Vehicle Dynamics Testing in Advanced Driving Simulators Using a Single Track Model

Examensarbete utfört i Fordonssystem vid Tekniska högskolan vid Linköpings universitet av Jonas Thellman

LiTH-ISY-EX--12/4589--SE
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Linköping, 1 July, 2012
**Sammanfattning**

The purpose of this work is to investigate if simple vehicle models are realistic and useful in simulator environment. These simple models have been parametrised by the Department of Electrical Engineering at Linköping University and have been validated with good results. The models have been implemented in a simulator environment and a simulator study was made with 24 participants. Each test person drove both slalom and double lane change manoeuvres with the simple models and with VTI’s advanced model. The test persons were able to successfully complete double lane changes for higher velocities with the linear tyre model compared to both the non-linear tyre model and the advanced model. The whole study shows that aggressive driving of a simple vehicle model with non-linear tyre dynamics is perceived to be quite similar to an advanced model. It is noted significant differences between the simple models and the advanced model when driving under normal circumstances, e.g. lack of motion cueing in the simple model such as pitch and roll.

**Nyckelord**

vehicle simulator, single track model, vehicle dynamics, magic formula, relaxation length, double lane change
Abstract

The purpose of this work is to investigate if simple vehicle models are realistic and useful in simulator environment. These simple models have been parametrised by the Department of Electrical Engineering at Linköping University and have been validated with good results. The models have been implemented in a simulator environment and a simulator study was made with 24 participants. Each test person drove both slalom and double lane change manoeuvres with the simple models and with VTI’s advanced model. The test persons were able to successfully complete double lane changes for higher velocities with the linear tyre model compared to both the non-linear tyre model and the advanced model. The whole study shows that aggressive driving of a simple vehicle model with non-linear tyre dynamics is perceived to be quite similar to an advanced model. It is noted significant differences between the simple models and the advanced model when driving under normal circumstances, e.g. lack of motion cueing in the simple model such as pitch and roll.

Sammanfattning

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Jonas Thellman, a warm summer day in Linköping 2012
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Nomenclature

$\alpha_f$  Front wheel slip angle
$\alpha_r$  Rear wheel slip angle
$\delta_f$  Angle at front wheel
$\delta_{stw}$  Steering wheel angle
$\mu$  Friction coefficient
$\Omega_z$  Yaw rate
$\sigma$  Relaxation length
$a_X$  Vehicle longitudinal acceleration
$a_Y$  Vehicle lateral acceleration
$B_i$  Magic formula parameter for front/rear wheel
$C$  Magic formula shape factor
$C_{\alpha_f}$  Front wheel cornering stiffness
$C_{\alpha_r}$  Rear wheel cornering stiffness
$E_i$  Magic formula curvature factor
$F_{x,f}$  Lateral force on front wheel
$F_{x,r}$  Longitudinal force on rear wheel
$F_{y,f}$  Lateral force on front wheel
$F_{y,r}$  Lateral force on rear wheel
$F_{z,f}$  Normal force on front wheel
$F_{z,r}$  Normal force on rear wheel
$g$  Gravity constant
$I_k$  Steering wheel ratio
\( I_z \)  \hspace{0.5cm} \text{Inertia about z-axis}

\( k_1 \)  \hspace{0.5cm} \text{Self align torque and lateral force ratio before } M_{\text{max}}

\( k_2 \)  \hspace{0.5cm} \text{Self align torque and lateral force ratio after } M_{\text{max}}

\( l_f \)  \hspace{0.5cm} \text{Length from CoG to front wheel axle}

\( l_r \)  \hspace{0.5cm} \text{Length from CoG to rear wheel axle}

\( m \)  \hspace{0.5cm} \text{Mass of the vehicle}

\( m_0 \)  \hspace{0.5cm} \text{Self align torque offset}

\( M_{\text{align,tot}} \)  \hspace{0.5cm} \text{The approximated combined align torque for both front wheels}

\( M_{\text{align}} \)  \hspace{0.5cm} \text{Self align torque at the front wheel}

\( M_{\text{max}} \)  \hspace{0.5cm} \text{Maximum self aligning torque at the front wheel}

\( M_{\text{meas}} \)  \hspace{0.5cm} \text{Validation data used for the align torque}

\( M_{\text{stw,power}} \)  \hspace{0.5cm} \text{The steering wheel torque after power steering}

\( M_{\text{stw}} \)  \hspace{0.5cm} \text{Torque in steering wheel}

\( S_h \)  \hspace{0.5cm} \text{Magic formula slip offset}

\( S_v \)  \hspace{0.5cm} \text{Magic formula force offset}

\( x \)  \hspace{0.5cm} \text{Constant used to scale the steering wheel torque}

\( X_i \)  \hspace{0.5cm} \text{Slip angle with offset for front/rear wheel used in magic formula equation}

\( y_a \)  \hspace{0.5cm} \text{Magic formula convergence for big slip angles}

\( \alpha_i' \)  \hspace{0.5cm} \text{Delayed slip angle for front/rear wheel}
Notations

Abbreviations

VTI the Swedish National Road and Transport Research Institute
DLC Double Lane Change
ST Single Track model
UDP User Datagram Protocol
STD Standard deviation
MV Mean value
VW Volkswagen Golf
FEC Friction Ellipse Curve
FS Fordonssystem (Vehicular Systems)
ISY Institutionen för Systemteknik (Department of Electrical Engineering)
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Chapter 1

Introduction

This thesis was made in cooperation with The Swedish National Road and Transport Research Institute (VTI) and Fordonssystem (FS) at Linköping University.

1.1 Background and Purpose

VTI conducts research and development in several areas such as traffic, infrastructure and transport, involving several areas of expertise. They work for several major clients such as Vinnova, EU, automotive industry and more. The research is often conducted using driving simulations. Two simulator facilities are located in Linköping and one in Gothenburg. The simulators are an essential part in researching human behaviour in different driving situations. The current vehicle model has been developed for over 40 years and is quite comprehensive and complex.

Modelling passenger cars can be extensive and requires advanced measurements on the specific car. It is possible though to reduce the model to a so called single track (ST) model [4, 10, 13, 17] and consequently reducing the necessary measurements. Combining single track model with tyre dynamic models has proven to be effective and a good approximation of reality. It is shown in [9] that the ST model fits well with measured data when driving a double lane change (DLC). Nissan did a comprehensive study modelling different vehicles using ST model and test them in VTI’s first simulator. The test persons could actually pick out exactly which vehicle each model were modelled from.

But how well can the ST model with its tyre dynamics convey the feeling of real driving in a simulator? And how can one evaluate the results in an objective way? This study will investigate how the ST model 'feels' in different driving situations compared to an advanced model. The advantages of using a ST model could be several: simplicity, easy to understand and analyse, time and money saving, new vehicles could be implemented into the simulator environment with small efforts.

---

1 It should be noted that the test persons were experienced test drivers working at Nissan who had spent much time driving each vehicle
of measurements making the simulator much more potent and diverse.

### 1.2 Goal of Thesis

The goal of this thesis is to implement several vehicle models into VTI’s simulator and evaluate the realism behind the models by conducting a simulator study. This is done by comparing the ST model with its different tyre dynamics with VTI’s own model when driving DLC manoeuvres.

### 1.3 Limitations

There are obviously limitations to how well the models of passenger cars are compared to current models in the simulator and reality. Also the evaluation of the single track model is based on test drivers biased opinion of the driving experience; it is difficult to evaluate the feeling of vehicle model objectively. The driving scenario consist of a double lane change manoeuvre [1] and a slalom track.

### 1.4 Method

These models have been implemented in the simulator environment using SIMULINK together with an interface written in C++. The evaluation has been based on a questionnaire answered by test persons after driving the simulator with the single track models. Evaluating the handling of the models was based on the test persons own experience of driving a real car combined with driving VTI’s own vehicle model. There were also an empirical analysis of the tests comparing the measured data from [9] with the data given from the simulator when doing the tests.

### 1.5 Thesis Outline

**Chapter 1** A short introduction of the thesis.

**Chapter 2** A short description of the simulator.

**Chapter 3** A theoretical background of the vehicle models used throughout this thesis.

**Chapter 4** Implementation and validation of the vehicle models.

**Chapter 5** The analysis of the study forms and data collected from the tests.

**Chapter 6** Conclusions including results and future work.
Chapter 2

Simulator Environment

This chapter describes the simulator in which the study has been conducted. The simulator is located at VTI in Linköping where they have three different simulators; one testbench (Sim Foerst), one truck simulator (SIM II) and one passenger car simulator (Sim III). Only Sim III is used throughout this thesis.

2.1 Sim III (The Simulator)

Sim III is an advanced simulator with four degrees of freedom of motion. The simulator is equipped with a linear system for sideways movement and it can also pitch, yaw and roll. Figure 2.1 depicts yaw, pitch and roll movements.

The platform is also equipped with a vibration table simulating road irregularities. Figure 2.2 shows the simulator platform and Figure 2.3 shows the control panel where each simulator run is supervised.

It is possible to accelerate the linear system up to $\pm 8 \text{ m/s}^2$ and it has a maximum velocity of $\pm 4 \text{ m/s}$. It can pitch from -9 to +14 degrees and it can roll from -24 to +24 degrees. The yaw is limited to 90 degrees.
Figure 2.2: Simulator platform.

Figure 2.3: Control panel.
2.2 VTI’s Vehicle Model

VTI runs a vehicle model written in Fortran 90 in Sim III and is an advanced model developed for several decades. It can be described as being divided into two masses: an unsprung mass and a sprung mass. The sprung mass is the vehicle body excluding the wheels and suspensions. The roll and pitch models are separated from each other making it easy to calculate the vertical tyre load variations during cornering and acceleration respectively. The tyre dynamics are modelled using the Magic Formula tyre model as outlined on p.187-190 in [13]. The platform’s movements are based on signals received from the vehicle model. The cabin is a Saab 9-3 and the Fortran model is a parametrized Volvo S40 with all data measured and received from the manufacturer.

2.3 Limitations

There are several limitations which must be accounted for when evaluating the vehicle models given by ISY FS. There are safety systems which triggers for certain lateral velocities which might be triggered during heavy turning such as a DLC manoeuvre. In reality one might still be able to handle the vehicle even for velocities where the simulator triggers the safety system.

Another limitation is the advanced model itself. The Fortran model can’t be run with a friction coefficient higher than 0.8. The available data from [9] is based on a friction coefficient of 0.95. The Fortran model is based on a Volvo S40 hence having different mechanics than the modelled VW, e.g. different suspensions, mass properties, tyres, etc.
Chapter 3

Vehicle Modelling

This thesis will focus mainly on the single track model with linear lateral forces and lateral forces modelled by Magic Formula tyre model with and without force lag. This chapter describes the theory behind the ST model and the three different tyre models. Only the lateral dynamics are modelled and analysed since the longitudinal force can be neglected during a DLC manoeuvre. Figure 3.1 illustrates how the coordinates are defined for the vehicle.

![Figure 3.1: Direction and coordinates definitions.](image)

3.1 Single Track Model

The Single track model simplifies the modelling by approximating the wheel-pair with one wheel, see Figure 3.2. The ST model outputs lateral velocity/acceleration, yaw rate and slip angles. However shifts in the vehicle mass center and roll angle is not modelled, nor is the weight shifts between the wheels modelled.
By analysing Figure 3.2 we can derive Equations (3.1) - (3.3) describing the forces acting on the wheels and the rotation of the vehicle.

\[ \begin{align*}
    \rightarrow: m a_X &= F_{x,r} + F_{x,f} \cos \delta_f - F_{y,f} \sin \delta_f \\
    \downarrow: m a_Y &= F_{y,r} + F_{x,f} \sin \delta_f + F_{y,f} \cos \delta_f \\
    \leftarrow: I_z \dot{\Omega}_z &= l_f F_{x,f} \sin \delta_f - l_r F_{y,r} + l_f F_{y,f} \cos \delta_f
\end{align*} \] (3.1) (3.2) (3.3)

The accelerations \( a_X \) and \( a_Y \) can be written, as derived on p. 387 in [17], as:

\[ \begin{align*}
    a_X &= \dot{v}_x - v_y \dot{\Omega}_z \\
    a_Y &= \dot{v}_y + v_x \dot{\Omega}_z
\end{align*} \] (3.4) (3.5)

Combining Equations (3.1) - (3.3) with (3.4) - (3.5), we get:
\[ \dot{v}_x = \frac{1}{m} (F_{x,r} + F_{x,f} \cos \delta_f - F_{y,f} \sin \delta_f) + v_y \Omega_z \]  
(3.6)

\[ \dot{v}_y = \frac{1}{m} (F_{y,r} + F_{x,f} \sin \delta_f + F_{y,f} \cos \delta_f) - v_x \Omega_z \]  
(3.7)

\[ \dot{\Omega}_z = \frac{1}{I_z} (l_f F_{x,f} \delta_f + l_f F_{y,f} - l_r F_{y,r}) \]  
(3.8)

To find the equations for the slip angles at the front and rear wheel one can use basic trigonometry. This gives:

\[ \tan \alpha_r = \frac{I_r \Omega_z - v_y}{v_x} \]  
(3.9)

\[ \tan(\delta_f - \alpha_f) = \frac{v_y + l_f \Omega_z}{v_x} \]  
(3.10)

### 3.2 Tyre Model

Having a tyre model for both the front and rear tyre is necessary for solving Equations (3.6) - (3.8) since the lateral and longitudinal forces are derived from the wheels, see p. 62 in [13]. This study focuses on a linear tyre model and a non-linear tyre model called Magic Formula with and without a force lag (relaxation length).

#### 3.2.1 Linear model

The simplest and most basic way to model tyre dynamics is using a linear relationship between the lateral force and the slip angle. This model works well at low slip angles but fails to model the eventual saturation in the lateral force, see Figure 3.4 where both the linear model and the non-linear model is shown. The lateral forces acting on the wheels using linear tyre dynamics model is described in Equations (3.11) - (3.12).

\[ F_{y,f} = C_{\alpha_f} \alpha_f \]  
(3.11)

\[ F_{y,r} = C_{\alpha_r} \alpha_r \]  
(3.12)

#### 3.2.2 Magic Formula

Magic Formula models the non-linear effects of the tyre, i.e. the saturation of the lateral force and the subsequently convergence to \( y_a \), see Figure 3.4. The magic formula tyre model is a mathematical curve fit to empirical tyre measurements.
and found to be [3, 13]:

\[ F_{y,i} = \mu F_{z,i} \sin \left( C \arctan \left( B_i X_i - E_i \left( B_i X_i - \arctan \left( B_i X_i \right) \right) \right) \right) + S_v \]  

\[ X_i = \alpha_i + S_h \]  

\[ B_i = \frac{C \alpha_i}{C \mu F_{z,i}} \]  

\[ F_{z,f} = \frac{l_r}{l_f + l_r} mg, \quad F_{z,r} = \frac{l_f}{l_f + l_r} mg \]  

for \( i = r, f \) representing rear and front wheel. Figure 3.4 shows the Magic Formula curve and interprets the parameters. \( C \) is a shape factor defining the shape of the curve, \( \mu F_{z,i} \) is the peak of the curve and \( E_i \) is the curvature factor defining the shape of the curve after the peak \( \mu F_{z,i} \) is reached.

![Figure 3.4: Velocities and moments acting on single track model taken from [7].](image)

### 3.2.3 Relaxation length

One can also introduce a force lag, which models the time it takes to develop the force on the tyre for a given slip angle. This can be done by introducing a so called relaxations length \( \sigma \) and model the slip angle as [13, p. 527]:

\[ \alpha_i' = -\frac{v_x}{\sigma} \left( \alpha_i' + \alpha_i \right), \quad i = f, r \]  

where \( \alpha_i' \) is the new delayed slip angle. The relaxation length is the distance the wheel has travelled during the time it takes to develop the lateral force on the wheel.
3.3 Modelling Volkswagen GOLF V

A Volkswagen (VW) was modelled according to measurements carried out at the Department of Electrical Engineering, Linköping University, using Equations (3.6) - (3.17) with values in Tables 3.1a - 3.1b.

Table 3.1: Vehicle and tyre parameters for a VW.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>1425 kg</td>
</tr>
<tr>
<td>$l_f$</td>
<td>1.03 m</td>
</tr>
<tr>
<td>$l_r$</td>
<td>1.55 m</td>
</tr>
<tr>
<td>$I_z$</td>
<td>2500 kgm$^2$</td>
</tr>
<tr>
<td>$I_k$</td>
<td>0.0628</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{\alpha,f}$</td>
<td>108.5 kN/rad</td>
</tr>
<tr>
<td>$C_{\alpha,r}$</td>
<td>118.6 kN/rad</td>
</tr>
<tr>
<td>$C$</td>
<td>1.455</td>
</tr>
<tr>
<td>$\mu^1$</td>
<td>0.8</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.4 m</td>
</tr>
</tbody>
</table>

Notice that several parameters from Equations (3.13) - (3.16) are left out in Table 3.1b. The vertical and horizontal offsets are ignored since the measured data in [9] suggests the curve going through origo. The curvature factor $E_i$ hasn’t been parameterized since there isn’t any measured data within that area of the curve and thus setting $E_i = 0$. The relationship between the angle $\delta_f$ and the steering wheel angle is given by Equation (3.18).

$$\delta_f = I_k \delta_{stw}$$  \hspace{1cm} (3.18)\[1\]

$\delta_{stw}$ is the steering wheel angle in degrees and $I_k$ is the steering wheel ratio.

Throughout this thesis, a simpler definition is used to separate the four different models, see Table 3.2.

Table 3.2: Definition of the different vehicle models.

<table>
<thead>
<tr>
<th>Definition</th>
<th>Number representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST with linear tyre dynamics</td>
<td>1</td>
</tr>
<tr>
<td>ST with magic formula</td>
<td>2</td>
</tr>
<tr>
<td>ST with magic formula/linear$^2$ tyre dynamics and</td>
<td>3</td>
</tr>
<tr>
<td>force lag</td>
<td></td>
</tr>
<tr>
<td>VTI’s vehicle model</td>
<td>4</td>
</tr>
</tbody>
</table>

$^1$This value differs from [9], which is explained in Section 2.3

$^2$Model 3 should have been only magic formula with force lag, it is explained in Section 5.2 why it isn’t
Chapter 4

Implementation of Vehicle Model

The goal of this thesis is to evaluate how a simple model compares to a more advanced model, a simple model being easier to understand and analyse. Throughout this chapter equations are kept simple to keep the theory easy to understand and easy to use. There are several things that needs to be added before the single track model with its tyre dynamics can be run in the simulator environment described in Chapter 2, thus this chapter extends the described model in Chapter 3. The modelling is based on very basic relationships, some only empirical derived. The theme throughout Chapter 4 - 5 is keeping everything as simple as possible.

4.1 Implementing single track model

When driving a DLC according to [1] the only longitudinal force acted on the vehicle is yielded by the engine braking. However the clutch is disengaged during a DLC manoeuvre in [9]. Combining this with neither braking force or acceleration, one can neglect the longitudinal forces acting on the vehicle. It is also assumed that \( \delta_f \) is small leading to the use of the small angle approximation [16]. This gives Equations (4.1) - (4.2).

\[
\dot{v}_y = \frac{1}{m} (F_{yr} + F_{yf}) - v_x \Omega_z \tag{4.1}
\]

\[
\dot{\Omega}_z = \frac{1}{I_z} (l_f F_{yf} - l_r F_{yr}) \tag{4.2}
\]

Here \( F_{yr} \) and \( F_{yf} \) depends on which tyre dynamics model we currently are using, see Section 3.2. The tyre dynamics models are all depending on the slip angle, thus it is necessary to solve Equations (3.9) - (3.10). Using the small angle approximation once again gives the Equations (4.3) - (4.4).
\[
\alpha_r = \frac{I_r \Omega_z - v_y}{v_x} \quad (4.3)
\]
\[
\alpha_f = \frac{\delta_f - v_y + l_f \Omega_z}{v_x} \quad (4.4)
\]

The slip angle are inputs to the tyre models yielding a lateral force on both wheels.

### 4.1.1 Implementation in SIMULINK

There are several reasons for implementing the vehicle models in SIMULINK. It is easy to solve differential equations and changing constants is easy and can be done outside the SIMULINK schematics and it is easy to understand. The differential equations were solved using the integrator block [11]. Figures 4.1 - 4.2\(^1\) shows the SIMULINK implementation of calculating \(\Omega_z\) and \(v_y\).

![Figure 4.1: Implementation of \(\Omega_z\).](image1)

![Figure 4.2: Implementation of \(v_y\).](image2)

Implementing the force lag in model 3 requires some calculations of Equation (3.17). Using Laplace transform [15] Equation (3.17) becomes:

\[
\dot{\alpha}'_i = -\frac{v_x}{\sigma} (\alpha'_i + \alpha_i) \implies \{\text{Laplace transform}\} \implies
\]
\[
\alpha'_{i}(s) = -\frac{1}{1 + \frac{\sigma}{v_x} s} \alpha_i(s) \quad (4.5)
\]

\(^1\)The saturation blocks are explained in Section 4.2.5
4.2 Extended Model

Equation (4.5) is identified as a first order transfer function between $\alpha'_i(s)$ and $\alpha_i(s)$ with a time constant $\frac{\sigma}{v_x}$. This is implemented in SIMULINK as a delay function with $\frac{\sigma}{v_x}$ as the input. However the first order transfer function in Equation (4.5) is only valid for constant $v_x$ since the Laplace transform used in Equation (4.5) assumes $v_x$ being time-independent. During the simulator study $v_x$ is approximately constant during the DLC manoeuvre making it possible to use this implementation for the simulator study.

4.1.2 Inputs and Outputs from SIMULINK

The platform on which the simulator is mounted on takes outputs from the models running in SIMULINK using xPC-target. However, since the single track model with its tyre dynamics has outputs limited only to yaw velocity/acceleration and lateral velocity/acceleration, there is no roll or vibrations when using the single track model. The motion cueing [6] is thus limited when driving the ST model compared to VTI’s own model. Table 4.1 summarizes the limitations of the motion cueing for the different models.

Table 4.1: Table comparing the limitations of motion cueing of the single track model with VTI’s current model.

<table>
<thead>
<tr>
<th>Motion Cueing</th>
<th>VTI</th>
<th>Single Track</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Pitch</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Vibrations</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Yaw</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Lateral movement</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The communication between the SIMULINK model and the rest of the simulator environment is handled by a C++ interface. This interface communicates with the xPC-target via UDP-protocol. The variables are then stored in a parameter map which the simulator platform reads and then executes its movement.

4.2 Extended Model

One very distinct property when driving a car is the inertia and torque of the steering wheel. As shown in [2] zero torque feedback makes driving almost impossible suggesting that adding a steering wheel torque is a necessity. Modelling the torque of the steering wheel involves concepts such as power steering and self aligning torque. However, since the single track model is quite limited, there is no possibility of modelling the steering wheel torque in this fashion. The self aligning torque is calculated by approximating the curves seen in Figure 4.3 with a linear relationship. The figure shows how the self aligning torque depends on both the normal load, cornering force and slip angle.
4.2.1 Self aligning torque

A simple way to find the self aligning torque is to approximate the graph in Figure 4.3 by two linear equations which depends on the normal load and a maximum self aligning torque. Equation (4.6) describes the two lines which approximate the self aligning torque. $k_1$ and $k_2$ are tuned such that they describe the accurate normal load of the front wheel tyre.

$$M_{align} = \begin{cases} k_1 F_{y,f} & |F_{y,f}| \leq M_{max} \\ -k_2 F_{y,f} + m_0 & |F_{y,f}| > M_{max} \end{cases}$$

(4.6)

Figure 4.4 shows the approximated self aligning torque. Here the lines are tuned to follow a normal load of about 4.7 kN and have a maximum self aligning torque of 60 Nm. It is important to understand that the self aligning torque on the front wheels in reality might differ between the left and right wheel. Since the
4.2 Extended Model

single track model only models one wheel in the front one can simply approximate
the wheel pair in the front by multiplying the approximated self aligning torque
with two, yielding Equation (4.7).

\[ M_{\text{align,tot}} = 2M_{\text{align}} \]  

(4.7)

Figure 4.4: Approximation of the align torque.

Validating \( M_{\text{align,tot}} \) is done by measuring \( M_{\text{align,tot}} \) for VTI’s model in the
simulator environment and duplicating the exact same scenario for the ST model
using all three different tyre models. Figure 4.5 shows the different models’ total
self aligning torque where data collection have been made during heavy turning,
i.e. driving slalom and performing DLC in the simulator for velocities ranging
from 30-100 km/h. This shows that Equation (4.7) is quite good despite the
non-physical relationship.
Figure 4.5: The approximated total self aligning torque.
4.2 Extended Model

4.2.2 Steering wheel torque

The relationship between $M_{\text{align,tot}}$ and the steering wheel torque without power steering\(^1\) can be modelled as:

$$M_{\text{stw}} = I_k M_{\text{align,tot}}$$

(4.8)

where $I_k$ is the same ratio as in Equation (3.18). However, if a comparison is to be made between VTI’s model and the single track model, one must add power steering to the steering wheel since power steering plays a major role in the driving experience. Adding power steering consists of modelling different mechanics as described on p. 8 in [8] and lies outside the scope of this thesis. Instead we make a linear assumption between $M_{\text{stw}}$ and the steering wheel torque after the effects of the power steering, $M_{\text{stw, power}}$. One method of finding this relationship is to use the least square method on Equation (4.9).

$$\min_x |M_{\text{stw}}x - M_{\text{meas}}|$$

(4.9)

$M_{\text{meas}}$ is the measured steering wheel torque with active power steering. The best way of finding this relationship for the VW is to measure the steering wheel angle and the steering wheel torque and then solve Equation (4.9). Due to lack of resources such as measuring equipment another way have been approached. Instead $M_{\text{meas}}$ is given by the simulator using VTI’s model. The velocity and steering wheel angle inputs made when driving VTI’s model is then used as input to the ST model and one can solve Equation (4.10).

$$x = \frac{\sum_{j=1}^{3} \min_{x_j} |M_{\text{stw,j}}x_{j} - M_{\text{meas}}|}{3},$$

(4.10)

where $j$ represents the different models as defined in Table 3.2 making $x$ the mean of $x_j$.

The result of Equation (4.10) is shown in Figure 4.6, where data collection have been made during heavy turning, i.e. driving slalom and performing DLC in the simulator for velocities ranging from 30-100 km/h. The measured data when the vehicle is standing still is removed. Doing so neglects the possibility of modelling $M_{\text{stw, power}}$ for scenarios which isn’t relevant to this thesis, modelling $M_{\text{stw, power}}$ during heavy turning is the priority.

\(^1\)Power steering reduces the torque in the steering wheel making it easier to turn
Even though the $M_{stw,power}$ is based on coarse approximations of both the power steering and the total align torque of the front wheels, it still clearly follows the measured data.

4.2.3 Longitudinal force

Although the longitudinal force is neglected in Section 4.1 it is still necessary to implement a longitudinal driving force to make the simulator drivable. Without a longitudinal force the velocity must be encoded in the driving scenario making it a tedious work. By adding a simple engine given by VTI into the ST model acceleration and deceleration is possible. Figure 4.7 shows the transient behaviour of the simple engine during a DLC manoeuvre compared to measured data with an initial velocity of 59 km/h.
Although adding a generic engine is not vehicle specific, it will not effect the outcome of the DLC manoeuvre when driving the ST model very much since the longitudinal effects during a DLC manoeuvre is neglectable. This is validated in Figures 4.8 - 4.9 where the slip angles, yaw rate and lateral acceleration from simulations made with and without engine is compared with data taken from [9]. The difference in the outcome with and without an engine model is neglectable, thus confirming that the longitudinal force can be neglected throughout a DLC manoeuvre.
Figure 4.8: Simulated slip angles with and without engine.

Figure 4.9: Simulated yaw rate and lateral acceleration with and without engine.
4.2 Extended Model

4.2.4 Friction Ellipse Curve

The friction ellipse curve (FEC) on p. 51-52 in [17] is a simple way of limiting the forces acting on the wheel. It is depicted in Figure 4.10. The purpose of the FEC is to couple the lateral and longitudinal forces acting on the wheel according to Equation (4.11).

\[
\left( \frac{F_y}{F_{y,0}} \right)^2 + \left( \frac{F_x}{F_{x,0}} \right)^2 = 1 \Rightarrow F_y = \sqrt{1 - \left( \frac{F_x}{F_{x,0}} \right)^2} F_{y,0} \tag{4.11}
\]

\( F_{y,0} \) is the lateral force without the FEC. Thus solving \( F_y \) from Equation (4.11) gives a new lateral force which is bounded by the longitudinal force. This is especially relevant when turning during braking or accelerating.

![Figure 4.10: The force ellipse curve.](image)

4.2.5 Instabilities and Singularities

Testing the models 1-3 with limited inputs, as in [9], increases the chance of leaving the system 'unprotected' meaning that inputs yielding instabilities is not observed. In a simulator environment it is essential to be able to drive the car in all kinds of velocities and not being limited to certain inputs. One example of this is the zero-velocity singularity which were not considered in [9]. There arises singularity both in \( \sigma_{v_x} \) from Equation (4.5) and in Equations (4.3) - (4.4) as \( v_x \to 0 \). To avoid this a lower limit to \( v_x \) has been added. There is also an upper limit added, modelling the limit of the longitudinal velocity, yielding \( v_x \in [0.01 \ 50] \) [m/s]. There was also residues in the system, meaning the system never ending to a zero-state. Thus a resetting level was inserted to several signals listed in Table 4.2 to avoid further potential instabilities. If e.g. \( |\alpha_f| < 0.0001 \) then it is set to zero and so forth.
Table 4.2: Reset levels.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Reset level</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{v}_y$ [m/s²]</td>
<td>±0.01</td>
</tr>
<tr>
<td>$\alpha_f$ [rad]</td>
<td>±0.0001</td>
</tr>
<tr>
<td>$\alpha_r$ [rad]</td>
<td>±0.0001</td>
</tr>
<tr>
<td>$\dot{\Omega}_z$ [rad/s²]</td>
<td>±0.01</td>
</tr>
</tbody>
</table>

4.2.5.1 Delay function

It was noticed strange behaviours such as oscillations in the forces and slip angles after simulating a DLC manoeuvre with model 3 in Table 3.2. Figure 4.11 shows the resulting error. The reason for this behaviour is most likely due to the time delay function in SIMULINK. It was noted that the oscillations were directly related to $\sigma$ and $v_x$, leaving a reason to believe that the effective time delay was the cause for this. However, since time was a limit it was solved by simply disengage the delay function when reaching a velocity lower of 8 m/s (28.8 km/h). Figure 4.12 shows the same scenario without oscillations. Worth mentioning is that the delay can not be lower than the step time in SIMULINK which is 1 ms. A lower limit of 0.001 was added to the effective delay time, however since the delay is disengaged for low velocities this has no impact since $\frac{\sigma}{v_x} > 0.001$ when engaging the delay function.

Figure 4.11: Oscillations in model 3.
4.2 Extended Model

4.2.5.2 Magic Formula

When the system was running with a more aggressive steering scenario offline, i.e. simulations with given inputs, it was noted that the system ended up in a state where the lateral velocity grew unreasonable high and would very slowly return to zero when running model 2. The most likely cause for this discrepancy is that there is not any force counter-acting the lateral force. Normally both friction and longitudinal force together with air resistance would stop the lateral force from growing unreasonable high. By adding saturations on every input and output in the system the phenomenon disappeared. The saturations values are depended on what values seems reasonable and somewhat higher than the measured data. Table 4.3 shows all saturation for each signal.

Figure 4.12: Disengaged delay time for velocities under 8 m/s.
Table 4.3: Saturation levels.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_y$ [m/s]</td>
<td>-3</td>
<td>3</td>
</tr>
<tr>
<td>$\dot{v}_y$ [m/s$^2$]</td>
<td>-8</td>
<td>8</td>
</tr>
<tr>
<td>$v_x$ [m/s]</td>
<td>0.01</td>
<td>50</td>
</tr>
<tr>
<td>$\alpha_f$ [rad]</td>
<td>-0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>$\alpha_r$ [rad]</td>
<td>-0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>$\Omega_z$ [rad/s]</td>
<td>-2</td>
<td>2</td>
</tr>
<tr>
<td>$\dot{\Omega}_z$ [rad/s$^2$]</td>
<td>-5</td>
<td>5</td>
</tr>
</tbody>
</table>

Magic formula model only

| $F_{y,f}$ [N] | -8000 | 8000 |
| $F_{y,r}$ [N] | -5500 | 5500 |

The reason for only bounding the lateral forces when running the MF model is that the calculations of the lateral forces in SIMULINK is separated from model to model, it would be preferable to only add saturations when running model 2. Figure 4.13 shows heavy turning without saturations and Figure 4.14 with saturations.
4.2 Extended Model

Figure 4.13: Model 2 when making heavy turning without any saturation.

Figure 4.14: Model 2 when making heavy turning with saturation.
Chapter 5

Simulator Study

The main purpose of this thesis is to compare a simple vehicle model with a more advanced model and evaluate the realism behind the simple vehicle model. We know that the ST model with Magic Formula seems to be very accurate in describing the slip angles, lateral forces and yaw rate. By doing a simulator study of the exact same scenario as in [9] one can compare how a person drives in real life with how a person would drive in real life with the ST model.

5.1 Driving scenario

The driving scenario consists of three parts. The first part is only exercise and lasts about ten minutes where the test person gets to drive slalom and also exercise the DLC manoeuvre. The second part consists of two slalom runs with a velocity of 40 km/h. The third part consists of several DLC manoeuvres. The last two parts are done in a similar fashion for all models listed in Table 3.2. The order of models 1-4 for each scenario is based on a balanced order (see Appendix C) [14]. The speed were maintained by the simulator during both scenarios.

5.1.1 Slalom Run

The purpose of doing a slalom run is to find out how realistic models 1-3 feels when driving under normal circumstances, i.e. moderate turning and velocities. This is done by driving a quite slow slalom and then ask questions about how realistic the test person thought it was and then compare the results with model 4. Figure 5.1 shows an overview of the slalom track. For this to give somewhat reasonable results we assume that model 4 is very close to real life driving. The test person is also asked if there was any significant difference from the previous vehicle model. Here the test person is specifically told that there are different vehicle models to be tested. The reason for this is to be able to ask the test person during the test if there were any noticeable differences between the models. After each slalom run
the test person was asked on how well they could control the vehicle model and how realistic it felt driving the model.

5.1.2 Double Lane Change Manoeuvre

The purpose of the DLC manoeuvres is to find out how realistic models 1-3 feels when driving under more extreme conditions. By comparing models 1-3 with both model 4 and measured data from a real driving scenario it is possible to analyse the results based on biased opinions and unbiased data. Figure 5.2 shows an overview over the DLC track.

One interesting aspect is to test how difficult the DLC manoeuvre is for model 1-3 and compare it to model 4. This is done by introducing a system which gradually increases the velocity of the model based on whether or not the test person successfully finished the DLC. This gives information if the models 1-3 behaves realistic in aggressive driving by looking at the maximum velocity for which the test person successfully completed DLC manoeuvre using model 4 and compare it with models 1-3. Table 5.1 shows the possible velocities for each model.
Table 5.1: Gradually increasing velocity levels.

<table>
<thead>
<tr>
<th>Velocity [km/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
</tr>
<tr>
<td>49</td>
</tr>
<tr>
<td>59</td>
</tr>
<tr>
<td>62</td>
</tr>
<tr>
<td>65</td>
</tr>
</tbody>
</table>

A successfully DLC manoeuvre is defined by not hitting a single cone during the whole manoeuvre and not triggering the simulator’s safety systems. The safety systems triggers when the lateral force input is too high. The test person has four attempts to successfully finish the DLC manoeuvre at the current velocity. A new model is running if the test person has failed four times in a row. The number of attempts are reset if the test person successfully finishes the DLC manoeuvre and moves on to a higher velocity. After either four failed attempts or a successfully attempt the test person answers how difficult the DLC for the current velocity was. Before moving on to the next vehicle model the test person answers how difficult the DLC manoeuvres were as a whole and how realistic the driving felt.

During the DLC manoeuvres the test person is to be unaware of the model changes. This is to reduce the possibility of influence the test person’s answer. It is important that the test person does not search for possible differences between the vehicle models but rather notices that something is strange and/or different. As far as the test person is concerned, the purpose of repeating the DLC manoeuvres is to gather data which is to be analysed and compared to the real DLC driving.

5.1.3 Participants

There were a total of 24 test persons ranging from ages 19-32, all with drivers license. Amongst these were two women. The average computer experience of the test persons was 5, where 1 is no experience at all and 7 is very experienced. They were told that the purpose of the study is to evaluate how a person drives in the simulator compared to a real car. Afterwards they were told about the real purpose and was asked to complement the form seen in Appendix A.

5.2 Results of the Questionnaires

A bug was found late in the study with the result of model 3 in fact was model 1 with a force lag. As such model 3 in Table 3.2 is a mixture of ST model with linear tyre dynamics with force lag and ST model with Magic Formula tyre dynamics with force lag. This makes it difficult to draw any conclusions of how adding a force lag affects the driver. It is still listed in the following tables though for completeness.
The standard deviation (STD) and mean value (MV) has been calculated using the form described on p. 228 in [5].

### 5.2.1 Slalom

Table 5.2 shows how realistic model 1-4 felt during slalom. Here 1 is not realistic at all and 7 is very realistic.

<table>
<thead>
<tr>
<th>Model number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV</td>
<td>5.4318</td>
<td>5.7500</td>
<td>5.2727</td>
<td>5.6364</td>
</tr>
<tr>
<td>STD</td>
<td>0.9549</td>
<td>0.7520</td>
<td>1.0771</td>
<td>1.2553</td>
</tr>
</tbody>
</table>

Table 5.3 summarize how well the test person could control the vehicle model. Here 1 is not very good and 7 is very good.

<table>
<thead>
<tr>
<th>Model number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV</td>
<td>6.9091</td>
<td>6.7727</td>
<td>6.5000</td>
<td>6.7500</td>
</tr>
<tr>
<td>STD</td>
<td>0.2942</td>
<td>0.5284</td>
<td>0.8591</td>
<td>0.5289</td>
</tr>
</tbody>
</table>

Comparing models 1 and 2 with model 4 in Tables 5.2-5.3 seems to suggest that model 2 have the same properties as model 4 when it comes to moderate driving while model 1 seems to feel not as realistic as model 2 and 4.

### 5.2.1.1 Questionnaire

When asked if there were any noticable differences between the models the test person usually noticed the differences of models 1-3 and 4 as listed in Table 4.1. 33% felt more bumps when driving model 4. Only 17% of the participants noticed the differences in steering wheel torque. 16.7% thought model 1-3 slided more in lateral direction, where 12.5% thought model 1 slided most. This seems strange since one would think non-bounded lateral force would slide less. However the feeling of sliding could be interpreted as lack of bumps in the road when driving model 1-3.
5.2 Results of the Questionnaires

5.2.2 DLC

There is a clear trend showing in Table 5.4 that model 2 and 4 are on the same level of difficulty when it comes to handling the DLC manoeuvre. Table 5.5 shows how difficult each DLC manoeuvre were for all models, where 1 is very difficult and 7 is very easy. The results from these tables suggests that linear tyre dynamics makes heavy turning much easier when comparing to more complex tyre dynamics.

Table 5.4: Number of successfully DLC manoeuvres for each model.

<table>
<thead>
<tr>
<th>Velocity [km/h]</th>
<th>Model number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4</td>
</tr>
<tr>
<td>36</td>
<td>22 20 22 21</td>
</tr>
<tr>
<td>49</td>
<td>18 19 14 18</td>
</tr>
<tr>
<td>59</td>
<td>15 5 12 12</td>
</tr>
<tr>
<td>62</td>
<td>11 1 11 3</td>
</tr>
<tr>
<td>65</td>
<td>6 0 9 0</td>
</tr>
<tr>
<td>68</td>
<td>1 0 1 0</td>
</tr>
<tr>
<td>71</td>
<td>0 0 0 0</td>
</tr>
</tbody>
</table>

Table 5.5: Mean value difficulty of the DLC manoeuvre.

<table>
<thead>
<tr>
<th>Velocity [km/h]</th>
<th>Model number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4</td>
</tr>
<tr>
<td>36</td>
<td>5.7727 5.4545 5.5455 5.9091</td>
</tr>
<tr>
<td>49</td>
<td>4.5455 4.5 4.0909 4.0476</td>
</tr>
<tr>
<td>59</td>
<td>4.0556 2.8421 3.5714 2.8889</td>
</tr>
<tr>
<td>62</td>
<td>3.3333 2.2 3.9167 2.3333</td>
</tr>
<tr>
<td>65</td>
<td>3.1818 2 3.6364 1.6667</td>
</tr>
<tr>
<td>68</td>
<td>2 0 1.6667 0</td>
</tr>
<tr>
<td>71</td>
<td>2 0 1 0</td>
</tr>
</tbody>
</table>

Table 5.6 shows the MV and STD of how realistic the models felt during the DLC manoeuvre. Here 1 is not realistic at all and 7 is very realistic. The interesting results here is that linear tyre dynamics seems to feel more realistic during heavy turning and that model 2 and model 4 is almost identical.
Table 5.6: MV and STD of how realistic each model feels.

<table>
<thead>
<tr>
<th>Model number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV</td>
<td>5.4091</td>
<td>4.9773</td>
<td>5.3636</td>
<td>4.9545</td>
</tr>
<tr>
<td>STD</td>
<td>1.0538</td>
<td>1.1389</td>
<td>0.9021</td>
<td>1.2141</td>
</tr>
</tbody>
</table>

Table 5.7 shows how difficult each model was during the DLC manoeuvres, 1 being very difficult and 7 very easy. Model 2 is still following model 4 quite closely. Comparing Table 5.6 with Table 5.8 shows some interesting results. It would seem that higher realism yields higher velocities for successful DLC manoeuvres. The reason for this could be several; either the test persons thought that an easy DLC manoeuvre is directly related to how realistic the model is, or just coincidence. In either case it would seem that it is easier to maintain control of the vehicle when driving aggressive using linear tyre dynamics.

Table 5.7: MV and STD of the total difficulty for each model.

<table>
<thead>
<tr>
<th>Model number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV</td>
<td>4.3636</td>
<td>3.6818</td>
<td>3.7273</td>
<td>3.8182</td>
</tr>
<tr>
<td>STD</td>
<td>1.0022</td>
<td>1.0414</td>
<td>0.8270</td>
<td>0.7799</td>
</tr>
</tbody>
</table>

Table 5.8: MV and STD of the highest successful velocity for each model.

<table>
<thead>
<tr>
<th>Model number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV</td>
<td>55.9091</td>
<td>49.6364</td>
<td>52.5909</td>
<td>52.5000</td>
</tr>
<tr>
<td>STD</td>
<td>10.9367</td>
<td>7.1284</td>
<td>13.6544</td>
<td>9.2929</td>
</tr>
</tbody>
</table>

5.2.2.1 Questionnaire

After the test persons were done with the whole test they were asked if they felt any noticeable differences when driving the DLC manoeuvres and what made the DLC difficult. The last question was added to get information on whether or
not the models themselves made it harder or if the underlying simulator platform was the reason for not successfully complete the DLC. 12.5% felt no differences at all during the DLC manoeuvres and once again 17% explicitly said there were differences in the steering wheel.

The more interesting result was the fact that only 8% felt the differences listed in Table 4.1 which was much less than when driving under normal circumstances. When asked about the difficulties with the DLC manoeuvre 42% explicitly expressed difficulties related to the simulator platform, e.g. not knowing where the edges of the car were or not knowing when to turn to avoid the corner cones.

5.3 Data Collection Analysis

The hypothesis is that if the vehicle models 1-3 are to be realistic then they should yield similar results as the data measured from real life driving. However one should note that model 4 is not a model based on a VW Golf which leads to differences in forces and velocities/accelerations. The most interesting data is generated from models 1-3. All the plots in this section are based only on successful DLC manoeuvres. Data plots for the initial velocities 36 km/h and 49 km/h can be studied in Appendix B.

5.3.1 Saturation levels

It was added saturations on several variables in the SIMULINK scheme in Section 4.2.5 to avoid unreasonable high lateral velocity. As a consequence the saturation levels can be reached when driving quite aggressive. Figures 5.3a - 5.3b shows the slip angles for all participants through the whole driving session together with the saturation levels.

![Slip Angle Plots](image)

Fig. 5.3

Only a handful of attempted DLC manoeuvres actually reaches the saturation levels for the slip angles thus implicating that the implemented saturation levels only effects a small portion of the DLC manoeuvres.
5.3.2 Trajectory

The trajectory for each successful DLC manoeuvre for $v_x = 59$ km/h is shown in Figure 5.4. It seems the trajectory of each successful DLC manoeuvre for all models 1-4 is very similar to each other. There is almost none deviation in the trajectory between the models when switching lane.

![Figure 5.4: Trajectory for 59 km/h.](image)
5.3 Data Collection Analysis

5.3.3 Lateral acceleration

Figure 5.5 shows the lateral acceleration. The magnitude of the acceleration in model 2 and 4 is on the same level whereas model 1 is somewhat higher. There are more outliers in model 1 than in both model 2 and 4 implicating that model 2 gives better lateral acceleration during aggressive manoeuvres. However there is significant more data when driving model 1 which can be the cause of the outliers.

![Figure 5.5: Lateral acceleration for 59 km/h.](image-url)
5.3.4 Steering wheel angle

Figure 5.6 shows the steering wheel angle. Here the differences in amplitude between model 1 and 2 is not as noticeable as the differences in the lateral accelerations. Once again there are more outliers in model 1 than in model 2 and 4.

Figure 5.6: Steering wheel angle for 59 km/h.
Chapter 6

Conclusions

This chapter summarizes the results of the study made with 24 participants. It is for various reasons difficult to make an objective analysis of the study since the experience of driving a car is highly individually. It is possible though to draw some conclusions based on analysis of the participants opinions of the driving scenarios. The conclusions are drawn only from two driving scenarios: non-aggressive slalom manoeuvre and double lane change manoeuvre.

6.1 Simplified Model Versus Advanced Model

One important question this thesis was to answer was: How does the single track model (ST) with different tyre dynamics behave compared to an advanced model and do they behave realistic? It is however difficult to answer this question. There are several obstacles discussed throughout this thesis which add uncertainty to the data presented. Comparing data from real life driving with data given by the simulator study is quite tricky. The friction coefficient had to be slightly smaller since the advanced model could not be modelled for $\mu = 0.95$. The velocity of the VW differed from reality and simulation since the ST model does not model any engine, making the DLC manoeuvres for low velocities longer in simulation. The cabin of the simulator is actually a Saab, which is about 10 cm wider than the VW modelled. This leads to a wider DLC track compared to when driving the VW in real life, since the width of the DLC track is directly related to the width of the car. Even if these obstacles would be better conditioned it would still be difficult making objective comparisons since the measured data is highly subjective, meaning the result would differ depending on who actually drove the car.

We can however draw some conclusions by comparing the ST model with VTI’s advanced model. This actually shows some significant difference between model 1, the linear tyre dynamics, and model 2, the Magic Formula tyre dynamics. The test persons successfully completed DLC manoeuvre for higher velocities when driving model 1 compared with model 2 and VTI’s own model. It would seem that linear
tyre dynamics makes driving, at least for a DLC, easier than in real life. But it also seems to suggest that the Magic Formula tyre makes driving more difficult and similar to model 4. Comparing the amplitude, of e.g. the lateral acceleration, during the DLC gives that model 2 and 4 lies around the same amplitude, whereas model 1 lies higher. This is also true for the steering wheel angle.

Analysing the questionnaire where test persons answered on how real each model felt, there isn’t much difference between each model, especially for non-aggressive driving. Now, even though statistically there isn’t much difference between the models, this implies that models 1-3 feels as real as model 4. Another interesting result was that the differences of the models listed in Table 4.1 seemed to have less impact during aggressive driving compared to non-aggressive driving. Many experienced 'bumps' during the slalom scenario while no one even mentioned 'bumps' during the DLC scenario. Of course 'bumps' can be interpreted in different ways, although it is highly likely to be related with vibrations and/or roll of the simulator platform.

There are disadvantages using a ST model. The inability to roll is noticeable under normal driving conditions. Even so people who tried the ST model thought it to be quite realistic, although a portion thought the steering wheel torque was a bit off. Since comparisons made with the VTI’s more complex and advanced vehicle model yielded no significant difference when using Magic Formula tyre dynamics, model 2 is actually quite robust and effective. It is also easy to understand and easy to change. Using the ST model one could easily add new vehicle models into the simulator if given the necessary parameters. It also yields similar data outputs as model 4 implicating that it does 'run' realistic even though the 'feeling' might be a bit wrong.

6.2 Discussion

During the implementation of the models in SIMULINK it was found several unexpected behaviours as discussed in Chapter 4. A result of this was adding several saturations. However, later tests showed that not all signals needed to be saturated. One possible explanation for not observing this in the early phase of this thesis is that the signals were not reset to zero for low values and could perhaps contribute to instabilities. The actual reason for this instability was the arctan function in SIMULINK. Tests made after the simulator study showed that only saturating $\dot{v}_y$ and $v_y$ was enough to remove the instability when driving model 2. As for the reason why it is still unknown and could also be worth investigating in more detail.

It was noted that using a relaxation length, model 3, resulted in heavy oscillations for low velocities. This was directly related to $\sigma$ and $v_x$. The solution was to simply disengage the delay function in SIMULINK when reaching velocities below 8 m/s. The cause of the oscillations was the delay function in SIMULINK. This
could also be worth investigating more, perhaps circumvent the delay function and substitute it with an S-function [12].

There is a problem with the measured data from real life driving not being very objective. Having several persons driving DLC manoeuvres and collecting data would make it possible to compare trajectories for the simulated DLC with real life DLC trajectory. Of course time and resources for doing broader tests would obviously get out of hand quite fast, so whether or not it would actually be worth doing should be carefully analysed.

The theme of this thesis was to keep things as simple as possible. This lead to adding a coarse approximation of the steering wheel torque as discussed in Chapter 4. 17% of all the participants felt that the steering wheel torque felt odd, both when driving slalom and executing a DLC. It would seem that the steering wheel torque is a big factor when evaluating how real a vehicle model feels. A more complex model of the steering wheel torque would probably make a big difference to the driving experience.

Using a simplified model is valid and reasonable for certain scenarios, e.g. DLC. It is certainly useful when the effects of roll and pitch is neglectable. Ratings of the realism when driving the ST model indicates that it feels realistic driving a ST model even during non-aggressive driving, although the lack of vibrations, roll and pitch were more noticeable.

6.3 Future work

A future work should primarily focus on extending the self aligning torque model since many participants thought the steering wheel felt strange, adding vibrations to the models and make a new study. If a study made from new refined models shows similar results as this thesis one might expand the work to several other areas. Below is a list of possible extensions.

- Use real life driving data where the friction coefficient is close to 0.8
- Model a Volvo S40 with a ST model and do a study
- Remove unnecessary saturations to avoid biased data
- Add vibration signals to the ST model
- Extend the steering wheel torque model and evaluate how it impacts the realism
- Extend the ST model to include the possibility to roll
- Implement a better delay function to cover the whole spectrum of longitudinal velocities
• Collect more data from real life DLC manoeuvres and compare the data with the results from a simulator study

• Make a study with more participants

• Investigate in methods to parametrize a vehicle car to a ST model with accessible equipment
Bibliography


Appendix A

Simulator forms
Testplan

Syfte
Undersöka fyra olika fordonsmodeller av varierad avancerad nivå för att utvärdera hur pass realistiska dom uppfattas. Dessa är följande:

- Cykelmodell med linjär däcksdynamik (1)
- Cykelmodell med Magic Formula (2)
- Cykelmodell med Magic Formula och längd relaxation (3)
- Standard fortranmodell (4)

Undersökningen
Varje testperson kommer inleda undersökningen med en ~10 minuters lång inlärningskörning på landsväg. Här ber man personen att lugnt och sansat lära känna simulatorn och få en känsla för körmiljön. Därefter kommer testpersonen få köra slalom med varje fordonsmodell. När testpersonen har kört slalom tre gånger för modellen frågar testledaren:

- Hur bra kontroll hade du över fordonet? 1-7
- Uppfattade du någon märkbar skillnad från föregående modell? Vadå? (anteckna åsikten)


1. DLC med ingångshastighet 36 km/h
2. DLC med ingångshastighet 49 km/h
3. DLC med ingångshastighet 59 km/h
4. DLC med ingångshastighet 62 km/h och därefter öka hastigheten med 3 km/h om testpersonen klarar av DLC utan att slå undan en kon. Här har man 4 försök på sig innan man anser att testpersonen har misslyckats på den angivna hastigheten.

Checklista

- Sätet kan ställas in
- Använd bälte
- Jag hör och ser dig, säg till om det är något. Öppna ej dörren själv.
- Körningen tar ca 45 minuter
- Påpeka olika modeller i slalom.
- Fråga hur kontrollen var, påpeka att 1 är dåligt, 7 är mycket bra. Anteckna skillnad mot föregående modell.
- Påbörja DLC, påminn om att släppa gas och broms under manövern. Påpeka syftet med testet.
- Fråga hur enkel den kändes, 1 är svår, 7 är mycket enkel
- Påpeka att säkerhetssystemet kan dra igång vid höga hastigheter
- Be FP fylla i standardenkät
Filled in by the test leader. The questions are asked during the test.

How was the handling of the vehicle?

<table>
<thead>
<tr>
<th>Very bad</th>
<th>Very good</th>
<th>Don’t know</th>
</tr>
</thead>
<tbody>
<tr>
<td>□□□□□□</td>
<td>□□□□□□</td>
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</tbody>
</table>

How realistic did it feel?

<table>
<thead>
<tr>
<th>Not realistic at all</th>
<th>Very realistic</th>
<th>Don’t know</th>
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</thead>
<tbody>
<tr>
<td>□□□□□□□□</td>
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</tbody>
</table>

Did you notice any significant difference from the previous model? (write it down)

1. ___________________________________________________________________________

2. ___________________________________________________________________________

3. ___________________________________________________________________________
### Modell:

**How difficult was the manoeuvre?**

<table>
<thead>
<tr>
<th>[km/h]</th>
<th>Very difficult</th>
<th>Very easy</th>
<th>Don’t know</th>
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<tbody>
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<td>71</td>
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</tbody>
</table>

**How difficult were all the manoeuvres?**

- Very difficult □□□□□□□
- Very easy □
- Don’t know □

**How realistic did the driving feel?**

- Not at all □□□□□□□
- Very realistic □
- Don’t know □
How realistic did the driving feel?  Not at all □□□□□□□ Very realistic Don’t know □

**Modell:**

<table>
<thead>
<tr>
<th>How difficult was the manoeuvre?</th>
<th>[km/h]</th>
<th>Very difficult</th>
<th>Very easy</th>
<th>Don’t know</th>
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</table>

How difficult were all the manoeuvres? Very difficult □□□□□□□ Very easy Don’t know □

How realistic did the driving feel?  Not at all □□□□□□□ Very realistic Don’t know □

**Modell:**

<table>
<thead>
<tr>
<th>How difficult was the manoeuvre?</th>
<th>[km/h]</th>
<th>Very difficult</th>
<th>Very easy</th>
<th>Don’t know</th>
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</tbody>
</table>
How difficult were all the manoeuvres? Very difficult □□□□□□□ Very easy □ Don’t know □

How realistic did the driving feel? Not at all □□□□□□□ Very realistic □ Don’t know □
You drove four different models during the double lane change manoeuvres. Was it something you noticed? If so, why?

___________________________________________________________________________

___________________________________________________________________________

___________________________________________________________________________

What was the hardest part with the double lane change manoeuvre?

___________________________________________________________________________

___________________________________________________________________________

___________________________________________________________________________
Simulatorenkät

Följande enkät ligger till grund för vidare utveckling av den tekniska biten på fordonsSIMULATORN.

Information om dig som förare:
Ålder: ______________________

Hur många mil kör du årligen?
0-1000 □ 1000-2000 □ 2000-3000 □ över 3000

Hur många olika fordon kör du?
1 □ 2 □ 3-4 □ fler än 4

Vilket/vilka fordon kör du?
bil □ lastbil □ buss □ mc

Hur många gånger tidigare har du kört i simulator?
0 □ 1 □ 2-3 □ fler än 3

Utgå från din egen körupplevelse och kryssa i det du anser stämma bäst:

Hur upplevde du att likheten var med att köra på riktigt?
mycket liten □□□□□□□ mycket stor □

torftig □□□□□□□ omväxlande □

orealistisk □□□□□□□ realismkisk □

Kunde du upptäcka detaljer i miljön i tid?
inte alls □□□□□□□ mycket bra □

Hur upplevde du dina omgivande medtrafikanter?
het överkliga □□□□□□□ helt realistiska □

Hur väl kände du fordontets placering på vägen?
inte alls □□□□□□□ mycket bra □

Hur upplevde du bilens styrning?
mycket dålig □□□□□□□ mycket bra □

Hur upplevde du bilens bromsar?
mycket dåliga □□□□□□□ mycket bra □

Hur väl kunde du hålla din önskade hastighet?
inte alls □□□□□□□ mycket bra □

Vilken vana har du av tv- eller datorspel?
ingen alls □□□□□□□ stor vana □

Upplevde du illamående under eller efter körningen?
ingen alls □□□□□□□ mycket □

Slutliga kommentarer:
Vad tycker du är mest angeläget att förbättra på simulerorn?
____________________________________________________________________________________________________
____________________________________________________________________________________________________
____________________________________________________________________________________________________
____________________________________________________________________________________________________

Övriga kommentarer?
____________________________________________________________________________________________________
____________________________________________________________________________________________________
____________________________________________________________________________________________________
____________________________________________________________________________________________________
Appendix B

Simulator study plots

This section contains plots for which it is difficult to draw any conclusion from using data given by [9]. However it can be interesting to see how the trajectory looks like for each model.

B.1 Trajectory

Figures B.1 - B.2 shows the trajectory for successfully completed DLC manoeuvres for each model.

![Trajectory plots for different models](image)

Figure B.1: Trajectory for 36 km/h.
B.2 Lateral acceleration

Figures B.3 - B.4 shows the lateral acceleration during a successfully completed DLC manoeuvre. The measured data is compressed because the generic engine added to the ST model has very low engine brake. It can be noted though that the amplitude of the accelerations seems to be quite similar.
Figure B.3: Lateral acceleration for 36 km/h.

Figure B.4: Lateral acceleration for 49 km/h.
B.3 Steering wheel angle

Figure B.5: Steering wheel angle for 36 km/h.

Figure B.6: Steering wheel angle for 49 km/h.
Appendix C

Scenario model order

The following tables show the balanced order for each scenario. Balanced order is necessary to reduce the effects of the learning curve giving better data.

Table C.1: Model order for each test person when driving slalom scenario.

<table>
<thead>
<tr>
<th>Test person</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP01</td>
<td>1 2 3 4</td>
</tr>
<tr>
<td>TP02</td>
<td>1 2 4 3</td>
</tr>
<tr>
<td>TP03</td>
<td>1 3 2 4</td>
</tr>
<tr>
<td>TP04</td>
<td>1 3 4 2</td>
</tr>
<tr>
<td>TP05</td>
<td>1 4 2 3</td>
</tr>
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<td>TP06</td>
<td>1 4 3 2</td>
</tr>
<tr>
<td>TP07</td>
<td>2 1 3 4</td>
</tr>
<tr>
<td>TP08</td>
<td>2 1 4 3</td>
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<td>2 4 1 3</td>
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<td>2 4 3 1</td>
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<td>TP13</td>
<td>3 1 2 4</td>
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<td>TP14</td>
<td>3 1 4 2</td>
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<td>TP15</td>
<td>3 2 1 4</td>
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<td>3 4 2 1</td>
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<tr>
<td>TP19</td>
<td>4 1 2 3</td>
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<td>4 1 3 2</td>
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<td>4 2 1 3</td>
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<td>TP22</td>
<td>4 2 3 1</td>
</tr>
<tr>
<td>TP23</td>
<td>4 3 1 2</td>
</tr>
<tr>
<td>TP24</td>
<td>4 3 2 1</td>
</tr>
</tbody>
</table>
Table C.2: Model order for each test person when driving DLC scenario.

<table>
<thead>
<tr>
<th>Test person</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP01</td>
<td>4 2 3 1</td>
</tr>
<tr>
<td>TP02</td>
<td>2 4 1 3</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>TP23</td>
<td>4 1 3 2</td>
</tr>
<tr>
<td>TP24</td>
<td>3 4 2 1</td>
</tr>
</tbody>
</table>
Appendix D

Validating the extended model

Figures D.1 - D.3 shows measured data from DLC manoeuvre plotted with same steering wheel angle input to the extended ST model. It validates the extended model with measured data. Thus using a different friction coefficient and adding a generic engine makes it possible to use the measured data as validation data.
Figure D.1
Validating the extended model

Using $\mu=0.8$ and $v_x=49$

![Graphs showing front and rear slip angles and yaw rate and lateral acceleration over time for $\mu=0.8$ and $v_x=49$.

Figure D.2
Using \( \mu = 0.8 \) and \( v_x = 59 \)

Figure D.3