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Parameterization and Validation of Road and Driver Behavior Models for CarMaker Simulations and Transmission HIL-Rig

Master's thesis

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CHALMERS UNIVERSITY OF TECHNOLOGY

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Cover:
Simulation in IPG CarMaker

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Abstract

The thesis analyzes whether the results from simulation and powertrain rig tests correlate to the actual loads of a vehicle driving in a real transport task. The rig used in the research uses the same software as the simulations, called CarMaker, but when conducting tests in the rig the models of transmission and engine are removed. Instead the actual components are used as Hardware-In-the-Loop (HIL). To be able to get good results from the simulation and rig tests, a representative model of the physical road had to be developed. The driver behavior model had to be parametrized in a way that resembles a real driver.

The road used in the thesis is a pre-defined city route in Göteborg, used to resemble normal driving situations which include large amount of accelerations and decelerations, since city driving has the most influence on the durability of the transmission. The road model is built up by using x and y coordinates which describes the physical roads' choice of path, surface friction and road attributes as speed limits and stop signs. The road model does not mimic the road on a micro but rather a macro scale, meaning that local abnormalities like potholes and stones are not modeled, the limitations are further explained in Section 1.4.

The driver model used in the thesis is included in the CarMaker software, therefore the task was to parametrize the model to ensure that it was good representation of actual drivers. The focus when developing driver models was to investigate a defensive, normal and aggressive driver type.

In order to shorten lead times and improve the economy of product development, testing and verification of products should be conducted earlier in the development process. An effective way to allow this is by the use of Computer Aided Engineering (CAE) tools. In order to be able to trust the results from the CAE tools, the models used must be trustworthy, which was the main focus of interest during the project.

During the thesis, a good correlation of the road model was achieved, both in terms of choice of path and the ability to perform test on the road equally in vehicle, rig and simulation testing. It turned out to be hard to represent a real driver using the driver behaviour model included in the CarMaker software. Instead, possible solutions to this problem is presented by using and developing suitable key indicators, which explain how the driver behaves and the limitations in the CarMaker driver behavior model. The research also showed that a valid vehicle model is crucial for the results.

All in all, the results from simulations, rig tests and vehicle tests correlate in a good way. The key indicators span approximately the same span when comparing the different tests. This is valid for both key indicators on transmission shaft fatigue load and energy consumption at drive shafts, which shows on a good potential for future development and use.

Keywords: CarMaker, Transmission development, HIL, Transmission load spectrum, Passenger car, Driver model, Road model, Vehicle model, City driving, Simulation

Nomenclature

- 4WD - Four-wheel-drive

- AVL Concerto - Pre/post process software used in the automotive industry.

- CAE - Computer Aided Engineering.

- CAN - Controller Area Network, data network used in vehicles.

- DIADEM - Software used for measurement and data analysis in vehicles.

- FlexRay - Data network used in vehicles, faster data transfer than CAN.

- GPS Visualizer - Website used to process GPS coordinates.

- GUI - Graphical User Interface.

- HIL - Hardware-In-the-loop.

- INCA - Software used for measurement and data analysis in vehicles.

- IPG CarMaker - Simulation software used in the automotive industry.

- MTF - Mean Tractive Force.

- PID controller - Proportional-integral-derivative controller.

CONTENTS

1 Introduction

A major transformation in product development is ongoing at Volvo Cars, called 202020. The goal of the transformation is to cut the time of a new car project, from go ahead to start of production from about 30 months to under 20 months. By doing this, the company hopes to cut lead times, save resources and improve quality. The objective is to reach the goal by the year of 2020, thus the name 202020 [10]. From research and development's point of view, this goal is to be reached by increasing the use of CAE and reduce physical testing. To be able to replace physical testing with simulations in a larger extent, the models used in simulation must be a good representation of the real system. This thesis is a step towards this objective by developing valid road and driver behavior models and evaluate the correlation of the results from physical, rig and simulation testing.

1.1 Background

Currently at Volvo Cars, testing and verification of systems and components of the powertrain are mostly done in rigs and complete vehicles. From transmission development's point of view, these tests mainly focus on fatigue stress and the endurance of the vehicle. Testing components in a complete vehicle is expensive since the test must be carried out when the car is at a late stage in the development process, where changes in design are more costly. However, to be completely certain that the vehicle as a system behaves exactly as intended, the test must be conducted in a representative vehicle. In order to conduct physical tests before the design phase is finished, the tests are performed on prototype vehicles which are complicated and expensive to produce.

Testing in rigs only require prototypes of the components used in the specific rig, such as the powertrain, therefore rigs can be used relatively early in the design phase. However, this still require prototypes to be produced, which makes it more expensive than simulation that only uses virtual models of the system. Volvo Cars uses multiple types of rigs to test and validate the powertrain. Some of them are pure engine rigs which only test the engine and are controlled by simple speed and load profiles. This poses a problem since in the end the vehicles will be driven by real people on real roads and it is therefore important to test the components in a way that represents the real customers, which is hard to achieve with such a simple way of controlling the rig.

There are also rigs that test the complete powertrain. In these rigs, prototypes of the components from the engine to the drive shafts are used and the wheels are replaced by electrical motors. At Volvo Cars, one of these rigs is connected to a simulation software that allows the engineer to control which type of road the car is driven on and how the driver should behave. At this time though, there is no real connection between the road and driver behavior model used in the rig and the way costumers use the cars.

To get a profound understanding of the requirements of the components, the loads applied to them during testing should be as similar as possible to the loads the components will endure during actual usage. In other words: the road and driver behavior should be as similar to the real conditions as possible. This problem is assessed in this thesis.

By investigating this, the simulations and rig tests can be used to a larger extent and the physical testing can be used only when needed. This makes it possible to conduct testing at an earlier stage in the development process and at a lower cost, which is a step on the way of reaching Volvo Car's vision 202020.

1.2 Problem description

The current situation in product development at Volvo Cars requires prototypes of the vehicles to be produced in order to be completely certain that the vehicles' systems and components behave as intended. This is a cost and time consuming process. To avoid this, CAE and rig testing can be used, but to rely on these tools they need to be properly validated. The task, to investigate this, is assigned to this thesis project.

1.3   Aim of the thesis

This thesis will develop the road and parametrize the driver behavior model in a commercial software called CarMaker, which is used for the simulations and also as input to the rig. These models should mimic, to a as large extent as possible, the output of an actual driver driving a complete vehicle on the modeled road. With use of tools as visual comparison of plots and key indicators with focus on transmission shaft fatigue load, a validation process will be performed on the output from the simulations and rig tests where the created road models and varying driver behavior settings are included. This in order to reach the final goal of the thesis, which is to evaluate if a larger proportion of the tests can be preformed in simulations and rigs rather than in complete vehicles. A change like this would make the development process more efficient and by that less time and cost consuming.

1.4   Limitations

- The thesis does not focus on the vehicle model, but rather keeps it unchanged to be able to see the impact caused by changes in the road and driver behavior models.

- The road model developed as a part of this thesis focus on a city driving cycle and a gravel road driving cycle, but no further types of roads.

- The model should be a good representation on a topographical scale, meaning that local abnormalities e.g the texture will not be included but an overall friction coefficient will be determined. The surroundings, like trees and buildings, will not be modeled while the focus is on the objects that affect the loads of the vehicle.

- Traffic is not modeled as a part of this thesis to ensure good repeatability of the simulations and rig tests.

- The driver behavior model, where the underlying dynamical equations are outside the scope of the thesis, will only be modified by parameterization and used in order to resemble a defensive, normal and aggressive driver.

- The driver is assumed to be driving a vehicle with automatic transmission, meaning that gear shifting schedules will not be developed as a part of the driver model.

1.5   Methodology

To a large extent the project has focused on shaping and using methods for road and driver model creation and validation. Therefore these methods are more profoundly explained under Methodology in Section 3, but the main part of the work methods are summarized as following.

In the beginning of the project literature studies were done in order to get a picture of existing knowledge within the area of road and driver behavior modelling. Several books and article on the topics were found, see References section, which gave a great base for the proceeding of creating the models. Modelling and simulation were main parts of the project and were performed continuously. The first essential task was to create reality resembling road models using suitable software products. When this was done the models could be implemented in the rig to test the usability. The next task was to parametrize and evaluate the driver model for the simulations and rig testing. Performing multiple simulations using different parameter settings created a data set for further evaluations. To gain data for comparison and validation, test runs driving real vehicles were performed, which also gave an understanding of the vehicle testing procedure and parameters influencing the driver's behavior. With the created models implemented in the simulation and in the rig testing environments, the last step was to make a validation of the project parts in order to finally be able to draw conclusions on the models' usefulness and give recommendations for future work.

2 Theory

This section aims to give an understanding of the parameters and systems that are used for product development in the automotive industry in general and in this project specifically. Since the project's main focus was model validation, the sub sections below describe parameters and modelling parts used and developed to achieve a good correlation between the development steps. These steps can further on be validated to secure the accuracy and reliability of the performed work.

2.1 Improving product development

The automotive industry demands continuous development of new products in order to be competitive and to satisfy the market [3]. Due to this it is of great importance to have an effective and well-elaborated product development strategy. The realisation of a new car is a complex process that includes all major divisions of the company, which sets high demands on the strategic groundwork, preparation in product definition and final implementation [10].

The development process can be simplified according to the model in Figure 2.1, which is a part of a product development model shaped by R.G. Cooper [3]. As seen in the model the development process is split up into steps, from the initial idea, to the final product that is ready for market launch. These steps have traditionally been performed in a sequence, but the trend is to try to for example perform the testing and validation part earlier as the red arrows symbolize. One reason for this approach can be that a common problem within the process is changes in the customer needs, which make adjustments of the concepts necessary. This can cause disruptions in the process and project delays [3]. If the parts in the process can be performed more simultaneously, the outcome of the changes and disruptions will not make as large impact on the project's success and cost.
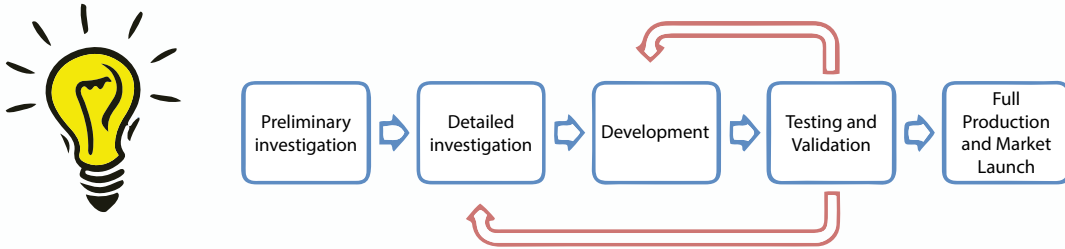
Figure 2.1: *Development process according to R.G. Cooper*

Focusing on the testing and validation part of the process the main tool to use is CAE. Simulation is the best way to understand the behavior of vehicle dynamics in advance [4]. During the simulation a product model can be created, evaluated and further on be tuned to satisfy predefined requirements. Mostly the simulations are done in a completely virtual environment, but an useful way of using simulations is to combine them with physical models. This is called a HIL setup, explained in Section 2.6. Such a testing approach is beneficial not only in terms of reducing the development time and cost, but also by removing the potential sources of disturbance which can occur during on-road vehicle testing [13]. If the HIL rig is used successfully, an additional advantage is that the models, test cases and parameters can be reused in all development phases or for other projects [1].

In order to manage the changes described above, which goes hand in hand with the 202020 vision described in Section 1, a bigger confidence must be placed in CAE and the work at all levels and divisions need to be optimized, this is where this thesis project comes in. With validated simulation and testing tools, the development can be rationalized and the testing and validation part of the process might be shortened and incorporated in earlier steps as in Figure 2.1.

2.2 System description

To gain an understanding of the parts and parameters involved in the project a system identification was made. This resulted in a schematic description of the system shown in Figure 2.2.
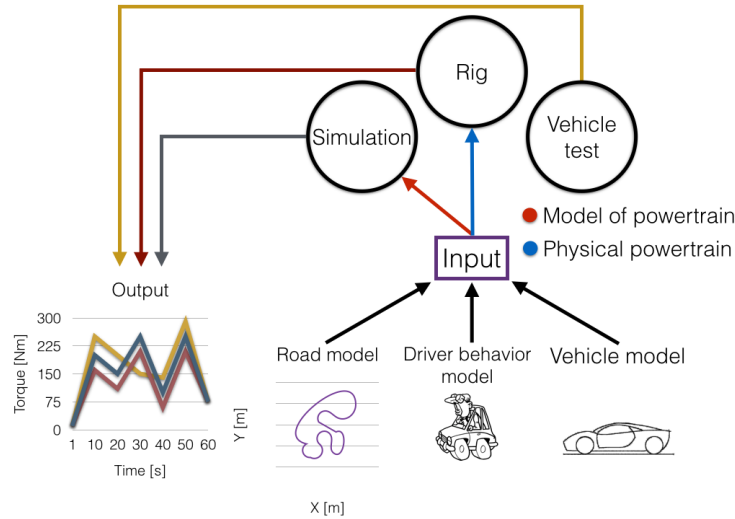
Figure 2.2: *Schematic system description*

The base of the system are the three analyzing methods represented of the circles:

- Simulation
- Rig test
- Vehicle test

A combination of these three methods are used today and will be used further on during the testing and validation part of the development process. The purpose of the thesis was therefore to investigate how well these correlates to each other and this part is represented by the output graph on the lower left in Figure 2.2.

In the lower right of the same figure, the three types of models creating input to the simulation and rig parts of the system are shown. These three are:

- Road model
- Driver behavior model
- Vehicle model

During the thesis, a road and driver behavior model was developed, while the vehicle model lied outside the scope. Due to this, vehicle models developed and utilized at Volvo Cars, were used as input to both the simulations and the rig, which obviously had influence on the results.

The input to the simulations and the rig has one crucial difference, the powertrain. In simulations the powertrain is based on a parametrized model, while in the rig the powertrain model is extracted and instead the physical powertrain is used. This is symbolized in Figure 2.2 by the red and blue arrows. This type of rig is a hybrid between simulation and prototype testing since it uses a mix of hardware and models, this type of rig is called HIL. There are many advantages with this technique, properly described in Section 2.6.

2.3   Road model

One of the most influential factors regarding demands on the powertrain is the characteristics of the road. When modeling a road for simulations and testing it is therefore important to resemble the real road as good as possible or create a road that includes the wished road attributes. This section summarizes how road models currently are used during the transmission development process and the theory used in this thesis related to road modeling.

2.3.1   Background

Road models are used during the transmission development process to test and validate the components in different load situations that occur during driving. A simple way of developing the road model is to use a velocity profile which symbolizes the road, for example the EPA Federal Test Procedure (FTP-75) [9]. The approach of using road models at Volvo Cars has earlier been to create road models that for example resemble a steep hill or a long straight road. By this the most extreme load cases on the vehicle have been investigated, but the connection to how and where the vehicle is driven in reality is lost. When comparing the result from the simulation and rig testing with the result gained from real test runs, it has been difficult to draw any conclusions due to this. The new approach used in this project is to create road models resembling real tracks, which will give a better traceability through the development process. A road that is driven in reality is then also used in simulation and rig testing and by that improves the correlation between the analysis steps.

In order to get a road model that is useful in the applications, the road segments must first be defined and then connected for creating an assembled road [7]. In CarMaker, the road model can include several parameters to reproduce the wished conditions. For the road itself the quantities to be modeled includes road gradients in longitudinal and lateral directions, road surfaces and the actual road coordinates.

When modeling the road the most important properties are the following:

- Coordinates in X - and Y directions, resembling straight parts and curvatures of the road. These coordinates can be created manually or be extracted from points on a map.

- Gradient. The gradient of the road is a parameter which is crucial, considering the loads the vehicle is exposed and is required to produce.

- Speed limits. A speed limit is an upper limit on the velocity of the vehicle, which restricts the driver's behavior while driving. These can be used as either a legal limit or as a desired velocity during the cycle. During this thesis, the legal speed limits were used.

- Road surface. The surface and friction of the road are of importance for the driver's handling capabilities and to keep the vehicle on the road.

- Road attributes. The attributes can be speed bumps, track width, stops and crossings which influence the dynamics of the vehicle.

2.3.2   Software for road model generating

To be able to create the road models in the project, certain software were used. These contributed in steps, shown in Figure 2.4, to the final generated models. The software are commercial tools, which were used during the research in order to generate the road model on a suitable format to perform the simulations.

Google Maps/Earth

The services called Google Maps and Google Earth are free commercial software used for navigation and map searches. Google Map is internet based, while Google Earth is a program which can be downloaded to your device of choice. In both software it is possible to create custom made tracks based on the user's settings, see Figure 2.3. Through that, the tracks that are used for physical vehicle testing can be recreated digitally.

From the visual tracks in the programs their GPS-coordinates can be extracted to an output file, an example is shown in Figure 2.4a. With this freedom of creating the requested track in a virtual environment, the user has the possibility to model a track which is not easily accessible in reality. An example of this feature would be if the track is situated in Asia, the user in Göteborg can use the software to create the track without physically visiting the track.

Figure 2.3: *Göteborg City Cycle in Google Earth*

GPS Visualizer

Using the Google Maps/Earth a file containing a track with its GPS-coordinates can be created, but this file does not include the altitude of the track. Influences from hills and valleys on the track can be a determining factor for how well the modeled track resembles the physical one and in that way decide if the simulation results will be valid. The altitude of the track can be added to the coordinate data using a internet service called GPS Visualizer. GPS Visualizer automatically adds the altitude parameters associated to the GPS-coordinates of the track to the output file from Google Maps/Earth, an example is shown in Figure 2.4b. With this done a good representation of the track, in coordinates, is shaped.

Concerto

The software Concerto is a data pre/post processing program developed by AVL. In this thesis, it is used to transform raw GPS-coordinates into a road model which can be used in simulations. Concerto connects the points of the coordinates using three different types of road building blocks: straight road segments, turns of constant radius and turns of linearly varying radius called clothoids. Each segment has a defined slope in order to resemble the elevation profile of the real road. By connecting thousands of these segments with varying length, a good representation of the road is created. As long as the input data are formed accurately, Concerto performs the transformation automatically, an example of the output is shown in Figure 2.4c. This transformation from raw track coordinates and altitude values to a continuous road model could also be made manually using direction vectors and gradients. However, this method would be more time consuming and a program managing this transformation has to be created and validated.

From Google Earth/Maps

Longitude	Latitude
11.85595,	57.73160,
11.85593,	57.73228,
11.85608,	57.73275,

(a)

From GPS Visualizer

Longitude	Latitude	Altitude
11.85595,	57.73160,	43.5
11.85593,	57.73228,	46.3
11.85608,	57.73275,	47.4

(b)

From Concerto

Maneuver	Length	Radius	Slope
TurnRight	3.220942	101.0260	0.012957

(c)

Figure 2.4: *Road data processing steps*

CarMaker

In the CarMaker environment the creation and representation of the road model can be done in several ways. The road segments are formed in the same way as the road explained in Section 2.3.2 and the user can choose which way to form the assembled road. A straight forward way is to create the segments by hand in the CarMaker interface. The segments then consist of the earlier mentioned attributes, which step by step builds up an assembled road. This road can instantly be viewed and verified using a overview tool called $BirdsEyeView$ and in 3D using $3DPreview$. If the goal is to create a simple road model, which might be used to try-out the program's functions, the manual assembling is useful. For more complex road models, which for example should resemble a real test track, the procedure used in this project is more suitable. The road model is then created using the tools explained earlier under Section 2.3.2 and can further on be implemented into CarMaker. Figure 2.5 shows a picture from a CarMaker simulation and a picture from Google Earth of the same location in Göteborg, Lilla bommen.

(a) *CarMaker*

(b) *Google Earth*

Figure 2.5: *Comparison of view of Lilla bommen in Göteborg*

Even though the road model is already defined and imported into CarMaker, it is possible to make corrections in CarMaker to further optimize the model. In CarMaker the user can add features to the road model which are used during the simulations. These features are for example speed limits, road bumps and markers, all of which can be defined to determine and restrain how the vehicle can be driven on the road. It is also possible to select which lane the vehicle is to be driven in or if the road is to be a single lane representation of the real road. For visualization, the road model can also include visual objects, such as guide post and houses, but these are only there to beautify the road and its environment.

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2.4 Driver model

To be able to model the stresses applied to a vehicle when driving, a good representation of the driver is important. One of the factors that has the largest impact on the powertrain in terms of endurance is the aggressiveness of the driver. Driver aggressiveness is characterized by high longitudinal and lateral accelerations, which results in high torques in the powertrain and therefore reduces the durability of the powertrain. A driver behavior model can be developed in many different ways but the model used in this thesis, which is predefined in CarMaker, is based on Proportional-integral-derivative (PID) controllers, a commonly used approach in the industry.

2.4.1 Background

Every person has their own way of driving and this results in a unique set of requirements on the vehicle's components. Of course, these are designed to withstand the costumer's toughest requirements but to fully understand how the components are used, it is important to know how the less aggressive drivers use the vehicle as well. Therefore driver models of different aggressiveness are needed in the product development process.

Drivers in general have a limit on acceleration, up to which they feel comfortable, which differs from driver to driver. The limit is a combination of longitudinal and lateral acceleration and is usually visualized in an acceleration diagram, shown in Figure 2.6. The area within the red line resembles all combinations of longitudinal and lateral acceleration that the driver is comfortable with. In the three Figures 2.6a, 2.6b and 2.6c acceleration diagrams for different types of drivers which are predefined in CarMaker are shown. Usually, lateral acceleration is less comfortable to withstand than longitudinal since there is no direct point of support like the steering wheel provides during longitudinal deceleration and the chair provides during longitudinal acceleration [5].
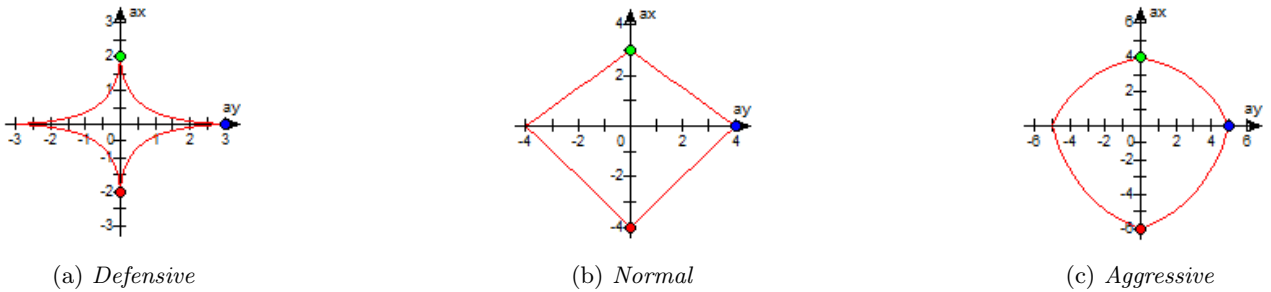

(a) *Defensive*   (b) *Normal*   (c) *Aggressive*

Figure 2.6: *Acceleration diagrams from CarMaker*

The classical approach used when modeling a driver is a continuous PID controller following a velocity profile. Usually, two almost independent PID controllers controls the longitudinal and lateral dynamics, which is a good way to reduce lateral errors but does not behave like a real driver [7]. The two controllers only get coupled when a critical driving situation occurs and the lateral controller reduces the throttle angle and applies force to the brake pedal. For simpler simulations, closed loop vehicle-driver simulations, the PID controller works sufficient. If the simulations are more advanced, a so called hybrid driver model is to prefer, which takes into account more situation based tasks as optimizing the position on the road and foreseeing the optimal speed.

2.4.2 Driver model in CarMaker

The driver behavior model in CarMaker is based on a PID controller, but far more complex. It does not control the current driving situation, but rather a preview point in the future using Taylor polynomials for the prediction. Furthermore it considers psychological studies and measurements from real test drivers to make the driver behavior as realistic as possible [11].

The driver model itself is already developed and included in CarMaker. Ergo, the task is to parametrize the model to fit actual drivers. Some of the most influential parameters are longitudinal and lateral acceleration and the combination of these like shown in Figure 2.6. These parameters have a great influence when controlling the aggressiveness of the driver. It is also possible to change how and when the driver changes gear and how fast he/she can change pedals. However, these parameters mostly concern manual transmissions which are outside the scope of the thesis.

To be able to model several different types of drivers, multiple driver parameter sets have to be developed, for example an defensive, normal and aggressive driver parameter set. In terms of damage to the powertrain, different combinations of these might be a way to model a large portion of the population using only a few parameter sets.
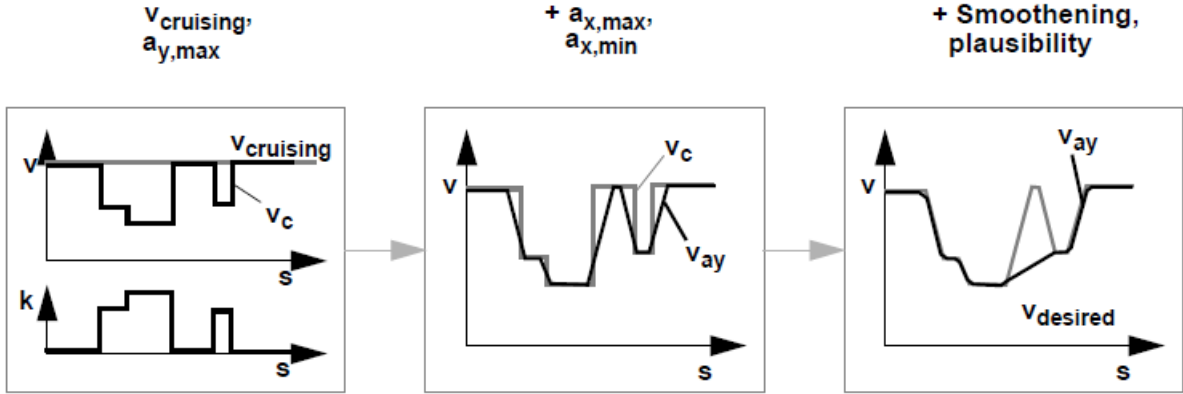

Figure 2.7: *The three steps for how desired speed is calculated for propulsion of vehicle*

According to [6] the driver model included in CarMaker calculates the static desired speed, v, in three steps, as seen in Figure 2.7. In the first step it uses the speed limits, the maximum allowed lateral acceleration, a_y, and the curvature, k, of the track to calculate the desired speed. In the second step the acceleration is smoothed to make sure no accelerations or decelerations, a_x, are above the maximum allowed limits. In the third step, very temporary velocity increases and decreases are smoothed out since a normal driver does not change pedals that often. In Figure 2.7, from [6] a schematic picture of the process is shown, where s in the plots is the distance driven.

2.5 Vehicle model

The vehicle model used for simulation and rig testing is shaped in a similar way as the driver model, through parameterization. The model is in turn constructed by multiple sub models, these are for example gearbox, suspension, differential, aerodynamics and engine model. As stated in Section 2.2, when running tests in the rig the engine and transmission models are replaced by the real physical components. parameterization of the vehicle model is outside of the scope of the thesis, but a model had to be used to be able to conduct simulations and rig tests. The vehicle model used in this thesis was mainly a model of the new Volvo XC90, but also a few other generic example models were used for comparison reasons. The model of the XC90 used in simulations is older and not as accurate as the one used in the rig. Since the vehicle model in the rig included no models of the powertrain components, it was not possible to use the same vehicle model in the CarMaker simulations. This resulted in that the vehicle model used in simulations and rig testing was not fully equal.

2.6 Rig equipment

Rigs are used to test components and systems without the need of a complete vehicle. By that the tests can be conducted earlier in the development process since the complete vehicle does not have to be ready for testing. There are several types of rig systems and the simpler ones only takes the longitudinal dynamics into account, meaning pure longitudinal accelerations and decelerations. The rig used in this thesis is a complete four-wheel-drive (4WD) powertrain rig, which means that every component from the engine to the drive shafts are used. This way, both longitudinal and lateral dynamics can be included.

Figure 2.8: *The rig setup at Volvo Cars*

In Figure 2.8 the physical setup of the rig is shown. As seen in the figure the wheels of the vehicle are substituted with electric motors that subjects the powertrain with the desired loads. The physical components as the engine, gearbox and differential are mounted on a fixture and assembled together as in a vehicle and are controlled by the real control units. The powertrain is connected to external measurement tools, but the transmissions internal Controller area network (CAN) system is also used to log data.

What makes the rig special is that it is a HIL rig. The rig is connected to a software, in this case CarMaker, and runs as a part of the simulation. The simulation is the same as running offline in CarMaker but instead of using the powertrain model provided by the software, the real components are used. This feature creates a possibility to use the same test setup in the rig testing as in the simulations, including for example the road and driver model. In Figure 2.9 a schematic explanation of this is shown.
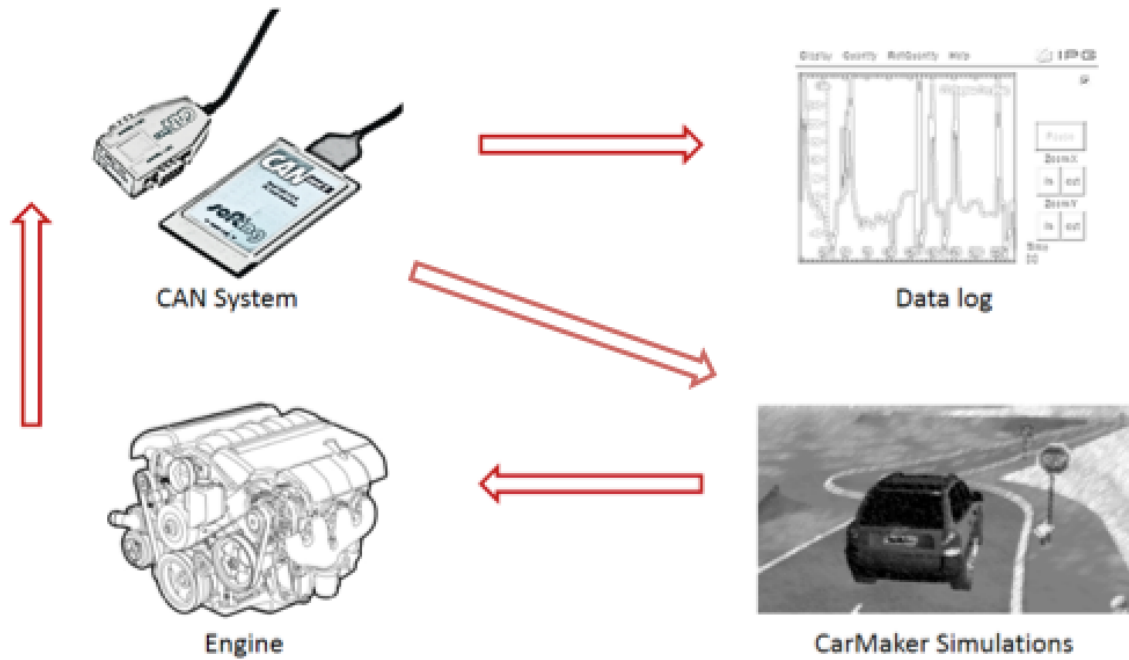
Figure 2.9: *Hardware-in-the-loop scheme*

Signals that would normally be sent, from the driver model to the engine model during simulation, will in this case be sent from the driver model in CarMaker to the real engine. This means that the rig has a good repeatability compared to a real vehicle test where variations and disturbances are more frequent. Running pure longitudinal dynamics in a rig does not give a good representation of the loads of the powertrain, since it is a product of both longitudinal and lateral dynamics. CarMaker connects the simulation to a model of the real driving environment which allows the lateral dynamics to affect the longitudinal dynamics. This also enables the user to study the influence of the environment, such as road friction, on the all-wheel-drive and anti-spin systems etc. [13].

2.7 Vehicle testing

The in-vehicle-tests are carried out in real production cars or prototypes that are fitted with different analysis tools. Most of the data used for the analysis is already provided by the vehicle in the CAN and FlexRay network since the different control units in the car already use this information when the car is running. The car does not store this information due to the large data quantities, therefore a computer with INCA or DIADEM installed is required. These programs connect to the car's network and store the requested information. This could be for example the velocity, lateral and longitudinal acceleration and torque on each wheel. To be able to get information of the torque on each wheel, special drive shafts equipped with torque sensors (wheatstone bridges) had to be used. Figure 2.10 shows the equipment that allows the signals from the sensors to be sent as radio waves to a antenna mounted just above the wheel in order to be processed like the other signals.

Figure 2.10: *Vehicle equipped with sensor for torque measurements*

There is a plethora of data from test runs conducted by professional test drivers available at Volvo Cars. However, to be able to understand the data properly and understand the abnormalities in the data, it is important to conduct some test runs where the drivers behavior is controlled and known.

2.8   Model validation

When developing any type of model, it is crucial to ensure that it is properly verified and to remember that models are only valid in the area they are designed to be valid within. Therefore, it is necessary to understand the model or at least, know when it is applicable. These conditions lead to that the following questions arose during the model validation:

- Do the model outputs correspond well enough to the measured data?

- Is the model suitable for the purpose for which it was constructed?

A way of attacking the validation process is to define for which purpose the model is designed for, which outputs must be precisely modelled and where certain errors can be accepted [7]. An example of this can be that during this project, some of the validation methods are suitable for validating the constructed road models, while other are intended to validate the driver's behavior during simulations and test runs. Also, an important aspect is that the more data that is available from the real system, the better the questions above can be answered and evaluated [7].

One way of validating a model is to use key indicators. If the model is a good representation of the actual system both the system and the model should show similar values of the key indicators when exposed to the same load case. Some key indicators used in this thesis are listed below in Section 2.8.1.

Another useful way to validate the sub parts of the project is a more visual investigation approach. This can for example be done by comparing plots of velocity profiles between test runs or visually comparing which torque classes a vehicle performs in during a test run. These methods are summarized in Section 2.8.2.

2.8.1 Key indicators

To be able to compare outputs from simulations and vehicle tests in a objective way, key indicators were used. Key indicators are effective since the behavior of the data is described in a scalar value which makes it easier to compare. However, the user must be aware of that the key indicators can be misleading if used in a wrong way. There is also a possibility that 'two wrongs make it right', which means that the data can be wrong but two independent errors results in a reasonable value.

To prevent the misjudgement to occur, a good approach is to use different key indicators. One indicator might for example be efficient to compare the impact of the vehicle's components, while another can be used to validate a road model. The key indicators presented below are based on both known approaches used in the industry and new developed indicators for this project. The first indicator, MTF value, is suitable for compare different driving cycles normally to measure the fuel consumption. In this thesis the value is intended to be used for evaluation of road models. The second indicator, DA value, is developed for investigation of how drivers behave during driving, in specific the acceleration and deceleration behavior. The last indicator, Duty Value, is used for evaluation of the durability of the vehicle's powertrain components, which is used during the thesis for validation of the driver behavior models.

Mean Tractive Force (MTF)

The first part of the project was to create valid road models, which can be used during simulations and rig testing. These models should be validated in order to see how well they cover the wished road attributes. In this case the aim is to create road models that resemble reality to have the possibility to compare the simulations and rig testing with real vehicle testing.

The key indicator used for this purpose is the Mean Tractive Force (MTF), which is based on an article by Nyberg et al. [9] which is based on research by Guzella et al. [8]. MTF is a mean value of the positive forces at the wheels produced by the engine [N]. The forces can be divided into three types of forces; forces due to air resistance, rolling resistance and acceleration of the vehicle. The MTF value is the mean of the sum of these types of forces over the entire run.

Tractive force means the force subjected to the vehicle during positive accelerations and the main equation is:

$$\bar{F}_{trac} = \frac{1}{x_{tot}} \int_{t \in \tau_{trac}} F(t) \cdot v(t) dt \tag{2.1}$$

where x_{tot} is the total distance, $v(t)$ is the vehicle's velocity and $F(t)$ is the total force, which can be divided into the sub parts:

$$F(t) = F_{air} + F_{roll} + F_m \tag{2.2}$$

F_{air} is the total force due to air resistance:

$$F_{air} = \frac{1}{2} \rho_a c_d A_f v^2(t) \tag{2.3}$$

where ρ_a is the density of air, c_d is the drag coefficient, A_f is the frontal area of the vehicle and $v(t)$ is the vehicle's velocity.

F_{roll} is the force due to roll resistance:

$$F_{roll} = m c_r g \tag{2.4}$$

where m is the vehicle mass, c_r is the roll resistance coefficient and g is the gravitation.

F_m is the force due to acceleration of the vehicle:

$$F_m = m a(t) \tag{2.5}$$

where m is the vehicle mass and $a(t)$ is the vehicle's acceleration.

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As seen in the equations above, the MTF value is dependant on both the velocity and the forces produced by the engine. The basic use for the MTF value is to be able to compare different driving cycles. A driving cycle is a representation of how vehicles are driven and the cycle is used for certification, comparison of vehicles or as an engineering tool in vehicle design. The basic idea of the driving cycle is that it should be representative for driving behavior in the region it is used and therefore the value could be a good way to verify the road model and also the driver model. This because if two road models are tested with the same vehicle and the MTF values of the runs are evaluated to be similar, the road models should be equally representative for the intended usage.

Driver Aggressiveness

To be able to quantify how aggressive a driver has been during a test and to validate the driver behavior models, a key indicator called *Driver Aggressiveness* (DA) was developed. The DA-value is dependent on velocity and acceleration which was identified as the most influential driver controlled parameters in terms of durability of the powertrain. A crucial presumption when using the DA-value to compare drivers is that the driven tracks must be similar since the equation does not take distance driven into account. Also the type of track must be similar since there are usually more accelerations in urban driving than in highway conditions et cetera.

A driver does not actually feel the velocity of the vehicle, but rather estimates this visually and the experienced velocity changes depending on previous circumstances, this is called speed blindness. Instead, the acceleration is felt as a force pushing the driver into the chair and the experienced acceleration does not, in the same way, change with the previous circumstances and is therefore a useful indicator on aggressiveness. By assuming that the driver does not demand the full available power from the engine, the acceleration is not limited by the mass of the car nor the engine, meaning that it is an even better indicator of driver aggressiveness. This is the equation used to calculate the DA value:

$$DA(a, v, n) = \sum_{k=1}^{m} |v_k^x| \cdot |a_k^y| \cdot n_k \tag{2.6}$$

Where a_k^y and v_k^x is the acceleration and velocity classes and n_k is the number of revolutions of driveshafts in the corresponding acceleration and velocity classes. During this thesis, the acceleration value is raised to the power of 4.5 since this has a bigger influence on the aggressiveness than the velocity which is raised to the power of 1. The values are chosen from empirical tests.

Duty Value

A more well-recognized key indicator in transmission development, at least at Volvo Cars is the *Duty Value* (DV) [12]. Duty-value is a key indicator used for relative comparison of torque load on the components of the transmission, which in turn induces fatigue. This is the equation used to calculate the DV value:

$$DV(T, n) = \sum_{k=1}^{m} n_k \cdot T_k^{We} \tag{2.7}$$

Where We is the Wöhler exponent and T_k is the torque in class k.

Duty value can be used to evaluate different parts of the transmission, depending on which component that is to be evaluated the definition of number of cycles in class, denoted n_k, changes. In this thesis, n_k is defined as number of revolutions in specific torque and velocity classes on the output shaft of the gearbox. By subjecting the components to different loads and measuring the stress, plotting these points and curve fitting, a Wöhler curve can be created. When using duty value it is important to notice that it is based on the simplification that the relationship between torque and stress is linear which is not true. The calculations are simplified since a constant slope value of the Wöhler curve is used as the Wöhler constant, We.

2.8.2 Visual validation methods

From transmission development's point of view, longitudinal dynamics is the most influential part in terms of component wear. Therefore, when performing test runs in both simulations and reality, the velocity profiles of the runs show if the vehicle maintains the correct speed limits and stops at the correct distances. If two profiles are equal, conclusions can be drawn both on how the drivers behaved and the similarity of the road sections.

Longitudinal acceleration is of great interest when evaluating the behavior of the driver, since it effects the forces and torques subjected to, and produced by, the vehicle. An aggressive driver usually use higher acceleration than a defensive driver, a behavior that can be evaluated through comparison between acceleration profiles of different test runs.

The fact that wear of transmission components is strongly connected to the torque transmitted is intuitive, one way of describing the relationship is the Duty value 2.7. What might not be as trivial is that the rotational velocity of the transmission when the torque is transmitted is important as well. Since high velocities decreases the time of contact between the cogs which increases the momentum, which in turn, increases the wear of the components. To get a good overview of the distribution of torque and rotational velocity distribution during a test run, a plot showing the distribution of drive shaft rotation in the different classes can be used, later called revolution in torque. These plots give an idea of how the driver behaves. Plots of the same kind, but where torque was replaced by acceleration can be used to evaluate the driver behavior, especially aggressiveness.

3 Methodology

In this section the performed steps of the project work are described. The thesis work started off with a literature study, this is described in the first section below. Since the task is to compare the result from simulations, rig testing and in-vehicle testing the section about literature studies is followed by sections about these parts, which in turn, are followed by a section about model validation. The sub sections are ordered in the sequence they were executed during the project, but obviously it was an iterative process between the parts to achieve an optimal outcome of the research.

3.1 Literature studies

To create a profound understanding of the problems and difficulties faced during the project, literature studies were performed continuously. At first, the main focus of the studies was to find references on how to form the models for the parts in the project. Later on, the issue of how to validate and compare different road models and driver models appeared. Literature studies were conducted to investigate whether research had been performed on the subject previously. It exists numerous books and articles about automotive development, but the difficulty was to find relevant information applicable on the project. Some were found and the most useful ones are briefly described below.

In order to gain knowledge on how product development is performed in the automotive industry the article: *Product development in the automotive industry: crucial success drivers for technological innovations*, by Daniel Gerhard, Alexander Brem and Kai-Ingo Voigt [3], gave an understanding on best practice for success and trends in product development. Their research is based on empirical studies and investigations on the German automotive industry.

The research in the thesis is based on modelling road and driver behavior models for simulations. These topics are well described in the book: *Automotive Control Systems*, by Uwe Kiencke and Lars Nielsen [7], which contains rigorous knowledge about controlling and modeling the engine and driveline of a vehicle and how sub parts as the driver and road should be modeled for the simulations.

A great focus during the research has been to develop input to the simulations that can be performed both virtual and in the rig. A paper that contains the same area of interest is: *Analysis of vehicle dynamics using Co-Simulation of AVL-CRUISE and CarMaker in ETAS RT environment*, by Sundaravadivelu.K, Shantharam.G and Prabaharan.P, Raghavendra.N [13], which deals with the same software and hardware as used during the project.

For the validation part of the project, both new and already known key indicators have been used. An example of a known indicator is the Mean Tractive Force (MTF), which is explained and evaluated in the paper: *Driving Cycle Adaption and Design Based on Mean Tractive Force*, by Peter Nyberg, Erik Frisk and Lars Nielsen [9].

3.2 Modelling and Simulation

To be able to compare the results from simulations, rig and in-vehicle testing, a good model of the road and driver had to be developed. As stated in the theory, Section 2, the models themselves are included in CarMaker, this means that they need to be parametrized to mimic the real road and driver.

3.2.1 Parametrize Road model

The procedure of parameterizing the road model involves multiple software and web sites, the methodology involved when performing these steps is listed below.

Google Maps/Earth, GPS Visualizer and Concerto

In Google Earth or Google Maps the desired route is described as a road description. The difference between them is that longer and more complex driving instructions are hard to create in Google Earth. When selecting the route in Google Earth, there is no possibility to select which streets the driver should choose, the program always chooses the closest route. This might not matter for long driving instructions, where the choice of street might have very small influence on the overall result. But when designing a route like the city cycle used in this thesis, the choice of streets are done in a way to make sure that there are many accelerations and decelerations during the run. Therefore there are many such maneuvers that would be lost if Google Earth would be used. In Google Maps however, the user can specify every single turn and was preferred to be used in this thesis.

The output file from Google Maps contains the geographical coordinates of the track. To get a fair representation of the loads on the powertrain during driving the altitude had to be included. This is done through a web site called GPS Visualizer. In order to make the data usable in CarMaker, the file is finally processed in Concerto.

CarMaker

When the previous steps are performed a relatively good representation of the road can be imported into CarMaker. The imported road consists of turns, straights and up/down hills. The final tweaking of the road model is to introduce environmental effects and signs, which are used to control the behavior of the driver. There are several different effects that can be implemented but the ones used in the thesis are listed below.

- Stop sign

- Velocity signs

- Road bumps

Stop signs are used to simulate red lights and stopping in front of roundabouts and intersections. These could be replaced by red lights with stochastic timing, but to ensure good repeatability stop signs were chosen instead. Velocity signs are used to set the desired speed for the driver. The road bumps, called beams in CarMaker, were designed to simulate the standard bump described in [2]. Bumps require a deceleration followed by acceleration, which sets further demands on the powertrain and are therefore important to include in the model. The speed limits were chosen based on the Swedish national road database (NVDB) [14] while the positions of the road bumps and stop signs were selected by looking through the city cycle in *Street view* in Google Earth.

Figure 3.1 shows how a road is modeled with hundreds of road segments. This is where the signs and road bumps are included.
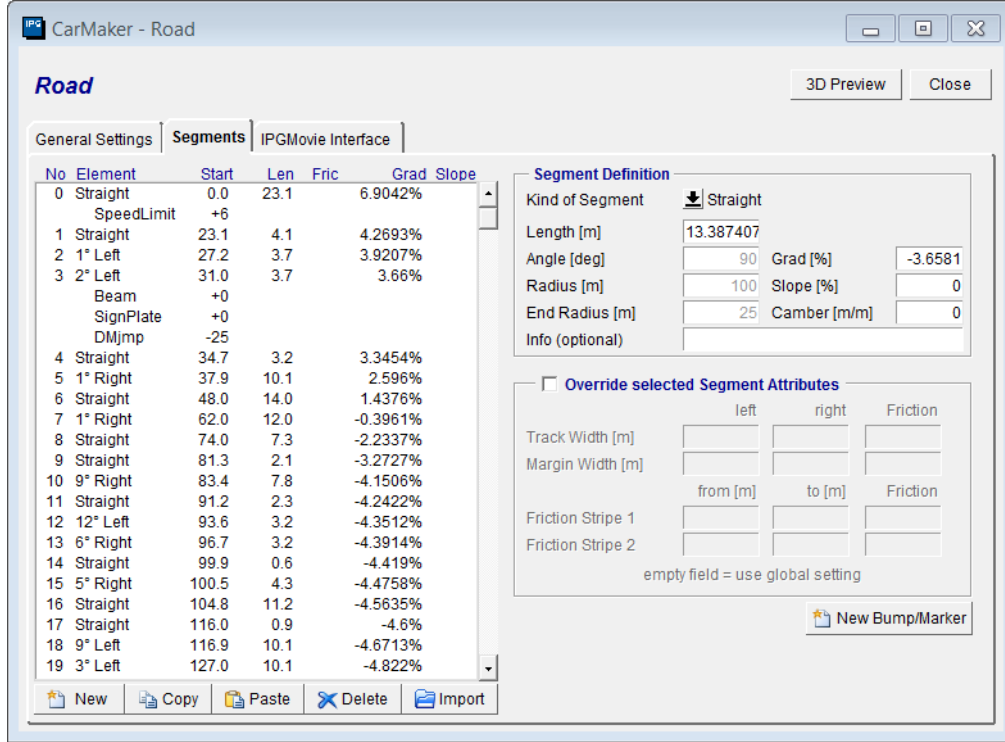
Figure 3.1: *Road interface in CarMaker*

3.2.2 Parametrize Driver model

As described earlier, the driver behavior model used for simulations and rig testing is included in the CarMaker software. Main task during the research were therefore to parametrize the input to this model in order to create a driver behavior which satisfies requirements and demands. Methods used for the parameterization are described below.

CarMaker

The driver in CarMaker is parametrized using quite few parameters, which can be defined using a GUI shown in Figure 3.2. A main goal throughout the project has been to investigate which kind of driver behavior to aim for and how it can be shaped in the simulations only by using the available parameters.

In CarMaker three predefined types of driver modes are available. These are shaped to resemble different kinds of real drivers [6]:

- Defensive driver. Slow and careful driver.

- Normal driver. Resembles 90 % of all drivers according to IPG Automotive [6].

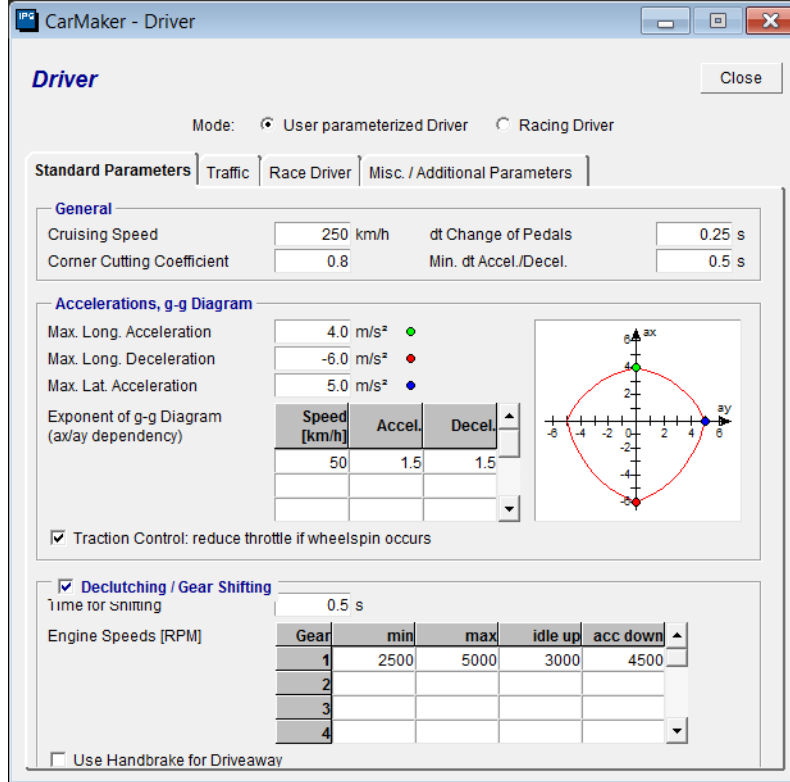- Aggressive driver. A sportive driver.

Figure 3.2: *Driver interface in CarMaker, Aggressive driver settings*

When choosing one of the predefined drivers available in CarMaker, the parameter settings change automatically. The main difference between the settings is the maximum tolerated longitudinal and lateral accelerations, which are shown in Table 3.1. Also other parameters change, such as corner cutting coefficient and the time consumed from moving the foot from the throttle pedal to the brake pedal. A combination of all the parameters define how aggressively the vehicle is driven.

Driver	Max long acc $[m/s^2]$	Max long dec $[m/s^2]$	Max lat acc $[m/s^2]$
Defensive	2	2	3
Normal	3	4	4
Aggressive	4	6	5

Table 3.1: Predefined driver parameter sets in CarMaker

During the project a large amount of different parameter settings for the driver has been set and evaluated. The investigations aimed to create a driver model that resembles real drivers, but the diversity in behavior of the real drivers made it hard to tune in a single driver model for the simulations. Therefore the three predefined driver parameter settings were used during simulations in order to create a useful data set, which could be a base for the validation process.

An important feature for parameterizing and optimizing the driver in CarMaker is using the so called *Driver Adaption*. In order to get good result from the simulation, the system needs to have knowledge about the road model, the vehicle model and how the vehicle in an optimal way should be driven on the road. Using the *Driver Adaption* feature, knowledge data is created and stored, including for example longitudinal and lateral dynamics of the model. Since the driver adaption data showed to be dependant on both the road and vehicle model, the adaption needs to be repeated when changing one of these models. The usage of the driver adaption was shown to be important both during simulations in computer and rig, while if not used the driver has issues keeping the vehicle on the road.

3.3 Rig testing

Almost no further configuration of the files used in CarMaker are required to make the files runnable in the rig, but there are two minor differences. The first one is that the rig needs to know in advance that the vehicle is going to stop, otherwise the powertrain can be subjected to large momentary peak forces due to computational errors. This is avoided by adding special signs along the road, called *DrivMan Jump*. These are used to trigger a defined code sequence which tells the rig that there is a stop ahead. The second difference is that the powertrain model used during simulation has to be deactivated since this is replaced by a physical model in the rig.

3.4 Vehicle testing

Three in-vehicle tests were preformed, the first two were conducted in a Volvo V70 where only data from the car's internal network was monitored and stored. During these tests longitudinal and lateral acceleration and velocity were of interest. The third test was performed in a Volvo XC90, where the same data from the internal network was stored but the car was also equipped with drive shafts that measured the torque on each wheel.

It was observed that CarMaker accelerated quickly to the desired speed and then maintained that speed strictly, a behavior which can be seen in Figure 4.2. During the first test, an attempt was made to drive with the same characteristics. The following two tests were driven as the driver would normally drive. The speed limits were kept to an as large extent as possible to ensure that the results would be as comparable to CarMaker as possible.

A problem that arose was other traffic on the road. This made it hard to maintain the speed limit, a problem that does not occur in CarMaker since other traffic is not modeled. Since a lot of the cycle is in urban areas in the city center of Göteborg this was an expected problem. To minimize the effect of this the tests were conducted between the morning and lunch rush hours, when the traffic is light.

3.5 Model validation

The validation of the created models and performed tests was conducted continuously through the project. Using Matlab programs and scripts, the gained data was analyzed. Due to the diversity in configuration of the outputs from the different systems; simulations, rig testing and vehicle testing, the output was to be transformed into comparable data.

The data logging systems, in vehicle, rig and simulations, log the data in different sample intervals. Before using the data for plotting profiles and calculating the key indicators, the data was interpolated into equal size. This was also done using Matlab scripts.

The validation process was based on visual validation methods and evaluation of key indicators. These two methods were performed in Matlab, where an user friendly program was created. In the program the user easily can choose input data and then decide which method to use and plot. With help from this, the validation can be made and conclusions for the models accuracy and usability be drawn.

4 Results and discussion

The results of the project are presented in Sections 4.1 and 4.2 for the road model respectively the driver model. In order to interpret the results, short discussions are included in the sections.

4.1 Road model

Choice of path

When investigating whether the road model is a good representation of the real track there are multiple parameters to consider. A first step is to make sure the choice of path is correct. By a visual comparison of a birds eye view of the track from CarMaker and Google Earth, the road model seems to give a good representation of the Göteborg city cycle. The images that were compared can be seen in Figure 4.1.
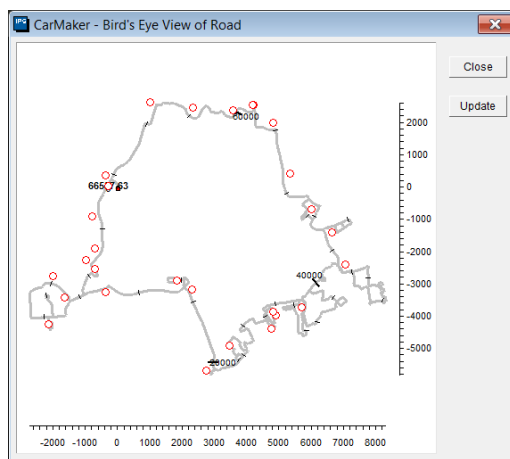
(a) *CarMaker*

(b) *Google Earth*

Figure 4.1: *Göteborg city cycle in CarMaker and Google Earth*

Time and Distance

To ensure that the tracks are equally long the distance was compared and the result is shown in Table 4.1a. As seen, the vehicle test is about 100 m longer than the simulation and rig test. This small error is because the start and stop positions used during the vehicle test were not exactly the same as the ones in the road model, which occurred due to outer circumstances in vehicle test situations, for example the measurement could have been initiated too early. Considering the long distance of the total cycle, this minor error in distance is deemed to be of less importance. The distance driven during simulation and rig test was expected to be equal but differs about 40 m, this is believed to be caused by the rig being allowed to cut corners to a slightly larger extent than the simulation. However, this has a insignificant influence on the results.

Test	Distance [km]
Vehicle Test	66.65
Rig Test	66.51
CarMaker Test	66.56

(a) Distance

Test	Time
Vehicle Test	2 h 17 min
Rig Test	1 h 52 min
CarMaker Test	1 h 57 min

(b) Time

Table 4.1: Road and road model comparison

In Table 4.1b, the time elapsed during one cycle is shown. As seen the simulations and rig tests are quite similar but the vehicle test stands out. This is mainly due to the traffic situation, which is not modelled in the road model, but is unavoidable in vehicle tests. Since traffic situations can be seen as stochastic processes, these are not modeled because it would constrain the repeatability of the tests. Red lights though have a crucial impact during urban driving modeling, because they contribute to a large amount of acceleration and deceleration situations. In the road model the red lights are modeled by stop signs where the vehicle is supposed to stop for 5 seconds. In real life the red lights can be red for about a minute or just a second. The impact of the transmission, which is of greatest interest during this project, is not specifically dependant on stand still situations. Due to this, the difference in time consumed between the testing methods is deemed as a less important factor.

Velocity profiles

Another important characteristic of the road model is that the driver stops the vehicle and maintains the correct speed along the track. A good way to get an overview of this is by comparing the velocity curves plotted against distance driven. This way, one can see if the correct velocity is maintained at a certain position. As seen in Figure 4.2, the velocity profile of the vehicle test, rig and CarMaker is quite similar on part 1 of the cycle, which is a part with calm traffic situation. The velocity of the vehicle test is a few kilometers per hour slower than the rig and simulation, this is because the speedometer of the vehicle shows a higher speed than what is actually driven. The error is still small enough to be irrelevant when concluding that the velocities are similar and that the road model is valid. As seen in Figure 4.2, part 1 of the city cycle consists of four 70 km/h sections and five 50 km/h sections.
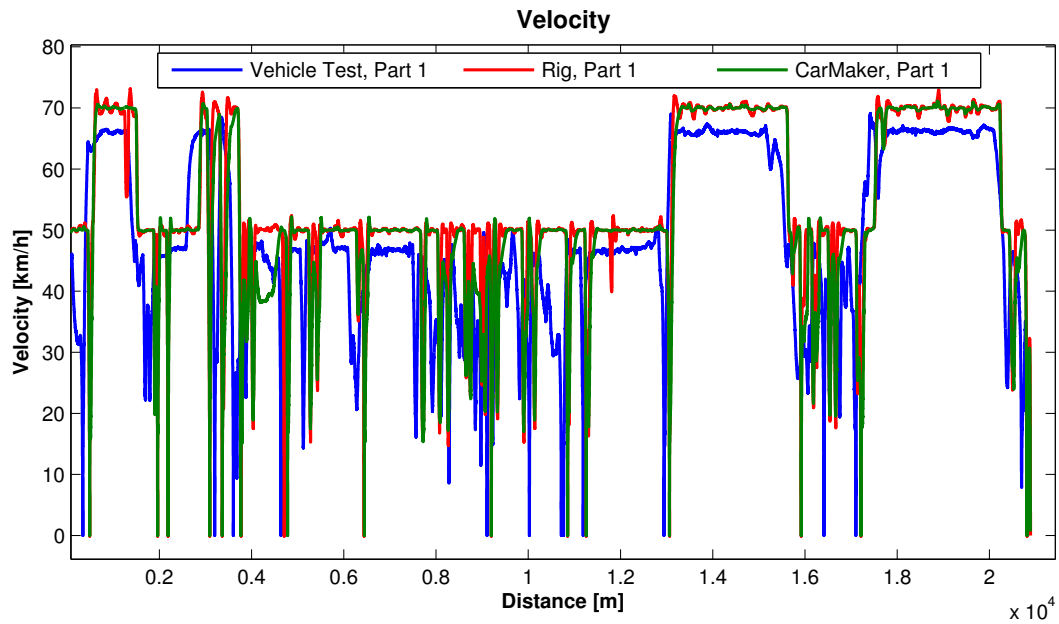

Figure 4.2: *Velocity profile of part 1 of the city cycle, low influence of traffic*

In Figure 4.3 on the other hand, which shows the velocity profile of part 3 which is mainly driven in the urban areas of Göteborg, the vehicle test almost always maintains a lower speed than the rig and simulations. This is because of the traffic situation which constrains the speed limits in this parts of the track. The many fluctuations in velocity are due to stops, road bumps and narrow corners. This behavior is not seen as clearly in part 1, Figure 4.2, since it mostly consists of country road conditions.
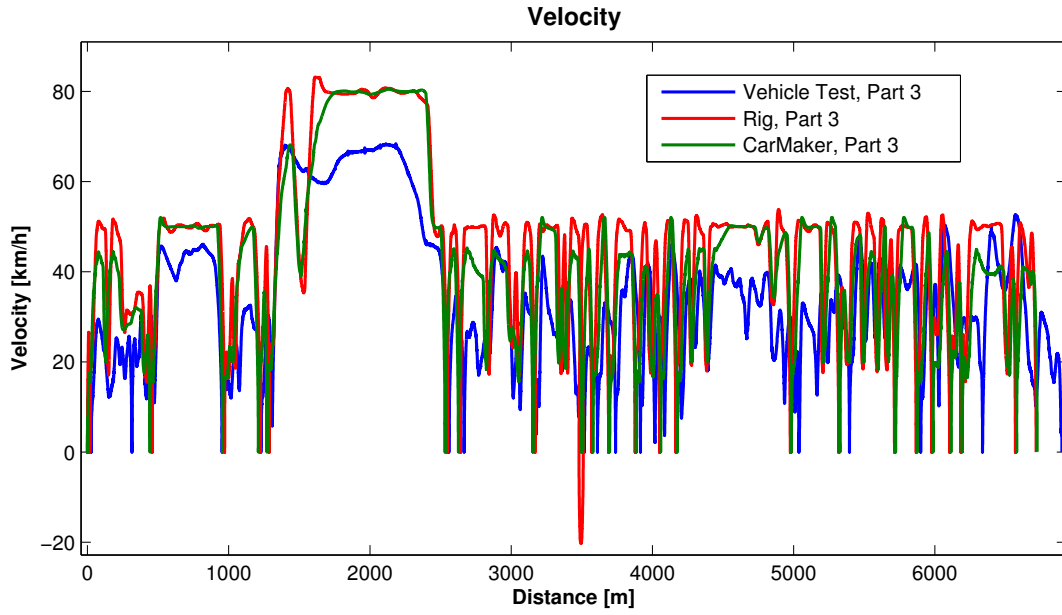
Figure 4.3: *Velocity profile of part 3 of the city cycle, high influence of traffic*

Considering the impact of traffic in part 3, Figure 4.3, the profile still shows a good correlation between the runs, which indicates that also this part of the road is modeled in a good way. This part of the city cycle has a speed limit of 50 km/h, except for one section with a limit of 80 km/h. It is also noticeable that the rig has a negative velocity for some time during the part 3 of the city cycle. This is because there is a reverse maneuver included in the driving instructions for this part. The maneuver is performed in the simulations and the vehicle test as well, but is then interpreted as a positive velocity by the sensors.

Mean Tractive Force

During the thesis, effort was put into finding objective ways to validate the road model. This resulted in the MTF value explained in the theory chapter under Section 2.8, and the outcome is shown in two figures below. In Figure 4.4a the MTF-value of every part of the cycle is shown for different tests, all in a Volvo XC90. In Figure 4.4b the MTF-value for different cars are shown, Volvo V70 and XC90, Volkswagen Beetle and Mercedes Benz M-class, but still divided into the different parts of the cycle. The vehicle tests were performed by the authors and a professional test driver from Volvo Cars, represented by the abbreviations MJ respectively TO in the figure legends.
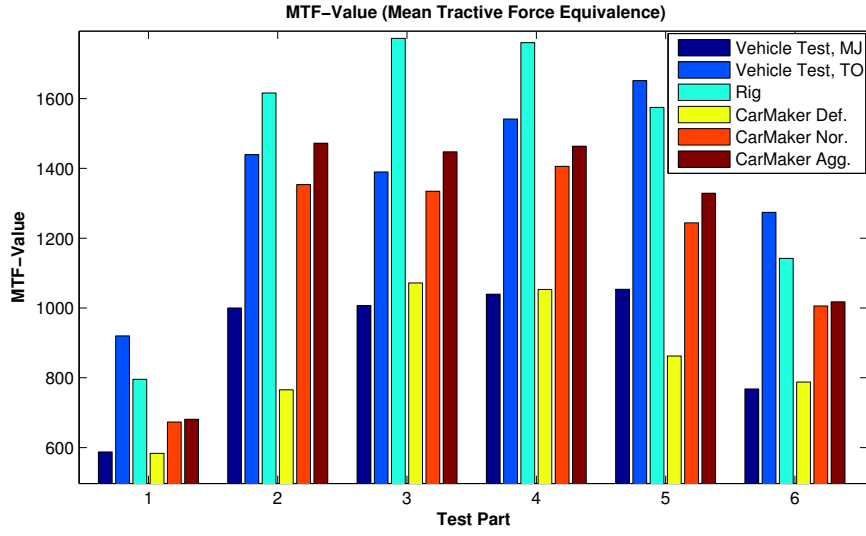
(a) *MTF-value for XC90*
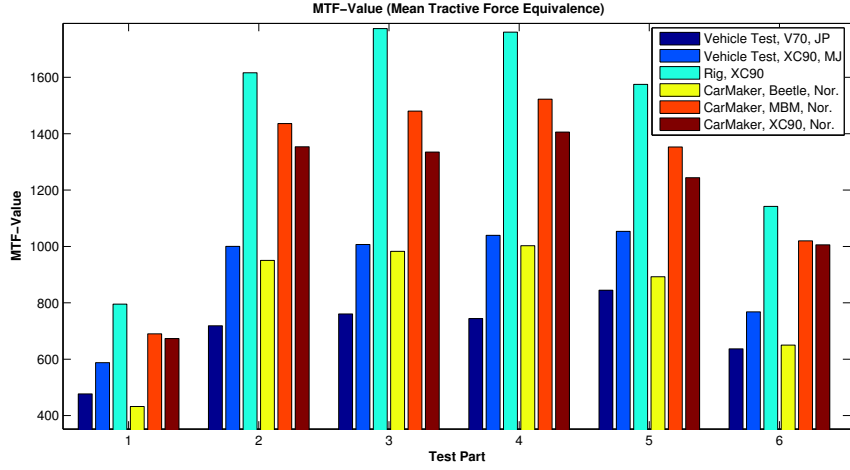
(b) *MTF-value for different cars*

Figure 4.4: *Comparison of MTF diagrams*

The aim of the MTF value is that vehicles driven according to equal driving cycles, should result in similar MTF-values and by that the road models could be validated. An advantage of this would be that the validation is less dependent of the driver behavior and the vehicle driven. However, it was hard to get any reliable results from the MTF-value since it was too dependant on a good vehicle model. The force required to propel the vehicle is a function of for example the mass of the vehicle and is limited by the force provided by the engine. An example of this is seen in Figure 4.4b, where the CarMaker simulations are run with the same road model and the same driver parameters. The only difference is the vehicle model and the variation in MTF-value shows that the validation in this case are too dependent on the vehicle model, which restrict the possibilities to draw conclusions on the road model's accuracy. Another interesting observation from Figure 4.4, is that the rig consequently gets higher MTF-values. This trend is discussed further in Section 4.2.

Gravel road model

During the thesis a road model of a gravel road was also developed. The gravel road is used as a complement to the city cycle during product development. Figure 4.5 shows the choice of path for the finished track, where the blue parts are so called transportation parts and the red parts are the gravel parts. Both the transportation and gravel parts are used during the research and development process and were therefore modelled. Using the same kind of road modelling methods as for the city cycle, the gravel road became an easy task to model. This shows a great usability of the methods, when creating new road models in the future. The gravel road model has been successfully implemented in the rig, but the data has not been evaluated as a part of this thesis.
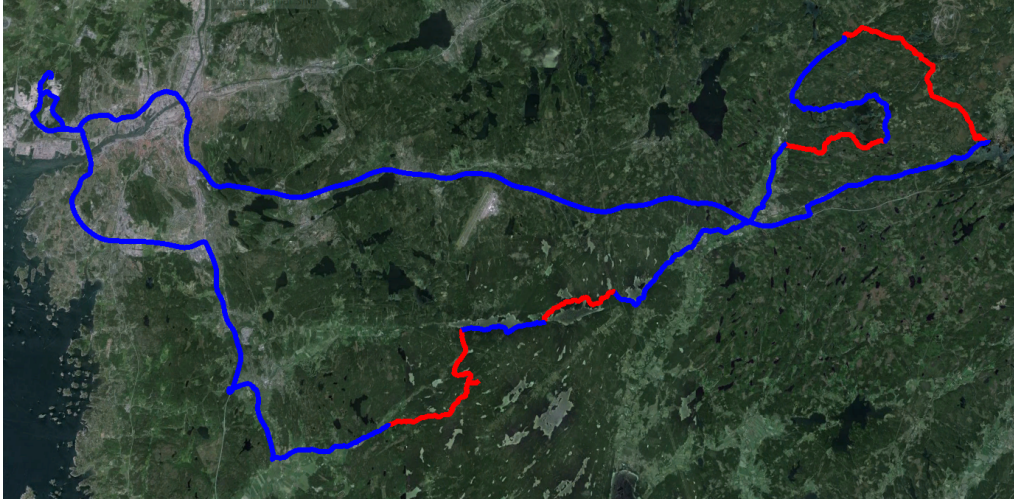
Figure 4.5: *Gravel cycle in Google Earth*

4.2 Driver model

Acceleration

The goal of the thesis concerning driver behavior model was to parametrize a driver that was a good representation of a real driver. Further along in the project it became clear that the driver model used in CarMaker was too simple to be able to fulfill that goal. Instead three standard driver configurations were used as examples, which are shown in Figure 2.6. One of the main problems when trying to parametrize the driver model in order to represent a real driver, is that the driver behavior model in CarMaker uses the maximum acceleration as a input when deciding the velocity. This means that the driver maintains the maximum acceleration for as long as it has a lower speed than intended, a behavior which is uncommon among real drivers since it causes a quite uncomfortable driving feeling. The behavior is seen in Figure 4.6, where Figure 4.6a shows a vehicle test where the accelerations are much more evenly spread than in Figure 4.6b, which shows a CarMaker simulation.
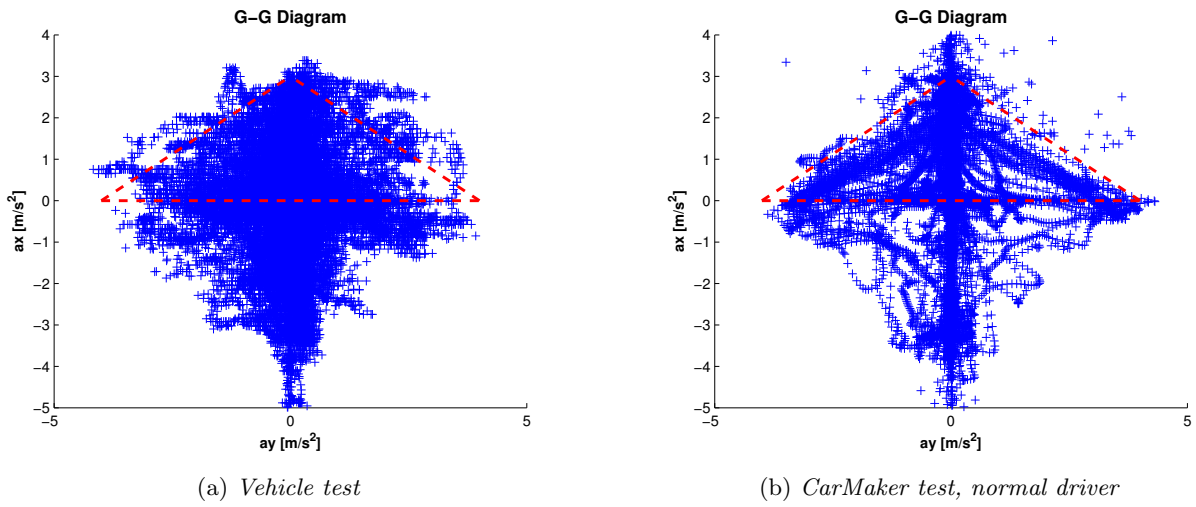

(a) *Vehicle test*   (b) *CarMaker test, normal driver*

Figure 4.6: *Comparison of acceleration diagrams*

Especially noticeable in Figure 4.6b are the data sets around the dashed lines. These symbolize the combinations of maximum allowed lateral and longitudinal acceleration. As seen, the CarMaker driver is much more consistent on using acceleration combinations corresponding to these lines. When comparing the data sets to the plot in Figure 4.6a from the vehicle test, no such trends are noticeable, which proves CarMaker's inability to represent a real driver. A possible way to work around this might be to combine output data from multiple simulations using different driver parameter sets, this idea is described further in Section 6.

Figure 4.7 shows the longitudinal acceleration of a vehicle test, rig, and CarMaker simulation during a segment of the first part of the city cycle. The driver behaviour model used in the rig is an aggressive driver, the same as the aggressive one used in CarMaker simulations. As seen, the rig achieves the highest positive accelerations, which indicates that the rig is more aggressive than both the vehicle test and CarMaker. This is a disturbing result since the driver parameter set is the same in the rig as in CarMaker. Regarding many other output quantities the rig and CarMaker are quite similar but when it comes to acceleration, the difference is evident. To be able to fully understand how and why this error occurs, the same vehicle model used in the rig with a correct model of the powertrain would have to be used in the simulations. Unfortunately, no such model exists, as mentioned in Section 2.5. By analyzing the shifting signals from the simulation and rig tests, a conclusion can be drawn that the shifting schedule in the simulation model does not fully correspond to the one in the real gearbox in the rig. Another contributing factor is also that the vehicle model used in the simulation has a diesel engine whilst the rig had a petrol engine at the time. This could be an explanation to why the rig is more aggressive.
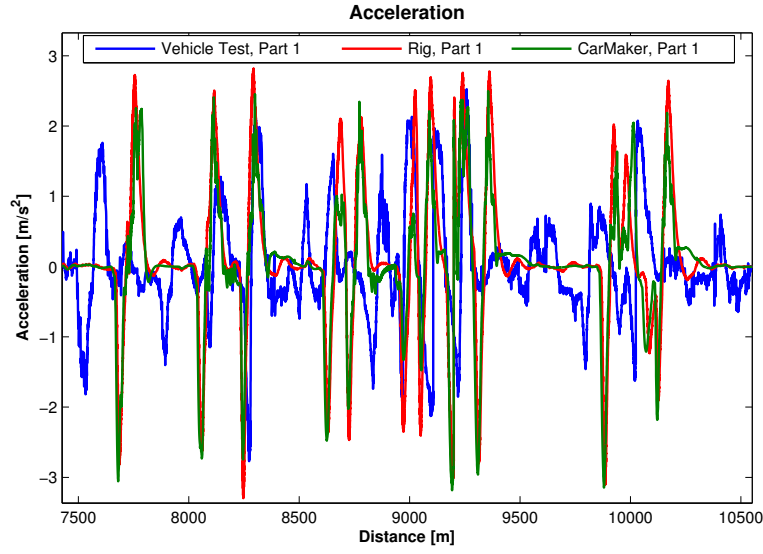
Figure 4.7: *Longitudinal acceleration in a segment of the first part of the city cycle, using XC90*

Revolutions in torque

In order to compare the torque distribution on the gearbox output shaft during the simulation, rig and vehicle tests, the amount of revolutions in different torque levels have been plotted and analyzed. By comparing the different data representations in Figure 4.8 one can see further proof of that the rig is more aggressive. This conclusion is drawn due to the domination of bars at torque levels above 3000 *Nm*. The vehicle tests and CarMaker simulations have much fewer revolutions at that torque level. The plot also shows in a good way the problems visualized in Figure 4.6b, that the rig has too few revolutions in the middle of the torque spectrum, from about 1000 - 2000 *Nm*, when using the same driver model as in CarMaker.
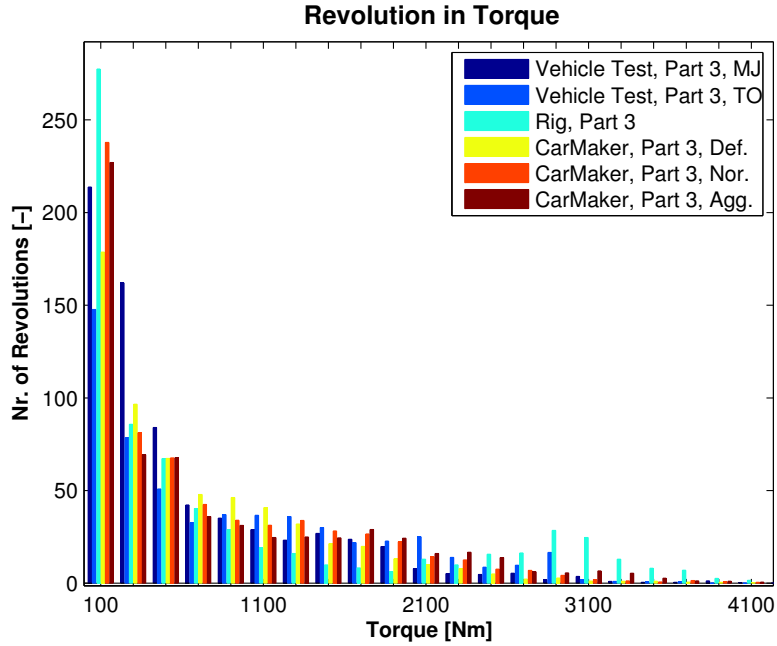
Figure 4.8: *Revolutions in torque, XC90 vehicles and models*

Driver aggressiveness

The results in terms of the developed key indicator DA, Equation 2.6 are interesting. Figure 4.9 shows results from simulations, rig and vehicle tests. There are three different CarMaker drivers, defensive, normal and aggressive and the DA value reflects their aggressiveness in a good way. There are also two vehicle tests, MJ is driven as a part of this thesis by the authors. The vehicle was driven as the drivers normally would drive a vehicle, which is estimated as a normal driver. The vehicle test called TO is driven by a test driver at Volvo Cars and is driven very aggressively. By comparing the vehicle tests, the difference in driver behavior is easily seen in the plot. The rig test however, is conducted with the same driver parameter set as the aggressive driver in CarMaker, which makes the results in the figure strengthen the hypothesis that the rig is to aggressive.
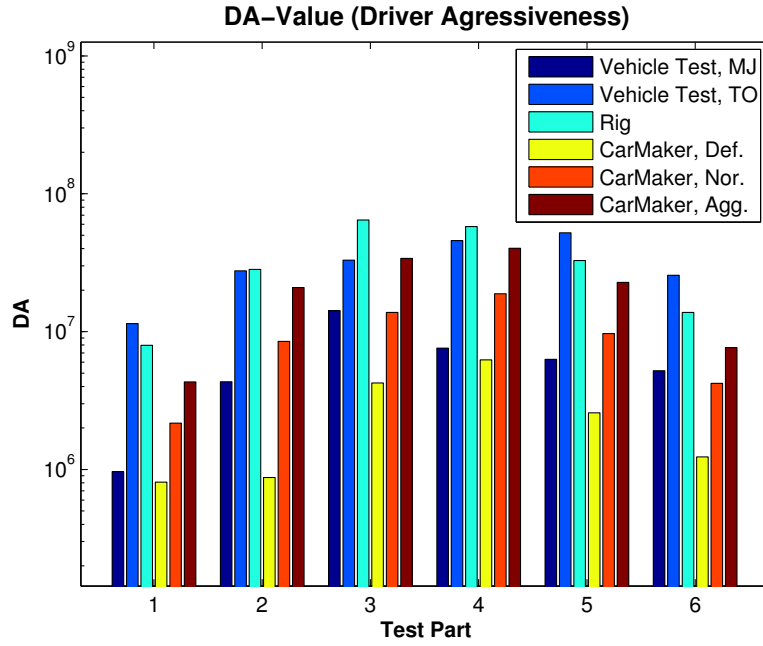

Figure 4.9: *Driver aggressiveness, XC90 vehicles and models*

Duty value

As stated in Section 2.8.1, the DA value is less connected to the mass of the vehicle than the Duty value, Equation 2.7. But since only XC90 vehicles and models are used to obtain the output in Figure 4.10 below, the mass is the same and therefore the plot look quite similar to Figure 4.9.
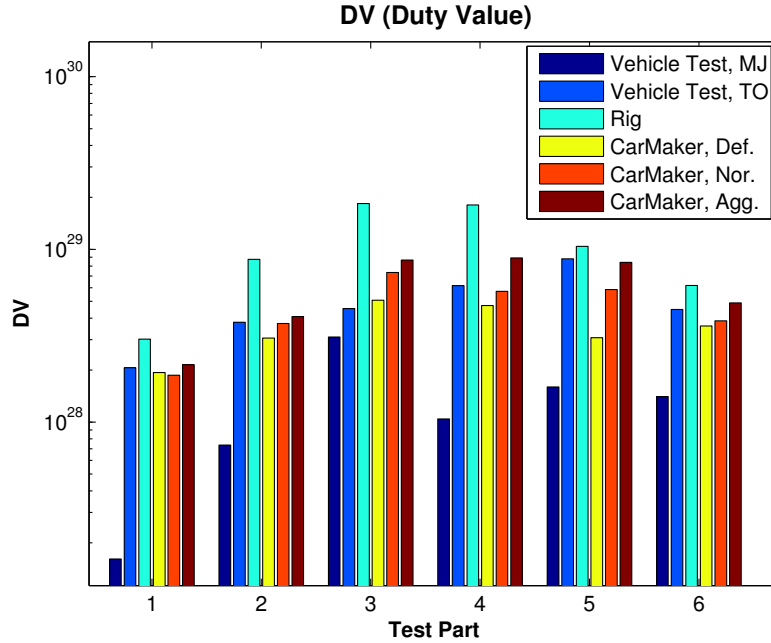

Figure 4.10: *Duty value, XC90 vehicles and models*

The Duty values for the different tests of the six parts of the Göteborg city cycle symbolizes the relative damage of the components. A high Duty value indicate that the components are more worn. The equality of configurations used in the tests leads to that the driver is, to a large extent, the reason for the difference in the Duty values. Noticeable is that the vehicle test called TO comes up to the same DV:s as the CarMaker simulations, while the vehicle test called MJ results in much lower DV value. This indicates how the difference in driver behavior affects the vehicle because the vehicle test with higher DV:s also felt remarkably more aggressive when executing the test. Also between the CarMaker simulations where different drivers were used, the resulting Duty values show that a more aggressive driver has a larger impact on the components than the defensive one.

5 Conclusions

To summarize the project, some main conclusions have been drawn. These are showing on how well the sub parts of the project have succeeded and which difficulties that have been faced and identified.

The road models generated in the project aimed to resemble a track in Göteborg city and a gravel road track, both used during vehicle testing at Volvo Cars. By using the software products and methods explained in this thesis, the generated road models showed a good representation of the real tracks, making them useful in future research and development.

The driver behavior modelling, which was the second topic of research, turned out to be more difficult to create and validate than the road models. Due to the diversity in behavior of different drivers, one simple parametrized driver model is not representative to use. Considering this, an approach could be to build up multiple load collectives, each consisting of simulations using drivers with different aggressiveness behavior, in order to resemble a whole population of costumers, this is further explained in Section 6, Recommendations.

The driver behavior model is regarded as a black box model since the underlying model is hidden and tuned through parameterization only. This limited the possible changes in the model and was regarded as a problem. The fact that the driver behavior model maintains the maximum acceleration as long as the velocity is to low, is one example of the problems that can not be fixed through parameterization of the black box model. If the model itself was possible to view and edit, a more profound understanding of the model would be available and through that it's functionality could be improved.

The analysis of the output data from the HIL rig showed that the rig behaved more aggressively considering accelerations than the simulations, which consequently impacts the transmission components. This was assumed to occur due to faults in the vehicle model used during simulations, which lead to the diversity of outcome. One reason for this is that the rig is using a outdated CarMaker software version, which meant that newer, more accurate, vehicle models were not compatible with the old version.

The developed and used validation methods in the project differed in their usability. Key indicators as Duty Value and Driver Aggressiveness Value are straight forward ways to investigate the impact of the transmissions components and how the driver has affected the vehicle. The MTF-value on the other hand did not give the validation of the road model as wished and expected. By that the conclusion can be drawn that it is possible to validate the created models, but it is of importance to choose the suitable tool considering what is the aim of the validation process.

The background for this project was the vision and goal of reaching a more effective and less costly research and development process at Volvo Cars. For the created models and research, the purpose was to provide help to achieve these aims at the transmission development department, within its work to ensure the connection between testing performed in vehicles, rig and simulations. The created road models which can be used on all these steps and the research done on the conditions considering modeling of driver behavior are useful steps on the way for further improvements of the research and development. Regarding the main question to be assessed during this thesis, whether simulation and rig testing can be a valid replacement for vehicle testing, a definite answer has not been reached. However, it shows great potential for a larger use of the methods in the future.

6 Recommendations

The research performed within the scope of this thesis is just a step on the way of improving the work with the discussed topics. Therefore, there are some recommendations below on future parts that should be investigated and performed.

In order to be up to date with the models and inputs to the rig and simulations, essentially the CarMaker inputs, effort should be made to always use the latest software. This would make it possible to use complete vehicle models of the latest version, which probably will improve the correlation between simulations and rig testing and in extension the accuracy when comparing with real vehicle testing.

Further, an available function in CarMaker is to use so called "Scripted" runs. The idea is that the engineer can create programming codes that automates the simulation process, instead of changing the input settings for each new simulation by hand. This would decrease the manual effort when a large set of simulations are to be performed, where for example the tracks or driver behavior differs.

Due to the difficulties with modelling driver behavior, as mentioned in the conclusions, a future approach to the problem could be to create simulation and rig load collective with several types of drivers. In this way a "human" driver could be successfully covered, but more research need to be done on the idea before realization. One way to do this might be by combining data sets from different driver parameter sets like the one shown in Figure 4.6b until the combination resembles the real one shown in Figure 4.6a. By addressing this as a purely mathematical problem, it might be easier to find the best solution. When doing so, the problem would even be possible to solve through optimization algorithms. One way to solve the problem could be to include an white box model of the driver behavior model, which could be altered. This way, the model would be easier to understand and tune in for optimal usage.

Another way to get a realistic driver behavior in CarMaker is to connect the software to a steering wheel and pedals. This way a real driver could control the vehicle in real time which would give a more realistic driver behavior. A potential problem with this approach is the decreasing repeatability.

As stated in Section 1.4, the traffic situation was not modeled. This could be a possible way to improve the models in the future to further make the them more realistic. The affect of traffic would be especially important to include in the urban parts of the cycle. If traffic is to be modeled, how and the purpose of it are crucial aspects, because the repeatability of the simulations might be decreased if the traffic for example is modeled as a stochastic process.

The last recommendation is to form a standardized procedure on how the rig is to be used in combination with simulations. If a continuous connection and correlation between the analysis of simulation and rig data is achieved, more and more of the developing and testing work can be moved to a virtual environment in the future.

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