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Vehicle dynamic models for virtual testing of autonomous trucks

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Abstract

The simulator in a testing environment for trucks is dependent on accurate vehicle dynamic models. There are multiple models at Volvo, all developed to support the objectives of individual research. A selection of four, named *Single Track model* (STM), *Global Simulation Platform* (GSP), *One-Track Model with linear slip* (OTM) and *Volvo Transport Model* (VTM), are evaluated to examine the usage of them. Four different scenarios are therefore generated to emulate common situations in traffic. Depending on the results, the models and their corresponding limits for usage are described. The evaluation is made by comparing all models to the best model for each scenario by measuring the normalized error distribution. It is shown that at certain thresholds, other models can perform close enough to the best model. In the end of the report, future improvements for the evaluated models and external models are suggested.

Acknowledgments

Endings often make us think about the beginning and therefore we would firstly like to express our gratitude to Volvo Technology AB for giving us the chance to conduct our master thesis in cooperation with you.

We would like to thank all the holders of the models, Niklas Fröjd (VTM), Per Nordqvist (STM) and Peter Nilsson (OTM), for having the patience and time to explain your models and supporting us during the thesis work. This thesis work would definitely not be the same without your replies to our dozens of last minute emails. We are especially thankful for our supervisor Per Nordqvist at Volvo for the unlimited support along the way. We would also like to thank Anders Holmström for pitching in and helping us to make the truck rollover.

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Contents

Notation

Abbreviation

Abbreviation	Meaning
AI	Artificial Intelligence
AEB	Automatic Emergency Braking
AVL	Anstalt für Verbrennungskraftmaschinen List
GSP	Global Simulation Platform
GPS	Global Positioning System
HIL	Hardware-in-the-Loop
KPI	Key Performance Indicator
LTR	Lateral Load Transfer Ratio
OTM	One-Track Model with linear tire slip
STM	Single Track Model
UDP	User Datagram Protocol
VTI	Statens Väg- och Transportforskningsinstitut
VTM	Volvo Transport Models

Model related notation

Notation	Meaning
a_y	Lateral acceleration
α	Slip angle
B	Stiffness, dimensionless coefficient
C	Shape, dimensionless coefficient
C_α	Cornering stiffness
D	Peak, dimensionless coefficient
δ_f	Steer angle of front tire
E	Curvature, dimensionless coefficient
f	Frequency
F_x	Longitudinal force, VTM
F_y	Lateral force, VTM
F_z	Load force, VTM
g	Gravity
κ	Slip ratio
L	Wheelbase
R	Turning radius
t	Time
v	Velocity of driving vehicle
v_{tire}	Velocity of orientation of tire
v_{wheel}	Velocity of wheel
v_0	Initial velocity
ψ	Yaw-rate, angular speed of z-axis, STM
v_i	Bin value, relative probability
c_i	Number of elements in the bin
N	Total number of elements in the input data
e	Error
v_{tbc}	Values of model to be compared
v_{pd}	Values of model with perfect data
G	Gain
δ_{amp}	Amplitude of the sinusoidal steering input
r_{amp}	Amplitude of the model outputs

1 Introduction

Autonomous vehicles and the development of such are a big topic of discussion nowadays. The development is going fast and the need for testing of the developed software is increasing in the same pace. Simulators are often used to avoid unnecessary waste of money and time to perform real tests on the field. Waymo [1], formerly the Google self-driving car project, does eight million miles in virtual reality every day in simulations. The simulator runs 24 hours a day on Google's data centers and there are 25,000 cars in the virtual fleet. Similarly, Audi AG owns a subsidiary with a fleet of test vehicles that are running an autonomous vehicle simulation platform [4]. Ultimately, in order to test the dynamic behaviour of a vehicle, one or more vehicle dynamics models are necessary to use in the simulator.

Volvo's development of AI systems for upcoming autonomous products is rapidly evolving. These AI systems will need to be heavily tested, especially in a closed-loop virtual environment, in order to guarantee safety and performance. There are multiple testing platforms for disposal; an in-house simulator, HIL(Hardware In the Loop) rigs and a 3rd party off-the-shelf software. The simulator used for testing is tied together with the AI system and fed with sensor data. Finally, the simulator receives control commands from the system. The importance of a fitting vehicle dynamics model is seen at this step, because the simulator needs to respond in a realistic way when it receives control commands from the system.

1.1 Motivation

Massive testing of autonomous vehicles in a virtual reality is of big interest from Volvo's point of view. In the aspect of hardware performance, a simpler vehicle model is required to speed up the execution. In the future, this simple model is desired to be the main model, which should be estimated to an usage of the vast majority of the entire simulation. But at the same time, it has to weight up against its' quality and how well it performs in different traffic situations, which is still unclear and has to be evaluated.

Currently, a complete vehicle dynamics model that models all the behaviour and dynamic of a real autonomous truck does not exist at Volvo. Complete in this sense means that the system should be able to respond to everything that the AI-system needs, i.e., throttle, brake, turn and reverse. However, there are a couple of models available that were created based on different purposes. Due to the field of research, different departments at Volvo have created specific models in order to test the main functionality that was of interest. Although those models are not complete enough, they have different strengths because of their different purpose.

As previously mentioned, there are four internal vehicle dynamics models available in total and those are not enough to model the real behaviour of the vehicle. They are either too simple, in a sense where only the simplified behaviour of the vehicle is reflected, too complex, leading to a long execution time or incomplete. The models are also not evaluated to the extent where it is known in which situations they are the most fitted to be used, to simulate and test autonomous trucks in a realistic sense. The motivation is therefore to carry out a study of the strengths and weaknesses of both the existing and external models in order to determine the most fitting model for different scenarios in traffic.

1.2 Purpose

The purpose of the thesis work is to perform an evaluation of already existing vehicle dynamic models. The models should be evaluated according to some testing criteria, which are not fully specified and have to be determined. Some of these criteria are predetermined (refer to Section 1.5), for example fidelity and performance of the models, but the evaluation of them are also to be established in the master thesis work. Furthermore, the models should be compared based on these to further specify the strengths and weaknesses of the corresponding models. Based on this information, it is possible to determine which model is the most fitting one for a specific scenario, in order to showcase the best usage of a model.

1.3 Problem formulation

The overall problem formulation is described with the following questions:

- ***What scenarios should be created in order to test the models properly?***
- ***How should fidelity be evaluated for each model?***
- ***What thresholds, as a result of changing the values of the model-parameters, can be found for the model behaviour in the various scenarios?***

1.4 Delimitations

Some delimitations are made throughout the master thesis work. The models evaluated must all have the following properties:

- The truck used is a 4x2 tractor (meaning it has 4 wheels and is driven by 2 of them) with a standard semitrailer with 3 axes, refer to Figure 1.1. This is the most common truck configuration.
- The truck is limited to a maximum speed of 80km/h. This is the speed limitation for the truck- trailer combination on highways.
- The mass of the truck is 8.5 tonne.
- Generated scenarios will focus on the truck itself, in other words, no interaction with other vehicles on the road.

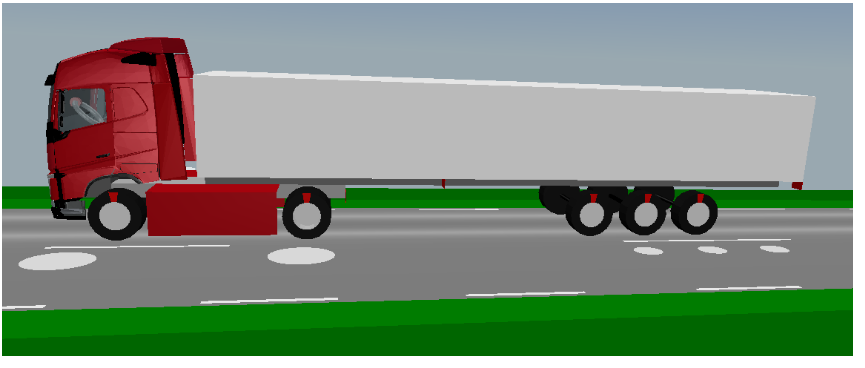

Figure 1.1: *Truck with a 4x2 tractor and a standard semitrailer with 3 axes.*

1.5 Testing criteria

The bullet points below are testing criteria (specified by Volvo), where the models should be tested against:

- **Fidelity** - describes how well the model agrees with the reality.

  This is to ensure that the out-coming result will be fair enough and to avoid properties of different computer that can give influence to the result.
- **Complexity** - parameter settings, i.e. the amount of parameters.
- **Re-usability** - when we switch truck configurations or update the vehicle dynamic models.

- **Pipeline** - the complexity of the way of working, for instance doing platform set-ups or modifying vehicle dynamic models.
- **Starting state** - research possibility of starting simulation when vehicle already has reached desired speed, for example initial speed $v \neq 0$.
- **Performance** - describes how fast each vehicle dynamics models executes in simulation.
- **Integration possibilities** - the possibility to integrate vehicle model into a simulator platform. This factor is categorized as last priority and will only be handled if the time allows.

1.6 Outline

The chapters of the remaining report will be presented with short explanations. The chapters following the first one will have the disposition as follows:

- **Chapter 2 - Models and Testing**
  Gives a description of different types of models that will be evaluated in the master thesis work. This chapter includes a description of each model.
- **Chapter 3 - Related research**
  Presents the outcome of the study of related research, e.g. modeling, testing of ADAS and so on.
- **Chapter 4 - Scenarios**
  Explains and motivates scenarios that are created.The different scenarios ran with the models are going to be described and the code used to implement them will also be featured, if possible.
- **Chapter 5 - Model evaluation**
  Describes the method that is used to evaluate the models. Descriptions of different thresholds that is out of interest as well as appropriate approach to find those thresholds for each scenarios are also available in this chapter.
- **Chapter 6 - Results**
  Presents the results from the simulations for each scenario plotted in graphs with the described strategy implemented.
- **Chapter 7 - Discussion**
  The results and insights from the master thesis work are discussed.
- **Chapter 8 - Conclusions & Future Work**
  The conclusions drawn from the master thesis work are summarized, the final "user-guide" to the models’ strengths and weaknesses and suggestions for future work are given.

1.7 Approach

This section describes the methodology and working process of the thesis work. The work is structured up into several different phases, which is shown as a block-diagram in Figure 1.2. Each specific phase is explained in detail below.

1. **Literature study and interviews**

   The working process begins with a study of the related research, where possible methods are reviewed. During this phase, the holders of each model were interviewed as well.

2. **Scenario creation**

   In order to perform model testing, some predefined traffic scenarios should be created. The approach for scenario creation is described in Section 4.

3. **Scenario implementation**

   An overview of the implementation of the predefined scenario should be done for each model in their simulator platform respectively. Continue with the next phase in the working structure if the implementation succeeds, otherwise skip the following phase and do the *Model evaluation* part directly.

4. **Model simulation**

   The same scenario should be simulated for each model. The final log data with the interesting parameters for the scenario will be selected and prepared for comparison of the models.

5. **Model evaluation**

   The models will be evaluated based on the approach described in Section 5 for each scenario.

6. **Future development**

   After some extensive research and familiarization with the models, the project will be put in a greater perspective and future improvements, as well as ideas, will be discussed.

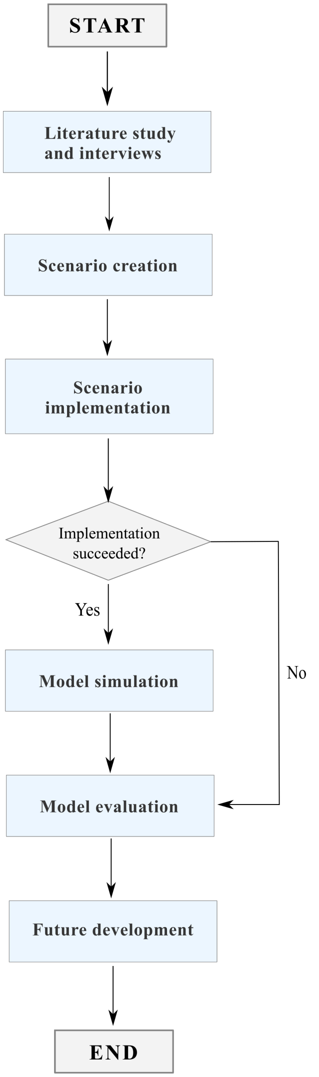

Figure 1.2: *The working process of the thesis work.*

2

Models and testing

In this chapter, the models are firstly brought into a bigger perspective where their function in the testing process is described, see Section 2.1. Later on, each model is individually described in depth in order for the reader to get an understanding of the internal qualities.

2.1 Overview of the testing process

Figure 2.1 shows a simplified description of how a testing process for an autonomous truck works. It also showcases where the thesis work comes in play. Explanation for each block of the figure can be found below.

- The entire testing process is controlled by a so-called **Conductor**, that is giving commands for instance to start the testing process, select and deliver unexpected scenarios to the test round. Today, the Conductor is a test engineer who is controlling the testing process manually.

- Once **DriveSim** (internal simulator) receives a start-command from the Conductor, it begins to load **3D-models**, i.e., vehicles, map of terrain, roads etc. into the simulator. In other words, 3D-models are models that build up the testing environment. If a test is desired to be made on a specific kind of road, the model can be generated from **Road generation**.

- The dynamic part of the vehicle is given by **Vehicle dynamic models**. A more detailed description of each model is referred to Section 2.3. Currently, the only dynamic model that has been integrated to DriveSim is the internal model, *Single truck model*.
  In the future, Volvo has an idea to additionally integrate the remaining

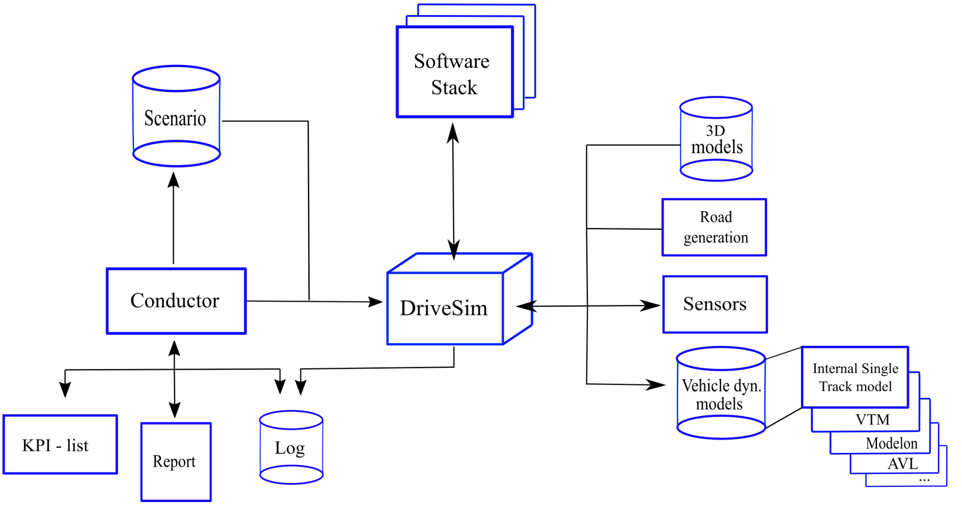

Figure 2.1: *Testing process*

models, displayed in the Figure 2.1, into the simulation platform (not necessarily to DriveSim, other platforms are also an option). The main idea is to present the possibility of interchanging models into the simulation platform. Since it is not clear what kind of traffic scenario (braking, turning etc.) the truck will end up in, it is assumed that a simple and less complex model is enough. Once a new scenario comes up and the current model is not good enough to handle this kind of situation, the model will be replaced by another stronger model in that field.

To solve this kind of problem, in-depth research regarding the vehicle models firstly has to be done, and here is where this thesis work comes in play.

- The truck which is going to be tested is equipped with different types of virtual **sensors** such as camera, LIDAR, radar and GPS. DriveSim delivers the out-going sensor data as input to the main computational unit, which is denoted as **Software Stack** in the figure, and responds with control commands such as steering, accelerating or braking.

- The block **Scenarios** is a database with different scenarios. Some conceivable scenarios that can emerge in traffic can be sudden braking, cornering and driving on icy road. To test how well the present Software stack is handling cases occurring in traffic, the Conductor chooses one of the scenarios depending on the result of previous outcome.

- When a test round is done, data of parameters are going to be saved in a **Log**. It is also here where the Conductor gets the data for evaluation. Based on the testing logs and **KPI**, *Key Performance Indicator*, a performance measurement of the test, a summary of the test is created as a **Report**. According to the result of the report, the Conductor makes a decision of which scenario should be executed in the next test round. And here is where the loop of testing is closed.

2.2 Vehicle dynamic models

Volvo currently suggests four internal vehicle dynamic models to be tested: one high fidelity model named *Volvo Transport Model* (VTM), described in Section 2.2.4 and two less complex models, *Single-Track Model* (STM), Section 2.2.1, and *One-Track model with linear tire slip* (OTM) described in Section 2.2.2. The last model is called GSP, which stands for *Global Simulation Platform*, and only describes and models the powertrain, see Section 2.2.3. The models are not to be considered to be equal, but instead to be treated as models with different qualities and complexion. The models that should be evaluated will be described in the following subsections.

2.2.1 STM

Single-Track Model (STM) is one of Volvo's internal vehicle dynamic models. The model is created in the programming language C++ and is integrated into their in-house simulator, named DriveSim.

The dynamics of the entire truck is divided into two parts; a tractor and a trailer, and those parts are modelled separately. The tractor represents the master of the truck and is modelled according to a *single-track model*. A single-track model, also called the bicycle model, is a simplified vehicle model where the front and the rear wheels are described by only one single front and rear wheel respectively, assuming that the wheels are equivalent to each other and connected by a body of vehicle[20]. As shown in Figure 2.2, the geometry of the tractor is defined as a front and a rear wheel, separated by a wheelbase L.

The direction of motion is determined by the steer angle of the front wheel δ_f, relative to the heading of the tractor body.
δ_f is directly proportional to the steering wheel angle and they are related by:

$$\delta_f = \frac{steering\ wheel\ angle}{STEER\_RATIO} \tag{2.1}$$

where STEER_RATIO is a predefined constant. Based on geometrical calculations, the model will handle lateral dynamics by calculating the yaw rate as:

$$\psi = \frac{v}{R} \tag{2.2}$$

where v is the velocity of the moving tractor and R is the turning radius, which is defined as:

$$R = \frac{L}{sin(\delta_f)} \tag{2.3}$$

However, both the lateral and longitudinal dynamics of this model are kinematic, which means that the position of motion is not affected by any forces and

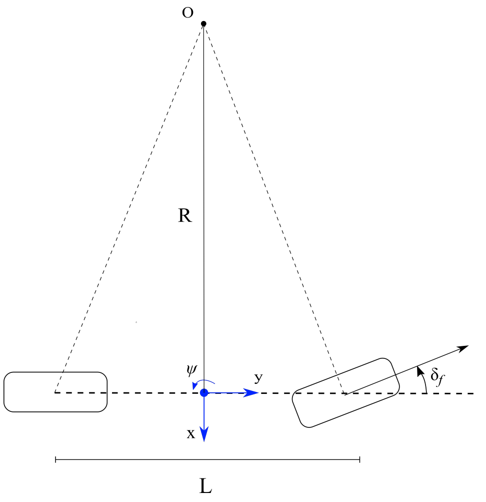

Figure 2.2: *Single Track model.*

is computed as function of time. With other words, phenomenons as slip will not appear in the simulation, since parameters as vehicle mass and forces of any kind are not available in this model. Despite that, the model provides a functional gearbox with twelve gears. The magnitude of the acceleration for up- and down-shifting is further calculated based on a mass equivalent that accounts for the vehicle mass and drive-line, all for the purpose of obtaining a propulsive dynamics.

Figure 2.3 shows the axis system which the truck is modeled in. The axis x, y and z are positive in the order of right, forward and upwards respectively.

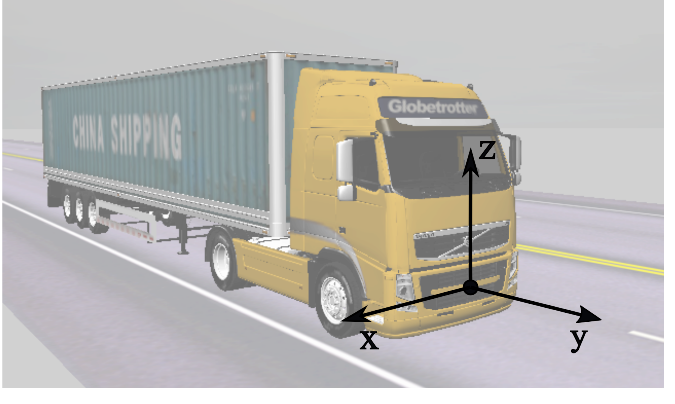

Figure 2.3: *The axis system of the STM.*

When the tractor is towing a trailer, the interaction between them are modeled in three main steps that are described below in Figure 2.4.

1. Assume that the entire truck is going to move forward in the next time step. Firstly, the tractor is moving forward to the next position.
2. The trailer rotates with a **differential angle** along the trailer origin toward a target point located on the tractor. The target point is called the **master fifth wheel**, which is the point where the trailer is going to be connected. The origin of the trailer is set on the second rear wheel axle.
3. The distance between the connection points, **kingpin** and the fifth wheel is calculated and the trailer moves forward and connects to the tractor.

This approach is also applicable for reverse maneuvers.

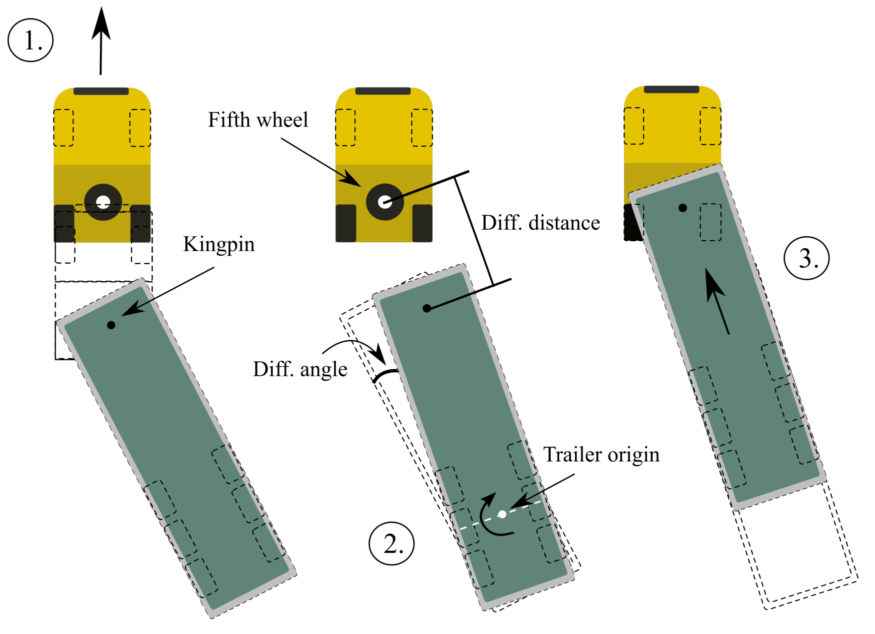

Figure 2.4: *Interaction between tractor and trailer unit divided in three steps.*

2.2.2 OTM

An additional model that describes the dynamic of the vehicle as a single-track model, mentioned in Section 2.2.1, is called OTM and stands for *One-track model with linear tire slip*. In contrast to STM, OTM is a dynamic model and is written as well as modeled in MATLAB®. The model is not integrated to any simulator, which means that no graphic animations are available in the scope of simulation.

To describe the model mathematically easier, the *Newton* formalism is used to derive the equations of motion. Another advantage is that the coupling forces between the vehicle units are clearly represented. The equations of motion for the first vehicle unit have the following appearance and all the including parameters and variables can be found in Figure 2.5. The Eqs. (2.4) and (2.5) express the longitudinal and lateral motions in X and Y axis respectively and Eq. (2.6) the rotational part of motion in the XY-plane.

$$\begin{aligned} m_1(\dot{v}_{Xv1} - \dot{\Psi}_1 \cdot v_{Yv1}) &= F_{Xw12} + F_{Xw11} \cdot \cos(\delta_{11}) - F_{Yw11} \cdot \sin(\delta_{11}) \\ &\quad + F_{Xc1} \cdot \cos(\Psi_1) + F_{Yc1} \cdot \sin(\Psi_1) \end{aligned} \tag{2.4}$$

$$\begin{aligned} m_1(\dot{v}_{Yv1} + \dot{\Psi}_1 \cdot v_{Xv1}) &= F_{Yw12} + F_{Xw11} \cdot \sin(\delta_{11}) + F_{Yw11} \cdot \cos(\delta_{11}) \\ &\quad - F_{Xc1} \cdot \sin(\Psi_1) + F_{Yc1} \cdot \cos(\Psi_1) \end{aligned} \tag{2.5}$$

$$\begin{aligned} -I_{ZZ_1} \cdot \ddot{\Psi}_1 &= F_{Yw12} \cdot l_{12} + (-F_{Xc1} \cdot \sin(\Psi_1) + F_{Yc1} \cdot \cos(\Psi_1)) \cdot l_{1_{c1}} \\ &\quad - (F_{Xw11} \cdot \sin(\delta_{11}) + F_{Yw11} \cdot \cos(\delta_{11})) \cdot l_{11} \end{aligned} \tag{2.6}$$

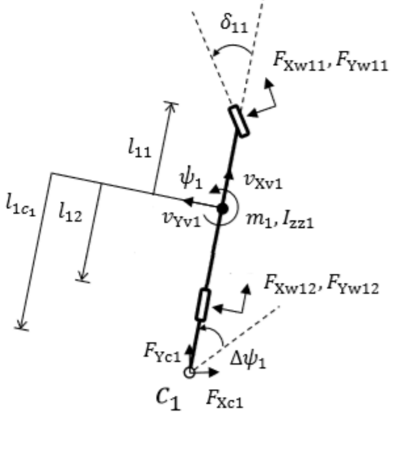

Figure 2.5: *Illustration of the first vehicle unit of OTM [14].*

m_1 is the mass, I_{ZZ1} is the moment of inertia, l_{11}, l_{12}, l_{1c_1} are the lengths measured from the center of gravity to the front, rear wheel axis and the articulation point c_1 (where the tractor and trailer are connected), F_{Xw11}, F_{Yw11} and F_{Xw12}, F_{Yw12} are the longitudinal and lateral forces acting on the front and rear tires, respectively, and v_{Xv1}, v_{Yv1} are the velocities in lateral and longitudinal motion. Finally, the steering angle of the front wheel is expressed as δ_{11}.

Corresponding equations of motion for the trailer, the second unit, are expressed by Eqs. (2.7), (2.8) and (2.9):

$$\begin{aligned} m_2(\dot{v}_{Xv2} - \dot{\Psi}_2 \cdot v_{Yv2}) = {} & F_{Xw21} + F_{Xw22} + F_{Xw23} \\ & - F_{Xc1} \cdot \cos(\Psi_2) - F_{Yc1} \cdot \sin(\Psi_2) \end{aligned} \tag{2.7}$$

$$\begin{aligned} m_2(\dot{v}_{Yv2} + \dot{\Psi}_2 \cdot v_{Xv2}) = {} & F_{Yw21} + F_{Yw22} + F_{Yw23} \\ & + F_{Xc1} \cdot \sin(\Psi_2) - F_{Yc1} \cdot \cos(\Psi_2) \end{aligned} \tag{2.8}$$

$$\begin{aligned} -I_{ZZ_2} \cdot \ddot{\Psi}_2 = {} & F_{Yw21} \cdot l_{21} + F_{Yw22} \cdot l_{22} + F_{Yw23} \cdot l_{23} \\ & - (F_{Xc1} \cdot \sin(\Psi_2) - F_{Yc1} \cdot \cos(\Psi_2)) \cdot l_{2_{c1}} \end{aligned} \tag{2.9}$$

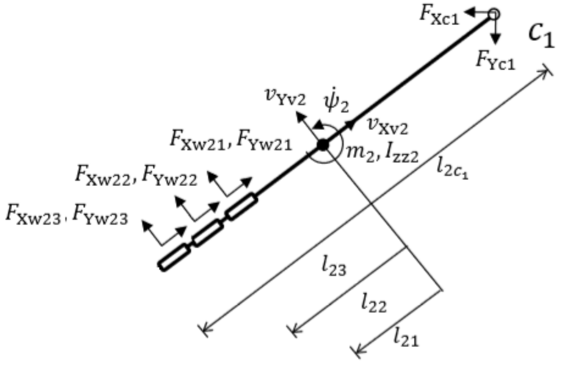

Figure 2.6: *Illustration of the second vehicle unit of OTM [14].*

For a similar description of the parameters and variables used in the second unit, refer to the first unit [14].

As the name of the model explains, OTM models the dynamics of the wheels linearly and the lateral tire force for each wheel is expressed according to the following equation:

$$F_{Y,ij} = -C_{\alpha,ij} \cdot \alpha_{ij} \tag{2.10}$$

where α is the slip angle, C_α is the cornering stiffness and the index i specifies the i:th vehicle unit and j the j:th wheel of the i:th vehicle unit. On the other hand, it can neither accelerate nor brake since no powertrain or braking system is implemented to this model at present.

2.2.3 GSP

GSP is an abbreviation for *Global Simulation Platform*, which is a vehicle model that describes a complete powertrain. The GSP model is not capable to operate by itself, but has to be supported by another model that models the dynamics of vehicle fairly complete. The existing GSP model is currently integrated with the STM model and is simulated in their in-house simulator DriveSim. Figure 2.7 shows a simple illustration of how GSP is integrated to the simulator that originally consist of the STM model, as well as in- and outputs that are sending between GSP and the simulator. Through an *User Datagram Protocol* (UDP), signals as throttle, gear, brake and inclination on the road are sent as input signals to the GSP model. As response from GSP, the simulator will receive signals as engine speed in rpm, fuel consumption and vehicle speed.

The model is modeled in Simulink but is, however, not visible for the user. In other words, this model can be seen as a blackbox, where only in- and outputs are known, as previously described. Therefore, any detailed information of how the model is structured or modeled is unknown for this model. By contrast, GSP shows characteristic of the physical internal trucks, where part of the model is created using specific components made by Volvo themselves.

Additionally, the speed vector of the model has a dimension of one, which reflects that it is adjusted for straight maneuvers only. The main purpose of developing GSP was for fuel economy evaluations. The model is also equipped with a complete gearbox that performs a realistic dynamic of gear shifting. The model describes the entire system as a single mass only and with no regards to the number of connected trailers.

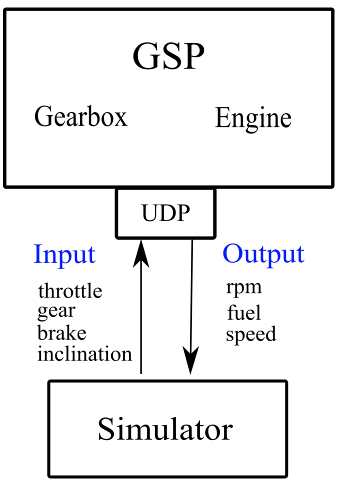

Figure 2.7: *Illustration of how GSP is integrated to the in-house simulator DriveSim, as well as communication signals that are used in between.*

2.2.4 VTM

VTM stands for *Volvo Transport Models*. The model is made in Simulink and parameterized using MATLAB® variables through m-files. The simulation of the model is performed in *Simscape Multibody*™, formerly SimMechanics™, which is a multibody simulation environment for 3D mechanical systems [10]. VTM has been used in multiple projects, for example in various research projects with automatic steering control for the Swedish state research institute for road and transportation (VTI).
The VTM plant model was developed by the chassi and handling department, hence it contains chassis, wheels, tires and suspension. However, there is no powertrain and there are no controllers, [2].

2.2.4.1 Truck and trailer definition

The model contains definitions of both the truck and the trailer, separately. The model chosen from the VTM library depends on the desired tire configurations. The entire truck is modeled with regards to the ISO 8855 convention for axis systems. [3] The simulation environment contains the definition for gravity, refer to Figure 2.8. [2]

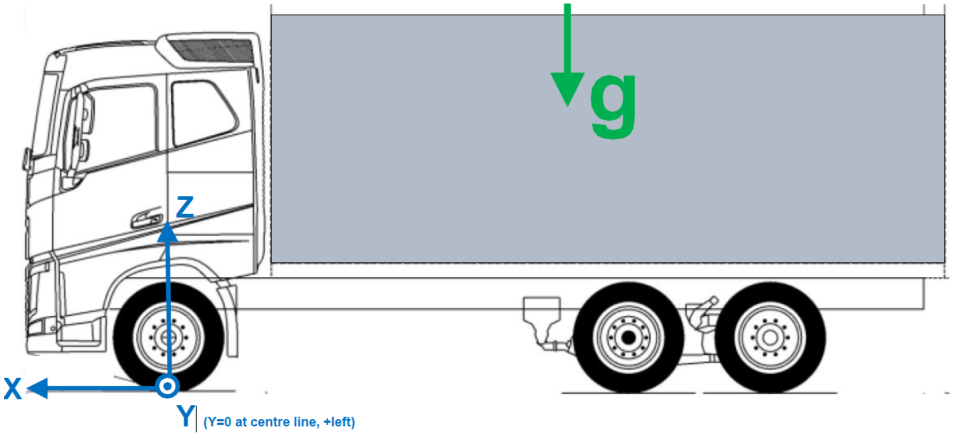

Figure 2.8: *The axis system of the truck according to ISO 8855. Additionally, gravity is defined,[2].*

The rear part of the frame and the payload is lumped into one rigid body with a mass, inertia properties and the location of the centre of gravity. See Figure 2.9 for the definition of trailer, [2].

The trailer, including all other bodies defined, have node positions defined for connection to other bodies or as sensor points (points of interest). One of the node positions connects the rear part with the front part of the chassis, the engine and the gearbox. These parts are lumped into one rigid body. Furthermore, the cab and the axles are also modeled individually as rigid bodies suspended to neighbour bodies, refer to Figure 2.10, [2].

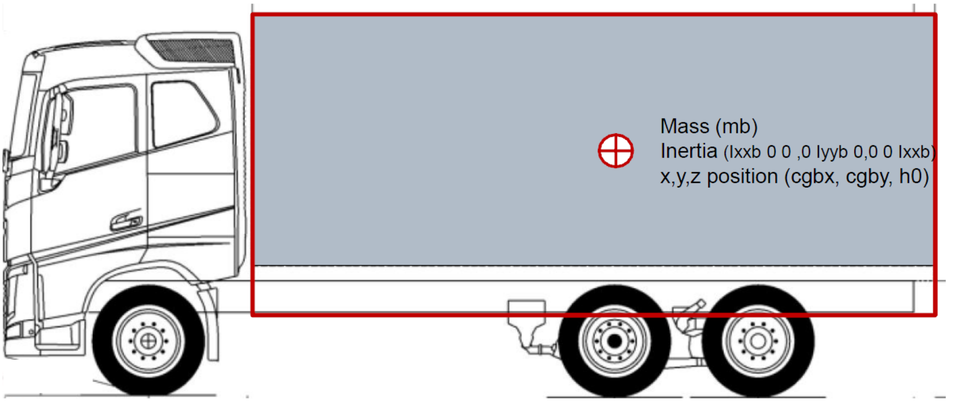

Figure 2.9: *Trailer denoted with mass, inertia and centre of gravity, [2].*

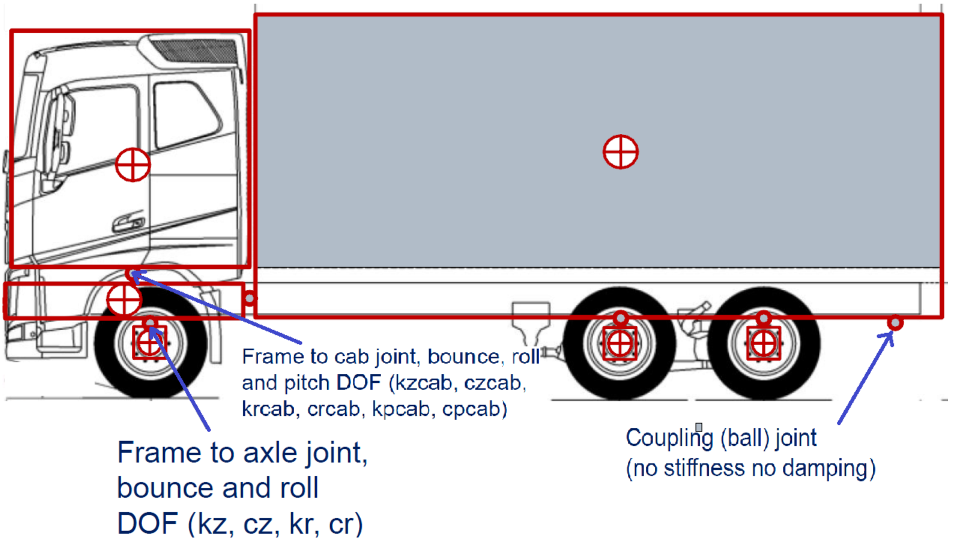

Figure 2.10: *The bodies and the joints that tie them together, [2].*

2.2.4.2 Tire definition

The steering axles are dynamic systems with wheels that have a turning inertia for steering and kingpin damping, as seen in Figure 2.11. The right and left wheel have a stiff mapped connection between them.

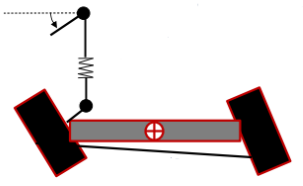

Figure 2.11: Visualization of the steering axles.

The wheel rotation, the lateral and longitudinal tire properties are modeled as Simulink S-functions, [2].
Pacejka's magic formula tire model is used to model the behaviour of the tires. The magic formula is an empirical equation that describes the interaction between the road pavement and the tires. As a result from the contact, a longitudinal force arises. The longitudinal force F_x, refer to Figure 2.12, is given by the magic formula, [8].

Figure 2.12: The forces on the tire used in Pacejka's magic formula,[8].

The longitudinal force F_x is exerted on the tire at the contact point. Furthermore, F_x represents a steady-state tire characteristic function $f(\kappa, F_z)$ of the tire, as defined below.

$$F_x = f(\kappa, F_z) \tag{2.11}$$

where F_z is the vertical load, [8].
The slip ratio κ is defined as tire slipping with respect to the road along the

longitudinal direction, as seen in (2.12).

$$\kappa = \frac{v_{vehicle} - v_{wheel}}{v_{vehicle}} \cdot 100 \quad [\%] \tag{2.12}$$

where $v_{vehicle}$ is the longitudinal velocity of the vehicle and $v_{wheel} = r\omega$, r is the radius of the tire and ω is the angular velocity of the wheel, [6].
The complete magic formula, with constant coefficients, is given below.

$$F_x = f(\kappa, F_z) = F_z \cdot D \cdot \sin(C \cdot \arctan\{B\kappa - E[B\kappa - \arctan(B\kappa)]\}) \tag{2.13}$$

where B, C, D and E are dimensionless coefficients standing for stiffness, shape, peak, and curvature, respectively. Figure 2.13 shows the longitudinal force F_x with varying κ, [8].

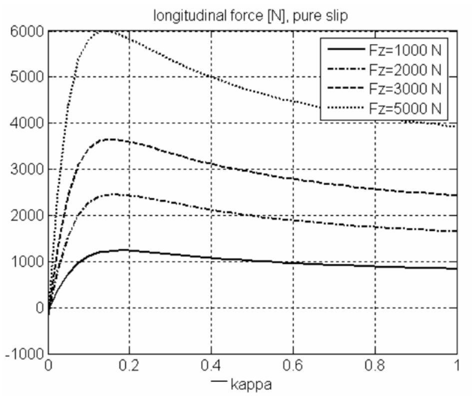

Figure 2.13: *The longitudinal force F_x with varying κ, [16].*

In order to calculate the lateral force, F_y, the same function as Formula (2.13) is used with the exception that slip ratio κ is exchanged to slip angle α, see the formula below.

$$F_y = f(\alpha, F_z) = F_z \cdot D \cdot \sin(C \cdot \arctan\{B\alpha - E[B\alpha - \arctan(B\alpha)]\}) \tag{2.14}$$

The slip angle α of a tire is described as the angle between the orientation of the tire with velocity v_{tire} and the orientation of the velocity vector v_{wheel} of the wheel, see Equation (2.15), [20].

$$\alpha = \arctan \frac{v_{tire}}{v_{wheel}} \tag{2.15}$$

2.2.4.3 Modeling in Simulink

The model in Simulink is built in different levels, see Figure 2.14. There is a top level with the inputs and outputs to the system. The next level is within the top level and contains multiple subsystems with different functionality. When creating scenarios, the modeling is usually made in the top model using the inputs and outputs of the system [2].

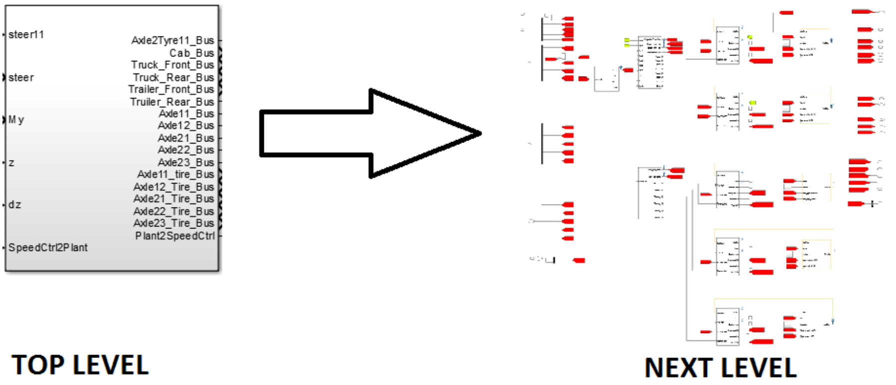

Figure 2.14: *Structure of the VTM model in Simulink with different levels, [2].*

3
Related Research

3.1 Testing

It is important to be aware of the basic concepts and methods that come along with the testing process. Such information, specifically model-based testing, is treated in [19]. Besides from the basic definitions in testing, along with general testing practices and techniques, the testing process for model based testing is defined. The testing process is divided in three steps: designing the test cases, executing the tests and analyzing the results and verify how the tests cover the requirements. When designing the test cases, it is said in [19] that each test should be defined by a test context, a scenario and some pass/fail criteria. Furthermore, the authors of the book define a script-based testing process, which will be of great importance since many of the models, for example the internal single track model, will be tested by writing scripts.

3.2 Comparison of models

The book [12] describes methods for analyzing data and designing experiments in the context of comparing models with each other, which is exactly what is needed in our master thesis work in order to present solutions for our problem formulations. The book begins with describing validity in a more general sense as the correspondence between a proposition describing how things work in the world and how they really work. In our master thesis work, this can for example be translated to comparing the data from field with the data induced from the models. Furthermore, the book suggests that four types of validity can be distinguished: statistical conclusion validity, internal validity, construct validity and external validity. The author of the book goes on with describing each of these more thorough. Clearly, this book can be used as a precious source for information within the subjects of interest.

The thesis work puts a great amount of importance on testing and therefore it is of interest to investigate different ways and scenarios for testing. The master thesis report in [15] describes the development and validation of two models of Volvo FH16 (tractor) and XC90 (passenger car). Each model has a simple model (single-track model) and advanced model(additional degrees of freedom). The simple and advanced vehicle models of the test vehicles are validated against experimental data and compared to each other. This is pretty similar to the relation of two of the models to be tested in this master thesis work, where the internal single track model is a rather simple model and the VTM model is rather advanced. In one of the tests in [15], the FH16 is tested to change lanes with both models and finally compared with each other and the log data by looking at the normalized error distribution of distance, velocity and acceleration. This research not only inspires to the construction of different scenarios that are relevant for testing, but also showcase approaches for comparing different models to each other.

The paper [18] is another research which describes how three different models handle seven different ground types (snow, ice, wet and dry asphalt, wet and dry gravel and dry concrete). Later on, a comparison is made between the three force models of wheel-ground contact in vehicle dynamics. The first model (known as Kiencke's tire model) is analytical, as well as the second one (known as Ben Amar's tire model) but with added geometric and dynamics characteristics of the vehicle. Additionally, Pajecka's empirical model, called the magic formula is observed in the research. The methodology for comparison of the models is of special interest for the master thesis work. Firstly, the forces for the seven road types are generated over the plan for each and every one of the models. Next step was to directly compare Kiencke's model with Amar's and finally with Pacejka's, by studying errors by direct difference and statistical error. However, it is worth noting that all of the simulations in [18] are made in MATLAB, which will not be the case for the models in the master thesis work.

One of problems to be solved in this master thesis is to determine accuracy, as well as the selection of models based on for instance accuracy. In the publication [5], different accuracy estimation methods are reviewed. Cross-validation and bootstrap are the two most common methods used for accuracy estimation and these are compared in the publication [5]. The study is made by conducting a large-scale experiment which in turn is based on a data-set D that is split into k mutually exclusive subsets (folds) $D_1, D_2, ..., D_k$ with approximately equal size. The result of the study shows that ten-fold stratified cross validation is the best method to use for model selection, in the case when real world data-sets are used.

3.3 Scenario generation

Since a part of the thesis work is to determine scenarios for model testing, it is of great importance to investigate different conditions of the road. In [13] the behavior of a vehicle in a time-critical maneuver under varying road conditions, e.g., dry asphalt and snow, is studied. Furthermore, the vehicle dynamics is modeled with an extended single-track model together with a wheel model and a Magic Formula tire model. This research will probably be of use since it resembles some of the models that are to be reviewed in this master thesis work and simultaneously suggests scenarios of this nature.

As previously stated, in [18] additional road conditions are used as scenarios, i.e., ice, wet asphalt, wet and dry gravel and dry concrete. Different road conditions are commonly used as scenarios and therefore relevant to this master thesis work.

Rollover is a common accident that truck drivers want to avoid when maneuvering on the road. According to [7], trucks have a bigger tendency to rollover, as opposed to light duty vehicles, since they have a higher center of gravity. Thus, while executing the testing process of the thesis work, it will be of great interest to know how well each vehicle models will handle situations where the truck is prone to rollover, or if the models would take rollovers in consideration at all. To determine the risk of a rollover, [7] proposes to analyze so-called rollover indices. Lateral load transfer ratio (LTR) and lateral acceleration, a_y were two rollover indices that were chosen for analyzing in that paper. Furthermore, two different maneuvers proper for testing rollover were also represented, which probably will be of use when creating scenarios for testing in this thesis work.

As [17] stated, rear-end collision is another common accident where heavy trucks are involved. Automatic Emergency Braking (AEB) system is therefore significantly important when it is about mitigating or avoiding frontal collisions. In this paper, testing and evaluation of heavy vehicle Automatic Emergency Braking (AEB) system were done in HiL (Hardware-in-the-Loop) system, which allows expansion of testing and even more aggressive scenarios that will be dangerous when testing it on reality. “Slower-moving lead vehicle” scenario and “Decelerating lead vehicle” scenario were two heavy vehicle crash scenarios that were tested in that research. For more details about the HiL setup or the validation testes between the experimental and HiL truck can be referred to [17].

4

Scenarios

In this chapter, the scenarios are created with code and modeling in the respective models. The models will be evaluated by testing how they react to different scenarios. The traffic scenarios will be created based on the strengths of each vehicle model, as well as scenarios that commonly occur in traffic. The list below is an overview of which field of maneuvers each model's strengths lays in and a detailed description of each scenario can be found in the subsections bellow.

- GSP - Acceleration and deceleration
- VTM - Lane change, sinusoidal manoeuvring
- VTM - Steady-state cornering
- GSP - Uphill driving

4.1 Scenario 1 - Acceleration and deceleration test

The first scenario is created based on the most simple, as well as common maneuver in the traffic, which is driving straight ahead on a flat paved road. This scenario will both test the dynamics of how a model handles acceleration and deceleration when full throttle and braking is applied respectively. An illustration of Scenario 1 is shown in Figure 4.1 and the exact instruction is as follows:

- Start the vehicle from standstill, $v_0 = 0 km/h$
- Accelerate to $v_1 = 80 km/h$ with full throttle
- Apply full brake until the vehicle reaches standstill, $v_2 = 0 km/h$

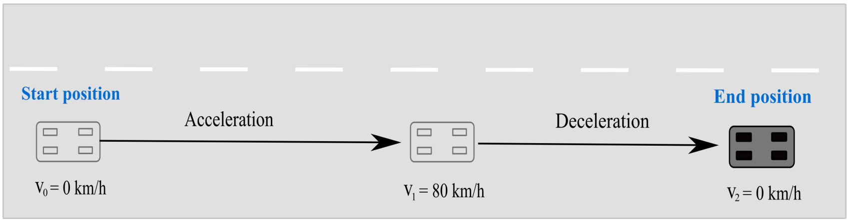

Figure 4.1: *Illustration of Scenario 1 - Acceleration and deceleration test.*

4.2 Scenario 2 - Sinusoidal maneuvering test

In order to investigate how well a vehicle evades a suddenly appearing obstacle, a sinusoidal maneuvering will be an adequate test to perform. Finding thresholds for when a specific model gives rise to skid will be of great interest to investigate in this scenario. The instruction of the scenario is as follows, (see Figure 4.2):

- Start the vehicle from $v_0 = 80km/h$
- Apply a sinusoidal maneuver and start with an amplitude of 2 and a frequency $f = 0.3Hz$ for the steering wheel. Keep the speed constant during the whole test, $v_1 = 80km/h$
- Repeat the test and vary the frequency of the steering wheel and/or the amplitude to reach same driving path as the other models.

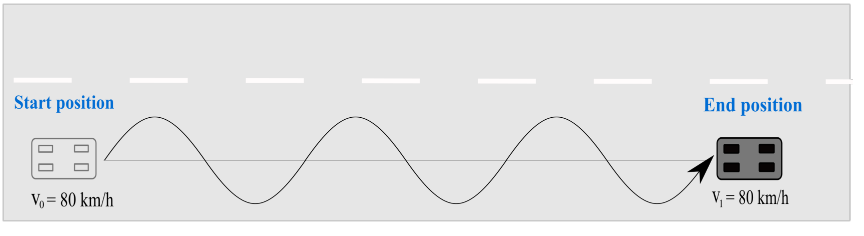

Figure 4.2: *Illustration of Scenario 2 - Sinusoidal maneuvering test.*

4.3 Scenario 3 - Steady-state cornering test

Since large vehicles as a truck has high center of gravity, it tends to have a bigger chance to rollover compared to light private cars when doing sharp turns. Therefore, this scenario will investigate each models capability of handling turns, as well as finding relevant thresholds to avoid rollovers. The third scenario basically tests what was described above. To find those thresholds, this scenario will be tested according to a *constant radius test*, depicted in Figure 4.3:

- Drive in a circle with velocity V_1 and keep the turning radius R constant
- Increase the velocity gradually and find the threshold for rollover

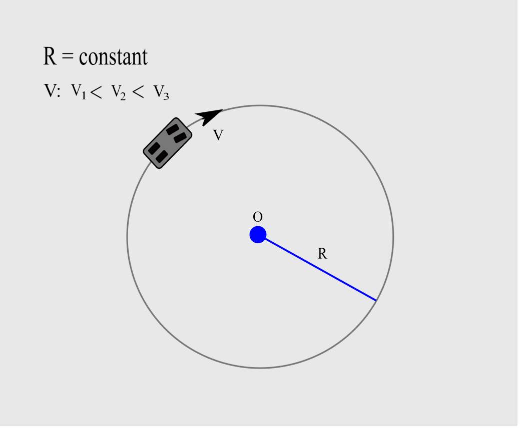

Figure 4.3: *Illustration of Scenario 3 - Steady-state cornering test with constant turning radius.*

4.4 Scenario 4 - Uphill driving test

Except for driving on flat horizontal roads, a vehicle should also be able to handle slopes with varying inclinations. This applies especially to uphills where the vehicle should keep driving upwards and not roll back. The fourth scenario will therefore test how each model handles uphills, shown in Figure 4.4.

- Start the vehicle from standstill, $v_0 = 0km/h$, in the beginning of an uphill with an inclination measured in percent (%)
- Apply full throttle and accelerate until the velocity reaches $v_1 = 80km/h$

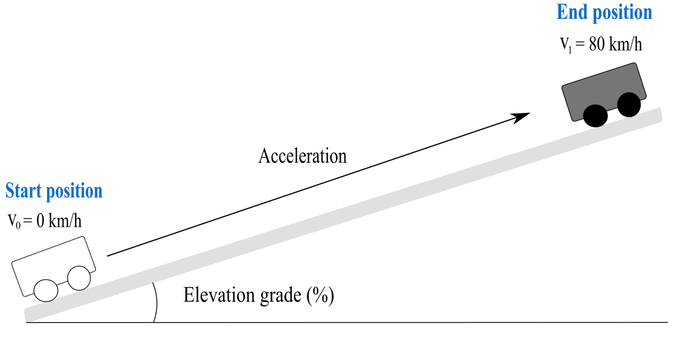

Figure 4.4: *Illustration of Scenario 4 - Uphill driving test.*

5

Model evaluation

This chapter describes the methods used to evaluate the performance of the models, in comparison to each other as well as the existing thresholds.

5.1 Model comparison

The models that are evaluated need to be compared to each other with reliable methods using the accessible information. Since an ideal vehicle model is not available (that can be used as reference model for comparisons), the following approach is applied instead. Assuming that the strengths of each model are given from the model creators, the performance of a specific model is evaluated by comparing it with the model that is the best within that field. For example, to know how well the STM performed during the sinusoidal maneuvering scenario, a comparison was made with the VTM model, since it is given that it is excellent in doing sinusoidal maneuvering.

Normalized error distribution is used as a method to compare the models with each other in this paper, as well as in several other papers, refer to Section 3.2. With the use of normalized error distribution, it is possible to determine the amount of data from which a model differs from the best model that it is compared to.
The normalized error distribution is generated in MATLAB with probability as the chosen distribution. The data of the histogram is grouped into multiple bars, so-called bins. The bin values are calculated according to the following equation.

$$v_i = \frac{c_i}{N} \tag{5.1}$$

Equation (5.1) is known as relative probability, where v_i is the bin value, c_i the number of elements in the bin and N is the total number of elements in the input data. Consequently, the sum of the bar heights is equal to 1. The data is sorted into the appropriate bin with the corresponding error magnitude, given in the fitting unit. The error is calculated in the equation below.

$$e = v_{tbc} - v_{pd} \tag{5.2}$$

The error e in (5.2) is calculated by comparing the values of v_{tbc} with the values of v_{pd}, where v_{tbc} are the values of the model to be compared with the values v_{pd} of the model which is considered to have the perfect data.

5.2 Thresholds

The performance of the models is likely to be different when the parameters are changed. Therefore, it is important to examine the thresholds of a certain behaviour, e.g., when a certain behaviour is transferred into another behaviour. This is furthermore important when determining which model is the most fitting to use in a scenario, since this changes along with the values of the parameters. In this thesis work, four different thresholds will be examined and those are:

1. Threshold of when the error between the strongest model in respective scenario and another model is as small as possible. The threshold is found when changing certain parameters, depending on the scenario, in the quest of finding the minimum error.

2. Threshold of when a certain behaviour for a specific model transfers into another behaviour, for instance when the truck goes from normal driving to rolling over during a corner maneuvering (see Section 5.2.3). The moment when the truck rolls over is the pivotal point.

3. Threshold of when the performance meets a specific limit predetermined by Volvo, e.g. find threshold for parameters or variables that affect the driving velocity with ±20% compared to the velocity driving on straight road with no inclination (see Section 5.2.4).

5.2.1 Scenario 1 - Acceleration and deceleration test

In the first scenario, the most simple function of a vehicle is tested, which is the ability to accelerate and decelerate. The approach is going to be that each model executes the same scenario described in Section 4.1 and then, the GSP model will be the reference model that the remaining models should be compared with. The aim is to find thresholds when the model error is as small as possible, which is referred to the first type of threshold described in Section 5.2. The searched thresholds is found by running the same test and gradually varying the constant driving speed until the models are look alike to GSP.

5.2.2 Scenario 2 - Sinusoidal maneuvering test

In this scenario, all models are compared to VTM, since it is known as the strongest model of doing maneuvers as sinusoidal. It will especially be out of interest to examine how similar a specific model is going to be in comparison with VTM. Therefore, the first and third type of threshold will be relevant to look up in this scenario, described in Section 5.2.

According to the creator of VTM, earlier investigation has been proved that this model presents excellent performance in sinusoidal maneuvers with amplitude $A = 2.0$ and frequency $f = 0.3Hz$. For this reason, those values are used as initial values in this test. With other words, the parameters are going to be tuned by starting from those values as recently described, where one of the parameter is kept constant while the other one is gradually increased/decreased.

Since VTM models the dynamics of the tires, threshold of type three (see Section 5.2) may also be out of interest, i.e. thresholds for when the tires lose the road grip and the tire forces saturate.

Finally, the gain G is also measured in order to determine the relation between the amplitude of the sinusoidal steering input δ_{amp} and the amplitude of the model outputs r_{amp}. Equation 5.3 shows the described relation.

$$G = \frac{\delta_{amp}}{r_{amp}} \tag{5.3}$$

5.2.3 Scenario 3 - Steady-state cornering test

When a vehicle is performing a turn with a relatively high speed, a centrifugal force causing from the inertia of vehicle is tending to push the vehicle away from the center of rotation. To balance the up-coming centrifugal force, the tires produce a side force resulted as a side slip angle. A fundamental equation that is used to describe the steady-state handling behavior of a vehicle can be expressed as:

$$\delta_f = \frac{L}{R} + K_{us}\frac{a_y}{g} \tag{5.4}$$

where δ_f is the steer angle of the front tire, L the wheelbase, R the turning radius, K_{us} the understeer coefficient (expressed in radians) that describes the sensitivity of a vehicle to steering, and finally a_y is the lateral acceleration. For different values of the understeer coefficient K_{us}, the handling property of the vehicle can either be neutral steer, understeer or oversteer [20]. To examine the changes in the handling behavior of road vehicles, especially borderlines for rollover in the third scenario, a so-called *handling diagram* is used. The handling behavior is going to be measured by conducting a type of test called the *constant radius test*. As the name explains, the test is about to drive along a curve with a constant radius at various speed. The result can be plotted as a handling diagram shown in Figure 5.1, where the steering angle δ_f is plotted against lateral acceleration a_y. The lateral acceleration a_y can in steady-state also be expressed by the driving speed and the turning radius, according to Eq. (5.5):

$$a_y = \frac{V^2}{R} \tag{5.5}$$

So for various speed it requires different angle of the steering wheel to keep the vehicle on course and that is what a handling diagram is showing. The slop of the curve in Figure 5.1 represents the value of understeer coefficient K_{us}. The vehicle is said to be neutral steer when $K_{us} = 0$, i.e. when the steering angle is kept constant as the lateral acceleration increases. This indicates the straight horizontal line in the figure. This behaviour can be seen as idealized, since the steering angle should either increase or decrease when the speed is getting higher.

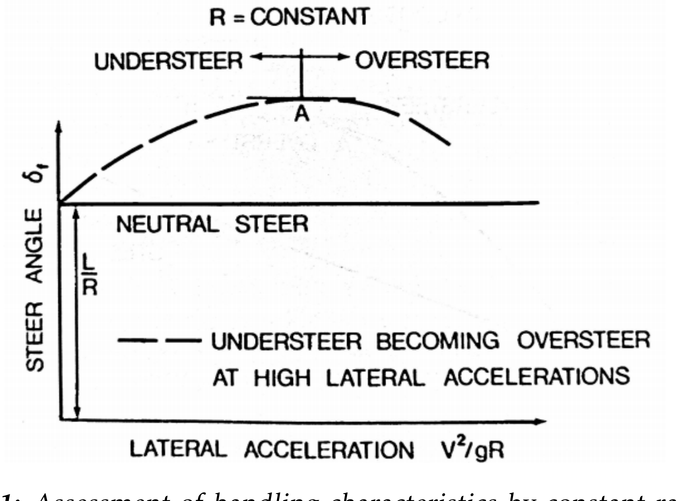

Figure 5.1: *Assessment of handling characteristics by constant radius test [20].*

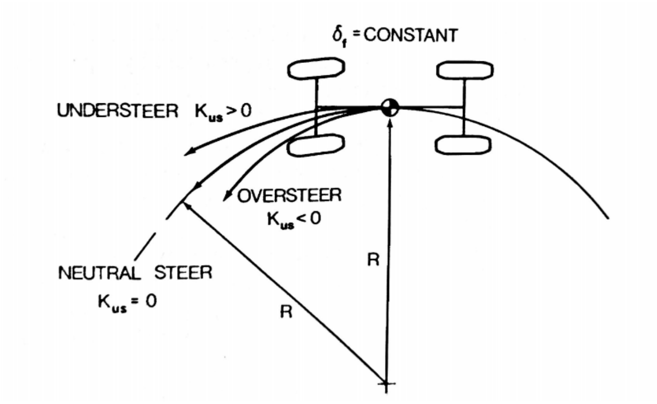

Figure 5.2: *Curvature response of neutral steer, understeer and oversteer vehicles at a fixed steer angle [20].*

On the other hand, if the understeer coefficient is greater than zero, $K_{us} > 0$, the vehicle is considered to be understeer. This means that the vehicle turns less than the steering command given from the driver and the turning radius R is getting larger than that of a neutral steer vehicle, shown in Figure 5.2. The driver has to increase the steering angle to keep the radius constant with increasing lateral acceleration, which explains why the slope of the curve is positive for an understeered vehicle for constant radius. However, an opposite behaviour is occurred when the understeer coefficient is less than zero. The vehicle is said to be oversteer, since the vehicle turns more than the steering command given from the driver and the turning radius R is getting less than that of a neutral steer vehicle. So to keep the vehicle on course with constant radius, the steering angle needs to be decrease, shown as negative slope on the curve in Figure 5.1[20].

Two different thresholds are out of interest to look up in this scenario. Those are the type of second and forth threshold described in Section 5.2. According to the forth threshold, Volvo desires to find thresholds around 20-30 % under the limit before the vehicle appears phenomenon of roll-over.

5.2.4 Scenario 4 - Uphill driving test

Thresholds of type one and three specified in Section 5.2 are out of interest to find in the fourth scenario. Especially the third type of threshold, Volvo has a request to find thresholds for parameters or variables, inclination for instance, that effect the vehicle speed with ±20% in comparison with driving on flat road with no inclination.

An appropriate method to solve this problem is to vary the elevation grade. Firstly, start the test with no inclination, i.e. from the grade of zero, and then repeat the same test by increasing the elevation grade gradually until the velocity differs with the requested limit. The elevation grade can be expressed in different ways such as decimals, percentage and degrees. In this report the second option has been chosen and that is also the most preferable one, since percentage is the most common way to express slopes in the context of traffic. The elevation grade is basically the ratio between the horizontal and vertical distance of the slope, which is measured by dividing the change of vertical distance y with the horizontal distance x, shown in Figure 5.3, and then multiplying with a factor 100 to get in percentage.

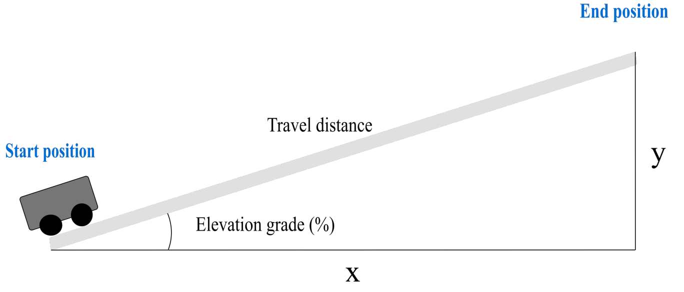

Figure 5.3: *Illustration of an uphill.*

6

Results

The aim of the results presented in this chapter is to clarify what has been accomplished and to present the solutions to the problem formulations set in Chapter 1.3. The results for the testing criteria, introduced in Chapter 1.5, are also presented in order to map out the qualities of every model evaluated in this report.

6.1 Fidelity

The method chosen in order to assess the fidelity for each model was to firstly choose the models best at performing the given scenario as determined by the model creators. Secondly, the error was calculated when the remaining models were compared to that model. Lastly, the normal error distribution was generated as seen in the graphs in the next section.

6.2 Scenarios

The following scenarios were generated and compared using the chosen method described in the previous Chapter 6.1. The scenarios were chosen with regards to common maneuvers in traffic and when driving. The intention was to base the research on realistic situations, thus the values of the parameters for the road and vehicle were chosen within the limits, according to laws and regulations.
Since there are different values to be chosen within the allowed limits, a computation of multiple values was made to assure that the respective model behaviour is not exclusively fixed to a certain value, but rather that it is independent or dependent (depending on the results of the evaluation) of the values chosen for the parameters. Simultaneously, thresholds were attempted to be found to assess

at which parameter values, more exactly, a behaviour is translated into another behaviour. Refer to Chapter 7 for discussion of results.

6.2.1 Scenario 1 - Acceleration and deceleration test

The models that were attending the evaluation of the first scenario, testing the behavior of acceleration and deceleration, were STM, GSP and VTM. Further below in this section, Figure 6.1, 6.3 and 6.5 illustrate the result of the vehicle speed v, acceleration a and yaw-rate ψ plotted against time t. A corresponding histogram, Figure 6.2, 6.4 and 6.6, describing the normal error distribution can also be seen next to the line graphs respectively. GSP models the behaviour of throttle situations the best and therefore all of the other models are compared to this model when the error is calculated. The normal error distributions are subsequently generated.

As illustrated in Figure 6.1, STM and VTM are steadily accelerated to the velocity of 22 m/s or 80 km/h when full throttle is applied. In contrast, the GSP model creates pattern of upwards stairs during the way of acceleration and reaches 80 km/h slightly slower in time compared to STM. On the other hand, when full braking is taken after the velocity reaches 80 km/h, the VTM model tends to take much longer time to decelerate to standstill. The same scenario was repeated for speeds up to 20, 40 and 60 km/h, respectively, in order to make sure that the difference in time to decelerate is not dependent on the speed from which the vehicle decelerates. The experiments showed that it indeed was not the case since each experiment showed approximately the same time delay for the VTM model. Finally, according to Figure 6.5 only the VTM model tends to have a twisting lateral motion when full-braking is taken, while the yaw-rate stays zero for both GSP and STM during the whole test. But due to the small lateral motion with a factor of 10^{-7}, the magnitude of yaw-rate can be assumed as negligible for the VTM model.

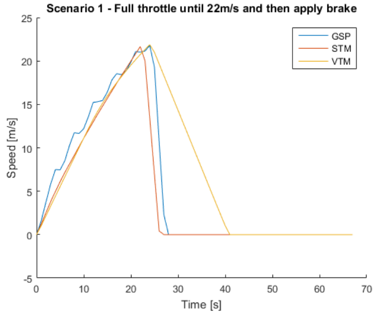

Figure 6.1: Graph of speed for STM, VTM and GSP.

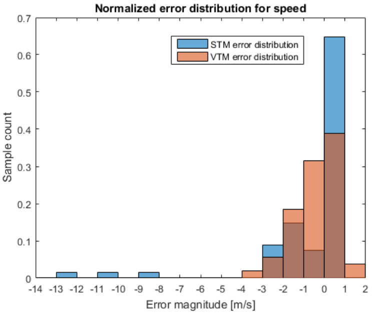

Figure 6.2: Normal error distribution of speed for STM and VTM.

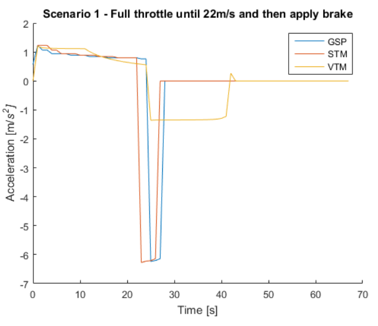

Figure 6.3: *Graph of acceleration for STM, VTM and GSP.*

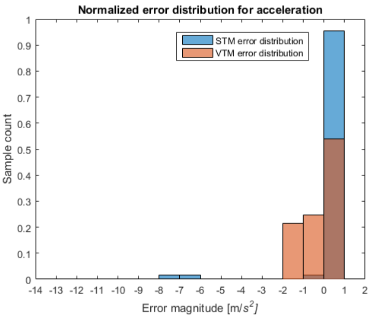

Figure 6.4: *Normal error distribution of acceleration for STM and VTM.*

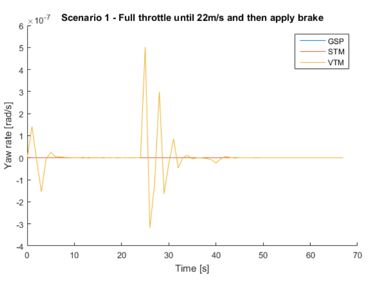

Figure 6.5: *Graph of yaw-rate for STM, VTM and GSP.*

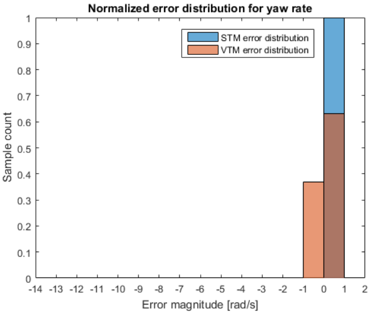

Figure 6.6: *Normal error distribution of yaw-rate for STM and VTM.*

6.2.2 Scenario 2 - Sinusoidal maneuvring test

The results of this scenario are split into two sections to showcase the behaviour of the models with changing parameters. Firstly, the amplitude of the sinusoidal steering input is kept constant with a varying frequency. Secondly, the frequency is kept constant while the amplitude varies. The models evaluated in this scenario are all of the models included in this research, except for the GSP model, which is not able to perform turns. The models are compared to VTM in histograms, since this is the model which performs turning motions the best.

6.2.2.1 Constant amplitude

In this section, the amplitude of the sinusoidal steering input is kept at a constant value of 2, while the frequency is different in each and one of the graphs. Figure 6.7 shows that all of the models are very similar in behaviour except for VTM that shows a lower amplitude. With a higher frequency, as in 6.9, it can be shown that the behaviour of the models is more different. This can be verified when examining 6.8 and 6.10, where the error is visibly greater in 6.10. For example, it can be seen that an error magnitude between -0.35 rad/s and -0.3 rad/s for OTM occurs almost the double as much for a frequency of 0.3 Hz than for a frequency of 0.1 Hz. The gain for VTM varies from 13.44 to 14.19 with increasing frequency and for OTM it varies from 9.72 to 10.20. On the other hand for STM, the gain is kept constant despite varying frequency.

In an attempt to find even less error between the models when decreasing the frequency, a threshold of 0.1 Hz was found. This threshold marks the limit for when the error between the models cannot be reduced further while changing the frequency.

It can also be seen that the VTM curve models a delay compared to STM, in the beginning of the curve at zero seconds, see Figure 6.7 and 6.9. The same can be observed for OTM, but with the delay being smaller than for VTM.

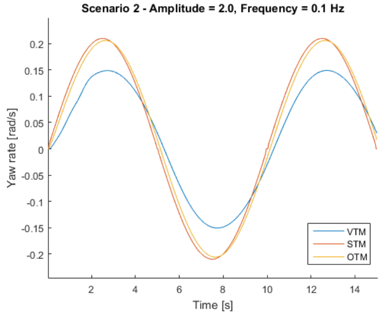

Figure 6.7: Scenario 2 with 0.1 Hz frequency steering input.

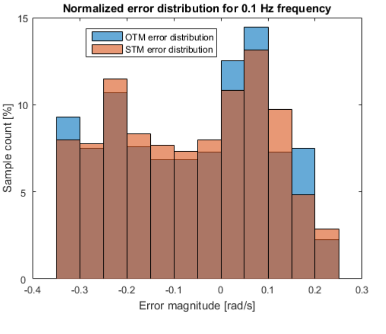

Figure 6.8: Normal error distribution of yaw rate for 0.1 Hz frequency.

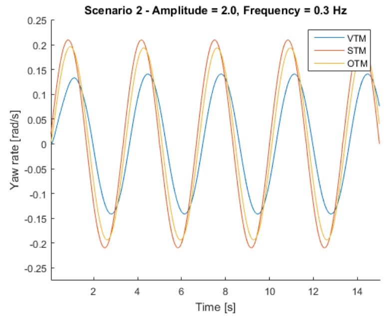

Figure 6.9: *Scenario 2 with 0.3 Hz frequency steering input.*

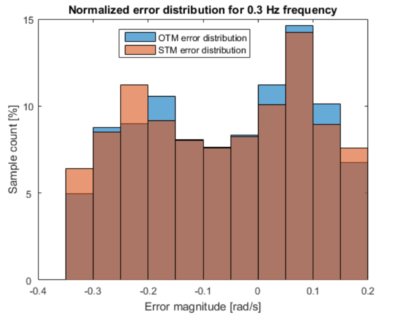

Figure 6.10: *Normal error distribution of yaw rate for 0.3 Hz frequency.*

6.2.2.2 Constant frequency

The graphs pictured below have a constant frequency of 0.3 Hz, while the amplitude is 0.5 and 1.5, respectively, in the respective graphs. The models seemingly act more alike with lower amplitude. This can be shown when looking at the histograms 6.12 and 6.14, where the difference between the models is much smaller when using the lower amplitude of 0.5. The error between the models in 6.12 vary in a span between -0.1 rad/s and 0.06 rad/s, while the error between the models in 6.14 vary in a greater span between -0.25 rad/s and 0.15 rad/s, hence indicate greater errors. However, the gain is constant for all models, despite varying amplitude. The gain for STM is kept constant at 9.54, for OTM it is kept constant at 10.33 and for VTM it is kept constant at 14.00.

It can also be seen, just as in the cases for constant amplitude in Section 6.2.2.1, that the VTM curve models a delay compared to STM. The delay beginning at zero seconds can be observed for OTM as well, but with the delay being smaller than for VTM.

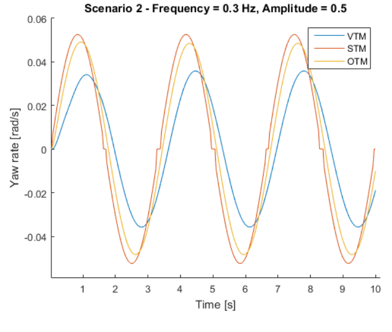

Figure 6.11: *Scenario 2 with 0.5 amplitude steering input.*

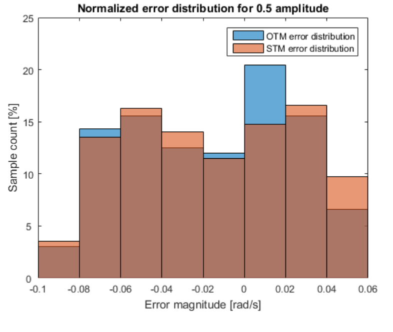

Figure 6.12: *Normal error distribution of yaw rate for 0.5 amplitude.*

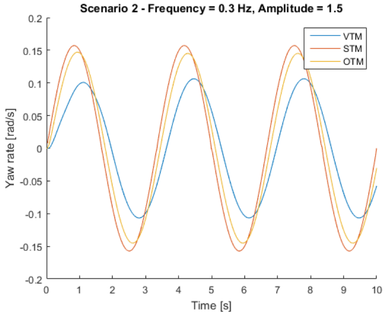

Figure 6.13: *Scenario 2 with 1.5 amplitude steering input.*

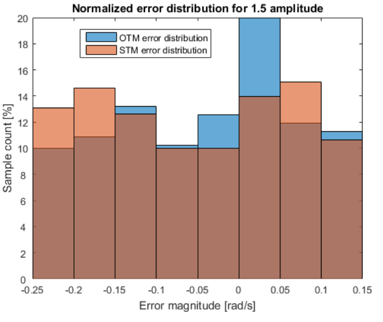

Figure 6.14: *Normal error distribution of yaw rate for 1.5 amplitude.*

6.2.3 Scenario 3 - Steady-state cornering test

This scenario involves all of the models that have been evaluated in this thesis, except for the GSP model which cannot perform turning motion. Figure 6.15 showcases the models when they are performing a circular motion with a radius 50 of metres. It can be seen that the STM and OTM model are performing a neutral steering motion, with $K_{us} = 0$, according to 5.2.3. In the other hand, once the vehicle enters the circular road, seen at approximately a lateral acceleration of 0.05 m/s^2 in Figure 6.15, it can be seen that the vehicle exhibits understeer behaviour, since $K_{us} > 0$. The vehicle later on keeps a neutral steering motion, as $K_{us} = 0$ once again. After the vehicle reaches its maximum velocity value around 15m/s, seen in Figure 6.16, it starts to get unstable and interchange between understeer and oversteer behaviour. This type of behaviour is caused by the vehicle's controller to keep a constant radius and is seen at about the lateral acceleration of 0.5 m/s^2. The vehicle then goes about to perform so called jackknifes, meaning the tractor is pushed by the trailer until it spins the vehicle around and ultimately causes it to face backwards. However, the tractor spins 360 degrees around its own axle in the simulation since there is no such limitation for this behaviour in the model. The jackknifes are visible in Figure 6.16 where the speed reaches values beneath zero.

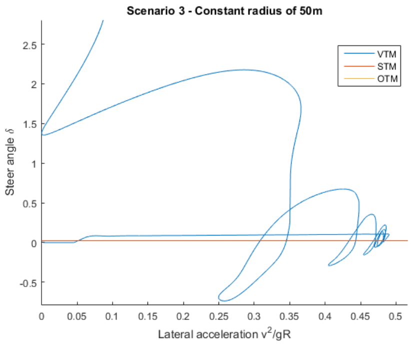

Figure 6.15: *Scenario 3 - handling diagram with radius R = 50 m.*

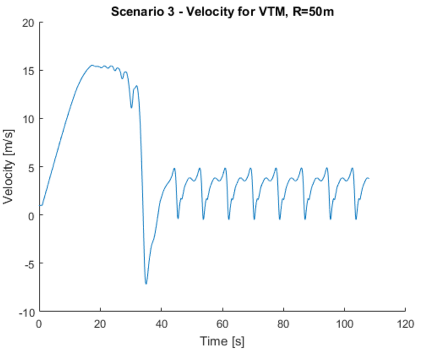

Figure 6.16: *Scenario 3 with velocity for VTM when R = 50 m.*

The same scenario is performed for a radius of 100 metres and 120 metres respectively, see Figures 6.17 and 6.19. It is furthermore shown that the truck rolls over with a radius between 100 metres and 120 metres. The truck rolls over just after it performs a jackknife and the truck returns to standstill, as seen in Figure 6.18 and 6.20 where the velocity is zero. Before that, the vehicle firstly exhibits neutral steer behaviour until about 80km/h. The behavioural pattern of the steering motion in 6.19 then is close to the pattern of when the radius is 50 metres, as in Figure6.15 where the steering motion is very variable in order to keep the truck on track and not roll over.

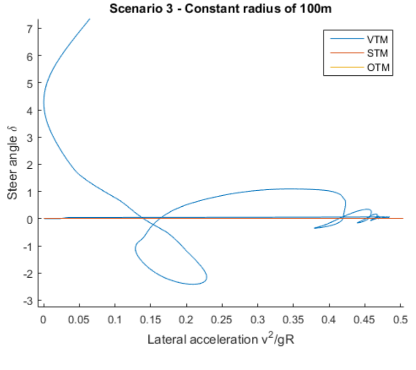

Figure 6.17: *Scenario 3 - handling diagram with radius R = 100 m.*

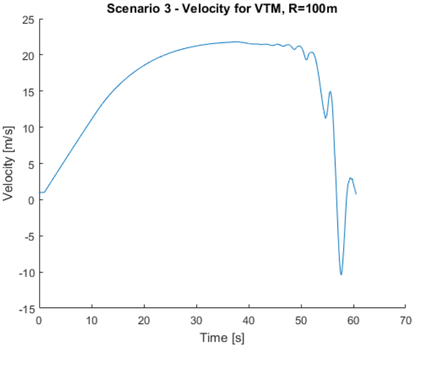

Figure 6.18: *Scenario 3 with velocity for VTM when R = 100 m.*

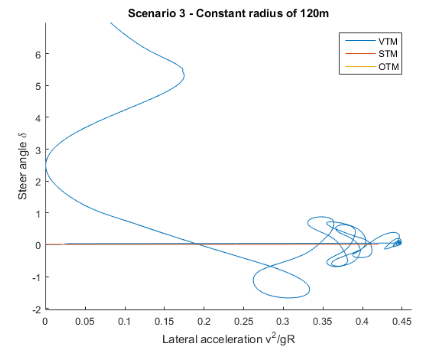

Figure 6.19: *Scenario 3 - handling diagram with radius R = 120 m.*

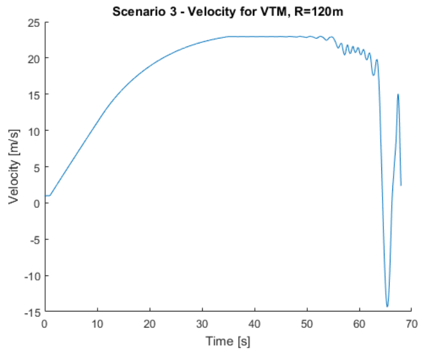

Figure 6.20: *Scenario 3 with velocity for VTM when R = 120 m.*

In the final test of scenario 4, the radius is set to 150 metres. The truck exhibits a rather stable behaviour and neutral steering motion until a lateral acceleration of about 0.35 m/s^2 is reached, refer to Figure 6.21. Thereafter, the vehicle steering angle alternates between ±0.1 radians, consequently causing the vehicle to alternate between understeer and oversteer behaviour. However, the angle of over-and understeer is small in comparison to the tests of lower radius, as previously described.

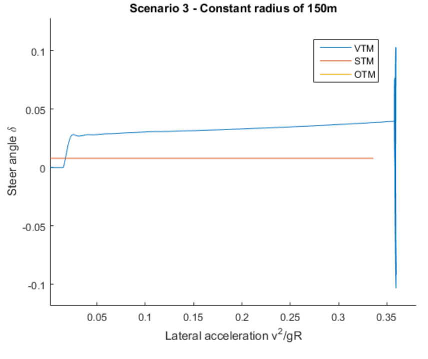

Figure 6.21: *Scenario 3 - handling diagram with radius R = 150 m.*

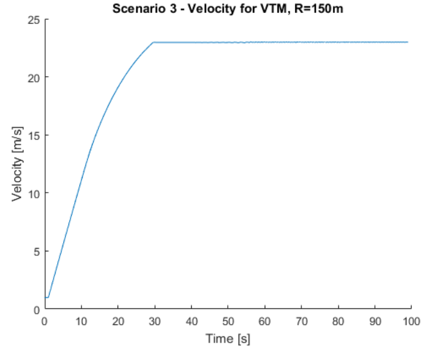

Figure 6.22: *Scenario 3 with velocity for VTM when R = 150 m.*

6.2.4 Scenario 4 - Uphill driving test

The result of the uphill driving test is shown in the v-t graphs below, Figure 6.23, 6.25, where 4 and 10 percent elevation grade were tested. The models evaluated in this scenario are GSP, STM and VTM, i.e. all models except for OTM, which is not able to accelerate. The evaluated models are in comparison with GSP and a corresponding histogram showing the error distribution for different elevation grades can be seen in Figure 6.24, and 6.26. From the v-f graph, it can be seen that the STM model follows the GSP quite well, whether the grade of the slope. Aside from the step-formed up-shifting phenomenon created by GSP, STM just differs with a velocity magnitude of $\pm 2m/s$ and further, reaches the end velocity of 22m/s or 80 km/h approximately 4-5 seconds before GSP. On the other hand, the curve for VTM begins quite similar to STM until the speed reaches 15m/s, where the slope of the curve gradually declines from the other models and reaches 22m/s around 10 seconds after GSP, shown in the Figure 6.23. When it comes to a higher elevation grade as 10%, refer to 6.25, the curve for VTM starts to flatten out already at 10m/s and does not seem to be able to accelerate anymore.

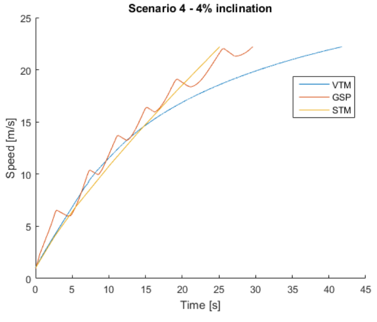

Figure 6.23: *Speed for hill with 4% slope.*

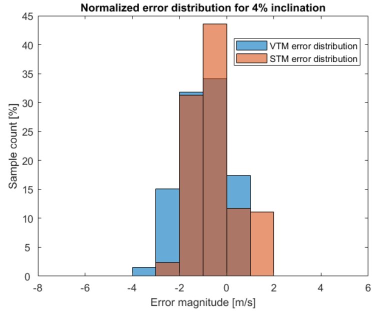

Figure 6.24: *Normal error distribution of speed for hill with 4% slope.*

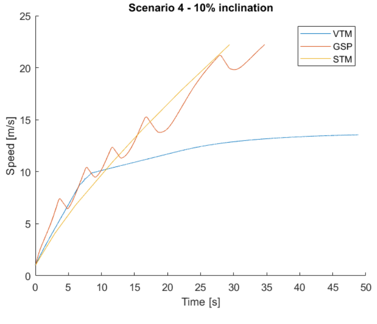

Figure 6.25: *Speed for hill with 10% slope.*

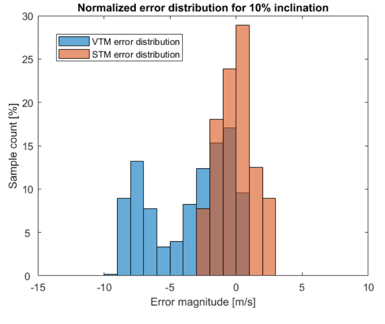

Figure 6.26: *Norman error distribution of speed for hill with 10% slope.*

The models were not exclusively compared to each other with varying inclination, but also individually. Figure 6.27 shows a vt-graph where STM is driving on a straight road with no, versus 10 % elevation grade. An error distribution of how much the speed of the test with 10 % elevation grade differs to the test with no elevation grade in percentage, is shown in Figure 6.28. It shows that for the highest inclination of 10% inclination predetermined for this test, the STM model can only manage to reach a difference in speed of -18 to -15%. The minus sign specify the compared model has a lower speed as opposed to the model that driving on a horizontal road). In contrast to GSP, the difference in speed in Figure 6.30 reaches -20% already for 5% elevation grade. However, the error is distributed over a wider span between -30 to 0% but it shows that big part of the samples are focused around -20.

The result showed that there were no thresholds to be found by the VTM model.

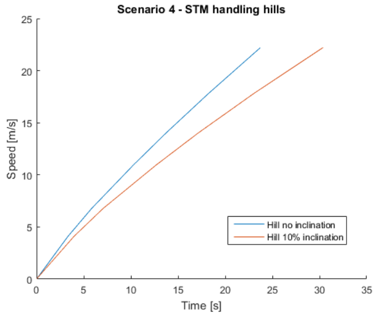

Figure 6.27: *STM handling hills, 10% vs. no inclination.*

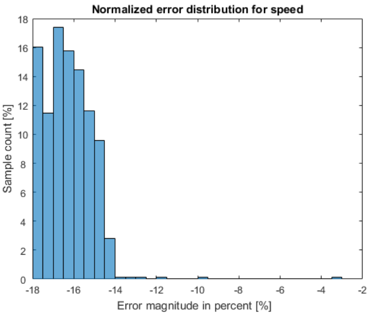

Figure 6.28: *Normal error distribution of speed for 10% inclination.*

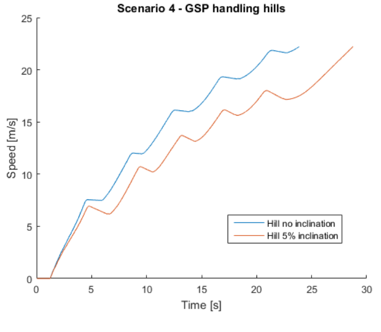

Figure 6.29: *GSP handling hills, 5% vs. no inclination.*

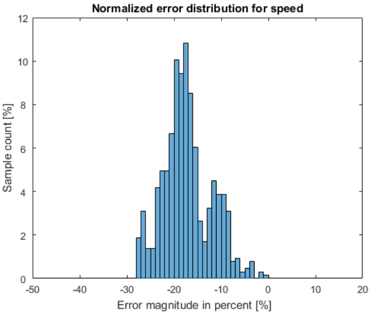

Figure 6.30: *Normal error distribution of speed for 5% inclination.*

6.3 Test criteria

The test criteria are used in order to give a better understanding of the models, which in turn were only able to be evaluated after extensive work with the models. These bullet points are out of most importance for Volvo in their mapping of the existing models. The test criteria include fidelity, complexity, re-usability, pipeline, starting state, performance and integration possibilities, all described in separate sub-chapters below.

6.3.1 Fidelity

Fidelity was assessed according to the method described in Chapter 6.1. The emphasis lays on finding the model(s) agreeing the best with the reality.

Scenario 1, where GSP models the best behaviour, shows a clear connection between the behaviour of GSP and STM. The results in Section 6.2.1 indicate that the error is negligible between the two models, with the exception that up- and down-shifts are not considered in STM. Therefore, in situations where up- and down-shifts are not of importance, it is possible to exchange GSP for STM if needed. VTM shows almost the same behaviour as STM for the acceleration, but not for deceleration. Consequently, if a more complex model is needed for example to showcase small lateral motion when braking and if deceleration is not to be considered, VTM is a good choice.

In scenario 2, on the other hand, VTM is chosen as the model that models the scenario the best. Comparing to the situation in scenario 1, the error magnitudes are much greater between the models, see Section 6.2.2. It was shown that when the frequency and amplitude are adjusted, smaller errors are found. Most prominently, STM and OTM model almost negligible differences from VTM when the amplitude is lower. Thus, when a less complex model is needed, it is appropriate to choose OTM or STM instead of VTM.

Section 6.2.4 shows the results for scenario 4 with a prominent trend of higher error with bigger slopes. GSP is chosen as the best model to perform this scenario and once again, similarly to scenario 1, STM closely follows the same behaviour as GSP with low error magnitude. As previously stated, STM can be used advantageously when up-and down-shifts are out of less importance. On the other hand, VTM shows a great difference in behaviour.

6.3.2 Complexity

The complexity of the models differ from one model to the other. The most complex model, out of all the models that were evaluated in this report, is undoubtedly the VTM model. The VTM model has a great amount of parameters, more exactly, about 64 parameters in total. However, not all of the 64 parameters are used depending on which truck configuration that is used. It is also worth noting that even though several of theses parameters are multidimensional, they are still counted as one parameter respectively. These parameters need to be fed into the consequently large amount of vehicle configuration files, also adding to the complexity of the model. The model in Simulink being fed these parameters, in turn, consists out of many complex layers of sub-models.

The OTM model, on the other hand, also uses a MATLAB script for the vehicle configuration with the same script containing the model itself. The parameters are counted to a total of 16 parameters. These parameters are processed directly into the model located in the one and only script for the model. This drastically puts down the complexity, in comparison to VTM which has a more complex structure as well as more parameters.

The STM model measures to VTM in the structural complexity. The model contains many files which refer to one another in ways that are hard to backtrack. Substantially, there are also many parameters to use with a total of 55 parameters. The number of parameters equivalents to a lower one than VTM which is to be expected since the functionality is more limited than VTM.

GSP is considered to be the least complex model. The background for this reasoning is that the model only describes the powertrain functionality and hence does not use as many parameters. However, it is worth noting that the structural complexity is not known since the model was only used in a similar matter to black box testing, meaning the model was fed input signals and responded with output signals.

6.3.3 Re-usability

In this report, we have exclusively worked with the truck combination of a 4x2 tractor with a standard semitrailer with 3 axes, see Section 1.4. However, Volvo has an interest to find out whether or not it would be hard to change this setting, if possible at all, in the respective models.

The VTM model already contains several parameter files which describe different combinations, both for the tractor and the trailer part of the complete truck. The tractors and the trailers have different number of axles. Switching into a different combination would be very easy, since it means only switching the files which are meant to be ran. There are in total seven parameter files to choose from, which respectively represent a dolly with two axles, a semitrailer with three axles, tractors with two or three axles and trucks with three, four or five axles.

The same simplicity comes to changing the truck configuration for the STM model. There are far more combinations than VTM to choose from, ranging from trucks to buses, cars and mopeds. However, the physical properties are not changed when changing the truck configurations. This depends on the fact that there is no mass defined in the model and hence no forces etc., refer to Section 2.2.1. The only difference seen in the simulation is the appearance of the vehicle.

As explained in Section 2.2.3, it is not possible to change truck configurations for the GSP model since it is not a stand alone model. Therefore, when changing the truck configuration in correlation to GSP, it has to be made on the model which is used together with GSP.

There is a rather more complex process in changing the truck configuration for the OTM model. Since the OTM model is highly mathematical with many equations describing the behaviour of the model and thus also the configurations, then the process of changing the truck configuration would mean adding or removing equations. The extent of doing so, depends on if axles should be removed or added. With that said, the OTM model does not have completed files for different truck configurations, like VTM and STM, but instead it is demanded that the changes are made manually with regards to mathematical calculations.

6.3.4 Pipeline

The complexity of the way of working, the so-called pipeline, goes hand in hand with the structural complexity described in Section 6.3.2. The more complex the structure of the respective model is, the harder it is to work with it and vice versa.

As previously established, see Section 6.3.2, the VTM model contains many configuration files and many levels of the model in Simulink. Nevertheless, both the files and the model in Simulink are well structured in relevant folders and well named with names indicating the case of usage. This structure enables the user to efficiently modify and find the files that are searched for. Moreover, the VTM model contains documentation of the physical properties and instructions on how to perform simulations. Even though the structure is easy to cope with once one is familiar with the file arrangement, it is on the cost of time. The procedure of running the appropriate parameter files, running the model in Simulink and finally starting the simulation environment, takes far more time than the other models.

The STM model, similarly to VTM, contains many files that reference to each other and thus create a large network of files. The difference from VTM is that the model is not as well structured which makes it hard to find and modify files. Additionally, the existing code barely has any comments to clarify the functionality of the code. The lack of documentation explaining the necessities and properties of the model was also an obstacle in the familiarization of the model. However, one was almost explicitly modifying one file only in the process of creating scenarios. Moreover, the process of compiling and running a simulation is effortless and takes substantially less time than for VTM.

The OTM model only consists of one file, but this file contains many elaborate equations. Thankfully there are many comments explaining the equations throughout the file. Furthermore, the complexity of running a simulation is nothing more complex than running an ordinary file in MATLAB.

Finally, the GSP model is the easiest to work with since it only includes feeding the model with inputs and expecting the outputs.

6.3.5 Starting state

The idea for being able to simulate vehicles in a virtual environment is among other thing to test aggressive scenarios that will be dangerous to test it on reality, but also in order to simulate large numbers of test in a fast and efficiently way. Therefore, one of the criteria is to research the possibility of starting the model at a predetermined velocity v, i.e. when $v \neq 0$.

All models excepting the GSP model have the ability to start in a specific velocity, that is not standstill. The STM model fully provides this kind of function and even allows to start in reversing mode as well, i.e. when $v < 0$. VTM and OTM also have the possibility to start in any speed, including from standstill. However, for OTM one should be aware of what ODE solver to use [9]. With the *Runge Kutta 4* solver, it is possible to start from small velocities as well. This possibility, however, is not available for the GSP model, since the fact that the velocity is directly dependent on the shifting.

6.3.6 Performance

The values for performance that are described in this subsection are merely an approximation. However, it is important to measure the performance in order to assess how many test kilometres the model can drive during one hour. Performance is hence a crucial point out of a time perspective since you want to save time in the process of verification and testing. Subsequently, it is possible to test the model to its fullest extent during a short period of time. It was shown by computational measurement that the models perform according to the below values.

- **VTM**: Fixed timestep dt with frequency $f = 1000Hz$. The time for one iteration is measured up to $1/1000 = 0.001s$.
- **STM**: Dynamic timestep dt with frequency in the range $f = 60 - 250Hz$. The time for one iteration is measured up to $1/25000 = 0.00004s$.
- **GSP**: Performance could not be measured.
- **OTM**: Performance could not be measured.

6.3.7 Integration possibilities

The integration possibilities were considered as last priority and unfortunately there was not time enough to look into this scientifically for either one of the models evaluated in this report. However, discussions were had about this for the future and the result of these can be found in the future work section, refer to Section 8.2.

7 Discussion

The discussion is divided into three separate discussions. Firstly, the scenarios are discussed based on the results and the statements made in the previous chapter. Secondly, the chosen methods are brought to light with discussions about relevancy and comparisons with other alternative approaches.

7.1 Results

7.1.1 Scenario 1 - Acceleration and deceleration test

In this scenario, the GSP model is seen to be the reference model since it is the strongest model in the field of acceleration. It can be seen in Figure 6.1, where a dynamic of gear shifting is appeared shown as upwards stairs in the graph. This phenomenon reflects the reality quite well. What actually really happen is that the throttle is unpressed when a gear shift is applied. That in turn slows down the velocity and creates plane stairs as seen in the graph. Another interesting observation is that VTM takes almost up to 3-4 times longer to decelerate to standstill, compared to STM and GSP respectively. That can be shown in the graph for acceleration, in Figure 6.3, where the VTM model only decelerate with -1 m/s^2 during a longer time period compared with the other two models. The explanation for this behavior is that VTM neither have a throttle or braking system implemented that are regulating the velocity. The braking system modelled only utilizes the driving wheels for braking, which is the the rear wheel-pair of the tractor. In general cases, a complete braking system is required if a realistic behavior of braking wants to be obtained.

7.1.2 Scenario 2 - Sinusoidal maneuvering test

The GSP model could not be evaluated in this scenario since it is unable to conduct a turning motion. The reason for this is the position vector of GSP, hence also the velocity vector, which is one-dimensional. This means that GSP cannot move in the xy-plane and therefore is unable to conduct anything but straight movement.

As previously noted, in 6.2.2.1, VTM models a curve with lower amplitude for the sine curve than STM and OTM. The reason for this behaviour is pretty straight forward when the internal qualities of the models are known. Since VTM describes the interaction between the road pavement and the tires, i.e., the lateral forces arising from that interaction, the vehicle will slip in turns and therefore not turn as much as STM does. In addition, the vehicle is kept at such a high velocity of 80km/h, which causes the vehicle to slip even though the amplitude or frequency is low. Therefore, the difference between VTM and STM will be remarkable even though the frequency or amplitude is low.

The VTM model describes the tires by using Pacejka's magic formula tire model which in turn describes nonlinear tire characteristics. The OTM model on the other hand, describes the tires with a linear tire model. For a linear tire model, the tire lateral force coefficients are considered as constant for a small lateral force. Moreover, longitudinal tire forces are not considered at all since it includes complex interactions between longitudinal and lateral tire forces. Consequently, linear models like the OTM model is mostly suiting for the evaluation of scenarios describing stable vehicle behaviour with low acceleration and small steering. Performing sinusoidal maneuvering means performing great steering which does not suit a linear model as OTM. This explains why the OTM model does not show as low amplitude as VTM does and as one would expect from a model that considers tire forces.

The OTM and VTM models also show a slight delay compared to STM, as observed in Sections 6.2.2.1 and 6.2.2.2, in the beginning of performing the maneuver. This could once again be explained by the fact that OTM and VTM model the tires, to varying levels indicated by the size of the delay. It takes time for the tires to deform in turning situations before the force is translated to the road.

However, with lower amplitude, the models act more similar, with only about 0.0037 rad/s of difference from top to top of the sine curves between VTM and the other models. Since this is a very small difference, it can be considered as negligible. This in turn means that in this case it is more beneficial to use a less complex model than VTM, i.e., STM or OTM for this scenario. Despite the variation of amplitude, the gain is kept constant for all of the models.

In contrast, for a varying frequency, it can be seen that the lowest difference between VTM and the other models is about 0.045 rad/s from top to top of the sine curve, which is a notable difference that cannot be ignored. Therefore, in this case, VTM is the preferred model.

7.1.3 Scenario 3 - Steady-state cornering test

There has been a common behaviour for both STM and OTM throughout all of the tests in scenario 3. This behaviour is characterized by the fact that OTM and STM both keep the same constant steering wheel angle regardless of the change of velocity. This in turn means that the vehicle performs neutral steering motion and hence keep the vehicle on track. The reason for this behaviour is explained by looking at the internal qualities of the models. The STM model does not model the dynamics of the tires, while OTM models the tires but in a linear sense. Since the trajectory of the vehicle is mostly heavily curved and hence requires that the vehicle need to turn a lot, the road and tire interaction in OTM is not reflected in the graphs in 6.2.3. Nevertheless, the VTM model takes the tires into consideration and it is shown that the steering angle fluctuates throughout the tests, refer to 6.2.3.

Jackknifes are a common phenomenon for the VTM model, but in the reality as well. The results of such an accident are mostly devastating for the environment and the truck driver and are therefore avoided whenever it is possible. For the VTM model it is seen that jackknifes occur both in situations before the truck rolls over, as well as when it does not roll over. It is seen that for a radius of 120 metres as opposed to all the tests with lower radius, as seen in Figure 6.19, the vehicle will steer more heavily as an attempt to keep the vehicle on track. This behaviour can be explained by the fact that the radius is set to 120 metres, which is the limit of when the truck rolls over or not.

It should be noted that the capability of the truck rolling over is highly dependent on the load of the truck and the position of the centre of gravity. In these simulation, the centre of gravity of the trailer load, as well as the height of the cargo space, was kept at an constant value for the VTM model. Theses parameters could be adjusted and the VTM model would exhibit a different behaviour of rolling over easier or harder (if at all). However, the other models do not have these parameters and hence do not possess the ability to turn over.

In the last test of scenario 3, with a radius of 150 metres, it is shown that neither jackknifes nor roll overs occur, refer to 6.22. This is to be expected, since the radius is big enough to not cause instability in the steering motion. However, this can only be considered to be valid until velocities up to 80km/h which have been kept during this scenario.

7.1.4 Scenario 4 - Uphill driving test

All models were evaluated in this scenario except for OTM. The model was considered as improper to be evaluated for this scenario, since it does not include systems that model the acceleration and braking part of the vehicle. According to both Figure 6.24 and 6.26, STM follows GSP the best since the speed error distribution differs with only $\pm 2m/s$ and $\pm 3m/s$ respectively, compared to VTM. Although STM accelerate slightly slower than GSP, the velocity is increased linearly during the whole shifting process and reaches 22m/s around 5 seconds before GSP. In contrast, it can be clearly seen that the VTM model is not a propitiate model for this scenario where the velocity deviates from GSP as higher the elevation grade becomes. It can be explained that the same solution for acceleration that was applied in scenario 1 was used for this scenario, which is not a proper solution for slopes.

A previously noted in Section 6.2.4, the models were analyzed individually with varying inclinations. Since the maximum inclination of hills in Sweden is 10% and the biggest inclination for projects involving hills at Volvo is 8%, then it is not relevant to generate scenarios with a higher inclination than 10%.

7.2 Method

The methods that have been used in this research unquestionably play a big part of the outcome. Therefore, their contribution is worth discussing.
A big part of this thesis work has been the generation of scenarios. The scenarios that were generated are basic maneuvers in traffic, but it is not given that these scenarios have to be able to be executed in order for the models to be considered as "good". The amount of scenarios that could have been chosen instead are unlimited. Furthermore, the motivation for performing other scenarios instead could also be more justified. With that said, it is important to understand the limitation of this research and the limitation of making a fair judgment of the models. The judgments made of the models are in this case limited to the scenarios generated using the models.

Furthermore, the approach for verification of models that have been used in this thesis work was to compare models with each other. This approach conducted, for instance limitations for creation of scenarios. To compare those models in a fair sense, the scenarios must therefore be created based on the strengths of each model. In additional, another approach for model verification is to verify the models against field-data. This method should definitely provide higher fidelity since the compared data is directly measured from the reality.

According to the part of scenario creation, there are some suggestions of improvements for each scenario if there is desire to repeat the same research to obtain better result. For the second scenario, no thresholds have actually been found for the VTM model of when the tire slip exactly occurs. Therefore, an suggestions is to choose other values for the parameters frequency f and amplitude A of the sinusoidal curve than those values that was used in this research. With varying values for frequency f as well as the amplitude A, a bunch of combinations with different look of sinusoidal curve will be resulted. Furthermore, except the radius constant test used in Scenario 3, there are two more options of test to measure the handling behaviour of a road vehicle under steady-state conditions. Those tests are *constant speed test* and *constant steer angle test*. All these tests are actually measuring the same thing, how the understeer coefficient varies as lateral acceleration increases. Thus the selection of test depends on the purpose of the research. For Scenario 4, instead of accelerating during the entire way up of the hill, the speed variation can also be examined with another method. For instance, starting the vehicle at constant speed $v \neq 0$ on a flat horizontal road and thereafter, driving upwards on a slope with a specific elevation grade. During the way upwards, the speed variation is measured and is compared with the speed driving on flat road, then the loss of speed depending on the grade of slope can be measured.

8

Conclusions and Future Work

This chapter concludes the entire thesis report while establishing the conclusions and the work which is left to be done for the continuation of this topic. In Section 8.1, the conclusions of the research are drawn and summarized to wrap up the results. The purpose of Section 8.2 is to provide an aspect for reflection and possibly give ideas for future thesis work.

8.1 Conclusions

In this section, the conclusions of the thesis work are drawn. The questions in Section 1.3 are answered in order to bring back the main problems that were evaluated in this thesis.

What scenarios should be created in order to test the models properly?

The four chosen scenarios that were created had the purpose to reflect realistic situations and maneuvers that occur in traffic. The limits for speed, inclination of hills, etc., were therefore kept according to the existing laws and regulations. Scenario 1 tests the ability to accelerate from 0km/h to 80km/h and after that to decelerate back to 0km/h on a flat road. Scenario 2 tests the models' ability to steer in a sinusoidal curve, keeping the speed at the value of 80km/h from start to finish. This scenario is important in situations where the vehicle needs to steer away from example an unexpected obstacle. Scenario 3 tests steady-state cornering, which challenges the models' ability to rollover. The test is performed when the truck drives in a circle with constant radius and gradually increasing velocity up to maximum 80km/h. Finally, scenario 4 tests the ability to drive uphill with a maximum inclination of 10%. In this test, the truck starts from standstill and accelerates to the maximum velocity of 80km/h. To add more credibility to the

evaluation and to assure that the results are not dependent on the numerical values, the values were varied. Consequently, the amplitude and frequency of the sine curve in scenario 2 were varied. Additionally, the inclination of the hill in scenario 4 was also varied.
The models and their ability to perform the described scenarios are summarized in Table 8.1. The models that were chosen as reference models, i.e., best models are also described in the table. STM and VTM both could simulate all of the described scenarios. All of the other models were furthermore compared to VTM in scenario 2 and 3. The GSP model could not model the behaviour of scenario 2 and 3, but was used as a reference for all the other models for scenario 1 and 4. The OTM model could model scenario 2 and 3, but not scenario 1 and 4.

Table 8.1: *Usage of models depicted in table.*

Model:	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
STM	✓	✓	✓	✓
GSP	✓ Best Model.	✗	✗	✓ Best Model.
OTM	✗	✓	✓	✗
VTM	✓	✓ Best Model.	✓ Best Model.	✓

How should fidelity be evaluated for each model?
The strategy for evaluating fidelity is to firstly choose a model which is the best within the respective scenario. The best model is chosen after discussion with the model creator. The best model is later compared to the other models in a graph. In order to give a numerical value of the difference, the normal error distribution is generated.

What thresholds, as a result of changing the values of the model-parameters, can be found for the model behaviour in the various scenarios?
For Scenario 1, see Table 8.2, it is shown that even though GSP is the best model showing up- and downshifts when changing gear, other models can be used when changing gear is not of importance. In these situations, STM can be used instead. If there is the need to use a more complex model when accelerating, VTM can also substitute GSP.

Table 8.2: *Thresholds for Scenario 1 - Acceleration and deceleration.*

Model:	**Scenario 1** - Threshold of type 1 (see 5.2)
GSP	Best model.
STM	**Type 1:** First model for acceleration up to 80 km/h and deceleration, <u>without</u> braking delay.
VTM	**Type 1:**Second model for acceleration up to 80km/h, <u>with</u> braking delay as GSP.

Thresholds of type 1, see Section 5.2, were found for Scenario 2, refer to Table 8.3. STM and OTM behave almost identically and with the same relations to VTM, hence their thresholds remain the same. The models can be used as substitutes for VTM when the amplitude is lower or equal to 0.5, which is appropriate when less complex models are needed. For frequencies below 0.1Hz it is also known that the error between VTM and the remaining models cannot become smaller.

Table 8.3: *Thresholds for Scenario 2 - Sinusoidal maneuvering test.*

Model:	**Scenario 2** - Threshold of type 1 (see 5.2)
VTM	Best model.
STM	**Type 1:** For low amplitude A <= 0.5 and for frequency f < 0.1 Hz.
OTM	**Type 1:** For low amplitude A <= 0.5 and for frequency f < 0.1 Hz.

For Scenario 3, thresholds of both type 2 and 3, were only found for VTM. The rollover occurs during an interval of radius $100 < R < 120$ metres and velocity $21.80 < v < 22.90$ m/s, according to the second type of threshold. In addition, the third type of threshold was found at radius $R = 70$ and velocity $18.20 m/s$, which is 30% below the limit of when the truck rolls over. Although no thresholds were found for both STM and OTM, they can be of good use in other ways. Simpler models as STM and OTM can be applicable in turning motions where the radius becomes bigger than the radius for rollover, which is $R > 120$.

Table 8.4: *Thresholds for Scenario 3 - Steady-state cornering test.*

Model:	**Scenario 3** - Threshold of type 2 & 3 (see 5.2)
VTM	Best model. **Type 2:** Rollover occurs in radius $100 < R < 120$ m and velocity $21.80 < v < 22.90$ m/s. **Type 3:** $R = 70$ m and $v = 18.20$ m/s (30% below the limit of roll-over).
STM	**Type 2:** No thresholds were found. **Type 3:** No thresholds were found.
OTM	**Type 2:** No thresholds were found. **Type 3:** No thresholds were found.

The Table 8.5 shows the conclusion of the thresholds of type one and three for the last scenario. For the threshold of type 1, the STM model is the preferred one to substitute GSP when it comes to the closest time by reaching the speed 80 km/h at a specific elevation grade. When it comes to threshold of type 3, only the GSP model meets the requirement and differs 20% in speed versus driving on flat horizontal road for 5% elevation grade. In contrast, the largest difference in speed for STM was only obtained to 18% for the maximum elevation grade, which is 10%. The VTM model does not reach up to the required speed of the scenario and can therefore not replace GSP. Furthermore, it is not fair to compare it to no elevation grade of the road and thus no thresholds of type 3 were found.

Table 8.5: *Thresholds for Scenario 4 - Uphill driving test.*

Model:	**Scenario 4** - Threshold of type 1 & 3 (see 5.2)
GSP	Best model. **Type 3:** Differs 20% in speed for 5% elevation grade.
STM	**Type 1:** First model to substitute GSP. **Type 3:** Differs 18% in speed for 10% elevation grade (maximum).
VTM	**Type 1:** Cannot replace GSP. **Type 3:** No thresholds were found.

8.2 Future Work

The topic itself which this thesis describes, the use of different vehicle dynamic models, is a topic that is undergoing great development within Volvo. Therefore, there is a lot to be said for the time ahead, both in a smaller, but mainly in a bigger context.

There are many things that could be developed, for example within the scope of a master thesis, when looking at the individual models that have been evaluated in this report. The relevancy and need of this should however be discussed with the model creators since the models have been developed based on the functions that need to be tested for their independent work.

Based on this research there are some areas of improvement that have been discovered and that would be beneficial in order to execute additional scenarios. The OTM model is mainly lacking a regulator for adjusting the speed to accelerate and brake. This regulator would probably not demand much effort, in either code in MATLAB or syncing the model with a regulator built in blocks in Simulink. The regulator built in Simulink for the VTM model can also be used for preference. Another point of improvement would be to introduce a graphical simulation environment for OTM instead of using graphs as a visualization tool, as it is done today. Since the OTM model is made in MATLAB there is a possibility to use the same simulation environment as VTM, i.e., *Simscape Multibody*™ [10]. This solution is highly recommended because it makes it easier to analyze the behaviour of the system with higher graphical precision.

On the other hand, given the simplicity of the model the STM model has been seen as a potential model, since it has been managed to create and execute all the scenarios that were specified in this thesis work. An improvement for this model might be a further development of the model in a more dynamically way. At present, the STM model is kinematic described and important phenomenon as tire slip and actual behaviour that occurs on hills effected by all kind of resistive force are neglected. Which has been shown in scenarios 3 and 4. Another thing that should be taken more into consideration is to keep document about the model after every new updates regularly, as well as writing more comments to describe the implemented code. Since there are lots of files that are used and invoked between each other, it will be much easier for other people to get familiar with this model if there are clearly descriptions available. It will definitely save lots of time and an efficient working process would be obtained as well.

Another thing that should be kept in mind if there would be additional research regarding the performance of the models, is the measurement of fidelity. Instead of choosing a model to use as reference for all the other models in the comparison, it would be for the best to have real data to compare the models to. This of course depends on the availability of such data, but this should definitely be prioritized in order to base the research on reliable and realistic behaviour of the truck. The real data would surely be useful to many other projects within the organization as well.
This report has described the evaluation of models that have been used purely within the company with the creators having the purpose to use them for their individual research. Ultimately, as this report also has shown, all of the models have different strengths because of their different purposes. This could be used as an advantage in the work of creating one model that can be used for as many purposes as possible. When merging all the existing models into one big model, all the resources are concentrated to one place or model. This way the models can be used to the maximum and be available for everyone, while saving time and resources. This concept has already been in the talks within Volvo, but the approach of doing so has been unclear.

This report would be the first step to creating a merged model, since their functionality and strengths have been mapped out. The next step would be to choose the platform where the models would merge. This would probably be a challenge, both from a person point a view and a machine point of view. The models in this report are made in C++, MATLAB and Simulink, refer to Chapter 2.2. Working with software in the context of programming in pure code versus graphical coding is often a matter of taste, so the choice of software would probably depend on the person creating the model and their preference. Furthermore, this could make it hard for people working in one of the two choices to work in one of the other choices after many years of exclusively working with one of the choices. The trend of working exclusively with code, or vice versa, during many years is very obvious at Volvo. However, if the advantages of usage are worth breaking from habits then surely people could adapt. In a machine point of view it could be beneficial going from MATLAB/Simulink to code in C++ since there are toolboxes in MATLAB generating code out of models in Simulink. The Simulink® Coder™ toolbox in MATLAB generates standalone C and C++ code from Simulink models for deployment in a wide variety of applications[11]. It would be easier to convert the functionality into one platform using this approach.

The models which have been evaluated in this report all have one common denominator - they are all made internally within Volvo. Another alternative, instead of creating one big model using the existing models, is to use external models. There are many established companies with the purpose of providing models on the market. Volvo has been in contact with one of these companies, an Austrian company going by the name AVL.

We had the opportunity to test the AVL software at the end of the master thesis work. The software has shown to be on a profoundly higher level, in comparison to the internal models at Volvo, with regards to functionality, graphical user interface and simulations. Most important, the AVL software manages to perform all of the scenarios generated in this research, something which only VTM manages to do from the internal models. Additionally, corresponding logs and graphs are generated simultaneously. However, the complexity of the model exceeds its high achieving software since it takes time to get familiar with the software and generation of scenarios. On top of that, AVL has a very helpful support which quickly replies to any problems that might occur, as well as documentation with detailed user instructions. Therefore, AVL is definitely a trace worth looking into in the quest of finding a model which covers most situations that occur when driving a truck.

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