety Administration
RTOS	Real-Time Operating System
SIL	Software-In-Loop
SUV	Sport Utility Vehicle
UDP	User Datagram Protocol
VEAS	Vehicle Engineering and Autonomous Systems Division at Chalmers
WC	Wheel Centre

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1 Introduction

This is a double master thesis within automotive engineering. This report will cover the master thesis project about developing a vehicle dynamics development process based on existing simulation software and driving simulator at Chalmers. The development process is intended to be used in the early development phases in automotive projects.

1.1 Background

The vehicle engineering development process in general and specifically the chassis engineering process were historically trial and error methods. The chassis engineers developed the concepts and system design solutions and then test cars were built to assess, further develop, and tune the chassis systems. In the latest 20 – 30 years, there have been several vehicle dynamics simulation tools developed that support the chassis engineers to develop improved and better tuned technical solutions and there are also test methods, including driving simulators, in place that shortens the lead times in development projects. The current chassis engineering includes mechanical design engineering of e.g., suspension systems, and also control systems, e.g., propulsion, brakes, steering and controlled suspension systems.

1.2 Problem Motivating the Project

With the development of computer science and simulation tools, most systems of a vehicle can be modelled, developed, and assessed. But there are still some systems that cannot be well predicted by simulations. One of the most important reasons is that the behaviour and subjective experience of the human drivers are difficult to be modelled and estimated. As a product, the development of vehicles should be human-oriented because human is not only the end-user of the product but also an important part of how the vehicle behaves when controlled by the human driver. Almost all the control signal comes directly or indirectly from the driver.

With such difficulties and demands, the vehicle industry has been using mule cars in the first development phases. After a vehicle concept has been developed and agreed upon in a project, the engineering team often developed a mule car to assess and further develop the selected concept and system design solutions. The mule car is traditionally built on the same type of car that the project is developing and then parts and systems are changed to suit the selected solutions, then test engineers and test drivers can assess the concept with the mule cars.

However, with the development of computer vision, real-time computing and mechatronic technologies, motion driving simulator that can provide motion, visual, and audio feedback have been invented, developed and used in the industry. With such a powerful tool, it is possible to turn many tests that previously needed a mule car to a motion driving simulator for the initial testing.

At Chalmers, a motion driving simulator ran by CASTER was installed and started in 2015, and the vehicle simulation tool IPG CarMaker is also available for students. However, there is no structured process that allows a fast transfer from CarMaker to CASTER. A potential of doing some path-breaking development based on Chalmers owned software and hardware could be seen.

In this thesis, the main target is to find a new process that allows developing engineers to develop concepts and system solutions to meet the targets in the automotive project involving a motion driving simulator. A preliminary idea is that a vehicle model should be developed, tested, and verified with offline simulation. Then the vehicle model should be transferred into a motion driving simulator to perform subjective assessments and do related tuning and development. The process will allow design engineers to acquire results and comments of the new vehicle concept even before the first test series is developed and manufactured, both from the offline simulation results and the test drivers' comments and opinions.

In industry, there are some similar processes that are internally used for vehicle dynamic development, but a process and solution based on Chalmers' software and hardware is still valuable to develop. The development process can also be helpful in other research and development activities.

1.3 Research Questions

- How can Vehicle Dynamics offline simulation tools be included in the engineering development process to support the concept development of chassis systems?
- How can motion driving simulators be included in the engineering development process to support the assessment, development and tuning of chassis systems?
- How will Vehicle Dynamics simulation tools and the use of Driving Simulators in the engineering development process improve the technical solutions and shorten lead times?
- The possibility to use the driving simulator for the development of e.g., vehicle dynamics, ride comfort and other driving parameters will be assessed in the project.

1.4 Deliverables

- Literature study about vehicle simulation tools and motion driving simulators
- A generic SUV model as a baseline vehicle model
- Testing manoeuvres to develop and verify the vehicle dynamics performance in the off-line simulations and the driving simulator.
- Developing tools and methods to work with offline simulations and the driving simulator for the first development phases in automotive projects.
- An analysis of different ways to run the vehicle model in offline simulation and the driving simulator.
- A process for developing vehicle dynamic performance with simulation tools and using a driving simulator.
- Methods to quantify the contribution of driving simulators in development processes.
- Case studies to prove the effectiveness of the process from different perspectives.

1.5 Limitations

- Limited real-world data will be used.
- The driving simulator has limitations in the moving range and action frequency.
- The seating position and the seat is not representative of production cars. Some manoeuvres will have reduced value.
- Z-axis frequency is limited due to the ability in the driving simulator, which will affect some tests like ride comfort, etc.
- No self-designed simulation tools will be introduced in the thesis. Only the existing simulation tools and the driving simulator at Chalmers will be used.
- Only specific solutions based on current available software and hardware will be given, but methods and results should be general.

2 Theories

2.1 Literature Review

In the past decades, motion driving simulators have been used widely to research vehicle dynamic problems and to accelerate vehicle dynamic system development. Some published articles have shown the development of vehicle dynamics simulation.

Research on vehicle dynamics can be traced back to the 1900s [1]. Since the 1930s, researchers started to have a basic understanding of the vibration during driving and started to research steering, suspension and stability. In the early 1930s, Lanchester[2] in the UK and Olley [3] in the US started to research independent suspension systems and started to analyse the influence of steering systems and suspension systems on vehicle performance. In the 1950s, researchers started to create the systematic theory of vehicle dynamics within the linear range (lateral acceleration less than 0.3 g).

The book *Handbook of Driving Simulation for Engineering, Medicine, and Psychology* [4]introduces that the use of driving simulation started in the 1960s and expanded in the 1970s.

In 1994, Gary P. Bertollini and his colleagues [5] introduced the motion driving simulator developed at General Motor, which is a good example of how motion driving simulators are used in the early years. The consistency between their motion driving simulator and real vehicles was proved to be very effective when the vehicle was in the linear range (lateral acceleration less than 0.3 g) and the yaw rate less than 8 °/s.

An article written by D. Toffi, G. Reymond, et al., in 2007 [6] used a motion driving simulator to research the effects of different steering models. The article shows that a motion driving simulator can simulate steering models with different torque feedback laws and shows a conclusion that human drive can be modelled as a displacement controller. This paper shows the possibility of research driving behaviour with a motion driving simulator, but the related technique was not directly used in this project.

An article written by Jesus Félez, Joaquin Maroto, et al., in 2007 [7] shows the development of a traffic system along with a motion driving simulator, that could simulate driving events within city traffic, even including accidents. The article also suggests using a simplified dynamic model in traffic-related simulations.

A PhD thesis issued by Gaspar Gil Gómez published in 2017 [8], which is a reference material in this project, shows several ways to increase the efficiency of vehicle dynamic development from many different perspectives. A motion driving simulator is also used in the PhD thesis, and a detailed comparison regarding efficiency has been made. The thesis also provides good documentation of different ways of objective and subjective assessments and related testing manoeuvres.

During the project, the book *Suspension Geometry and Computation* [9] and the *Chalmers Vehicle Dynamics Compendium* [10] are important reference materials for vehicle dynamics problems, and the book Robotics: *Modelling, Planning and Control* [11] is important reference material for problems like coordinate system, coordinate transformation, etc.

With the research outcomes above, the great possibility of integrating a motion driving simulator into a vehicle dynamic process has been shown.

2.2 General Simulation Steps

With the vehicle dynamics development process, the following steps will be taken. The whole process could be used both in the concept design phase and the system development phase.

1. Step 1: Development of vehicle model and manoeuvres for simulations
   A representative vehicle model and testing manoeuvres will be developed. Models of some vehicle systems, e.g., suspension systems, will also be added to the vehicle model.
2. Step 2: Offline simulation and development
   Offline simulations will be conducted. The vehicle model will be developed and verified with different testing manoeuvres. Development with the offline simulation should meet the target of the concept design before transferring the vehicle model into the motion driving simulator.
3. Step 3: Transfer the model into the motion driving simulator
   To transfer an offline simulation vehicle model into a motion driving simulator, a connector that connects signals between the simulation tools and the motion driving simulator needs to be developed. In the connector, related signals need to be connected, and perhaps extra sensors are also needed.
4. Step 4: Verification of the transferred model
   After the transfer is done, verification is required to make sure that there is a good correlation for the vehicle dynamics performance between the offline simulations and the testing in the driving simulator. The same manoeuvres should be tested both in online and offline simulation and the result should be compared and analysed.
5. Step 5: Development with a driving simulator
   Online (DIL) simulations will be conducted in this step. The vehicle model will be assessed mainly with subjective testing manoeuvres in this stage. Tuning of the suspension systems, for example, springs, dampers, etc., should also be conducted in this step. If any problems are found in this step, development engineers should move back to Step 1 or Step 2, which depends on how and where the problems are. There will be several rounds of simulations that go back and forth from Steps 1 to Step 5 until the vehicle model meet the target of the project.
6. Step 6: Data analysis, target review and decision making
   The results from both the offline simulations and the DIL simulation will be used to review how well the proposed vehicle model and systems are meeting the targets in the automotive project. The results of this assessment will be either to continue the concept and system development or to use the results for the next development phase.

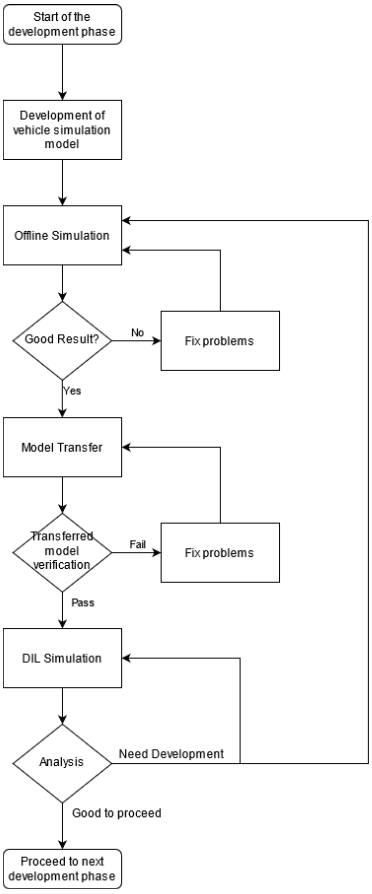
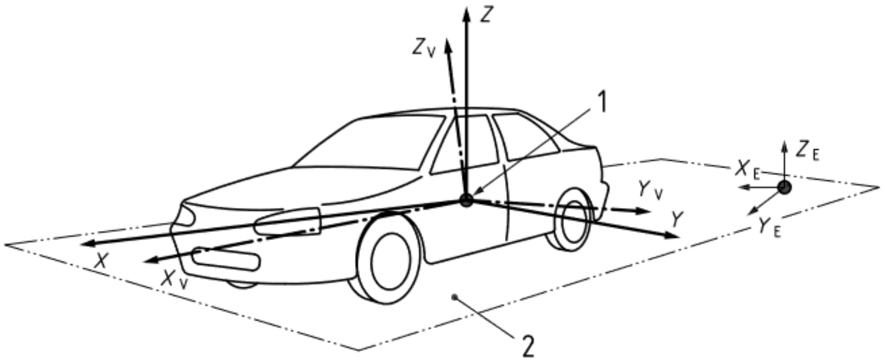


Figure 2-1 Flow Chart of the development process

2.3 Coordinate System

In this report, the vehicle coordinate systems are set according to the standard ISO 8855. According to the standard, $x(u)$ direction points toward the front of the vehicle, $y(v)$ direction points toward the left side of the vehicle, and $z(w)$ direction points upward.



Key

1 vehicle reference point
2 ground plane

Figure 2-2 Coordinate System Defined in ISO-8855:2011 [12]

2.4 Simulations and Testing in a Driving simulator

2.4.1 Offline Simulation

In this thesis, offline simulation refers to traditional simulation processes that only contain calculations, which could include MIL to SIL processes. The word “offline” here refers to that the driver is not included in the process.

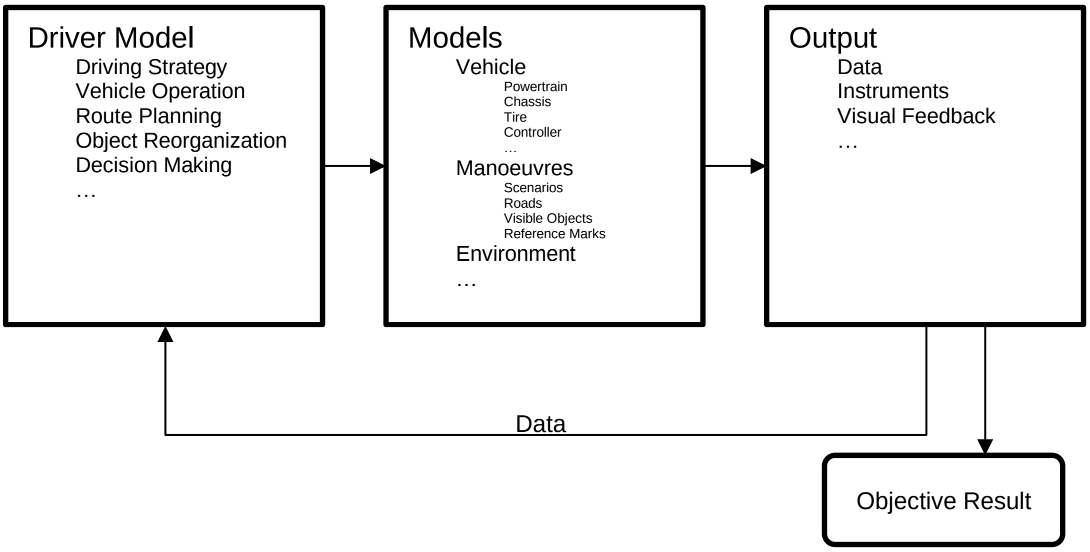


Figure 2-3 Offline Simulation Model

2.4.2 Driver-In-the-Loop Simulation

In this thesis, when a driver is included in the simulation process, it is called Driver-in-the-Loop (DIL) Simulation, or online simulation. By transferring the offline simulation model to a motion-driving-simulator-compatible one, a real driver can replace the driver model. Objective and subjective results, the drivers’ comments and opinions, subjective assessments can be analysed after the DIL simulation.

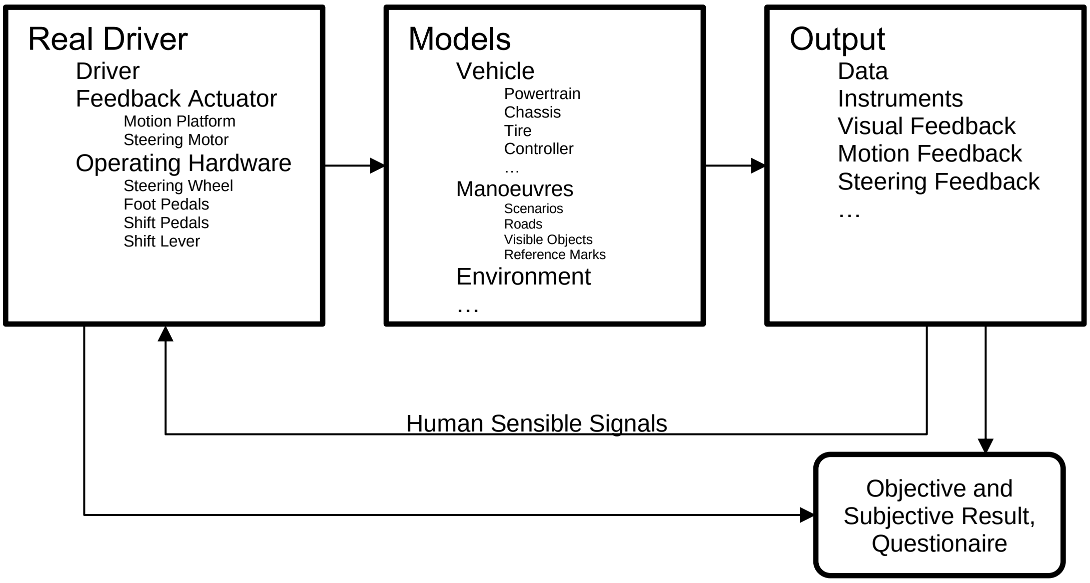


Figure 2-4 DIL Simulation Model

2.4.3 Motion Driving Simulator

In this thesis, the motion driving simulator refers to the simulator that includes basic driver inputs, motion feedback and steering torque feedback. The driver inputs include steering, accelerator, brake, clutch, and gear selection.

The motion feedback refers to that the platform can provide 6-DOF motion in a limited space. The steering torque feedback means that the steering wheel will either take steering torque as input and steering angle as output (angle mode) or take steering angle as input and steering torque as output (torque mode).

2.4.4 Scenarios and Manoeuvres

The definitions of Scenarios and Manoeuvres used in this report are as following:

- Manoeuvre
  A manoeuvre is a motion plan or a path that a test driver or driver model should execute, for example, a DLC manoeuvre or a Sine-with-Dwell manoeuvre.
- Scenario
  A scenario is a set of configurations that serve for the manoeuvre, including terrain, roads, road marks, traffic cones, barriers, reference paths, etc. With a proper scenario could a manoeuvre be executed easier and with higher efficiency and accuracy.

2.5 Vehicle Dynamics

2.5.1 Suspension model

The development begins with a linear model. Both models provide 2 DOFs for the front wheels (steering and vertical moving), and 1 DOFs for the rear wheels (only vertical moving).

2.5.1.1 Linear model

The linear suspension models are developed according to the IPG CarMaker Reference Manual [13]. The linear suspension models are based on IPG CarMaker models and more detailed K/C data have been added to the generic model to improve the vehicle dynamics performance. The vehicle model is developed and simulated at kerb weight with no driver or passenger weight included.

Vehicle models with linear suspension models can be used for the simulations in the initial concept and system development. Once the suspension specification is selected it is important to develop non-linear suspension models to give better accuracy. This is especially important when simulating on-the-limit driving manoeuvres.

2.5.1.1.1 Linear Kinematic Model

With a conventional independent kinematic suspension model without the steering function, the wheel carrier moves according to the hardpoints geometry for the control arms and link arms, which is 1 DOF for the suspension. The wheel also steers around the kingpin axis, which is another 1 DOFs. Thus, a conventional independent kinematic suspension with the steering function usually contains 2 DOF. The one without the steering function on the rear axle contains usually 1 DOF.

In CarMaker, the number of DOF is being used to classify different linear kinematic suspension models. For the front axle, a linear 2-DOF model refers to the wheel carrier both moves in the vertical direction and steers around the kingpin axis. In the vertical direction, the input to the model is the vertical motion of the wheel carrier (q_0); in the steering direction, the input to the model is the steering coordinate (q_2). For the rear axle, a linear 1-DOF model refers to that the wheel only moves in the vertical direction, and the only input to the model is the vertical motion of the wheel carrier.

Both models are based on the following equation. More details can be found in the IPG manual [13] starting on page 150:

$$k = c_{off} + c_0 \cdot q_0 + c_1 \cdot q_1 + c_2 \cdot q_2$$

This formula describes how the wheel is moving with the input parameters.

With:

k	See below.
c_{off}	The static offset of the variant.
q_0	Displacement of the related wheel in the vertical direction.
q_1	Displacement of the opposite wheel in the vertical direction. This input is not used in independent suspension systems.
q_2	Displacement of the steering mechanism.
c_0	Gradient depending on q_0.
c_1	Gradient depending on q_1. For independent suspension in this project, it is set to 0.
c_2	Gradient depending on q_2. For the rear axle in this model, it is set to 0.

Explanation of the variants of k:

t_x	Displacement of the wheel in x direction.
t_y	Displacement of the wheel in y direction.
t_z	Displacement of the wheel in z direction.
r_x	Rotation of the wheel in x direction.
r_y	Rotation of the wheel in y direction.
r_z	Rotation of the wheel in z direction.

l_{Spring}	Length changing of the spring.
l_{Damp}	Length changing of the damper.
l_{Buf}	Length changing of the buffer.
l_{Stabi}	Length changing of the ARB.

For each of the variants of k, a set of c_{off}, c_0, c_1, and c_2 is called from a table, and the same group of q_0, q_1, and q_2 is used for each of the variants.

The following static and linearized parameters are implemented into the linear model:

- Static Toe
  Static toe is the angle from the X-axis of the wheel to the X-axis of the vehicle body if looking from the top of the vehicle. For simplification of the model, only rotation around the Z-axis is being considered. Toe-in is negative and toe-out is positive according to the coordinate system.
  The unit in the model is rad.

$$c_{off\_r_z} = -\text{Static Toe}$$

- Static Camber
  Static camber is the angle from the vertical axis of the wheel to the vertical axis of the vehicle if looking from the rear of the vehicle. A positive camber refers to that the wheel leans towards the outside of the vehicle. The unit in the model is rad.

$$c_{off\_r_x} = -\text{Static Camber}$$

- Bump Camber
  The bump camber shows the change of camber at wheel travel. The unit in the model is rad/m.

$$c_{0\_r_x} = -\text{Bump Camber}$$

- Kingpin Inclination and Caster Angle
  The kingpin inclination and caster angle are calculated together because they are the projection of the kingpin on different planes. Kingpin inclination is the projection of the kingpin in the Y-Z plane, and the Caster angle is the projection of the kingpin in the Z-X plane. To merge the two parameters, according to the CarMaker Reference Manual, an Euler ZYX rotation matrix needs to be worked out for the steering system.
  The rotation matrix is initially represented with an axis-angle system, then transferred to a quaternion system, then to an Euler rotation matrix. Both transformations use the internal function of MATLAB.
  Mark the Kingpin Inclination as φ, the Caster Angle as $-\vartheta$, and the steering angle as δ, it has:

$$R^{Axis-Angle}(\delta) = \left\{ \begin{bmatrix} -\tan\vartheta \\ -\tan\varphi \\ 1 \end{bmatrix}, \delta \right\}$$

  And the rotation matrix is:

$$R^{ZYX}(\delta) = Quat2Eul\left(Axang2Quat\left(R^{Axis-Angle}(\delta)\right), 'ZYX'\right)$$

  The rotation matrix will only be used to calculate the steering movement. Other wheel alignment parameters that rotate around the kingpin axis were simplified to a rotation around the Z-axis.

- Steering
  The steering is how much the wheel turns around the kingpin axis by the moving of the steering rack. The unit in the model is rad/m. Due to the kingpin inclination and the caster angle, the rotation around the kingpin axis will be projected to X-, Y-, and Z-axes. To do the projection, the rotation matrix $R^{ZYX}(\delta)$ from the previous bullet is used, and only the numerical result is calculated. Note that this is not the steering ratio
  Assume a small rotation around the kingpin $\mathrm{d}\delta$, it has:

$$\left(R^{ZYX}(d\delta)\right)^{-1}/d\delta \cdot Steering = \begin{bmatrix} Steer_x^{Euler\_ZYX} \\ Steer_y^{Euler\_ZYX} \\ Steer_z^{Euler\_ZYX} \end{bmatrix} = \begin{bmatrix} c_{2\_r_x} \\ c_{2\_r_y} \\ c_{2\_r_z} \end{bmatrix}$$

  By calculating with $d\varphi$ at a small value, for example, 0.001, the result can be worked out.

- Bump Steering
  Bump Steering is how much the wheel rotates around the kingpin axis as a function of wheel travel. For simplification of the model, only rotation around Z-axis is being considered. The unit is rad/m.

$$c_{0\_r_z} = -\text{Bump Steer}$$

- Roll Centre Height (RCH)
  Roll centre height in this project refers to only the geometric roll centre height. To find this parameter, connect the instantaneous centre of the wheel carrier (Point E in Figure 2-5) to the centre of the tire contact patch (Point F in Figure 2-5), the intersection of the line and the central plane of the vehicle body (Point R in Figure 2-5) is the static roll centre. The distance from the point to the ground is the RCH.

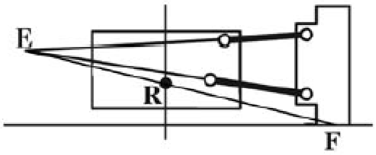


Figure 2-5 RCH Explanation Figure [9]

  However, in the linear model, the motion of the wheel carrier is linearized at the design position, i.e., must be a straight line. Thus the instantaneous centre of the wheel carrier falls in the normal direction of the linearized motion path and the distance to the wheel carrier is infinite (see the blue arrow dashed arrow in Figure 2-6). The connection from the centre of the tire contact patch to the instantaneous centre (the orange arrow in Figure 2-6) will be approximately parallel to the blue arrow. Thus, only the gradient of the linearized wheel carrier motion path will affect the static RCH. The formula is:

$$Gradient = \frac{c_{0\_t_y}}{c_{0\_t_z}} = \frac{\text{Roll Center Height}}{\text{Track Width / 2}} \quad ,with\ c_{0\_t_z} = 1$$

  The track width is already known, and the RCH is designated, so the $c_{0\_t_y}$ can be calculated and put into the model. Figure 2-6 shows how the calculation proceeds.

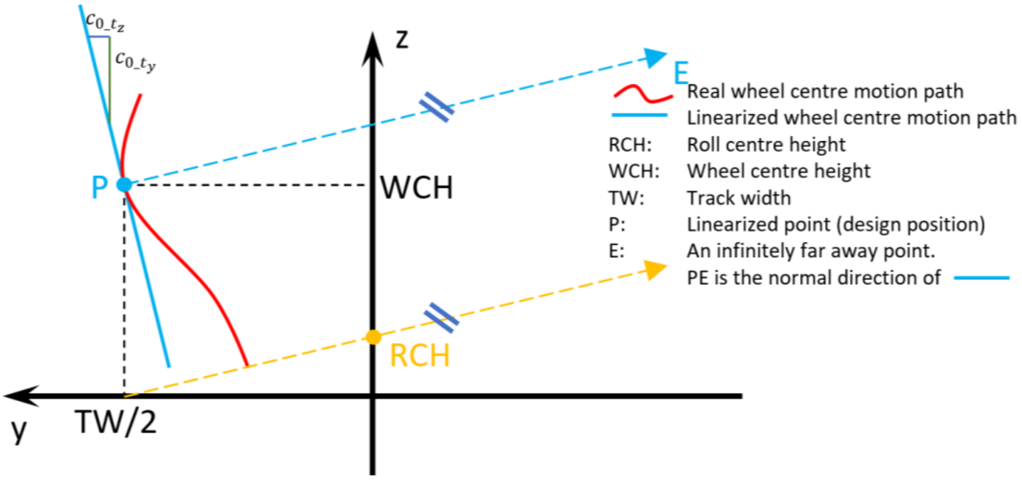


Figure 2-6 Roll Center Height Calculation

- Spring Ratio
  Spring ratio is how much the length of spring changes with the vertical motion of the wheel travel. When the wheel carrier moves upwards, the spring is being compressed, so the sign is negative. For simplification of the model, a 1:1 ratio is selected.

$$c_{0\_lSpring} = -1$$

- Damper Ratio
  The damper ratio is how much the length of the damper changes with the vertical motion of the wheel carrier. When the wheel carrier moves upwards, the damper is being compressed, so the sign is negative. For simplification of the model, a 1:1 ratio is selected.

$$c_{0\_lDamp} = -1$$

2.5.1.1.2 Suspension Compliance

Based on the kinematic linear suspension model described in the previous model, elastic parts were added in the suspension compliance model. The inputs of this model are Forces and Torques, and the outputs of this model are motions in all 6 directions. The compliance model works independently as an addition to the springs, dampers, buffers, ARBs, and the kinematic linear suspension model. The model works as the following equation:

$$W = K \begin{bmatrix} F \\ T \end{bmatrix} + K_{opp} \begin{bmatrix} F \\ T \end{bmatrix}_{opp}$$

With:

$$\begin{bmatrix} F \\ T \end{bmatrix} = [F_x \quad F_y \quad F_z \quad T_x \quad T_y \quad T_z]^T$$
$$W = [dt_x \quad dt_y \quad dt_z \quad dr_x \quad dr_y \quad dr_z]^T$$

While K is a coefficient matrix transferring force and torque into displacements and rotations of the wheel carrier, and K_{opp} is the one for the opposite side, which represents the force transferred through ARBs. The table in CarMaker should be typed in with $\left[K^T \quad K_{opp}^T\right]^T$.

The following parameters are implemented into the compliance model:

- Lateral Compliance Steer
- Longitudinal Compliance Steer, braking and traction
- Camber Compliance
- Wheel carrier longitudinal stiffness
- Caster Compliance, braking

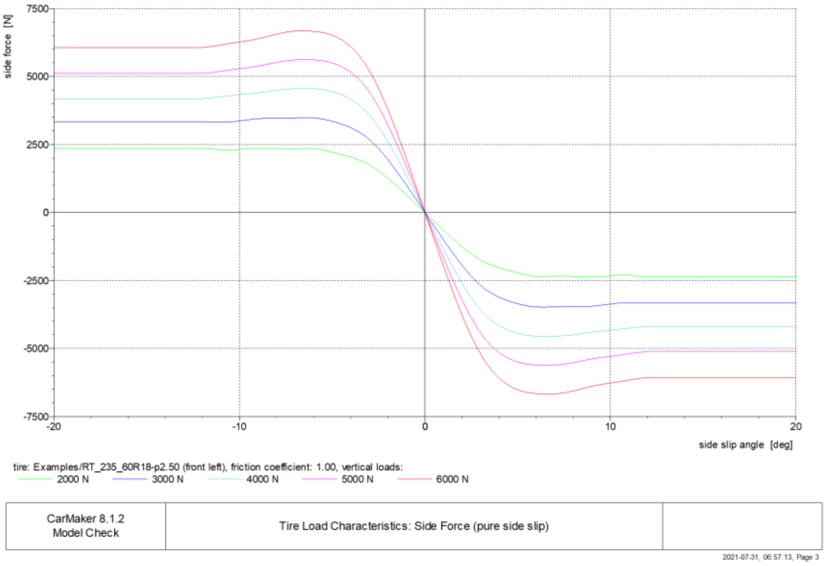
2.5.2 Tire model

Two kinds of tire models were used during the thesis: a look-up table model and a Magic Formula model. The generic model for development and verification was used generally, and a better magic-formula model was used in case study 1 (See Section 5.1.4.4). In a real development process, the tire model should be as precise as possible for better simulation results.

2.5.2.1 Look-up Table Tire Model

The look-up table model is generated with an internal tool of IPG CarMaker named *Tire Data Set Generator*. The generated table covers the longitudinal slip rate from -15% to +15%, lateral side slip angle from -12° to +12°, and vertical force from zero newtons to the maximal working range of the tire. See Figure 2-7 and Figure 2-8 for the tire characteristic that has been used.

For those working conditions out of the covered range, no extrapolation will be performed, which means that the edge values will be used directly for those working conditions outside the table range. Out-of-range use of the tire model is not considered unreliable but should be avoided as much as possible.



CarMaker 8.1.2 Model Check	Tire Load Characteristics: Side Force (pure side slip)	

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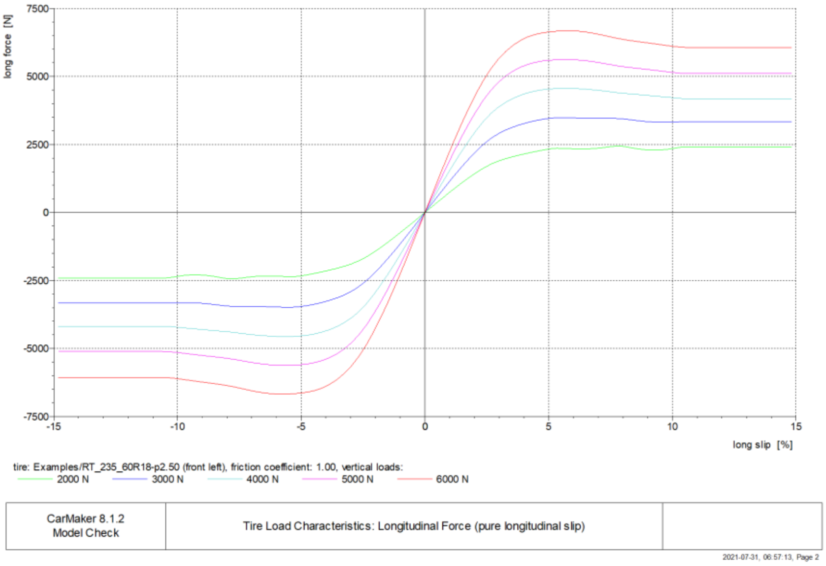
Figure 2-7 Lateral Character of the tire model



CarMaker 8.1.2 Model Check	Tire Load Characteristics: Longitudinal Force (pure longitudinal slip)	

2021-07-31, 06:57:13, Page 2

Figure 2-8 Longitudinal Character of the tire model

3 Tools and Methods

Only generally used tools and methods will be listed and explained here. There are some special tools and methods for each case study session, which will be introduced under the chapters of each case study.

3.1 Tools

3.1.1 Offline Simulation Tool

There are many tools that can conduct a vehicle dynamics offline simulation. Some research was carried out to decide which tools should be used for this project.

- MSC Adams Car
  Adams Car is a vehicle simulation tool, with the ability to simulate multi-body dynamic models in real-time. It allows co-simulation with Simulink that could be combined with the motion driving simulator. Adams is an outstanding tool when a detailed design is required. However, in the concept development phase, Adams Car requires too many details about the suspension system, which is very inefficient because of all changes in the early development phases.
- IPG CarMaker
  IPG CarMaker is a time-discrete vehicle simulation tool. It provides a good environment to create vehicle models and run simulations. It allows developing vehicle systems with its own GUI, or with C language, Simulink, FMI/FMU, and other real-time systems (like Xeno).
  The CarMaker accepts models with different accuracies, from a linear function to a precise elastic multi-body system through boundary simulation, which is very practical in all developing phases.
- CarSim
  CarSim is a simulation tool similar to CarMaker, which provides similar functions as CarMaker. Comparing with CarMaker, it focuses more on the vehicle itself, and the GUI is more user friendly to the vehicle developing engineers. It also provides convenient interfaces to run co-simulation with Simulink, FMI/FMU, LabVIEW and ASCET.

By comparing these tools, CarMaker and CarSim both appears to be a very good tool for the early development phases, and considering the easy access to the software, IPG CarMaker has been selected as the simulation tool in this thesis project.

3.1.2 Motion Driving Simulator

Considering the easy access to the motion driving simulator, the driving simulator at Chalmers will be used in the project.

The motion driving simulator, previously called A464-D3 and now called AS-1 by Cruden, contains the following components:

- A 6-DOF limited motion platform.
- Direct drive steering system.
- Accelerator, brake, and clutch pedals.
- Gear selectors, either shifting pads or a shifting lever.
- Audio and video feedback system with multiple speakers and 3 screens.
- Panthera software and related Simulink interface.

Panthera is the name of the software and control system for the simulator. It provides algorithms that safely operate the motion driving simulator within its limit and combine the input rotation signal and acceleration signal to the motion driving simulator, which provides the driver with motion feedback that is as real as possible to the real world within its ability limit. During this project, the Panthera software was upgraded. This project is mainly based on the old Panthera software, but the updated version will be involved in the discussion.

The Panthera software and related rendering tools are not running on a real-time system and communicates mainly with Ethernet through UDP, which can potentially cause delay, glitch, and unreliable behaviour.

Figure 3-1 Photo of the motion driving simulator at CASTER

3.1.2.1 Limitations of the Driving Simulator

Through testing and study the simulator, some limitations are found. These limitations affect the testing process in the driving simulator.

- Latency
  By looking through the software and hardware environment at CASTER, there is a potential to cause latency. The CASTER is running crossing several computers, and they are connected through ethernet. The system is not a real-time system but a regular computer system. Simulation signals mainly go with the UDP protocol. Delays and glitches can be expected due to network latency and package losses.
- Limited moving space
  The motion driving simulator has limited moving space, thus the motion of the vehicle model cannot be completely feedback to the test driver.

The actuators (servos) also have a limited frequency band that only respond to signals within certain amplitudes and frequencies.

- Irregular seating position
  The seating position at CASTER is more like a race car or sports car, and not regular driving seating positions. The motion feedback will be applied differently from what in a regular vehicle, which can potentially affect the subjective testing result.
- Lack of Stereoscopic Vision
  As shown in Figure 3-1, the motion driving simulator at CASTER uses 3 monitors for visual feedback. This configuration provides a wide range of views which is helpful when driving in the simulator. However, three plain monitors do not provide stereoscopic vision. The viewpoint does not change with the moving of the driver's head, and the focus point is different from what is in a real vehicle. The difference can potentially cause the driver to have less driving performance or easily get tired.

3.1.3 Driver-In-the-Loop Simulation

The DIL simulation will use the same vehicle model and offline simulation tool (IPG CM) as the calculator and data processor and use the motion driving simulator at CASTER as the driving simulator.

There are multiple methods to transfer the vehicle model from the simulation software to the simulator. An assessment of different methods has been made.

- Simulink
  Simulink is an easy option here. Both CM and the motion driving simulator have provided their Simulink interface, which is easy and fast to develop. However, Simulink has limited use in the industry. There are also efficiency problems because Simulink is usually more demanding on computer performance than other developing tools.
- C language
  Both the motion driving simulator and CM provides a C interface. However, using the C interface for the motion driving simulator means that there will be no algorithm support from Panthera software, which indicates a large amount of mechatronics system development. An RTOS would also be needed for real-time performance, which adds extra complexity to this solution.
- Simulink and C as a standard Windows HID hardware
  This method transfer the Panthera Simulink interface into standard Windows HID hardware, which is similar to a joystick. Then the fake "joystick" can be connected to CM through its Cockpit Package.
  The advantage of this method is that it provides a good base if other desktop simulators would be used, and with an upgrade of Panthera software and their new interface, there is a chance that gets rid of Simulink in the whole process. However, developing a windows driver requires a lot of developing time, and is quite complicated.

With the assessment of these methods, the Simulink is finally selected since it is currently the most practical method and will give good accuracy and real-time performance. It will be used in developing the transfer process.

3.2 Methods

3.2.1 Offline Simulation

The first step of developing a chassis system would be developing the concept and system solution by using the offline simulation, including vehicle models, driver models, manoeuvres, etc.

3.2.1.1 Vehicle model

A representative model that matches the developing target should be set up in the first phase of the simulation. Although the CM already contains a number of models that are possible to use in simulations, these models are not specifically designed for vehicle dynamic testing purposes, thus more details are added to the vehicle model, and the other components also need to be doublechecked to guarantee proper performance.

In this project, generic vehicle models instead of representative vehicle models were used to suit the development of tools and methods.

3.2.1.1.1 Suspension System

One important part of the simulation within this thesis is the suspension system. Depending on the starting phase, a linear kinematic model is recommended. Both front and rear suspension models require tuning of geometry and kinematics, springs, ARBs and dampers to suit the targets for the vehicle model.

With the definition of a linear model in Section 2.5.1.1.1, a linear suspension model presented in Section 4.1.1 can be created.

Following geometric data and K-C data listed in Table 3-1 and Table 3-2 are used as the developing target.

Table 3-1 Front Suspension K-C Data

Parameter	Unit	Value
Front Static Camber	Deg	-1
Front Static Castor	Deg	5.5
Front KPI	Deg	9
Front Suspension Frequency	Hz	1.5
Front Damper Ratio	-	1
Front Spring Ratio	-	1
Front Bump Steer	Deg/m	-4
Front Bump Camber	Deg/m	-21.0
Steering Ratio, On-Centre	-	15.0
Front Aligning Torque - Toe	Deg/kNm	2.10
Front Lat Compliance Steer	Deg/kN	-0.1
Front Camber Compliance	Deg/kN	0.1
Front Roll Centre Height	mm	130
Front Long Compliance Steer	deg/kN	0.040
Front WC Longitudinal Stiffness	N/mm	950
Front Castor Compliance, Braking	deg/kN	-0.60

Table 3-2 Rear Suspension K-C Data

Parameter	Unit	Value
Rear Static Camber	Deg	-1.0
Rear Suspension Frequency	Hz	1.6
Rear Damper Ratio	-	1.0
Rear Spring Ratio	-	1.0
Rear Bump Steer	Deg/m	3.00
Rear Bump Camber	Deg/m	-34
Rear Lat Compliance Steer	Deg/kN	0.030
Rear Camber Compliance	Deg/kN	0.1
Rear Roll Centre Height	mm	150
Rear Long Compliance Steer	deg/kN	0.040
Rear WC Longitudinal Stiffness	N/mm	1050
Rear Castor Compliance	deg/kN	-0.40

3.2.1.1.2 Brake System

The brake systems of different CM models are not specifically tuned for different vehicles. Tuning of the brake system is necessary to ensure the vehicle can at least lock all four wheels during hard brake. The default brake system does not contain any EBD, ABS, or ESC function. To apply these functions, separate vehicle control models need to be developed, which is not a part of this project.

3.2.1.1.3 Steering System

The default steering system is under *Static Steer Ratio* mode, which provides a linear relationship between the steering wheel angle and the steer angle at the wheel. The steering wheel angle is the input signal to the steering system model and the model feedback with a steering wheel torque. This mode is the most used in this project.

The other modes including the *Dynamic Steer Ratio*, the *Pfeffer with Powersteering*, and other self-developed models. The *Dynamic Steer Ratio* and the *Pfeffer with Powersteering* models would use the steering wheel torque as the input signal and the steering wheel angle as the output, which works reversely as the *Static Steer Ratio* mode.

3.2.1.2 Manoeuvres

To test and verify the modelled vehicle, some manoeuvres were used in this project.

3.2.1.2.1 Double Lane Change Manoeuvre

The double-lane-change testing manoeuvre is designed based on ISO 3888-2 standard. The shape of the manoeuvre is shown in Figure 3-2. The data of each section is shown in Table 3-3.

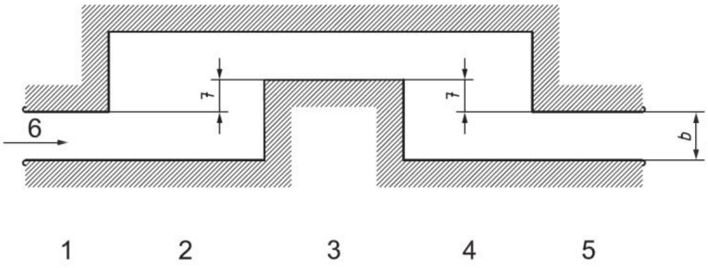


Figure 3-2 ISO 3888-2 Severe Lane Change [14]

Table 3-3 DLC Scenario Data [14]

Section	Length [m]	Width [m]	Width in the thesis [m]
1	12	1.1×vehicle width + 0.25	2.46
2	13.5	-	-
3	11	vehicle width + 1	3.01
4	12.5	-	-
5	12	1.3×vehicle width + 0.25, but no less than 3	3.00

Note:

1. The lane offset marks as Label 7 in Figure 3-2 is always 1 m.
2. Vehicles always enter from mark 6 and follow their direction.
3. According to the standard, the vehicle should use the highest gear position that guarantees a minimum engine speed of 2000 r/min while entering section 1. For vehicles with automatic transmission, the gear lever should be put in the drive position (D).[14]

3.2.1.2.2 Steady-State Cornering Manoeuvre

The steady-state cornering (SSC) manoeuvre refers to the manoeuvre that the driver or driver model are given a designated cornering radius and cornering speed.

A complete test process includes several manoeuvres with different radius and speeds; thus, a yaw rate response could be plotted, and the understeer or oversteer characteristic of the vehicle could be determined, see Figure 3-3.

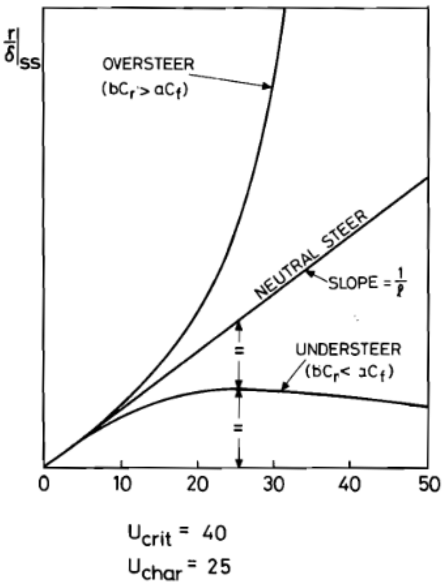


Figure 3-3 Typical plots of yaw rate response [15]

3.2.1.2.3 Sine with Dwell Manoeuvre

The Sine with Dwell (SWD) manoeuvre is based on the standard ISO 19365-2016 [16]. The test vehicle is required to cruise at 80 km/h and then the steering input shown in Figure 3-4 is given. In the real world, this manoeuvre is usually performed by a steering robot, thus in this project, this manoeuvre was only performed with a driver model.

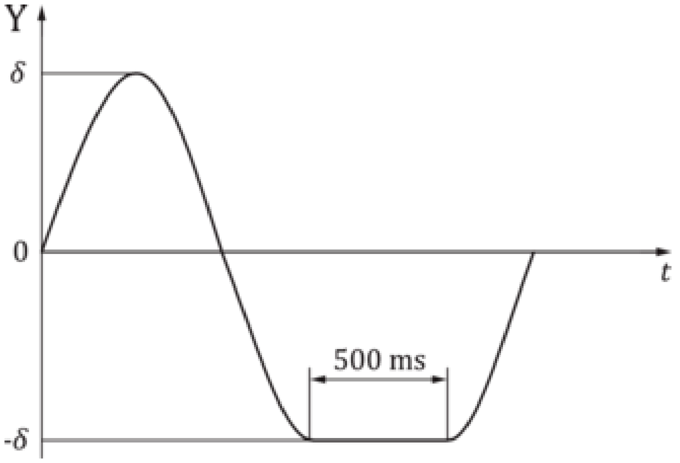


Figure 3-4 Steering-wheel input for a sine with dwell test [16]

3.2.1.3 Driver Model Tuning

To obtain a good result in the offline simulation, the driver model needs to have the information of the vehicle model, thus a Driver Adaption needs to be executed. IPG CarMaker provides this function, however, it is not very reliable.

To execute a Driver Adaption in CarMaker, the only parameter needed is the road friction, then a series of pre-designed manoeuvres will be simulated to generate a set of "knowledge" data, which will be part of the driver model.

For some manoeuvres, the driver model needs to be finely tuned, which could be conducted in two ways:

- Provide a biased road friction
  Although IPG suggests that executing the Driver Adaption with the same

road friction as what will be used in the testing scenario, a changing to the road friction can sometimes give a better result. Higher road friction input will lead to more aggressive driving behaviour, and a lower road friction input will lead to more conservative driving behaviour.

- Tune the “knowledge” data directly
  For more precise tuning, the knowledge data located in the *TestRun* files could be directly tuned. Different parameters provide different tuning effects. The explanation of each parameter can be found in the helping document of the IPG Driver [17] on page 52.

3.2.2 Transferring from Offline Simulation to Simulator

To transfer the offline simulation into the driving simulator, several key steps should be taken, including connecting vehicle signals, set up the motion and vision feedback, etc.

3.2.2.1 The connector between the motion driving simulator and CM

To run a DIL simulation, signals are connected between CASTER and CM through Simulink. The following signals are simply directly connected:

- From Panthera to CM
    - Pedal positions (including the accelerator, brake, and clutch)
    - Steering wheel angle
    - Shifting pedal signals
- From the motion driving simulator to CM
    - Shifting lever signals
- From CM to Panthera
    - Engine rotation speed
    - Vehicle gear number
    - Vehicle steering torque
    - Wheels longitudinal and side slip signals
    - Vehicle speed
- From CM directly to the motion platform
    - Vehicle speed
    - Inertial sensor signals (details in Section 3.2.2.2)
    - Steering torque
- Looping inside Panthera software
    - Throttle signal
    - Brake signal
- Generated by the Simulink model
    - Steering friction
    - Steering damping

3.2.2.2 Inertial sensor signals

To provide the motion driving simulator with correct velocity, acceleration, rotation angle and angular velocity, an inertial sensor has been implemented in the vehicle model, at approximately the position of the head of the driver. After a rearrangement of signals, these signals are sent to the Panthera software for filtering and composing. The motion of the motion platform is controlled from these signals by the Panthera software.

3.2.2.3 Visual feedback

To simplify the development process, the IPG Movie is used to provide feedback to the test drivers. IPG Movie generates scenarios from the road file, including terrain, lanes, road marks, visible objects, etc. The original visual rendering system of Panthera is covered. This simplification avoids 3D modelling works during the developing process.

However, with the upgrade of Panthera software, to use its internal socket to connect CarMaker, Unity 3D engine is designated as the rendering software. Although it provides a better visual feedback quality, the 3D modelling work of both the scenario and the testing vehicle becomes unavoidable.

3.2.2.4 Road Surface Generation

During the development of the motion driving simulator, a problem showed up that the lack of motion platform vibration caused the driver feeling lacking a sense of driving. Thus, a road surface profile was introduced to generate the needed vibration.

A Class A road surface has been created according to the standard ISO 8608:1995 [18]. The road surface information was compressed into a *.crg file with ASAM OpenCRG [19].

MATLAB has been used as the tool to generate road surface information. Data from Table 3-4 regarding road size has been used.

Table 3-4 Road Surface Size and Resolution

Surface file length	u	13000 m
Surface file width	v	15 m
Longitudinal resolution	u_{inc}	0.1 m
Lateral resolution	v_{inc}	0.1m

There are many ways to generate a random road surface from the desired power spectral density (PSD). The method used here came from a journal of C. S. Dharankar, M. K. Hada and S. Chandel [20], and the superposition of harmonics (SOH) method was selected.

The generated road special spectrum is:

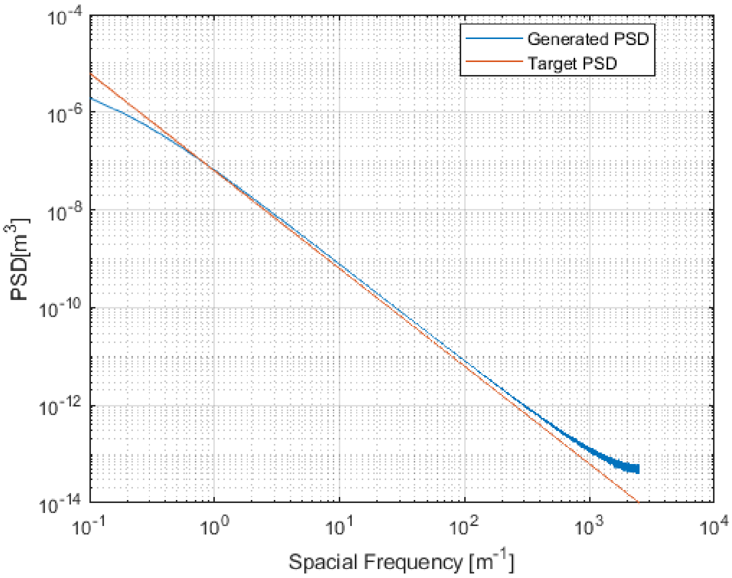


Figure 3-5 PSD averaged at U direction for Road Class A

3.2.3 DIL Simulation

With the offline simulation working, and with the vehicle model being transferred to the motion driving simulator, and with the correlation of the vehicle dynamics performance between the offline simulation and the testing in the simulator has been verified, the DIL simulation can be performed.

3.2.3.1 The Outcome of DIL Simulation

Before the DIL simulation begins, a verification that guarantees the correlation with the offline simulation is necessary. The target of DIL simulation is to involve the subjective opinion from the test driver during the early development phase. The outcome includes the objective and subjective data, subjective assessment results, and comments from the test drivers.

3.2.3.2 Subjective Assessment

To perform a subjective assessment, questionnaires and assessment matrixes are required. The development engineer should raise the relevant questions regarding the test targets and gather the questions into questionnaires. Test drivers are required to fill out the questionnaires. The responses in the questionnaires should be collected, evaluated, and analysed toward the developing target.

Signal triggers were also used as a method for subjective assessment. With the vehicle model set with an automatic transmission, the signal from the shift pedals on the simulator was loopback as a trigger signal. Test drivers were required to pull shift pedals at the required condition.

3.2.4 Conclusive Simulation Process

With the previous methods, the following steps of proceeding a whole developing process could be developed.

3.2.4.1 Function Model Design

The first step is to design a baseline of a representative model. In our case, it is a generic vehicle model. The model should be verified in general simulation tools, for example, MATLAB or Adams before being implemented into CarMaker for simulation.

3.2.4.2 Offline Simulation

With the representative model implemented, there are several steps before coming to the offline simulation.

1. Development of the vehicle models
   To develop a vehicle model, the recommendation from this project is to start from an example vehicle implemented in IPG CarMaker. Besides implementing the developed representative model, other models also need to be carefully checked to confirm that they are general and meaningful. In this project, instead of a representative vehicle model, a generic vehicle model has been created.

2. Select test manoeuvres
   Based on the development target, related manoeuvres should be designed or selected. Related standards, rules, or guidelines should be gone through, especially for those standard manoeuvres. Selected manoeuvres for this project can be found in Chapter 3.2.1.2

3. Development of test scenarios
   Test scenarios based on the selected manoeuvre need to be developed. The scenarios should include the terrain of the testing ground, visible references (road marks, pylon alleys, barrels, etc.), and reference routes for driver models (optional). With the old version of Panthera software, all these items are developed in the *CarMaker Scenario Editor*.
   However, with the new Panthera software, the visual feedback would be handled by the Unity game engine, thus the terrain of the testing ground and the visible references should be modelled both in CarMaker Scenario Editor and Unity and must be identical.

4. Development of the driver models
   Based on the experience from this project, the CarMaker implemented driver models are good enough for most of the test manoeuvres. Besides input manoeuvres into CarMaker, a *Driver Adaption* is needed to feed vehicle characteristics into the driver model.
   In some cases, the driver model would need manual tuning. One method is to change the given friction for the *Driver Adaption* process. Higher friction would lead to more aggressive driving behaviour. The other method is to find the related parameters directly from the *TestRun* file, for example, what was done in Section 4.2.2.1.

5. Collecting the test results
   There are multiple methods to collect simulation results from CarMaker. The method recommended by IPG is to use IPG Control. For some special purposes, collecting data directly from Simulink can be a better alternative.

6. Tune the vehicle model
   The offline simulation is not only a base for the DIL simulation but also an important step during development. The vehicle model needs to be developed to meet the vehicle dynamic target before being transferred to the DIL simulation.

3.2.4.3 Model Transfer

When the vehicle model has been developed to meet the targets, it should be transferred to the driving simulator for the next phase of development. Following steps should be taken:

1. Choose a proper link between CM and Panthera
   As stated in Chapter 3.1.3, there are several ways to connect CarMaker with Panthera. In this project, Simulink was selected as the tool, and the following steps are all based on it.
2. Start with the given Simulink template from CarMaker
   To use Simulink as the connector, the recommendation from this project is to start with the default Simulink model given by CarMaker, in which the CarMaker has already been implemented.
3. Implement Panthera Simulink Library
   The Panthera Simulink Library and the implementation steps were provided by the CASTER team. A copy of the Simulink blocks and a configuration in the *ephysenet.ini* was required.
4. Implementation of the inertial sensor
   An extra inertial sensor is needed to provide the velocity, acceleration, rotation angle and angular velocity signals from the driver’s position. See Section 3.2.2.2.
5. Connect all the signals
   All required signals need to be connected within Simulink. See Section 3.2.2.1.

3.2.4.4 DIL Simulation

With the offline model ready and transferred, DIL simulation can be performed. During the DIL simulation, both subjective assessment and objective analysis should be conducted. The test drivers’ answers to questionnaires and their driving data could be cross analysed for more results. The comments from test drivers are very important inputs in the development process.

3.2.5 Verification of Vehicle Model

To verify the model, both with offline and online simulation, several manoeuvres should be gone through. In the offline simulation, a verified model should provide simulation results that are both reasonable results and match the development targets. In DIL simulation, a verified model should provide results that are highly consistent with the offline simulation, and also a good driving experience.

4 Results

The results in these sections are about the development process. Specific results regarding different case studies are reported under the case study sections (See Chapter 5.1.5 and 5.2.5).

4.1 Outcomes

For offline simulation, a generic big-size SUV model was developed. Manoeuvres were tested and meet the targets in the project. Specifically, the driver model was tuned for better offline simulation results.

For DIL simulation, a transfer from the offline simulation to the DIL simulation was executed and verified. A connector based on Simulink was developed for connecting signals crossing different software. Case studies have also been conducted to practically test the simulation configuration. With the experience from the case studies, it is possible to assess and develop the vehicle model in the motion driving simulator.

By developing the simulation process, it is possible to run an offline simulation and transfer it to the motion driving simulator in a short time. By selecting IPG CarMaker as the simulation tool, most of the simulation models and configurations can be used both in the offline simulation and the DIL simulation.

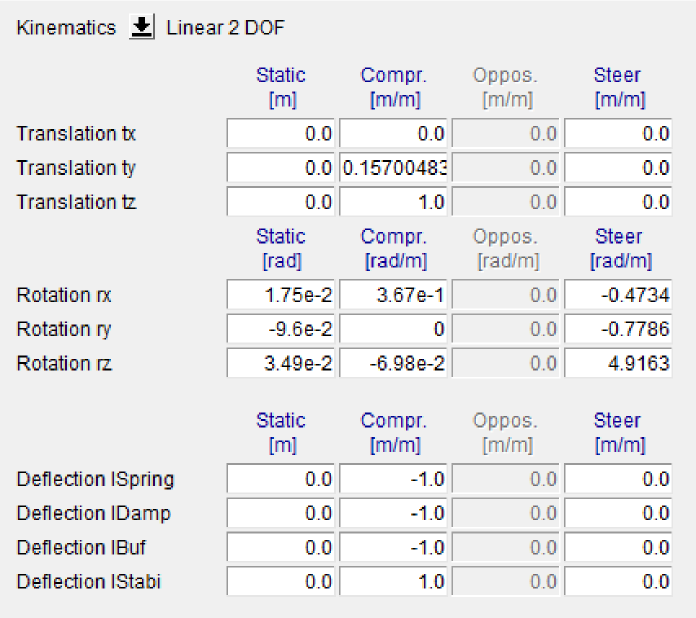
4.1.1 Vehicle Model

During the project, a generic big-size SUV model was developed. The general parameters of the vehicle model are listed in Table 4-1.

Table 4-1 General Vehicle Model Parameters

Parameter	Unit	Value
Total mass	kg	2078
Sprung mass	kg	1804
Wheelbase	mm	2984
Track width	mm	1676
Total roll inertia	kgm^2	1262
Total pitch inertia	kgm^2	4072
Total yaw inertia	kgm^2	4256
CoG height	mm	682
CoG to the front axle	mm	1492
Tire	235/60 R18	

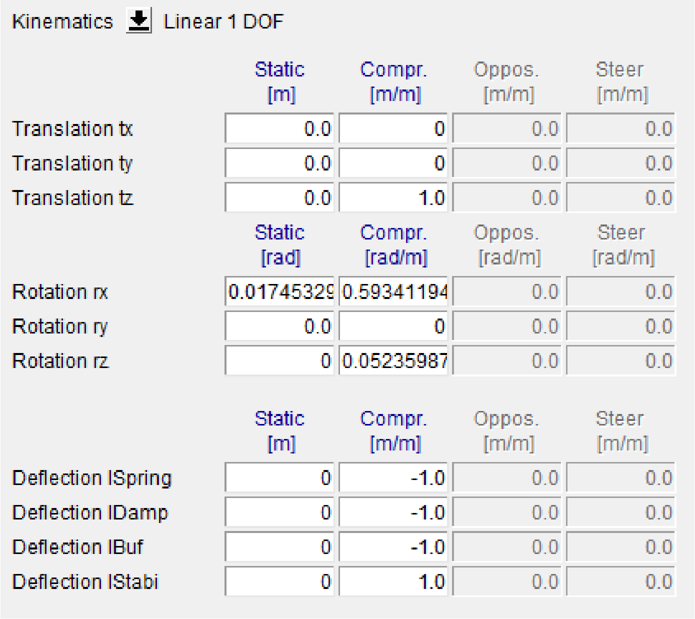
The generic linear suspension models developed with the theory from Section 2.5.1.1.1 and K-C data from Section 3.2.1.1.1 are shown in Figure 4-1 and Figure 4-2. With the linear kinematic model definition in section 2.5.1.1.1, in each row, from left to right are c_{off}, c_0, c_1, c_2 (including the grey blanks).



Kinematics Linear 2 DOF

	Static [m]	Compr. [m/m]	Oppos. [m/m]	Steer [m/m]
Translation tx	0.0	0.0	0.0	0.0
Translation ty	0.0	0.15700483	0.0	0.0
Translation tz	0.0	1.0	0.0	0.0
	Static [rad]	Compr. [rad/m]	Oppos. [rad/m]	Steer [rad/m]
Rotation rx	1.75e-2	3.67e-1	0.0	-0.4734
Rotation ry	-9.6e-2	0	0.0	-0.7786
Rotation rz	3.49e-2	-6.98e-2	0.0	4.9163
	Static [m]	Compr. [m/m]	Oppos. [m/m]	Steer [m/m]
Deflection lSpring	0.0	-1.0	0.0	0.0
Deflection lDamp	0.0	-1.0	0.0	0.0
Deflection lBuf	0.0	-1.0	0.0	0.0
Deflection lStabi	0.0	1.0	0.0	0.0

Figure 4-1 Linear Front Suspension Model



Kinematics Linear 1 DOF

	Static [m]	Compr. [m/m]	Oppos. [m/m]	Steer [m/m]
Translation tx	0.0	0	0.0	0.0
Translation ty	0.0	0	0.0	0.0
Translation tz	0.0	1.0	0.0	0.0
	Static [rad]	Compr. [rad/m]	Oppos. [rad/m]	Steer [rad/m]
Rotation rx	0.01745329	0.59341194	0.0	0.0
Rotation ry	0.0	0	0.0	0.0
Rotation rz	0	0.05235987	0.0	0.0
	Static [m]	Compr. [m/m]	Oppos. [m/m]	Steer [m/m]
Deflection lSpring	0	-1.0	0.0	0.0
Deflection lDamp	0	-1.0	0.0	0.0
Deflection lBuf	0	-1.0	0.0	0.0
Deflection lStabi	0	1.0	0.0	0.0

Figure 4-2 Linear Rear Suspension Model

4.1.2 Verification Results

4.1.2.1 Double Lane Change Manoeuvre

With the configuration above and with a linear suspension model, the vehicle dynamics performance in both offline simulations and testing in the driving simulator has been correlated. In the offline simulation, a finely tuned IPG Driver model passes the test with an entry speed of 75 km/h. In the online simulation, a human driver passes the test with an entry speed of 60 km/h. Figure 4-3 and Figure 4-4 shows the offline simulation result of the DLC manoeuvre. Explanation of this difference will be discussed in Section 6.1.1.

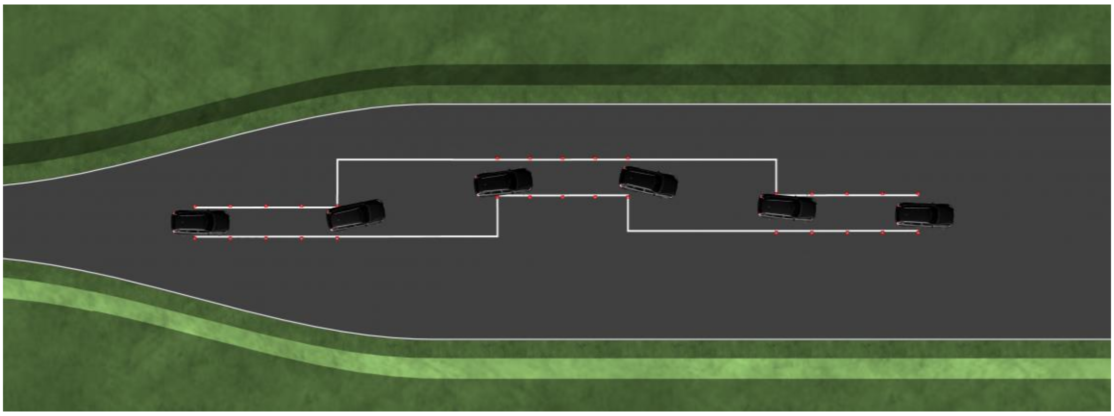


Figure 4-3 DLC with a driver model at 75 km/h

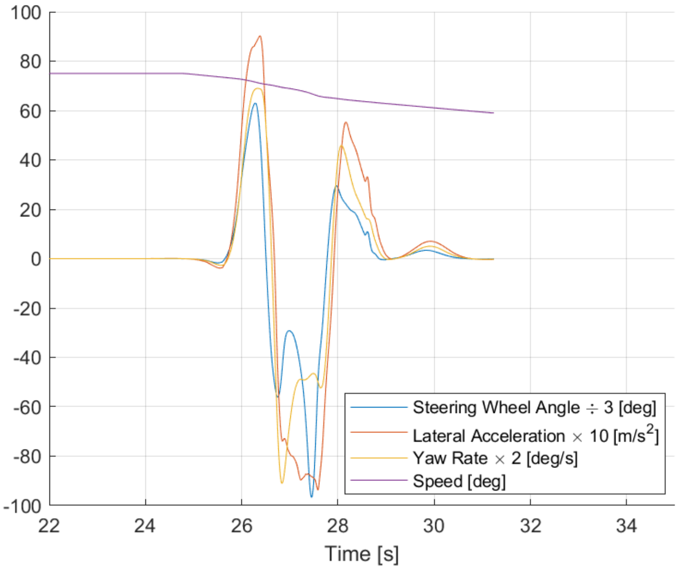


Figure 4-4 DLC with a driver model at 75 km/h

4.1.2.2 Steady-State-Cornering Manoeuvre

By driving on a circle with a radius of approximately 100 m, and drive from 0 km/h to 100 km/h with small acceleration, the yaw rate gain could be calculated and plotted. From Figure 4-5, the generic vehicle model shows a good correlation between offline and DIL simulation Due to that the human driver does not drive as smooth as the model driver both in the longitudinal and lateral direction, the data distribute around the offline simulation result.

The figure also shows that the vehicle model has an understeer character with a characteristic speed of about 82 km/h. This is important for the vehicle model without an ESC system.

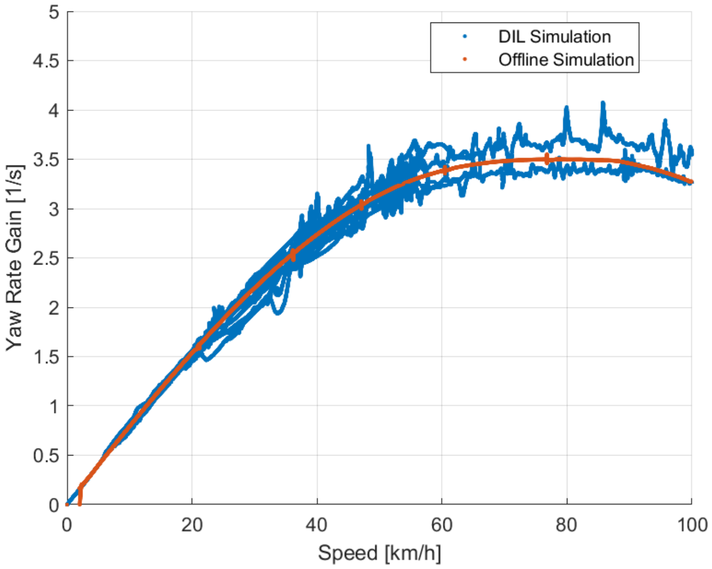


Figure 4-5 SSC results for both Offline and DIL simulation

4.1.2.3 Sine-with-Dwell Manoeuvre

The Sine-with-Dwell manoeuvre was executed with the following configuration:

- Vehicle speed: 80 km/h
- Steering wheel amplitude: 180 deg on each side
- Steering frequency: 0.7 Hz
- Dwell length: 500 ms

Note that the generic vehicle model was not installed with an ESC system, and it rolls over if the steering wheel amplitude is set to 270 deg according to the standard. Other values are the same as the standard ISO 19365-2016 [16].

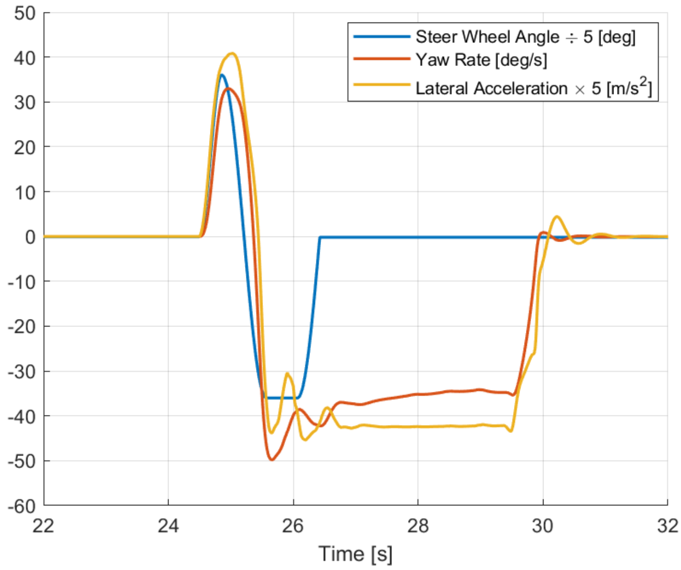


Figure 4-6 Sine-with-Dwell Offline Simulation Result

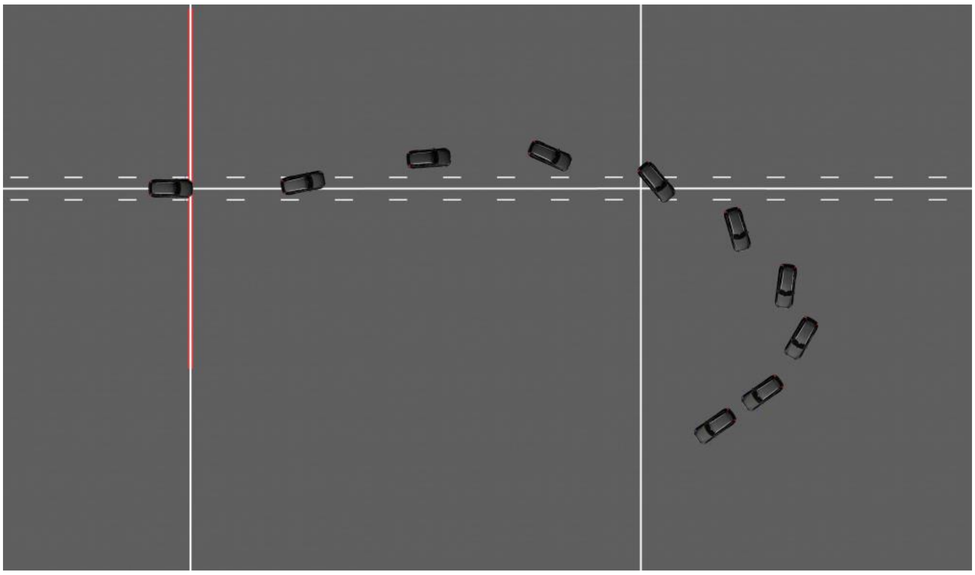


Figure 4-7 Sine-with-Dwell Offline Simulation Result

The offline simulation result shows a close-to-edge but not roll-over situation. The test vehicle behaves severe oversteer and the inner wheel almost lift over the ground. The vehicle could not stop the yaw motion until it slowed down quite much and acquired the grip on all four wheels again. To avoid this situation, introducing an ESC system, reducing the speed or reducing the steering wheel amplitude could all be helpful.

A test driver also sat in the motion driving simulator but with the model driving, as if there is a steering robot. However, the motion was not so intense as expected. This manoeuvre should mainly be used for offline simulation.

4.1.3 Development Process

During the developing process, a vehicle dynamics development process with both offline simulation and motion driving simulator involved and with Chalmers hardware and software was developed. Figure 2-1 shows the process. Detailed description could be found in Chapter 3.2.4.

The development process worked well in both case studies and has proofed its effectiveness. However, some specific problems appeared and should be resolved in future development.

4.2 Specific Problems

This chapter lists the problems that showed up during development.
The problems were based on CarMaker v8.1.1. Some problems could already have been resolved in the later version.

4.2.1 Vehicle Model Issues

The generic vehicle model that was created with CarMaker did not have the details that are required for on-the-limit development for vehicle dynamics performance. Some details in the vehicle model and the suspension systems had to be refined.

4.2.1.1 Suspension System

The suspension system did not have the system solutions that are required to meet the performance targets for the generic vehicle. The original CM model has very basic suspension systems that are fine to drive the vehicle, but it does not have the required vehicle dynamics performance. During the model verification, the front axle appears severely un-match to the vehicle, and the rear axle gives an abnormal camber value.

Thanks to some general K-C data that were available at Chalmers, a new version of the kinematic model was developed for the vehicle, which used a linear 2-DOF model on the front axle and a linear 1-DOF model on the rear axle.

4.2.1.2 Vehicle Model Data

The original vehicle model indicated issues with its inertia value.

According to the NHTSA Testing Result [21], the average inertia of an SUV is:

$$\text{Inertia around the X} - \text{axis: } I_{xx} = k_{xx} \cdot M \cdot (T/2)^2,$$
$$\text{Inertia around the Y} - \text{axis: } I_{yy} = k_{yy} \cdot M \cdot (L/2)^2,$$
$$\text{Inertia around the Z} - \text{axis: } I_{zz} = k_{zz} \cdot M \cdot (L/2)^2.$$

With the given data of our generic vehicle:

$$\text{Mass of the vehicle: } M = 2078 \text{ kg},$$
$$\text{Track width of the vehicle: } T = 1.889 \text{ m},$$
$$\text{Wheelbase of the vehicle: } L = 2.984 \text{ m}.$$

By looking up the figure from the NHTSA report [21], it tells:

$$k_{xx} = 0.65 \sim 0.72,$$
$$k_{yy} = 0.85 \sim 0.91,$$
$$k_{zz} = 0.90 \sim 0.95.$$

By picking a value at about the centre of the above ranges, the calculated values of inertia were:

$$I_{xx,orig} \approx 1261\ kgm^2,$$
$$I_{yy,orig} \approx 4071\ kgm^2,$$
$$I_{zz,orig} \approx 4256\ kgm^2.$$

The calculated values are used in all cases, instead of the default values which are smaller than average.

4.2.1.3 Powertrain System

The powertrain system in the vehicle model required further development. The acceleration pedal was set at torque mode and cannot provide a correct engine brake torque to the transmission. This problem has been fixed by changing the gas pedal to a load pedal, thus the fuel is completely cut off when the gas pedal is released.

4.2.2 Offline Simulator Issues

4.2.2.1 Driver Model Issue

During the offline simulation, a problem with the DLC manoeuvre showed up. The driver model did not reach the limit of the vehicle performance, thus cannot pass the DLC test even at very low speed, for example, 50 km/h.

By searching through the model driver parameter file, three parameters are found related to this problem:

- Driver.Knowl.Lat.tPreview
- Driver.Knowl.Lat.tYawPro
- Driver.Knowl.Lat.tPreDyn

All three parameters were generated from the model adaption process that the driver model learns the attributes of a vehicle model. However, they are not generated specifically for the DLC test.

By manually tuning these three parameters, as mentioned in Section 3.2.1.3, *Driver.Knowl.Lat.tPreview* provides the most significant influence and should be tuned first. The other two parameters are only used for fine-tuning.

The tuned result is:

- Driver.Knowl.Lat.tPreview = 0.565
- Driver.Knowl.Lat.tYawPro = 0.035
- Driver.Knowl.Lat.tPreDyn = 0.095

The experience from the tunning is that a too-small *Driver.Knowl.Lat.tPrevie* usually leads to an oversteered result, and a too-big *Driver.Knowl.Lat.tPrevie* causes the model to be too conservative.

4.2.3 DIL Simulation Issues

Some issues that showed up during the DIL simulation are listed here. Some of them have already been resolved while some are not.

4.2.3.1 Steering Torque Issue

The steering torque feedback needs to be further developed. When driving, it does not feel like a real car. Objectively, the feedback torque is too sensitive to the vehicle longitudinal acceleration. In hard braking conditions, the torque even appears in the wrong direction, which pushes the steering wheel to the edge of either side.

4.2.3.2 Data Collection Issue

The data collection was not a problem for offline simulation because the CM included *IPG Control* (Datalogger and viewer) was good enough for data analysis, but at CASTER it caused some problems. With the default setting of CM, simulation data was saved in the project folder. However, at CASTER, the project folder is at the university server, and CM needs to pause for a little while during the simulation to save data, which causes glitches during the DIL simulation. This problem was solved by moving the data saving location to the local computer manually.

4.2.3.3 Low Frame Rate Visual Effect Issue

The motion driving simulator sometimes runs at a quite low frame rate (below 30 fps), which is believed to be caused by the limited performance of the motion driving simulation computer. The problem shows up randomly and usually lasts for dozens of seconds, then it recovers itself.

4.3 Answers to the Research Questions

- **How can Vehicle Dynamics offline simulation tools be included in the engineering development process to support the concept development of chassis systems?**
  Offline simulation tools are used in several steps of the development process. A representative vehicle model with system solutions will be developed by using selected manoeuvres, scenarios, and driver models. Offline simulations will be used throughout the automotive project to develop the systems to meet targets and for problem-solving if required.

- **How can motion driving simulators be included in the engineering development process to support the assessment, development and tuning of chassis systems?**
  When using the driving simulator for test and development, the subjective results from the test drivers are important outcomes that can reduce the need for mule cars and early prototypes, which saves both time and cost. With the use of motion driving simulators, test drivers can drive a concept vehicle model before the first mule car being produced and before the first test series being conducted. The driving simulator can also be used for general development, sensitivity studies, tuning and problem solving throughout the automotive project.
- **How will vehicle dynamics simulation tools and the use of driving simulators in the engineering development process improve the technical solutions and shorten lead times?**
  The vehicle dynamic simulation tools provide an efficient and low-cost solution for vehicle dynamics development. With the introduction of the motion driving simulator, some tests that require the use of a mule car can be tested with a motion driving simulator. The time and cost for manufacturing mule cars and different components can be much reduced and time spent on manufacturing components and tuning the hardware system can now be shortened.

- **The possibility to use the driving simulator for the development of e.g., vehicle dynamics, ride comfort and other driving parameters will be assessed in the project.**
  By conducting two case studies, the possibilities to use the motion driving simulator for developing vehicle dynamics systems are now proved. However, there has not been a possibility to use the driving simulator

for the development of ride comfort and other driving parameters in this project. This is mainly because of limited time.

4.4 Check of Deliverables

- **Literature study about vehicle simulation tools and motion driving simulators.**
  A literature review about the vehicle dynamics modelling and simulation, and motion driving simulator has been done.
- **A generic SUV model as a baseline vehicle model.**
  A generic big-size SUV model with a linear kinematic suspension system based on the example case of CarMaker and general K-C data has been created.
- **Testing manoeuvres to develop and verify the vehicle dynamics performance in the off-line simulations and the driving simulator.**
  The Double-Lane-Change, Steady-State-Cornering, and the Sine-with-Dwell manoeuvres are developed to verify the generic SUV model and to be used to develop the vehicle model and the systems both in offline simulation and in DIL simulation.
- **Developing tools and methods to work with offline simulations and the motion driving simulator for the first development phases in automotive projects.**
  Tools and methods that work with the offline simulation and the motion driving simulator were developed using CarMaker as the offline simulation tool and CASTER as the motion driving simulator. However, due to the limited time, tools that work with the updated Panthera software was not finished.
- **An analysis of different ways to run the vehicle model in offline simulation and the driving simulator.**
  Comparisons among different connectors and different simulation tools have been performed. An optimal solution based on the existing tools has been selected and developed.
- **A process for developing vehicle dynamic performance with simulation tools and using a driving simulator.**
  A process including vehicle model development, offline simulation, vehicle model transferring, DIL simulation and final analysis has been created and tested.
- **Methods to quantify the contribution of driving simulators in development processes.**
  Through the project, quantified results were gathered to roughly estimate the contribution of the development process. However, methodologies to precisely calculate the contribution was not developed.
- **Case studies to prove the effectiveness of the process from different perspectives.**
  Case study 1 was developed and executed as planned. Case study 2 was half-finished due to the time limit.

5 Case Studies

5.1 Case Study 1 - Driving Stability under Crosswinds

5.1.1 Introduction

This Case Study is a co-work with the Industrial PhD project at VEAS / M2 at Chalmers about Driving Stability under Crosswinds, see reference [22]. An aerodynamic model with a gust wind generator was developed and tested through the test process. The purpose of this Case Study is to see how a driving simulator can be used to assess crosswinds and to develop solutions to improve the vehicle dynamic performance under crosswind conditions.

5.1.2 Deliverables

- Create a vehicle model to suit the vehicle that is used in the PhD project
- Develop an offline simulation model of the crosswind that applies configurable wind gusts to the vehicle.
- Transfer the offline vehicle model and the crosswind simulation model to CASTER.
- Study the subjective experience when driving.
- Study the drivers’ response to wind gusts.
- Study the influence of suspension parameters and other vehicle configurations.

5.1.3 Limitations

- Limited real-world testing data will be used as references in the test.
- The configuration of the vehicle model and design of the test plan was based on the experiences from the previous work in the PhD project and are specific to the work in the PhD project.
- Only limited results from the evaluation will be reported here. Mainly results regarding the testing method and process will be demonstrated here. More results will be extracted in the PhD project.

5.1.4 Methods

5.1.4.1 Aerodynamic Model

An aerodynamic model based on a look-up table of time-averaged aerodynamic coefficients has been implemented with C language. The model contains several basic functions:

- Applies forces and moments to the vehicle body, based on relative air flow velocity and direction.
- Transfer wind direction from global coordination to vehicle body coordination.
- Generate gust and add the gust to total wind speed and wind direction.

The aerodynamic model has the following limitations:

- The aerodynamic model is based on a look-up table that came from steady-state CFD results, transient behaviours are not considered.

- The transfer of wind direction only applies in the X-Y plane, i.e., direction-changing causing by roll and pitch motions are ignored because motions in these two directions are very small in this case study.
- Only the old version of Panthera software in CASTER was used.

The linear interpolation technique is used with the look-up table. CarMaker libraries are used here to read the table and to execute the interpolation.
The detailed look-up table is not allowed to demonstrate here due to confidential requirements.

Gust winds are generated according to the methods described in the paper [23]. Profiles used in this case study are the same as the paper [24], see Table 5-1.

Table 5-1 Gust Wind Profiles

	w_y^{start} [m/s]	w_y^{max} [m/s]	w_y^{min} [m/s]	w_y^{end} [m/s]	t_b [s]	t_p [s]	t_d [s]	t_{gust} [s]
Profile 1	0	5	-5	0	0.5	0	0.6	1.6
Profile 2	0	5	-5	0	0.7	0	0.2	1.6
Profile 3	0	5	5	0	0.3	0.5	0	1.6

The gust was generated according to Equation 1 from the paper [24].
The explanation of each parameter can be seen in Figure 5-1.

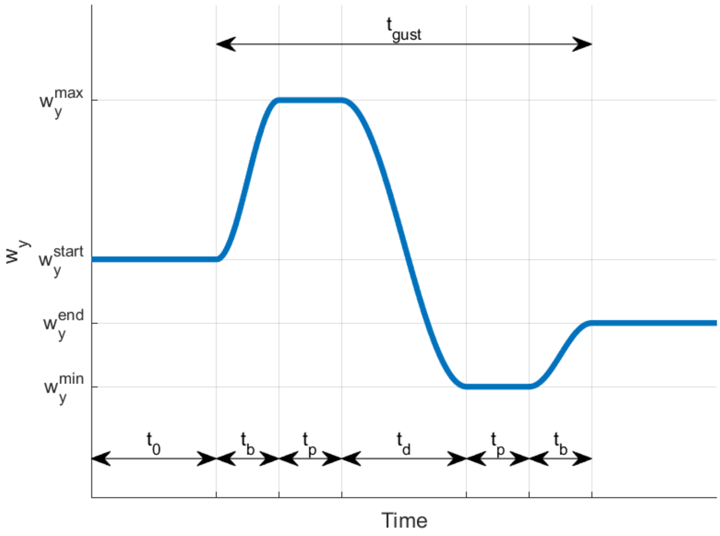


Figure 5-1 Explanation of the use of parameters

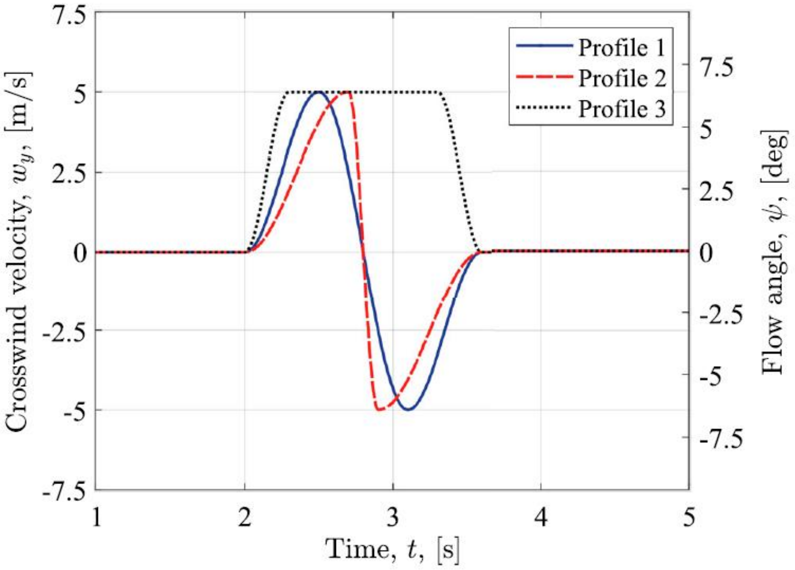


Figure 5-2 Generated gust wind [24]

In the actual test plan, t_{gust} will be changed with different gust configuration, which indicates a scale on t_b, t_p, t_d at the same time, i.e., only scale the time but keep the shape of the gust curve.

5.1.4.2 Wind and Road Vibration generator

For a more realistic driving experience, wind disturbances were added to the model.

In the aerodynamic model, a disturbance was added directly to the gust speed w_y. The disturbance was a normal distributed random number between ± 5 m/s.

In the design of the test scenario, a CRG file with Road Class A described in Section 3.2.2.4 was used.

5.1.4.3 Steering system

During the development process, oscillation on the steering system was noticed. Due to the limitation that the Panthera software was not updated when conducting this case study, *Static Steer Ratio* mode was the only option to run the simulation, CarMaker does not support any mechanical system simulation under this mode. Therefore, extra damping and friction were added directly to the steering motor through Panthera software. The steering feeling was not quantitatively precise, but qualitatively acceptable.

5.1.4.4 Tire Model

A general MF-5.2 standard magic formula model was used in this case study. It was inherited by the PhD project [22]. Due to the confidential requirement, no more details can be published here.

5.1.4.5 Testing Setup

Two kinds of testing setups are used in this case study.

5.1.4.5.1 Sequence test with different gust profile

In this test scenario, the driver is required to accelerate to a target speed, keep steady and drive under several gust conditions. A sequence of gusts with different w_y^{max} are introduced in the simulations after the vehicle reaches the target speed. The applying time of each gust is given with a rough interval of 10 seconds with a random time shift. The direction of the gust, which would be either from the left or from the right, is also random, which prevents the driver from any estimation of the gust.

In this case study, the sequence of w_y^{max} is given as follow:
0.5, 1.0, 1.5, 3.0, 4.5, 6.0, 8.0, 10, 8.0, 6.0, 4.5, 3.0, 1.5, 1.0, 0.5

The unit is m/s.

5.1.4.5.2 Single gust test with different vehicle configurations

In this test scenario, the driver is required to accelerate to a target speed, keep steady and drive under a single gust condition. One parameter of the testing vehicle is changed every time.

5.1.4.6 Test Plan

5.1.4.6.1 Offline Simulation

In the offline simulation, a comparison has been made between the result from this model and the result from the PhD project. The comparison included the following parameters with the same gust:

- Yaw rate
- Lateral velocity

5.1.4.6.2 DIL Simulation

The test plan showed in Table 5-2 is designed for this case study.

Table 5-2 Test Plan for DIL Simulation

Scenario	Gust Profile	Target Speed [km/h]	Gust Duration [s]	Changed Vehicle Parameter	Changing Direction
Sequence Tests	Profile 1	120	0.8	None	N/A
		140			
		160			
		180			
		200			
		120	1.6		
		160			
		200			
	Profile 3	160	3.2		
Single Tests	Profile 1	160	1.6	None	N/A
				CoG_x	+
					-
				Yaw Moment Coeffiency C_{ym}	+
					-
				Mass	+
					-
				Wheelbase	+
					-
				Rear Axle Side Force Steering	+
					-
				Front Axle Side Force Steering	+
					-
				Rear Axle Roll Steering	+
					-
				Front Axle Roll Steering	+
					-

5.1.4.7 Subjective Assessment Matrix

Two subjective assessment matrixes were used in this case study, one aims at the subjective assessment of the gust and vehicle, and the other aims at collecting the opinions of the DIL simulation.

The subjective assessment matrix regarding the gust and vehicle contains 4 independent questions that are about gust, stability, controllability, and the driver’s own driving.

The Subjective assessment matrix regarding the DIL simulation contains 5 independent questions that are about vehicle model, driving experience, visual lag, motion lag, and motion sickness.

Questions regarding driving under crosswind are:

- QT1: [Gust] How did you experience the gust?
- QT2: [Stability] How stable do you think the vehicle is when affected by the gust?
- QT3: [Controllability] How controllable do you feel the vehicle is?
- QT4: [Driving Assessment] How well could you as a driver stabilize the vehicle?

Questions regarding the motion driving simulator are:

- QDS1: [Vehicle Experience] How well is the simulator correlate with a real car?
- QDS2: [Driving Experience] How much difference are there comparing driving in a simulator with driving in a real vehicle?
- QDS3: [Real-time Problem] Do you feel any lag between operating and visual feedback?
- QDS4: [Real-time Problem] Do you feel any lag between operating and motion feedback?
- QDS5: [Motion Sickness] Do you feel any motion sickness during the operation?

All these questions require the test drivers to give a score from 1 to 10, where 1 represents the worst, 5 represents the neutral, and 10 represents the best.

Only QDS1-5 are discussed and displayed in this case study. QT1-4 will be the outcome of the PhD project.

5.1.4.8 Signal Triggers

A pair of signal triggers were used as a method of conducting subjective assessments in this case study. With the test vehicle set to automotive transmission, the signals from the shift pedals were reconnected into the data pool, which was logged for analysis. The drivers were required to pull the left shift pedal (down-shift pedal) when they felt the gust wind, and to pull the right shift pedal (up-shift pedal) when they felt they were about to lose control of the vehicle.

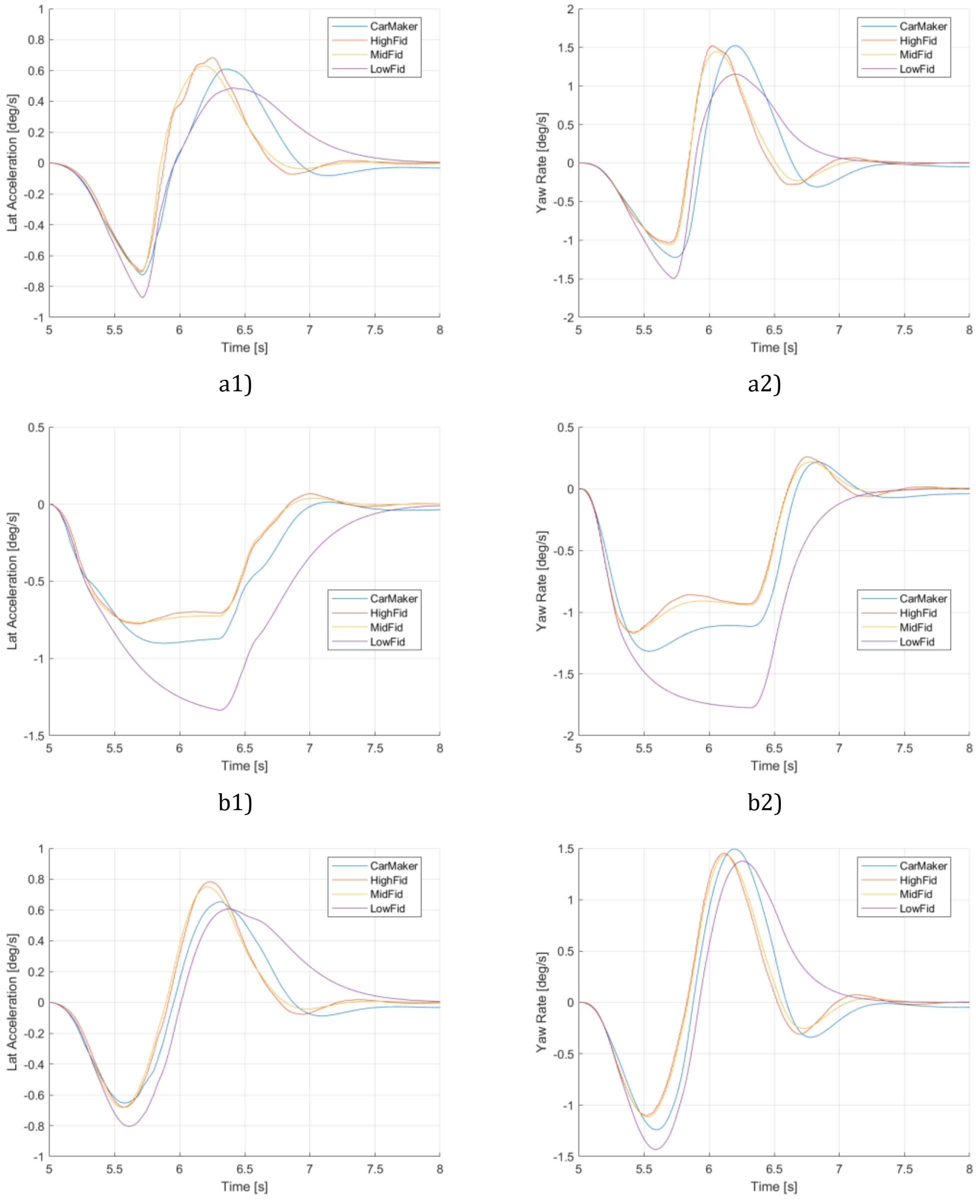
5.1.5 Results and Conclusions

5.1.5.1 Simulation Development

By applying the vehicle dynamic development process, a vehicle simulation model including an aerodynamic model and a gust wind generator was developed. The model was verified in offline simulation, transferred to the motion driving simulator, and conducted a user study involving 5 users. The users give an average of 5.3 out of 10 on QDS1, and an average of 7.1 out of 10 on QDS2, which indicates that the vehicle model is not so close to a real vehicle, but it can be driven with a similar method.

A comparison with the simulation result from paper [24] also shows a good correlation between the CarMaker model and the model from the PhD project, which and be seen from Figure 5-3. In Figure 5-3, the yaw rate and the lateral acceleration response are compared among the CarMaker model and the High- Mid- and Low-Fidelity model under different gust profiles. The vehicle speed during the simulation is 160 km/h and the steering wheel is locked to the centre to avoid any driver model impact. The model created in CarMaker is closer to Mid- and High-fidelity models. Explanation and definition of High- Mid- and Low-Fidelity models can be found in the paper [24]. Possible reasons to cause the differences are:

- A linear suspension system was used
- The axle delay was not implemented



a1) a2)

b1) b2)

b1) b2)

Figure 5-3 Model Comparison with the Data from Paper [24].
a) Gust Profile 2 b) Gust Profile 3 c) Gust Profile 1

5.1.5.2 User comments

During the user study, many good opinions and comments are given.

- Many users mentioned the lack of feeling of longitudinal motion.
- Some users reported a slight oscillation on the steering wheel at high speed (over 160 km/h).
- After about 1.5 hours of continuous simulator driving test, drivers usually report fatigue, and the ability to distinguish different vehicle configurations became weaker.

5.1.5.3 Subjective assessment results

Only the subjective assessments regarding the simulation are being discussed here.

For the questionnaire, the results are shown in Figure 5-4.

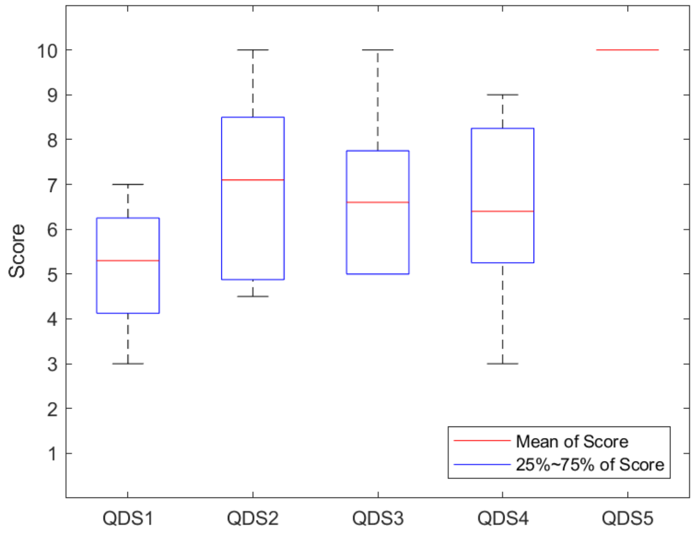


Figure 5-4 Questionaire result regarding the motion driving simulator

The result shows that, although the vehicle feels not so close to a real one (QDS1), the test drivers' driving behaviour is not very different (QDS2). All drivers felt some lagging between their operation and the vehicle response (QDS3, QDS4). No test driver has ever felt any motion sickness (QDS5, all test drivers gave 10).

Besides the questionnaire, test drivers also gave the following comments:

- By collecting and counting the questionnaire, most drivers gave a positive score to the vehicle model and driving experience.
- All of the test users reported lag both on motion and visual feedback. One comment said that he feels a lag between motion feedback and his input but cannot tell whether it is the vehicle model that responded slow or the motion platform delay.

5.1.6 Future Possibilities

From the user study, some potentials of improving the simulation and simulator in the future are found. Possible improvements include:

- Develop a better aerodynamic model with the axle-delay algorithm
- Develop a wind disturbance model came from real-world sampling, instead of the normal-distributed disturbance.
- Add wind noise through the audio system
- A better road disturbance model using a 2D surface generator that provides the same disturbance in all directions.
- Change the gust selection and the test plan to more realistic ones.
- Shorten the whole test plan, or separate the test into several sections, to avoid driving fatigue.

5.2 Case Study 2 – Steering Feel

5.2.1 Introduction

This case study aims to research the possibility of using the developed tools, methods, and processes to assess and develop the steering feel. In this case study, the front suspension of the vehicle model was improved into a geometrical kinematic model to be able to vary design parameters.

5.2.2 Deliverables

- Propose a development process using offline simulation tools and the driving simulator to assess and develop steering feel
- Establish parameters that are required for steering feel and propose targets
- A generic vehicle model
- A front suspension geometry where parameters that are important for steering feel can be changed for sensitivity assessment and development
- Select parameters in the suspension that affect steering feel and propose changes to assess sensitivity and develop steering feel

5.2.3 Limitations

- Only the front suspension is modelled as a geometrical kinematic model
- Bushes, springs, and dampers are still linear
- Due to project time limitations, the simulations are only done in offline simulation, but the models are prepared for the motion driving simulator.

5.2.4 Methods

5.2.4.1 Steering Feel

The steering feel can be assessed from many different perspectives. In this case study, not all perspectives would be assessed. On page 23 of [8], the PhD thesis listed an overview of subjective assessments used for steering feel. Only some of the assessments are selected for this case study. See Table 5-3. Only the manoeuvres with a medium speed (from 20 km/h to 80 km/h), and small steering wheel angle (less than 90 deg.) are selected.

Table 5-3 Selected Subjective Assessments

Level 2	Level 3	Level 4	Level 5
Steering feel	First Impression		
		Response	
		Torque Feedback	
		Manoeuvrability	
		Compliance Feel	
		Friction Feel	
		Efforts	
	Cornering Controllability		
		Response	
		Roll Control	
		Torque Feedback	
			Torque Buildup
		Returnability	
		Modulation	

5.2.4.2 Geometrical Kinematic Model

The geometrical kinematic model was created and tuned with the tool named IPG Kinematics provided by IPG. A double-wishbone suspension was selected. The letter and name of hardpoints are defined by IPG [25].

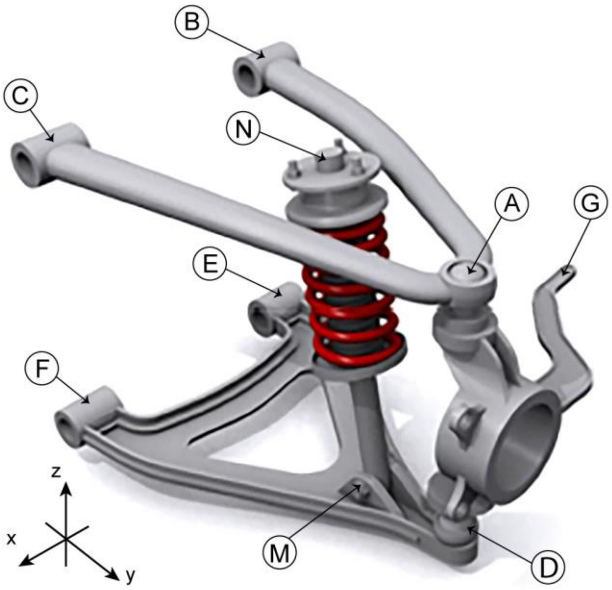


Figure 5-5 Double-Wishbone Front Suspension Hardpoints (Left) [26]

Table 5-4 List of Hardpoints

Location in Figure 5-5	Name
-	Wheel centre
D	Control Arm Lower Outer
A	Control Arm Upper Outer
G	Steering Rod Outer
F	Control Arm Lower Inner Front
E	Control Arm Lower Inner Rear
C	Control Arm Upper Inner Front
B	Control Arm Upper Inner Rear
-	Stabilizer Bar Inner
-	Stabilizer Bar Outer
-	Ground contact
-	Steering Rod Inner
N	Spring & Damper Upper
M	Spring & Damper Lower

* Point with "-" is not listed in the figure.

5.2.4.3 Adjustment to the suspension

To assess the influence of different parameters on the steering system, several changes are planned.

5.2.4.3.1 Ground Offset

To adjust the Ground Offset (GO) while keeping the Kingpin Inclination, the hardpoint connecting the wheel carrier and the upper control arm (Point A), and the hardpoint connecting the wheel carrier and the lower control arm (Point D) must be changed in parallel. Due to the definition of GO, increasing GO means moving the two points towards the negative direction of the Y-axis.

Table 5-5 Parameters Adjusted for GO

Parameter	Axis	Base	Change 1	Change 2
GO	-	10 mm	+25 mm	-25 mm
Point A	Y	-	-25mm	+25mm
Point D	Y	-	-25 mm	+25 mm

5.2.4.3.2 Caster Trail

To change the Caster Trail while keeping the Caster Angle, the hardpoint connecting the wheel carrier and the upper control arm (Point A), and the hardpoint connecting the wheel carrier and the lower control arm (Point D) must be changed in parallel. According to the definition of Caster Trail, increasing Caster Trail means moving the two points towards the positive direction of the X-axis.

Table 5-6 Parameters Adjusted for Caster Trail

Parameter	Axis	Change
Caster Trail	-	+25 mm
Point A	X	+25mm
Point D	X	+25 mm

5.2.4.3.3 Ackermann Rate

To change the Ackermann Rate, the hardpoint connecting the steering rod and the wheel carrier (Point G) needs to be adjusted in the Y-direction. To avoid significant changes to the Bump Steer, the hardpoint connecting the steering rod and the steering rack also needs to be tuned. Due to the complexity of steering geometry, the accurate changing value cannot be given now. However, generally, moving Point G towards the centre of the vehicle increases the Ackermann Rate.

5.2.4.4 Manoeuvre

Besides that, the manoeuvres mentioned in section 3.2.1.2 are used for model verification, other manoeuvres introduced here are also tested.

5.2.4.4.1 Swept Sine Manoeuvre

Sine steering manoeuvre is to have the vehicle driving straight at the designated speed, then steer using a sine signal with increasing frequency. This manoeuvre can demonstrate the frequency response of the vehicle. A Hysteresis Curve (see Figure 5-11 as an example) between the steering wheel angle and steering wheel torque at different frequencies can also be plotted, to assess the friction, damping and linearity of the steering feel.

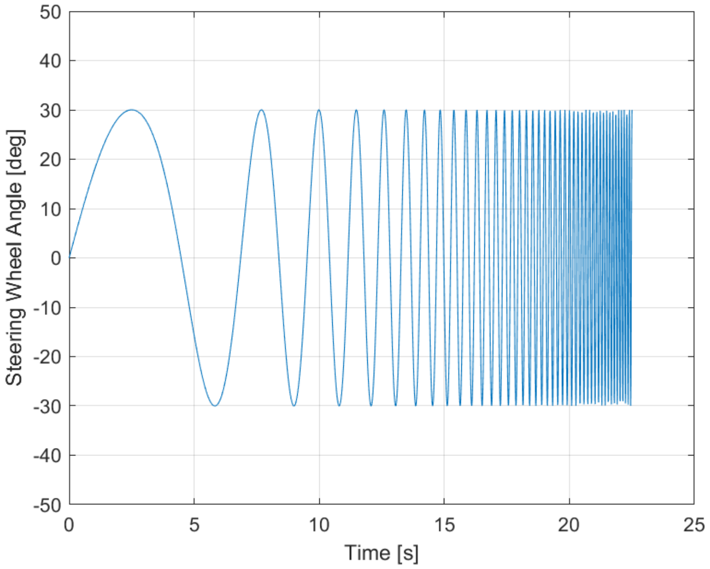


Figure 5-6 An Example of the Steering input in the Swept Sine Manoeuvre

Figure 5-6 Shows an example of Swept sine signal with the following parameters:

- Amplitude: 30 deg on each side
- Starting Frequency: 0.1 Hz
- End Frequency: 10 Hz
- Duration: 20 s

The first quarter of the first sine signal is at a constant frequency of 0.1 Hz. This is due to that MATLAB supports only swept cosine signal which starts from the maximum amplitude. The function of the quarter is to make the signal continuous and start from 0 deg.

5.2.4.4.2 Step Steering

Step steering is to steer the vehicle with a step steering input when the vehicle is been driven at a constant speed. This manoeuvre can simulate the step response of the vehicle. A steering wheel torque response could also be measured.

5.2.4.4.3 Slalom Manoeuvre

To allow a subjective assessment in the future, the slalom manoeuvre is selected as the manoeuvre that will both be driven by the driver model and the real driver. The initial design includes an acceleration path, a slalom testing ground with the distance between cones being set to 30m and the designated speed would be 50 km/h. The distance between cones and the manoeuvre speed can be adjusted in the future test.

One suggestion is that do not do precise tuning on the driver model just for a better offline simulation result. This manoeuvre is more about subjective assessment and DIL simulation, and offline simulation will just be used as a verification to the vehicle model and the testing scenario, and also to have a rough concept about the performance of the vehicle model.

5.2.5 Results

5.2.5.1 Front Suspension Model

With some tuning and adjustment, the front suspension model was designed as shown in Table 5-7 and Table 5-8. The coordinates show only the relative position of the left wheel suspension system, which is different from what is usually used in the vehicle industry. The suspension system on the other side will be symmetric about the X-Z plane.

Table 5-7 Hard Point List

Point	Name	Coordinate [mm]		
		X	Y	Z
-	Wheel centre	0.0	793.7	358.7
D	Control Arm Lower Outer	4.078	755.6	217.3
A	Control Arm Upper Outer	-23.09	710.9	499.4
G	Steering Rod Outer	-200.0	720.0	324.5
F	Control Arm Lower Inner Front	167.5	375.13	239.0
E	Control Arm Lower Inner Rear	-167.5	375.13	239.0
C	Control Arm Upper Inner Front	142.5	383.68	470.66
B	Control Arm Upper Inner Rear	-142.5	383.68	470.66
-	Stabilizer Bar Inner	100.0	750.0	150.0
-	Stabilizer Bar Outer	100.0	750.0	305.0
-	Ground contact	0.0	800.0	0.0
-	Steering Rod Inner	-220.0	300.0	328
N	Spring & Damper Upper	0.0	780.0	600.0
M	Spring & Damper Lower	0.0	790.0	200.0

Table 5-8 K-C Data of the Vehicle Model

Parameter	Unit	Target	Result
Front Castor Trail	mm	25	25
Front Static Camber	Deg	-1	-1.00
Front Static Castor *	Deg	5.5	5.50
Front Static Toe *	Deg	-	-2.0
Front KPI	Deg	9	9.00
Front Ground Level Lateral Offset, Scrub radius	mm	10	10
Front Ride Frequency, Incl. tyres *	Hz	1.4	1.37
Front Damper Ratio	-	1	1.00
Front Spring Ratio	-	1	1.00
Front Bump Steer	Deg/m	-4	-3.37
Front Bump Camber	Deg/m	-21.0	-25.0
Front Roll Steer	Deg/m	-4.0	-2.6
Front Roll Camber	Deg/m	-21.0	-19.0
Steering Ratio, On-Centre	-	15.0	15.0
Front Roll Centre Height	mm	130	130.8
Front Roll Centre Migration	mm/mm	-1.8	-0.18
Ackermann Rate @ 20 Deg Inside Wheel	%	50	52.8
Front Spring Stiffness *	kN/m	-	45
Front Damper Stiffness *	kNs/m	-	2.5 (Compress) 5.4 (Rebond)
Front ARB Stiffness *	kN/m	-	25

* Starred Data is not only decided by hardpoints

The table shows that most of the parameters meet the design target.

The compliance is not designed in this model due to complexity. The bushings are set to as stiff as possible to reduce the elastic part of the suspension model.

5.2.5.2 Model Verification Result

Manoeuvres in this section are not for steering feel research and development, only for verification of the vehicle model. Due to the progress of this case study, all of the results are only from the offline simulation.

5.2.5.2.1 DLC

The vehicle model with the geometric kinematic model above passed the DLC manoeuvre in the offline simulation with an entry speed of 70 km/h. The driver model parameters are:

- Driver.Knowl.Lat.tPreview = 0.63
- Driver.Knowl.Lat.tYawPro = 0.03
- Driver.Knowl.Lat.tPreDyn = 0.10

The parameters are only used for designated speed and do not guarantee a pass result at a lower speed. Different speed requires different parameters.
The scenario is the same as described in Section 3.2.1.2.1.

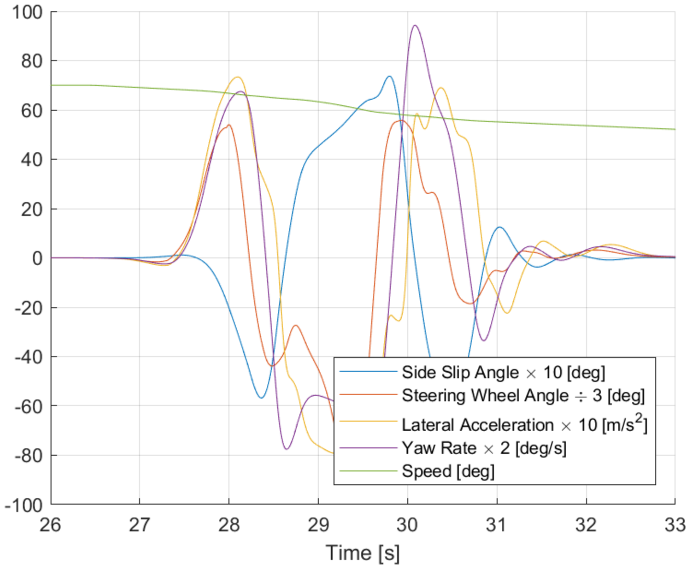


Figure 5-7 DLC Simulation Result

5.2.5.2.2 SSC

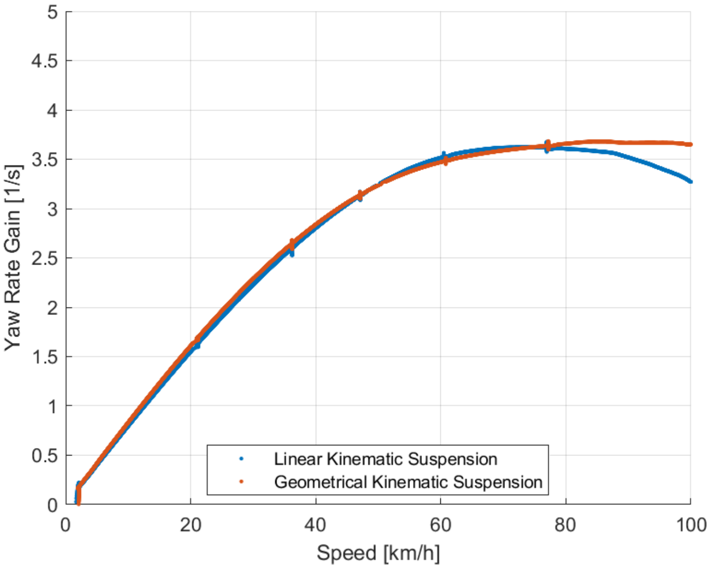


Figure 5-8 Yaw Rate Gain of Vehicle Models

Figure 5-8 shows the yaw rate gain of the modelled vehicle, which shows a good understeering character.

A comparison was also made between the linear model and the geometrical model. The two models show a good correlation, especially at the lower speed (< 80 km/h). The glitches on the curve are caused by unsmooth gear shifting, which is not caused by the suspension system.

5.2.5.2.3 SwD

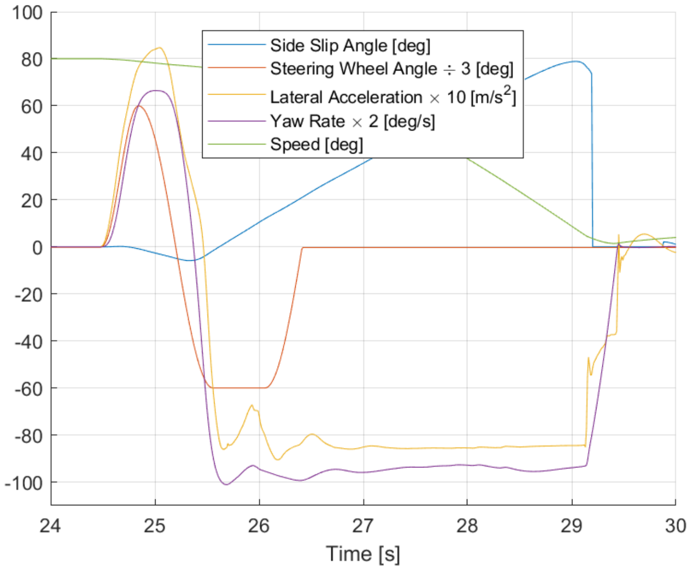


Figure 5-9 Sine-with-Dwell Manoeuvre Result

The Sine-with-Dwell result shows an unstable case. The vehicle model appears to be very oversteer in this manoeuvre. Note that this vehicle model is not equipped with any ESC system, which is actually expected to go oversteer.

5.2.5.3 Manoeuvre Result

The vehicle model was verified as a functional general model in the previous manoeuvres. Thus other research manoeuvres can be conducted.

5.2.5.3.1 Swept Sine Steering

The swept sine steering manoeuvre was tested with the following parameter:

- Vehicle Speed: 100 km/h
- Frequency range: 0.1 Hz ~ 10 Hz
- Sweeping duration: 500 sec
- Steering Amplitude: ± 60 deg

The steering input is shown in Figure 5-10. During the simulation, the driver model is designed to keep the vehicle model at a constant speed and will do necessary actions to maintain the speed.

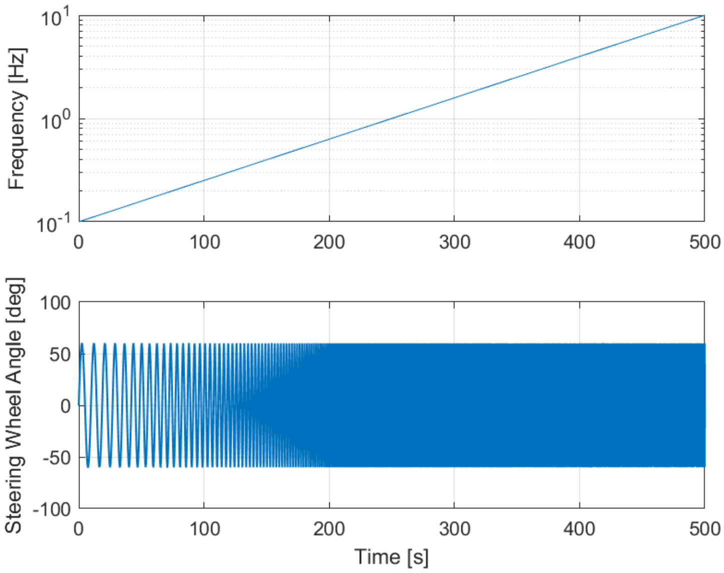


Figure 5-10 Steering Wheel Input Signal

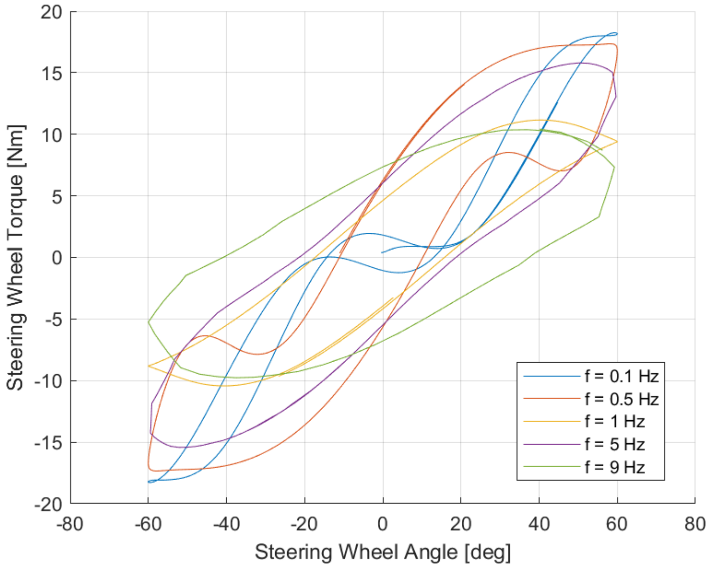


Figure 5-11 Swept Steering Hysteresis Curve

Figure 5-11 is the hysteresis curve plotted with the simulation data from the swept sine manoeuvre. The vehicle is not equipped with a complete mechanical steering system model; thus, the curve is mainly caused by the tire torsion, suspension compliance, and suspension system inertia.
The implementation and tuning of a mechanical steering system model will be part of future work.

Figure 5-11 shows that the linearity of the base model is not so good, especially at low frequencies. The amplitude of the steering wheel torque is decreasing with the rise of steering frequency. Further tuning is required before the vehicle model being ready for a DIL simulation.

5.2.5.3.2 Step Steering

To simulate the step steering manoeuvre, the following parameters are used:

- Steering Wheel Amplitude: 90 deg.
- Vehicle Speed: 50 km/h
- Ramp-up Time: 400 ms

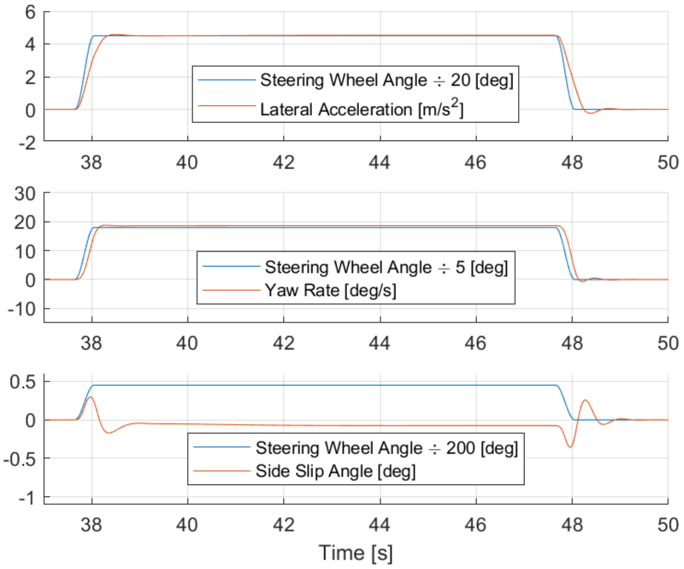


Figure 5-12 Vehicle Dynamics Step Response

Figure 5-12 showed a good vehicle dynamic response with the step steering signal input. There are some delays and slight overshoots, which is unavoidable. The model stabilized in just 1 second, which is good enough as a general model.

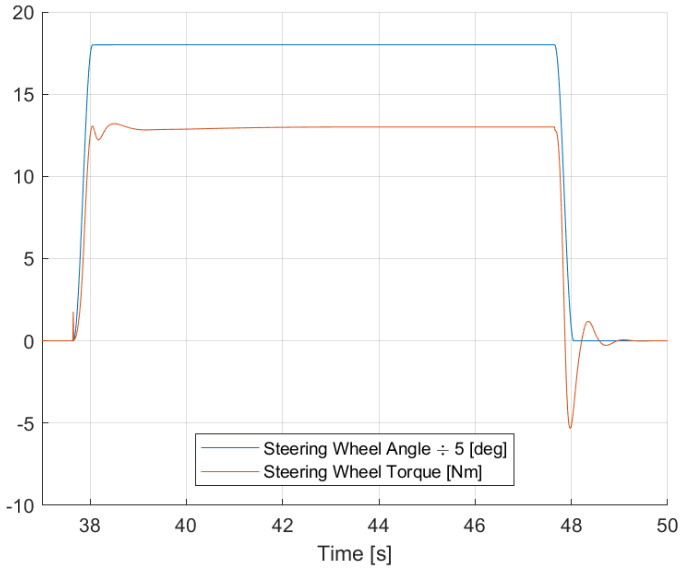


Figure 5-13 Steering Torque Step Response

Figure 5-13 shows the steering torque response with step steering angle input. The figure shows a good response when steering up, with only slight oscillation. However, when steering back, the steering wheel torque overshoots till about -5 Nm, which is not good as a production vehicle. Note that the mechanical system from steering wheel to steering rack is not included, which could bring some non-accuracy.

5.2.5.3.3 Slalom Manoeuvre

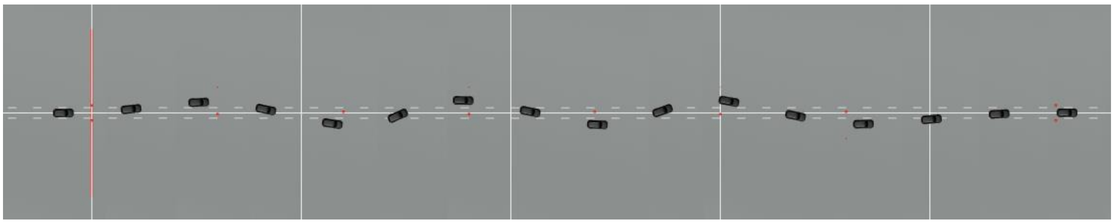


Figure 5-14 An Example of Slalom Manoeuvre

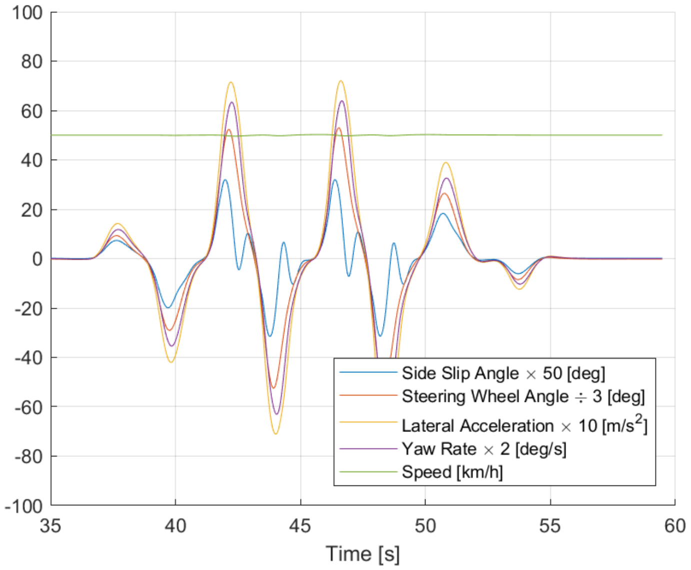


Figure 5-15 Slalom Data from Offline Simulation

The result shown in Figure 5-14 and Figure 5-15 is an example of a slalom manoeuvre. The test vehicle goes through the slalom testing ground with a constant speed of 50 km/h. Although Figure 5-14 shows that the vehicle is not going through an optimal path, the manoeuvre can still be seen as verified and can be seen as ready to be transferred. The speed and cone distance can be a good start point for the DIL simulation.

5.2.6 Conclusion

A generic vehicle model with a geometric front suspension system was developed. With the vehicle dynamics simulation process, offline simulations were able to be conducted and the vehicle model was verified with several manoeuvres. A good base has been set for offline tuning and simulation of the suspension system. Testing and tuning in the motion driving simulator need further development. Due to the lack of time in the project, it was not possible to run the DIL simulations in the simulator.

5.2.7 Future Work

Due to the time limit, this case study was only conducted with offline simulation. Future work includes:

- Implement a mechanical steering system model
- Transfer the model to the motion driving simulator with the new Panthera software
- Conduct a user study with subjective assessments
- Development of the power steering system

6 Conclusions

By developing the vehicle dynamic development process and verifying the process with case studies, the following conclusions could be drawn:

- Accuracy
  By developing the simulation process, it is possible to run an offline simulation and then transfer it to the motion driving simulator in a short time. By selecting IPG CarMaker as the simulation tool, most of the vehicle models, manoeuvres, and configurations from offline simulations can be used both in the DIL simulation.

- Efficiency
  By involving the motion driving simulator, the time from a concept design to a driveable vehicle model in the motion driving simulator could last only some weeks. If the vehicle model has already been ready before the concept phase starts and only require mild changes, the time could be further reduced to days.
  The testing efficiency of the new developing process is also higher than the traditional process. Many vehicle configurations could be tested within several hours and very limited time will be needed to switch between configurations.

- Cost
  By using the motion driving simulator, the build and modifications of mule cars can be reduced, i.e., both labour costs and material costs can be reduced.

- Other Benefits
  There are many other benefits found during the development of the process.

  - Repetitiveness
    The repetitiveness is a unique advantage when using the offline simulation and the DIL simulation. For example, during Case Study 1, the same gust was possible to be generated for both the offline simulations and the testing in the simulator.
    The testing conditions can be the same in all tests which is important for the results.

  - Finer Tuning
    By using the simulator, the study and selection of hardware parameters, like suspension stiffness and damping ratio, are no longer limited by components and packaging conditions. Finer tuning is also possible due to that it is easy to change parameters in the offline model and the DIL simulation.

  - Better and safer working conditions
    The use of motion driving simulators turns many outdoor works into indoor activities, which provides better working conditions for the test drivers and development engineers. Test accidents can also be avoided since what happened in the motion driving simulator does not harm the test drivers.

  - Environment
    In the development process, the use of a mule car can be reduced, which is more environmentally friendly.
- Issues
  - High demands on the model precision
    During the DIL simulation, not only the vehicle behaviour but also the subjective feeling from the test drivers will be assessed. It is important to refine details in the vehicle model as much as possible throughout the process to get the best possible precision in the simulation processes.
  - Extra works needed to transfer the vehicle model
    A good correlation of the vehicle model between the offline simulation and the DIL simulation is important to guarantee the effectiveness of the DIL simulation result. Transferring the vehicle model from offline simulation to DIL simulation with good correlation requires extra work.
  - Limitations of the driving simulator (see Section 3.1.2.1)

6.1 Discussion about specific results

6.1.1 DLC Results

As mentioned in Section 4.1.2, in the DLC test, the model driver reaches 76 km/h however the human driver reaches only 60 km/h, which is not a good correlation and cannot be explained only by the driving technique. By interviewing the test driver, possible reasons are:

- Unchanged viewpoint
  As mentioned in Section 3.1.2.1, the viewpoint on the simulator is not changing with the head of the driver, and not moving during the whole driving process, and it causes some difficulties to see and to sense the position of pylons. The driver had to drive by guessing the position of the pylons after entering the testing ground.
- Lack the feeling of hitting pylons
  The pylon in the scenario is not a real object but just for visual reference and signal collection. The driver does not know where and which wheel hit a pylon when driving, which caused difficulties for the driver to improve his driving.
- Driving technique
  The driving technique is also part of the reason but is not a major part. By practising more, the test driver could get a better result.

6.1.2 “Lack of motion” Comment

During the development of the simulation system, it is noticed that the driving in the motion driving simulator lacks a feeling of motion. Some test drivers in Case Study 1 also raised a similar comment. Possible reasons are:

- Missed wind noise and tire noise
  Wind disturbance and road disturbance were added to the simulation system to provide motion feedback; however, they are not added through audio. Drivers could only hear the noise from the engine, which is only a part of the noise at high speed. Figure 6-1 shows the noise level from

different sources at different speeds, which indicates that involving wind noise and road noise is important for future work.

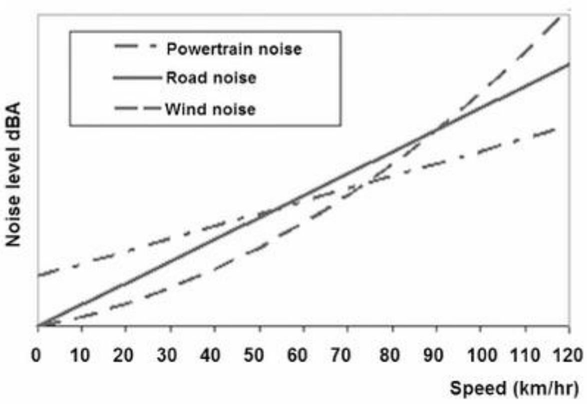


Figure 6-1 Noise of vehicle at different speeds [27]

- Low quality of the visual effect
  The low-quality visual effect constantly reminds the drivers that it is a simulator, which could decrease the immersive feeling of the drivers. Research [28] showed that although the visual quality is not the only factor that affects immersion, it is still quite an important one.
- Simulator specific limitations
  - Motion limitation
    The driving simulator used in this project only has limited movements and can therefore not give completely realistic feedback to the driver. More advanced driving simulators with linear movements will give improved feedback to the driver.
  - System latency
    As mentioned in Section 3.1.2.1, there are latencies between visual feedback and motion feedback. From the user study, 5 users give an average of 6.3 out of 10 on the question regarding visual latency, and an average of 6.4 out of 10 on the question regarding motion latency (see Figure 5-4). One driver commented that it is hard to tell whether the latency is caused by the simulation system or by the vehicle model, which would need further study.

7 Future Works

7.1 Remained Issues

Some issues that remained from the project are listed here. Further development should be conducted to solve these issues

- Transfer the simulation system to the new Panthera software
- Implement a better road and wind disturbance model
- Involve wind and road noises and disturbances

7.2 Improvement in the offline tools

IPG CarMaker is the main simulation tool being used in the project. Generally, it provides a good platform for combining different vehicle systems and connecting different simulation tools. It provides a good base for general-purpose offline simulation, especially for simulation under a virtual traffic environment. However, for other purposes, like developing vehicle dynamic systems, the example cases delivered with IPG CarMaker did not provide a good enough base for a quick start, and it requires that more details are added to the vehicle model.

7.3 Further developments

During the project, some points were identified that can be improved for future work with the tools and methods.

7.3.1 Development Process

Although a successful development process was developed and tested in this project, there are still more to improve.

- Testing with other vehicle dynamics topics
  Other vehicle dynamics topics, for example, ride comfort, can be tested with the process to see if it is effective and efficient. Other non-vehicle-dynamics topics like driveability, ergonomics, user-interactive design and verification can also be tested to verify the effectiveness of a similar process.

- Using the process in other developing phases
  In this project, the development and use of the process focus on the concept phase. However, there is a possibility to use the process in other development phases, like the system development phase, which can also be facilitated with the offline-to-DIL simulation process.

7.3.2 Tools and Methods

This section is specifically for the software and hardware of Chalmers.

7.3.2.1 Offline Simulation

During the development process, some deficiencies show up that worth further development. Possible developing directions include:

- Chalmers Representative Vehicle Models
  During the project, much of the workload was to create an acceptable generic vehicle model. Having several representative vehicle models prepared at Chalmers of different vehicle types and with different fidelities, which can be instantly used for both education and research,

can be good to provide convenience to other research and development activities within VEAS.

7.3.2.2 DIL Simulation

With the update of the Panthera software, new tools and methods are required. Possible developing directions include:

- Connection tools between CarMaker and the Panthera software
  With the update of the Panthera software, related APIs and Simulink libraries were also updated. New development activities are required to transfer the process from the old Panthera software to the new one. With the new software, better visual feedback effect and higher simulation performance are expected.
- Scenario generator
  During this project, an upgrade of the Panthera software (control software of the motion driving simulator) was conducted, which brings many new features and possibilities to the motion driving simulator. However, with the upgrade of the new software, Unity was used as the visual rendering system instead of IPG Movie, which provides a better visual effect than IPG Movie but also increases the difficulties and workloads of developing the simulation scenario. 3D modelling software is now mandatory for the development. By developing a scenario generator that generates testing scenarios automatically from the CarMaker Road file, the development of the new Panthera software can be simplified.
- Better testing plan
  During Case Study 1, it is noticed that drivers in a simulator might be easier to gain fatigue than on the road. A better test plan with smaller sessions and more breaks may be helpful.

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