Institutionen för systemteknik
Department of Electrical Engineering

Examensarbete

Optimization of Vehicle Powertrain Model Complexity for Different Driving Tasks

Examensarbete utfört i Fordonssytem
vid Tekniska högskolan vid Linköpings universitet
av

Olof Zetterlund

LiTH-ISY-EX–15/4897–SE

Linköping 2015

Linköpings universitet
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Sammanfattning
Abstract

This master thesis has examined how the understanding of different driving tasks can be used to develop a suitable powertrain model to be used in the Sim III simulator at VTI. Studies performed in the simulator have been statistically analyzed using parameters commonly used to describe driving patterns in drive cycles. It has been shown that the studies can be divided into three driving tasks: "High constant velocity", "High velocity with evasive maneuver", and "Mixed driving". Furthermore, a powertrain model from a former master thesis has been further developed. The new model utilizes a 3D torque map that takes engine speed, accelerator pedal position and gear as input. Using measurements, from the chassis dynamometers laboratory at LiU, that resembles the derived driving tasks, it has been shown that the performance of the new model has significantly increased for high velocity driving and during maximum acceleration. However, when using the clutch at low speeds and gears the model still performs poorly and needs further development.

Nyckelord
Keywords

Model validation, Powertrain, Driving tasks

Abstract

This master thesis has examined how the understanding of different driving tasks can be used to develop a suitable powertrain model to be used in the Sim III simulator at VTI. Studies performed in the simulator have been statistically analyzed using parameters commonly used to describe driving patterns in drive cycles. It has been shown that the studies can be divided into three driving tasks: "High constant velocity", "High velocity with evasive maneuver", and "Mixed driving". Furthermore, a powertrain model from a former master thesis has been further developed. The new model utilizes a 3D torque map that takes engine speed, accelerator pedal position and gear as input. Using measurements, from the chassis dynamometers laboratory at LiU, that resembles the derived driving tasks, it has been shown that the performance of the new model has significantly increased for high velocity driving and during maximum acceleration. However, when using the clutch at low speeds and gears the model still performs poorly and needs further development.

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Linköping, 2015
Olof Zetterlund

Contents

Notation

Variables

Variable	Description
A_f	Vehicle frontal area
a	Acceleration
c_d	Drag coefficient
c_r	Rolling friction coefficient
F_{air}	Aerodynamic drag force
F_{grav}	Gravitational resistance
F_{prop}	Propulsion force
F_{res}	Resistance force
F_{roll}	Rolling resistance
g	Gravitational constant
i_f	Final drive conversion ratio
i_t	Transmission conversion ratio
J_e	Engine inertia
M_c	Clutch torque
M_e	Engine torque
M_{losses}	Driveline friction losses
M_w	Wheel torque
m_v	Vehicle mass
r_w	Wheel radius
v	Velocity
v_0	Relative wind speed
α	Slope of the road
θ_e	Engine angle
$\dot{\theta}_e$	Engine angular velocity
$\ddot{\theta}_e$	Engine angular acceleration
θ_w	Wheel angle
$\dot{\theta}_w$	Wheel angular velocity
ρ_a	Density of air

Abbreviations

Abbreviation	Description
CAN	Controller Area Network
ECU	Engine Control Unit
ISY	Department of Electrical Engineering
LiU	Linköping University
MVEM	Mean Value Engine Model
NEDC	New European Driving Cycle
OBD	On-Board Diagnostics
PID	Parameter IDentification
RPM	Revolutions Per Minute
RPS	Revolutions Per Second
TP	Test Person
VTI	The Swedish National Road and Transport Research Institute

1 Introduction

This chapter is an introduction to this master thesis report. It contains motivation for the given problem, purpose and goal of the assignment, limitations, and finally an outline of the rest of the report.

1.1 Motivation

One major part in every vehicle is the powertrain, which transfers power from the engine to the road, making the vehicle move in the longitudinal direction. The powertrain consists of an engine and a driveline. The driveline in turn, consists of a clutch, gearbox, drive shafts, and wheels. Depending on configuration of the driven wheels, fuel and engine type, the powertrain can have different appearances.

Due to environmental impact from vehicles in general and stricter requirements on exhaust emissions in particular, several new technologies, e.g. hybrid vehicles with different powertrain configurations, have been introduced to the market. With new technologies comes the need for testing and evaluation of its performance. A proven way for testing is to perform simulations of the system.

The Swedish National Road and Transport Research Institute (VTI) has developed a platform for distributed powertrain co-simulation in collaboration with Linköping University [1]. The platform consist of the Sim III driving simulator located at VTI connected to a chassis dynamometer laboratory at Linköpings university. The dynamometers are attached to a real vehicle and the input from a test person at VTI is interpreted by a pedal robot that controls the vehicle. The measured wheel speed and wheel torque are then sent back to the simulator, making the test person experience a real powertrain during a simulation. By attaching different vehicles to the dynamometers, different powertrain configurations can be tested.

When the simulator is not connected to the dynamometers, a good model of the vehicle and its powertrain is needed to perform realistic simulations. In a previous master thesis, a powertrain model and a method to parametrizes it were developed [11]. However, the model must be further developed and be thoroughly tested with realistic reference data. This thesis continues the performed work in [11]. The performance of the powertrain model is improved and validated against driving tasks that are commonly performed in the simulator.

1.2 Purpose and Goal

The purpose of this master thesis is to investigate how the knowledge of different driving tasks can be used to choose a suitable vehicle model for a certain simulator study. Different simulator scenarios can be described by the same driving task since they consist of similar driving behavior, e.g. driving on highway could be a driving task and the change in acceleration a driving behavior. To perform simulations were the simulator behaves like the studied vehicle, a suitable vehicle model is needed. Currently there exist a powertrain model developed in a former master thesis project. This model needs to be improved to give satisfying results for more demanding driving tasks. The goals of this master thesis are to

- classify different driving tasks with respect to different driver behavior
- improve the performance of existing powertrain model
- verify the model with real measurements.

1.3 Limitations

Since the purpose of this thesis is to investigate the powertrain of a vehicle, it will focus on longitudinal movement and forces and the vehicle speed will be considered to be known. Only non-invasive sensors are used to parametrizes the powertrain model, which is a demand from VTI.

1.4 Outline

Chapter 2 contains an overview of research related to driving tasks and powertrain modeling. Chapter 3 gives an overview of the vehicle, the simulator, and the equipment used in the experiments. In Chapter 4 different driving tasks are classified using statistical parameters and simulator data. Chapter 5 evaluates the performance of the former powertrain model. In Chapter 6 an improved powertrain model is developed and presented. Chapter 7 validates the new model using real measurements corresponding to the driving tasks. Chapter 8 contains a discussion of the methodology and the results and also some final conclusions and possible future work.

2
Related Research

This chapter is reviewing related research of this thesis. The first part presents how drive cycles are generated and how this can be used to classify different driving tasks. The second part presents how engines and drivelines have been modeled.

2.1 Drive Cycles

Drive cycles are mainly used for evaluation of vehicle emissions and fuel economy [13]. The development of drive cycles is used in this thesis as an approach and inspiration for the classification of different driving tasks. They are also used in the laboratory to get realistic validation data. This is done by following the drive cycle when driving the vehicle in the chassis dynamometer laboratory.

Drive cycles can be divided into two main categories, steady-state and transient cycles. The steady-state cycles consist of sequences of constant speed and acceleration while the speed and acceleration changes continuously in the transient cycles [2]. The New European Drive Cycle (NEDC) and the Japanese 10-15 mode cycle are examples of steady state cycles while the FTP75 cycle in U.S.A. and the Artemis Urban drive cycle are examples of transient cycles [9]. Transient drive cycles are derived using actual driving behavior, whereas the transition between sequences in the steady state cycles are somewhat unnatural. This can be seen in Figure 2.1 where a steady state and a transient drive cycle are pictured.

In [4] and [12] drive cycles for the cities of Tehran and New Delhi were developed and they show similar ways of categorizing different parts of collected data. They define four different traffic condition: Congested Urban, Urban Condition, Extra Urban, and Highway. The classification is done with respect to average speed and

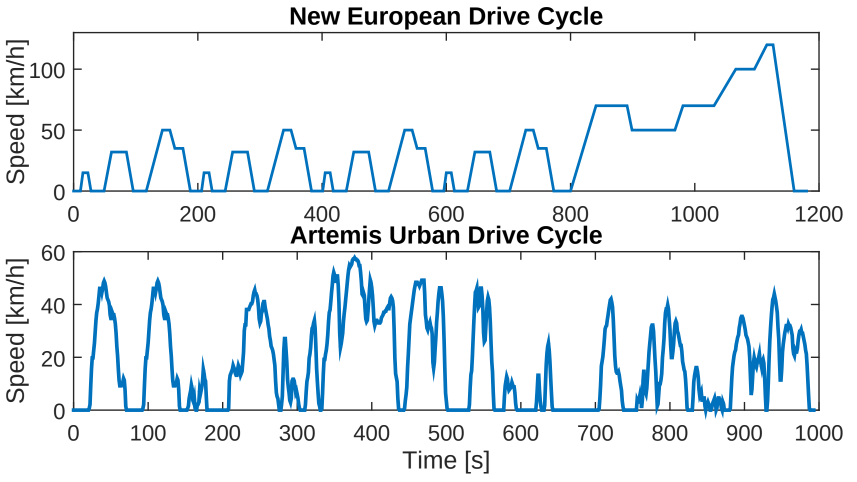

Figure 2.1: *Two different drive cycles that show the differences between steady state and transient drive cycles. The upper figure shows the steady-state drive cycle NEDC and the lower figure shows the transient drive cycle Artemis Urban.*

idle time.

Several driving pattern parameters are presented in [6, 7, 15] which can be used for classification of different driving tasks. The parameters are used for describing driving pattern and how they can be used to synthesize real-world driving cycles. Average values and standard deviation of acceleration and velocity are examples of such parameters.

2.2 Powertrain

The powertrain in a vehicle consists of the parts responsible to move the vehicle in the longitudinal direction. It can be divided into two major subsystems, the engine and the driveline. Both the engine and the driveline can be modeled in different ways depending on purpose and what the models will be used for. Figure 2.2 shows a schematic overview of a powertrain configuration.

2.2.1 Engine Models

The purpose of the engine is to convert chemical energy to mechanical work. The output of the engine is torque, which is generated from the combustion of fuel mixed with air in the cylinders. This can be model with a Mean Value Engine Model (MVEM) [8]. However, such a model requires different measurements that cannot be obtained without using invasive sensors. For example air mass flow past throttle, intake manifold pressure and fuel mass injected in the cylinders.

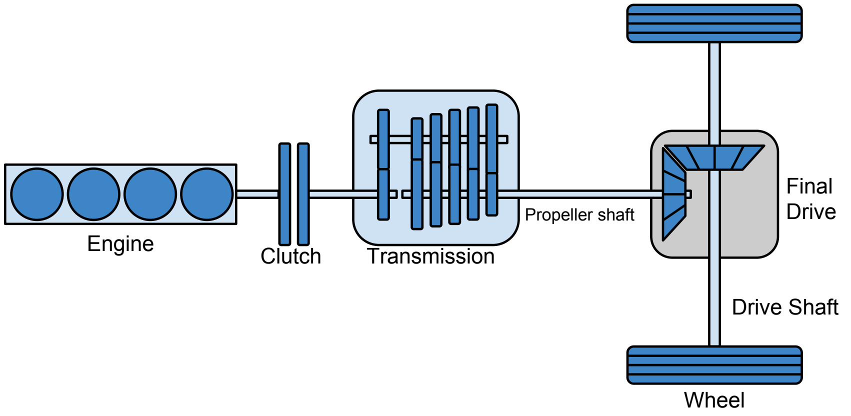

Figure 2.2: *Schematic overview of a vehicle powertrain.*

Since each subsystem cannot be modeled separately, performance maps that interpreters the accelerator pedal position as demand for torque, can be used instead. As the pedal position is linked to the throttle angle, a static map can be generated for different engine speeds [5]. In a similar way an engine map can be obtained by mapping engine speed and throttle angle to engine torque. It is also possible to use a single map by mapping accelerator pedal position and engine speed to engine torque.

2.2.2 Driveline Models

Depending on the location of the driven wheels of a vehicle, the driveline can have different appearances. Typically it consists of a clutch, gearbox, propeller shaft, final drive, drive shaft, and wheels. The purpose of a driveline model is to capture the behavior of the transmitted torque and the angular velocity from the engine to the wheels.

A driveline model which assumes that there are no flexibilities in the driveline and that the transmission and final drive multiply the torque with a conversion ratio is called a rigid or stiff model. With this model, the torque and the angular velocity at the engine corresponds to the torque and angular velocity at the wheels scaled with a gear and final drive ratio. The unknown parameters in this model is the engine inertia and the combined final drive and gear ratios [8].

A stiff driveline model is not able to capture the behavior of oscillations in the driveline. By modeling the different parts in the driveline with springs and dampers, more complex models of the driveline can be obtained. A model with drive shaft flexibility is presented in [10]. This model amongst other with different complexity is used in [3] to develop a controller to dampen the oscillations in the driveline.

3
System Overview

This chapter gives an overview of the systems used in this thesis. The first part describes the vehicle simulator located at VTI, the second part is about the chassis dynamometer laboratory at LiU and the last part describes the studied vehicle.

3.1 Driving Simulator

The driving simulator, called Sim III, is located at VTI, Linköping. The driver space consists of a cabin from a SAAB 9-3 mounted on a cradle. The cradle allows for a four degree of freedom movement and can simulate lateral or longitudinal movement. Three projectors provide the driver with a 120° field of vision. To simulate the rear view mirrors, three displays are used. The system has also several speakers providing the driver with realistic sounds from the vehicle and road [16].

3.2 Chassis Dynamometer Laboratory

The chassis dynamometer laboratory is located at Linköping University. It consists mainly of four dynamometer units, a vehicle, a wind fan, measuring equipment and a control room. The dynamometers are attached to the hubs of the driven wheels, see Figure 3.1. If the vehicle is front or rear wheel driven only two dynamometer units are needed. The purpose of the wind fan is to cool the engine and its components and it can generate wind speeds up 100 km/h [14]. Various signals can be obtained from the rig and in this thesis the wheel torque M_w and the wheel speed $\dot{\theta}_w$ is measured with this system.

Depending on the purpose of an experiment, the chassis dynamometers can be

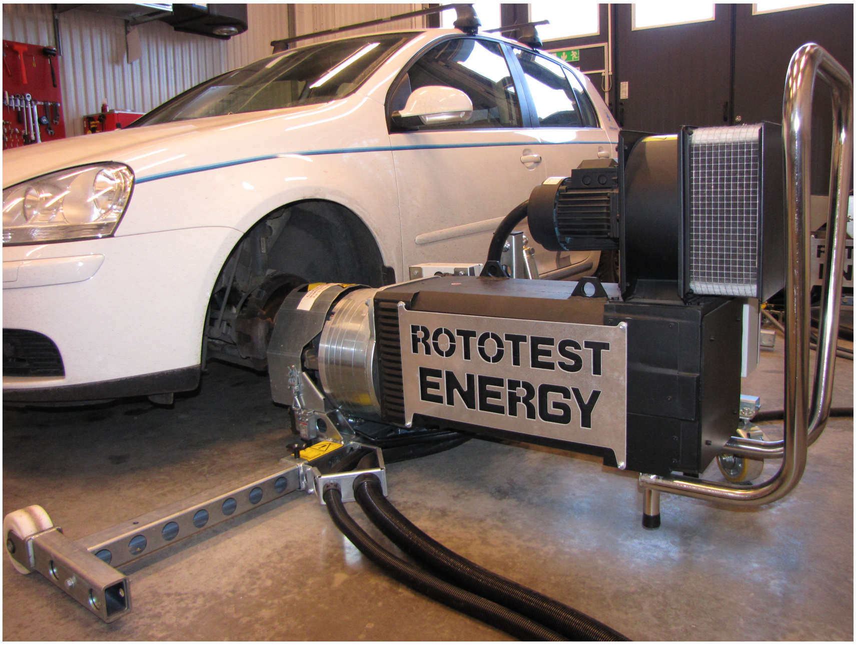

Figure 3.1: Dynamometer attached to one of the driven wheel hub of a VW Golf V.

used in two different modes. The two modes are constant speed mode and road resistance mode.

Constant Speed In this mode, the chassis dynamometers keep the wheels rotating at a constant predefined speed, even if the driver changes the pedal position. This mode is used to measure the torque at specific operating points. The engine and pedal maps in the previous master thesis [11] were constructed using this mode.

Road Resistance In this mode, the forces that the vehicle has to overcome are simulated and it is used to simulate real driving. This mode is used in this thesis to get validation data for the vehicle model. Using Newtons second law of motion, the acceleration of the vehicle is given as

$$m_v a = F_{\text{prop}} - F_{\text{res}} \tag{3.1a}$$

$$F_{\text{prop}} = \sum_i \frac{M_{w,i}}{r_w} \tag{3.1b}$$

$$F_{\text{res}} = F_{\text{roll}} + F_{\text{air}} + F_{\text{grav}} \tag{3.1c}$$

$$\tag{3.1d}$$

where m_v is mass of the vehicle, a the acceleration, F_{prop} is the propulsion force calculated from the wheel torque $M_{w,i}$ and the wheel radius r_w. The resistance force F_{res} consists of the rolling resistance F_{roll}, the air drag F_{air} and the gravitational force F_{grav}. These forces are given by

$$F_{\text{roll}} = c_r m_v g \cos(\alpha) \tag{3.2a}$$

$$F_{\text{air}} = \frac{1}{2}\rho_a c_d A_f (v + v_0)^2 \tag{3.2b}$$

$$F_{\text{grav}} = m_v g \sin(\alpha) \tag{3.2c}$$

where c_r is rolling resistance coefficient, g the gravitational constant, ρ_a the density of air, c_d the drag coefficient, A_f the vehicle frontal area, v_0 the relative wind speed and α is the slope angle of the road [14].

3.3 Vehicle

The vehicle studied in this thesis is a Volkswagen Golf V multifuel from 2008. It is a front wheel driven car with a manual gearbox with five gears. Table 3.1 contains necessary data of the vehicle for the chassis dynamometer software.

Table 3.1: *Vehicle parameters needed to perform experiments with chassis dynamometers. Adapted from table 2.2 in [11].*

Parameter	**Symbol**	**Value**
Weight - left front	-	427 kg
Weight - right front	-	382 kg
Wheel circumference	-	1992 mm
Wheel radius	r_w	314 mm
Drive train	-	2WD
Vehicle mass	m_v	1380 kg
Vehicle frontal area	A_f	2.460 m^2
Drag coefficient	c_d	0.330
Rolling friction coefficient	c_r	0.015

Several vehicle parameters belonging to the driveline was estimated in [11]. Table 3.2 contains these estimated parameters, necessary to run simulations with the powertrain model.

To get measurements from the vehicle, the On-Board Diagnostics (OBD) is used. The OBD is a self diagnosis tool used in the vehicle. By sending Parameter IDs (PIDs) to the Engine Control Unit (ECU), the user can get access to requested vehicle data. The Golf V utilize the OBD-II standard and several parameters

Table 3.2: Vehicle parameters estimated through experiments in [11].

Parameter	Symbol	Value
Engine inertia	J_e	$0.21\ \mathrm{kg \cdot m^2}$
Combined final drive and gearbox ratio (1^{st} gear)	$i_{t,1}i_f$	15.7218
Combined final drive and gearbox ratio (2^{st} gear)	$i_{t,2}i_f$	8.8973
Combined final drive and gearbox ratio (3^{st} gear)	$i_{t,3}i_f$	5.8313
Combined final drive and gearbox ratio (4^{st} gear)	$i_{t,4}i_f$	4.4375
Combined final drive and gearbox ratio (5^{st} gear)	$i_{t,5}i_f$	3.6984

are available through an OBD-connector. There exist several PIDs but the manufacturer is not required to implement all of them. In addition to the OBD-II connector, the user of the Golf V also has access to raw data directly through the CAN-bus. Since this data is not normally accessible, it will only be used for validation of the models.

In this thesis the engine speed, $\dot{\theta}_e$, the throttle and the accelerator pedal position are acquired through this measurement tool.

3.3.1 Gear signal

Neither the CAN-bus or the OBD tool log the current gear. However, the gear signal is needed in the vehicle model to get correct gear ratio during a simulation. To solve this, one can either log the gear manually, which was done in [11] or calculate the gear using engine speed, wheel speed and combined final drive and gear ratio. The quotient between engine speed and wheel speed is close to the gear and final drive ratio when the clutch is engaged. This method is used in this thesis.

3.3.2 λ-Control

When making a model of a fully developed vehicle, one has to consider that the engine and the driveline is already controlled by the Engine Control Unit (ECU). The purpose of the ECU is, among other things, to provide the driver with desired torque and driving comfort, while trying to reduce exhaust gas emissions and maintain a good fuel economy. This is achieved through λ control, where λ is defined as

$$\lambda = \frac{(A/F)}{(A/F)_s} \tag{3.3}$$

where (A/F) is the air/fuel-ratio normalized with the stoichiometric mixture $(A/F)_s$, which vary for different fuel types. The value for gasoline is approximately 14.7. A mixture that gives $\lambda < 1$ is called rich and will provide good performance, but the fuel conversion efficiency is reduced. A mixture that gives $\lambda > 1$ is called lean and will provid good fuel economy but generates high NO_x emissions. The ECU is trying to maintain a mixture that gives $\lambda = 1$. This is the main operating mode for engines with a three way catalyst and gives good reduction of emission gases, such as CO, NO_x and HC. However, during acceleration when a high torque is demanded, the λ-value is allowed to drop below one. [8].

4

Driving Task Classification

This chapter describes how the simulator data provided from VTI and the measurements from ISY is processed. The different statistical parameters are processed and then used to classify different driving tasks.

4.1 Introduction

The purpose of the driving task classification is to examine how the understanding of a certain simulator study can be used to optimize the powertrain model. This is done by examining differences and similarities between simulator studies performed in the Sim III simulator. With this information, relevant and appropriate experiments can be performed with the chassis dynamometers. Using the measurements from the experiments, the developed vehicle model can be thoroughly validated and if possible optimized for the different classes of driving tasks.

4.2 Available Data

The driving task classification is performed on data from different simulator studies done at VTI and real world driving data from ISY. Each study is listed in Table 4.1 along with number of test persons (TPs) in each study and a short description. The selected studies correspond to driving cases normally performed in the simulator. In most of the studies, the driver is told to maintain a constant high velocity. However, there are also studies performed in urban environments.

Study number 4 in Table 4.1, is performed using a real vehicle on the roads around Linköping University. The vehicle is a VW Golf and it is the same vehicle used in the chassis dynamometer laboratory which was described in section 3.3. The vehicle was equipped with GPS, IMU and optical sensors to measure position, velocity, acceleration and inclination of the road. Figure 4.1 shows a map of the road that the test drivers were supposed to follow. The drivers were told to drive the distance twice and data was recorded during the second lap. As can be seen in the figure, the route consist of both city driving and countryside driving with velocities up to 90 km/h. The test persons were told to drive as they would normally drive. The measurements from this study is used to compare the behavior of driving in a simulator to driving in real traffic.

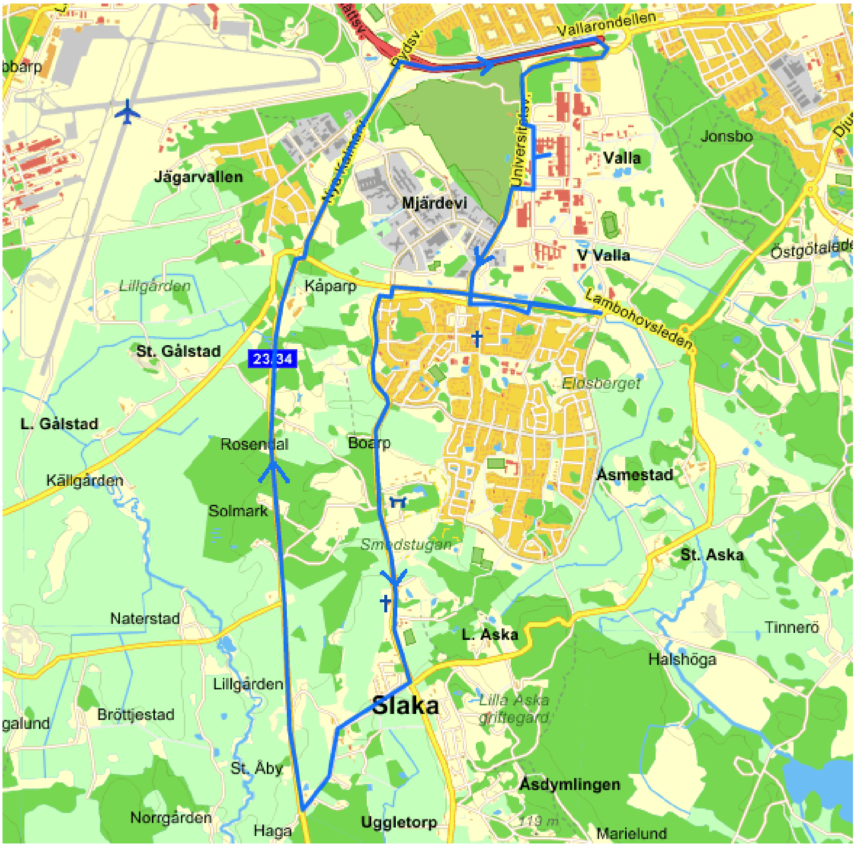

__Figure 4.1:__ Map of the route for the test persons in the real driving study. The solid line shows the road the test persons were to follow and the arrows shows the direction. The map shows the outskirts of Linköping.

4.3 Data Pre-Processing

Before the data can be analyzed, it must be examined to ensure that unrealistic values do not affect the results. This is the case for outliers and parts of the simulation where the data is not to be consider part of the study.

In some studies, the test person is supposed to perform the simulation several times. The data then contain values when the simulated vehicle is idling. Since this is not part of the simulation, that data has to be removed. This is done by removing the idling period along with the preceding and succeeding acceleration. The reason for this is that this data should not affect the analysis. This is also the case when the velocity data contains leading and trailing sets of zeros. For some studies the data contains sequences where the driver learns how to use the simulator and this data is not used in the analysis. For studies where the driver is supposed to drive with a high constant velocity, the last part of the simulation is removed. The reason for this is that the driver is told to brake the simulated vehicle and this is a forced behavior.

Study number 5 and 8 in Table 4.1 are studies where the driver has to perform evasive maneuvers during the simulation. For these studies only the part where the actual maneuver takes place is analyzed. This is to get statistical data for the explicit maneuver and not for parts where the test person is driving normally. Furthermore, all simulations where it is clear that the test person has not performed the same drive as the other test persons in the study are removed. Finally all simulations where the driver has crashed the vehicle are also removed.

Table 4.1: *Different studies performed at VTI and ISY. The data from the different studies is used to classify different driving tasks.*

Study No.	Name of study	No. of TPs	Description of study
1	Synfältsbortfall	28	Simulation to examine if people with reduced vision are supposed to keep their driving license. The runs consist of mixed driving from highway to urban conditions.
2	Vip LDW	24	The test person was told to follow the speed limit of 90 km/h. During the run, the vehicle started to drift which and the driver had to reposition the vehicle in the right lane.
3	Tema TEK	10/9[1]	The drivers were told to drive to an airport to catch a plane. Half of the drivers had plenty of time to reach the airport whereas the other half had to drive faster to catch the plane. Most of the driving was on highway.
4	ISY Data	23	Measurements from real world driving provided from ISY. Mixed driving.
5	Slitna rutor	24	A study to examine the impact of worn windshield. The TP drove on a highway with a speed limit of 90 km/h and had to perform evasive maneuvers during the run.
6	FSS MTO	24	The drivers were supposed to drive in the middle lane in a tunnel with speed limit 100 km/h. There was light traffic in both the right and left lane.
7	Sleepeye	27	A study to see how sleep deprivation affect driving. The driver were supposed to drive on a motorway with speed limit 110 km/h. For one km the speed limit dropped to 90 km/h. In the beginning and at the end the driver had to overtake some slower vehicles.
8	Fica III	30	A study to test Forward Collision Warning systems. The TP drives on a two lane motorway with speed limit 90 km/h. During the run, the driver is overtaken by another vehicle and in some cases the overtaking vehicle brakes in front of the driver.

[1] This study is divided into two parts with 10 TPs in the first part and 9 TPs in second part.

4.4 Statistical Analysis

To analyze the behavior of the drivers and classify the different studies into driving tasks, different statistical parameters are used. The parameters can be divided into the three categories: velocity, acceleration and driving characteristics. Table 4.2 contains all parameters that will be used. For definition and how to calculate each parameter, see Appendix A.

Table 4.2: *Statistical parameters used for the driving task classification.*

Category	Statistical parameter	Unit
Velocity	Average velocity	[km/h]
	Average running velocity	[km/h]
	Standard deviation of velocity	[km/h]
Acceleration	Average positive acceleration	[m/s^2]
	Average negative acceleration	[m/s^2]
	Maximum positive acceleration	[m/s^2]
	Maximum negative acceleration	[m/s^2]
	95th percentile maximum acceleration	[m/s^2]
	95th percentile minimum acceleration	[m/s^2]
	Standard deviation of acceleration	[m/s^2]
Driving characteristics	Percentage of time idling[1]	[%]
	Percentage of time creeping[2]	[%]
	Percentage of time cruising[3]	[%]
	Percentage of time accelerating[4]	[%]
	Percentage of time decelerating[5]	[%]
	Number of times the brakes are used	[-]
	Percentage of time in each gear	[%]

[1] $v = 0$ km/h
[2] $0 \leq v \leq 18$ km/h, $|a| \leq 0.1$ m/s^2
[3] $v > 18$ km/h, $|a| \leq 0.1$ m/s^2
[4] $a > 0.1$ m/s^2
[5] $a < -0.1$ m/s^2

All statistical parameters used in this analysis are based on velocity and acceleration except the number of brake sequences. The velocity and acceleration are available in the data sets for all studies performed in the simulator. For the study performed on the real vehicle the acceleration has to be calculated from the velocity, see Appendix A. The number of brake sequences performed in a simulation are not given and has to be calculated from the brake pedal active signal. The signal contains discrete values of zeros and ones, where one means that the brake pedal is pressed down. All consecutive series of ones are then counted to get how many times the brake has been used in a run.

The classification is performed by finding parameters that shows similarities within a group of studies and distinct differences between other groups of studies.

4.5 Results

Table 4.3: Statistical evaluation of simulator and real data. The table shows mean values for each statistical parameter. Study number 4 is real measurements. For description of each study, see Table 4.1

Study No.	1	2	3a	3b	4	4, v>80	5	6	7	8
Ave. velocity	64.2	88.6	55.1	62.1	45.6	86.1	78.4	98.5	109.8	87.0
Ave. running velocity	68.0	88.6	55.6	63.1	47.6	86.1	78.4	98.5	109.8	87.0
Std. of velocity	32.3	6.0	17.3	21.7	24.0	2.6	12.14	6.9	7.5	10.07
Ave. positive acc.	0.65	0.33	0.54	0.82	0.46	0.16	0.69	0.23	0.30	0.56
Ave. neg. acc.	-0.49	-0.23	-0.37	-0.54	-0.42	-0.16	-0.77	-0.19	-0.23	-0.48
Max. pos. acc	3.86	3.30	4.99	4.68	3.77	1.30	1.68	3.58	2.99	2.34
Max. neg. acc	-9.29	-2.36	-8.96	-9.43	-3.96	-1.15	-5.67	-0.93	-2.02	-8.43
95th % max. acc.	1.36	0.66	1.19	1.60	1.16	0.37	1.34	0.45	0.59	1.36
95th % min. acc.	-0.73	-0.44	-0.78	-1.25	-1.07	-0.38	-1.90	-0.42	-0.45	-0.56
Std. of acc.	0.89	0.35	0.82	1.07	0.66	0.24	1.15	0.33	0.33	1.01
%-time idling	6	0	1	1	4	0	0	0	0	0
%-time creeping	1	0	1	1	2	0	0	0	0	0
%-time cruising	14	27	27	14	22	52	11	40	28	25
%-time acc.	34	29	29	33	34	24	39	30	32	35
%-time decel.	45	45	42	51	38	25	50	30	40	40
No. of brakes	59	4	35	39	30	0	N/A	0	2	4
%-time gear 0	N/A	N/A	3	3	2	0	N/A	N/A	N/A	N/A
%-time gear 1	N/A	N/A	3	4	3	0	N/A	N/A	N/A	N/A
%-time gear 2	N/A	N/A	5	13	14	0	N/A	N/A	N/A	N/A
%-time gear 3	N/A	N/A	19	30	22	1	N/A	N/A	N/A	N/A
%-time gear 4	N/A	N/A	27	30	23	1	N/A	N/A	N/A	N/A
%-time gear 5	N/A	N/A	43	21	36	98	N/A	N/A	N/A	N/A

All statistical parameter value from Table 4.2 can be seen in Table 4.3. By examining the table, the studies in Table 4.1 can be categorized into different driving tasks. This is done by finding similarities and differences between the studies. Studies that show minor differences with each other are grouped into a driving task. A driving tasks has also distinct differences between other driving tasks.

Each subsection contains a table with statistical parameter values that show significant differences between and similarities within each classification. Table 4.3 contains a compilation of all statistical parameters for each and every study. The values are averages over all test persons. As one can see in the table, some values are missing. The brake pedal active signal was too distorted in study number five and thus could not be used to calculate the number of brakes during the simulation. The reason that there is no data of the percentage of time on each gear for some studies, is that these studies were performed with an automatic gearbox.

4.5.1 High Constant Velocity

The first type of driving tasks is the most common amongst studies performed in the simulator at VTI. As the name suggest the test person is told to drive on a highway and keep the given speed limit. During the simulation, there is light or no traffic and the test person does not have to perform any major evasive maneuvers. Since the simulations have been carried out at high speeds, the test persons did not have to perform any gearshifts.

Table 4.4: *Statistical parameter values for studies classified as "High Constant Velocity". Study number 4 is performed on a real vehicle and the parameter values are calculated for velocities higher than 80 km/h.*

Study No.	Ave. velocity	Std. of velocity	Ave. neg./pos. acc.	Max. neg./pos. acc.	Std. of acc.	%-time cruising
2	88.6	6.0	-0.23/0.33	-2.36/3.3	0.35	27
6	98.5	6.9	-0.19/0.23	-0.93/3.58	0.33	40
7	109.8	7.5	-0.23/0.30	-2.05/2.99	0.33	28
4, v>80	86.1	2.6	-0.16/0.16	-1.15/1.30	0.24	52

Table 4.4 contains characteristic values of studies classified as *"High Constant Velocity"*. The table shows that these studies have a high average velocity with a low standard deviation of velocity and acceleration. Compared with the other studies, these simulations have a much lower average negative and positive acceleration. The maximum negative acceleration is also lower due to the test persons using the brakes a lot less than the drivers in the *"Mixed Driving"*-studies. The percentage of time cruising is as expected higher than for the other studies. However, compared to study number 4 the values are much lower.

Figure 4.2 shows speed and acceleration for a test person from study number 6. The test person drives with high speed around 110 km/h and the acceleration is low for longer periods of time. The drive serves as a good example of how a study classified as *"High Constant Velocity"* could look like.

4.5.2 High Velocity with Evasive Maneuver

The second type of driving tasks is similar to the first one, with the exception that during the simulation the test person must perform different evasive maneuvers. Such evasive maneuvers can be to swerve to avoid upcoming obstacles or sudden and rapid deceleration. These studies, like the first one, are conducted during relative high speeds.

Table 4.5 shows characteristic values for this class of studies. Compared to *"High Constant Velocity"*-studies the standard deviation of velocity is higher. The average velocity is high, but lower than the first class. The high percentage of time

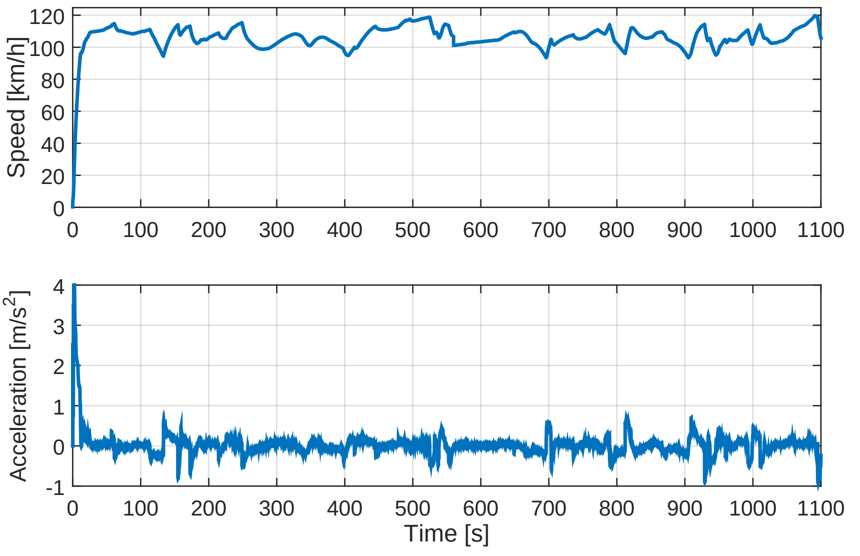

Figure 4.2: *Example of a "High Constant Velocity"-study. The figure shows speed and acceleration for a test person from study number 6.*

Table 4.5: *Statistical parameters values for studies classified as "High Velocity with Evasive Maneuver".*

Study No.	Ave. velocity	Std. of velocity	Ave. neg./pos. acc.	Max. neg./pos. acc.	Std. of acc.	%-time decel.
5	78.4	12.14	-0.77/0.69	-5.67/1.68	1.15	50
8	87.0	10.07	-0.48/0.56	-8.43/2.34	1.01	40

spent decelerating is expected since only the part where the actual evasive maneuver takes place is examined.

Figure 4.3 shows two evasive maneuvers performed by a test person from study number 5. The gaps in the figure are due to the maneuvers not occurring after each other. The data has been extracted from a longer simulation. The test person drives in 90 km/h and has to perform a sudden deceleration. After the deceleration the test person brings the vehicle back to the previous velocity.

4.5.3 Mixed Driving

The third and final type of driving tasks is the most complex one. The simulation can consist of both high and low speed driving, using all gears and the drivers are frequently using the brakes. It is not unusual that the simulation consists of urban environments where the driver must start and stop the vehicle.

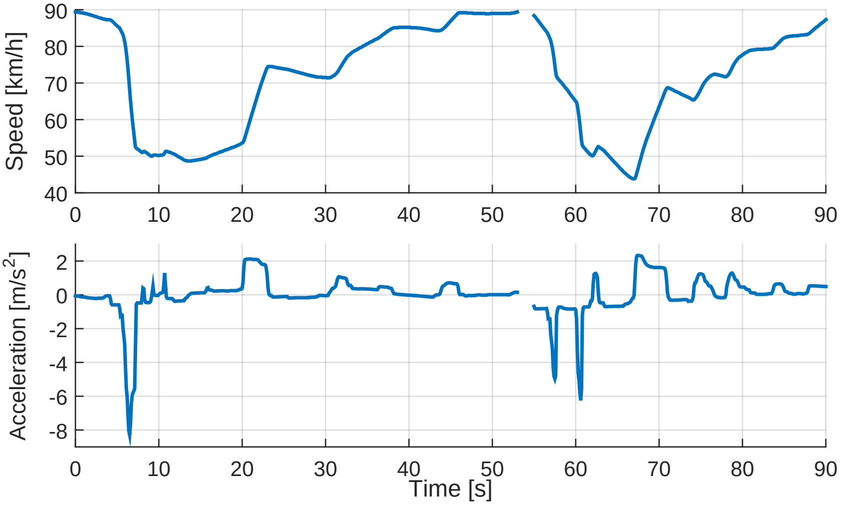

Figure 4.3: *Example of a "High Velocity with Evasive Maneuver"-study. The figure shows speed and acceleration for a test person from study number 5. The two parts are from different evasive manuevers performed during the test.*

Table 4.6 contains statistical parameter values, distinguished for the *"Mixed Driving"*-class. As can be seen, the average velocity is lower and the standard deviation of velocity is higher compared to other simulations. As in actual driving all gears are used, but the lower ones a lot less. The maximum positive acceleration is much higher compared to the other simulations. Which is explained by starting the vehicle from rest and driving on the lower gears. The maximum negative acceleration is very large negative compared to actual driving, the values are even unrealistic for the driving conditions.

An example of a *"Mixed Driving"*-study is shown in Figure 4.4. The figure shows speed, acceleration and gear for a test person from study number 3. It is seen in the Figure that the speed varies between 0 and 80 km/h. The driver is using different gears and the phenomenon of very high deceleration is seen around *t=90 s*.

4.5.4 Summary

In this chapter, simulator studies performed at VTI have been examined and can be categorized into three different driving tasks, using a variety of statistical parameters. The driving tasks derived in this chapter are:

- High Constant Velocity
- High Velocity with Evasive Maneuver
- Mixed Driving.

Table 4.6: Statistical parameters values for studies classified as "Mixed Driving". The simulations performed in study number 3 are divided in two parts, where the test persons in the first part had longer time to reach the destination. Study number 4 is performed using a real vehicle.

Study No.	Ave. velocity	Std. of velocity	Max. neg./pos. acc.	%-time idling	No. of brakes	%-time gear 0,...,5
1	64.2	32.3	-9.29/3.86	6	59	-
3a	55.1	17.3	-8.96/4.99	1	35	3, 3, 5, 19, 27, 43
3b	62.1	21.7	-9.43/4.68	1	39	3, 4, 13, 30, 30, 21
4	45.6	24	-3.96/3.77	4	30	2, 3, 14, 22, 23, 36

The first driving task the most common among the studies. The second one is a special case of the first driving task, where something happens during the simulation e.g. the vehicle in front suddenly brakes. The last driving tasks is the most complex and consists of stopping the vehicle, driving at low speeds and performing gear shifts.

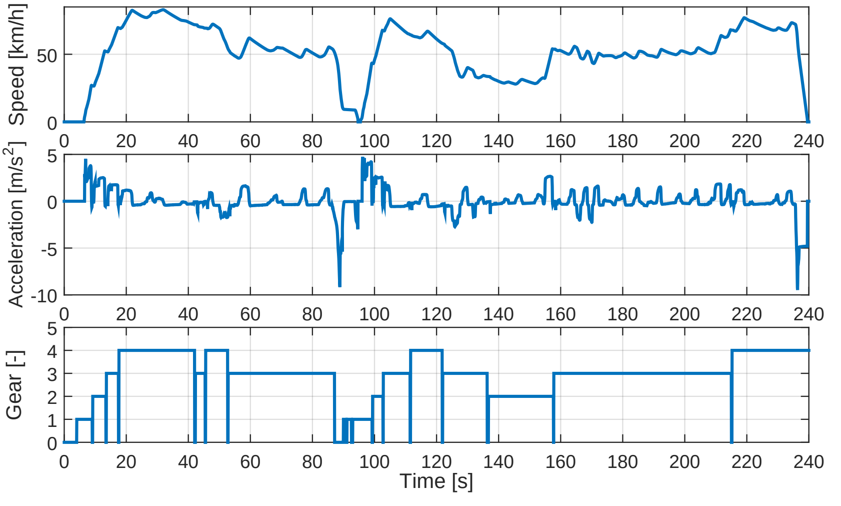

Figure 4.4: *Example of a "Mixed Driving"-study. The figure shows speed, acceleration and gear for a test person from study number 3.*

5

Evaluation of the Former Powertrain Model

In this chapter the former powertrain model is thoroughly examined to estimate its performance and find ways to improve the model. This is done using both constant and dynamic test data measured with the chassis dynamometers.

5.1 Former Powertrain Model

The powertrain model developed in [11], consists of two subsystems, an engine and a driveline model. The engine model is composed of a static throttle map and a static torque map. The two maps are directly connected to each other and input/output for each map is shown in Table 5.1. Since the maps lacks dynamics, a lag element with time constant $\tau = 0.21$, is added after the engine map. The lag element is a first order system that works like low pass filter for the engine torque. Figure 5.1 shows a Simulink schematic of how the two maps and the lag element are connected. Figure 5.2 shows a Simulink schematic of the implemented driveline model. The soft switch in the figure handles engine speed calculation. When the clutch is pressed, the engine speed is calculated from the engine torque and otherwise it is equal to the wheel speed, scaled with the final drive and transmission ratio. The two subsystems on the right hand side handles two special cases when large negative spikes occur in the torque. For further description and implementation, see Chapter 3 in [11].

When reviewing [11] it can be determined that the validation of the powertrain model and its subsystems should be validated further. The model was validated with three different experiments. First the two maps were validated separately, then the complete powertrain model was validated with some basic driving cases.

Table 5.1: *Input and output of the two maps.*

Name	Input	Output
Throttle map	Engine speed Acc. pedal pos.	Throttle pos.
Engine map	Engine speed Throttle pos.	Engine torque

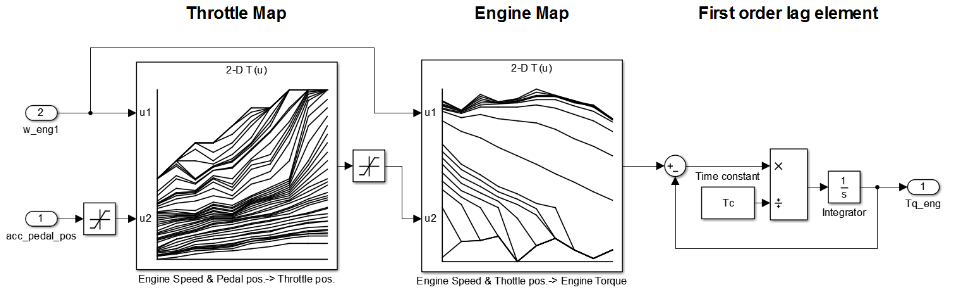

Figure 5.1: *Simulink schematic of the former engine model. The accelerator pedal position is saturated between 0 and 1. The throttle position is saturated between 4 and 100. The time constant is 0.21.*

Finally the developed powertrain was inserted in the vehicle model and was compared to an existing model.

The first experiment used the constant speed mode in the chassis dynamometer, where the dynamometers maintain a predefined engine speed regardless of the driver input. However, this method does not give relevant results, since it test areas in the maps that are not used in real driving. In the report a test is performed and shown for an engine speed of 2000 RPM and second gear. During the test, the accelerator pedal is pressed and the torque is measured. However, during most of the test, the accelerator pedal is pressed more than 60% but during real world driving it is more likely that the pedal position is less than 20% at lower engine speeds. Another problem with the validation is that all gears were not used.

In order to improve the performance of the model, a more thorough evaluation of the model must be performed. This is done by performing constant speed tests on each gear. Instead of using the constant speed mode in the chassis dynamometer, the road resistance mode is used instead. This mode corresponds to actual driving and provides more credible results, since the engine speed is not held constant by the dynamometers. By measuring pedal and throttle position, engine and wheel speed and wheel torque, the performance of each map and the full powertrain model can be investigated separately. To evaluate the dynamic performance of the model an acceleration test is conducted with third, fourth, and fifth gear.

The performance is determined with the Matlab function `goodnessOfFit` with the cost function NRMSE (Normalized Root Mean Square Error). This function measure how well data fit to reference data and is defined as

$$\text{fit} = 1 - \frac{||x_{ref} - x_{meas}||}{||x_{ref} - \bar{x}||} \tag{5.1}$$

where $||$ is the $\mathcal{L}^2$-norm, x_{ref} is the reference data, x_{meas} is the measured data and $\bar{x}$ is the mean value of the reference data. By multiplying the result with 100 the fit can be represented in %. The fit vary between $-\infty$ and 1 and a value of zero means that the measured data is no better than a straight line equal to the mean value of the reference data.

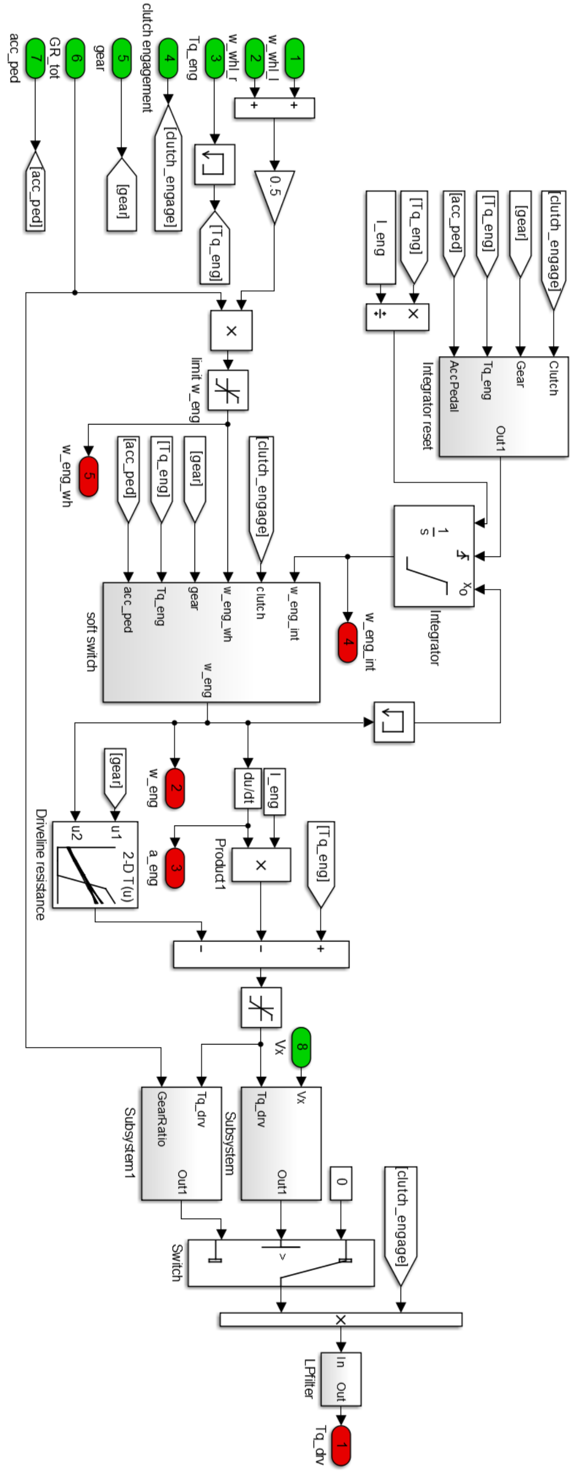

Figure 5.2: Simulink schematic of the former driveline model.

5.2 Driveline Model Complexity

The driveline model is a modified version of the basic driveline model in [8]. The following set of equations describe how the torque and angular velocity from the engine, is translated through the driveline, to the wheels

$$M_w = i_t i_f (M_c - M_{\text{losses}}) \tag{5.2a}$$
$$\dot{\theta}_e = i_t i_f \dot{\theta}_w \tag{5.2b}$$
$$J_e \ddot{\theta}_e = M_e - M_c \tag{5.2c}$$

where M_w is the torque at the wheels, $i_t i_f$ is the combined gear and final drive ratio, M_c is the torque at the clutch, M_{losses} is the estimated, gear dependant friction losses in the driveline, $\dot{\theta}_e$ is the angular engine speed, $\dot{\theta}_w$ is the angular wheel speed, J_e the engine inertia and M_e is the engine torque.

Since the engine torque can only be measured indirectly at the wheels, the performance of the driveline cannot directly be evaluated. However, it can be determined if there exist dynamics in the driveline, which are not explained by Equations 5.2. This is done with a step response test with the accelerator pedal position. By comparing the engine and wheel speed, conclusions can be drawn from the results. If they overlap, the rigid driveline model can be assumed to be valid. However, if they do not, a more complex model is needed to capture the dynamics of the driveline.

In [11] it is determined that the modeled friction losses did not improve the overall performance of the model. To determine if the friction losses should be included in the driveline model, the model will be evaluated both with and without the losses.

5.3 Experiment Plan

5.3.1 Constant Speed

Signals to be measured: Pedal position, Throttle position, Engine speed, Wheel torque.

Control signal(s): Accelerator pedal position, Gear.

Test mode: Road resistance.

Measurement description: The purpose of the test is to evaluate the performance of the maps at constant operating points. This is done by changing the accelerator pedal position and letting the wheel speed be brought to steady state. This is performed for all five gears.

5.3.2 Max Acceleration

Signals to be measured: Pedal position, Throttle position, Engine speed, Wheel speed, Wheel torque.

Control signal(s): Accelerator pedal position, Gear.

Test mode: Road resistance.

Measurement description: The purpose of this test is to see how the former model performs during maximum acceleration i.e. fully pressed accelerator pedal. Due to limitations in the dynamometers, this is only performed with gear three and higher. Two accelerations is performed on each gear.

5.3.3 Driveline Dynamics

Signals to be measured: Engine speed, Wheel speed.

Control signal(s): Accelerator pedal position, Gear.

Test mode: Road resistance.

Measurement description: A step response test is performed by pressing the accelerator pedal. The engine speed is measured using the OBD-tool and the wheel speed is measured with the dynamometers. The first gear is used in this test.

5.4 Results

This section presents the results from the evaluation. First the performance of the two maps are presented separately, after that the performance of the full powertrain model is shown. Then the performance during a full throttle test is presented. Finally the complexity of driveline model is examined.

5.4.1 Constant Speed

Throttle Map The performance of the throttle map is shown in Figure 5.3. The figure shows a comparison between modeled and measured throttle position for all gears and different engine speeds. The accelerator pedal position is used as input to the map and it is held constant during the test. The figure shows that the performance of the throttle map is slightly better for gear three and higher than for the lower gears. However, a data fit of 70% is not bad, considering that the map was created using the higher gears. It can also be noted that the output from the throttle map is higher than the references data for the lower gears.

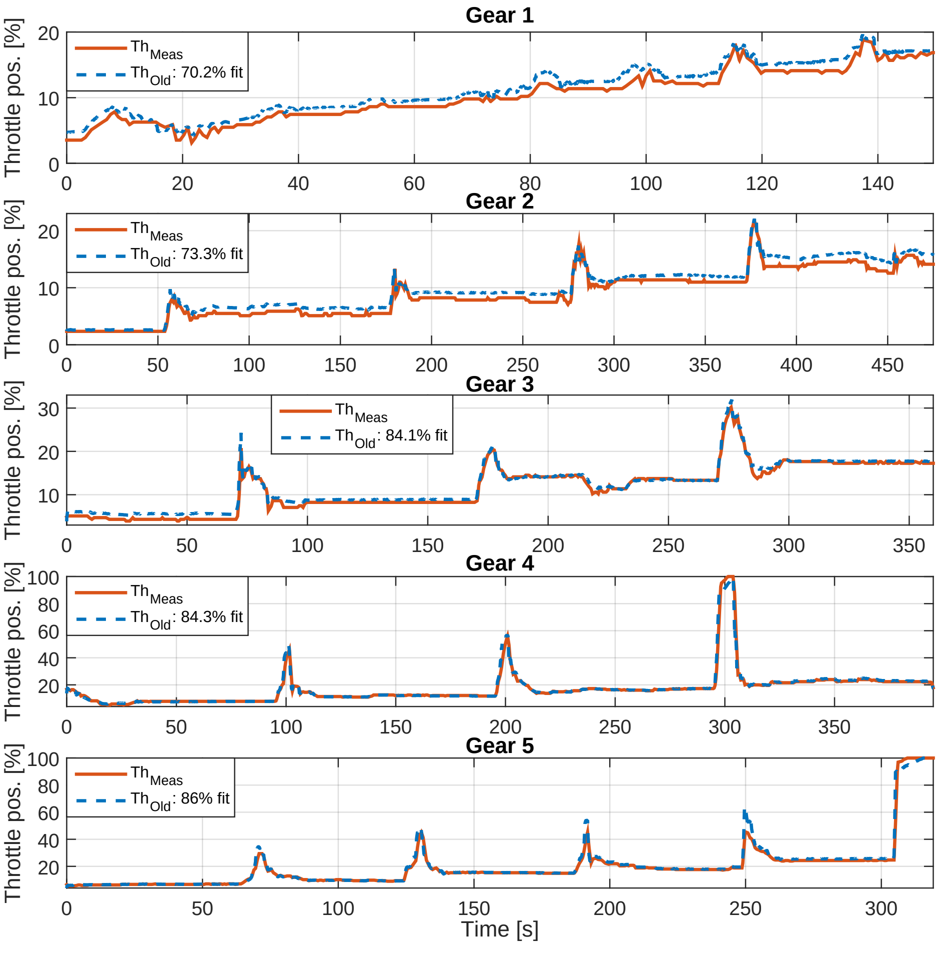

Figure 5.3: *Comparison of measured and modeled throttle position. The figure shows throttle positions for each gear. During the experiment, the engine speed is held constant at different levels ranging from 1500 to 5000 RPM. Measured accelerator pedal position is used as input to the throttle map.*

Engine Map The performance of the engine map is evaluated using measured throttle position and wheel torque, during a constant speed test for all gears and different engine speeds. Figure 5.4 shows a comparison between modeled and measured torque. Measured throttle position and engine speed are used as input to the engine map. Since the engine torque cannot be measured directly, the wheel torque is used instead. By using the output from the engine map along with the driveline model without the friction losses, the wheel torque can be estimated and compared to measurements. The wheel torque is scaled with the combined final drive and gear ratio to be able to compare the performance between the gears.

Figure 5.4 shows that the performance of the first two gears are very poor. During most of the test, the output from the engine map is negative and the overall behaviour of the curve is different from reference data. With a data fit of -252% and -178%, a straight line would had given a better result. The data fit for gear three is 32.7% and it is better than for the lower gears but it is not a satisfying result. The performance of gear four and five on the other hand is much better with around 70% fit to reference data. It can be noted from the last part of the figures that the modeled torque is slightly lower than the measured torque for all gears. During these parts are the engine speed and the accelerator pedal at their highest.

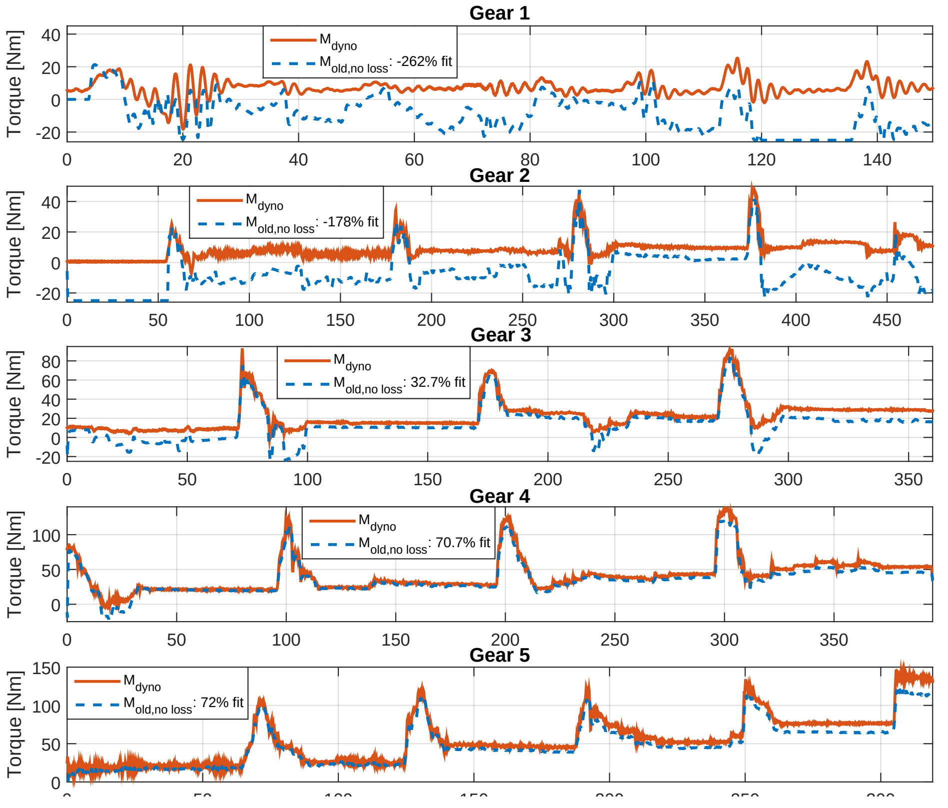

__Figure 5.4:__ Comparison of modeled and measured torque at the wheels, using the engine map and the driveline model. The measured torque is scaled with the combined final drive and gearbox ratio. The engine speed is held constant at different levels between 1500 to 5000 RPM. The oscillations in the first figure come from the dynamometers when performing measurments on the first gear.

Powertrain The performance of the full powertrain model differs quite a lot from the engine model, which can be seen in Figure 5.5. Instead of using measured throttle position as input to the engine map, measured pedal position is used with the throttle map to get the throttle position. The figure shows the same measured data as in Figure 5.4.

The data fit has increased for all gears and more notably for the lower gears, where it has increased with over 100 percentage points. The data fit for gear three has increased with around 22 percentage points and for the highest gears around 7 percentage points.

These results are remarkable since according to [11] the engine map performs well and it should give good results with measured throttle position. However, this is clearly not the case. According to the results in this chapter, it seems that faults in the two maps are canceling each other. This means that the faulty behaviour of the engine map does not show when using the full powertrain model.

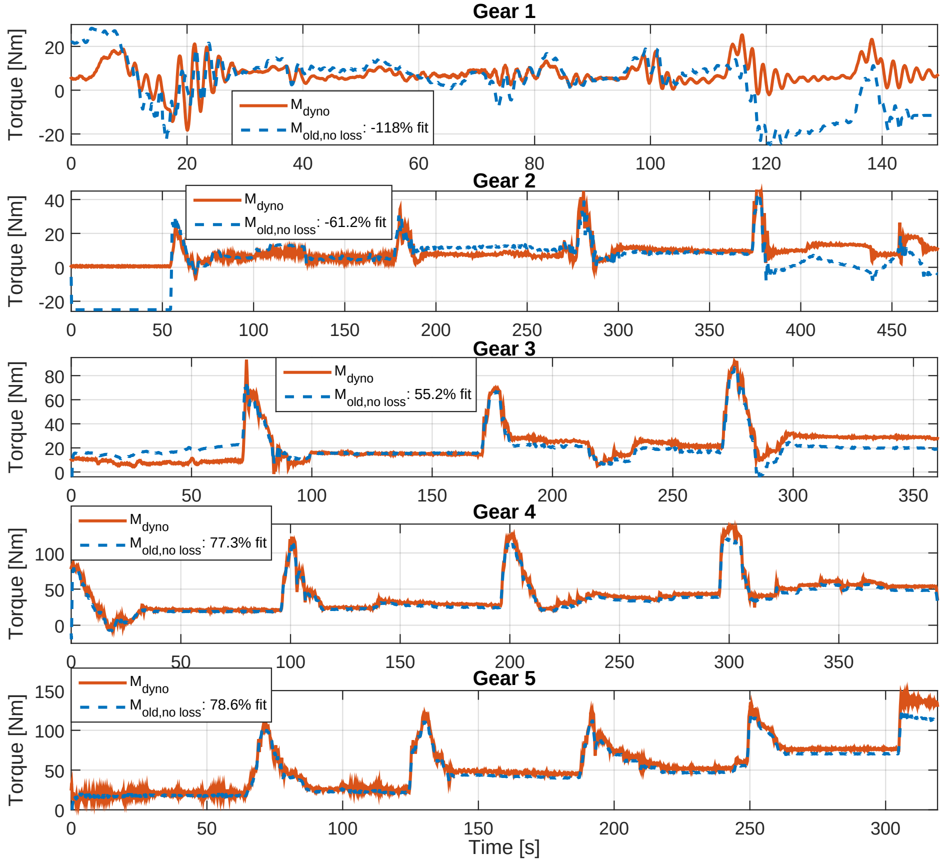

Figure 5.5: *Comparison of measured and modeled torque, using the full powertrain model. Accelerator pedal position is used as input to the model. The engine speed is held constant at different levels between 1500 to 5000 RPM during the experiment. The torque is scaled with gear and final drive ratio to get it in the same range for all gears.*

5.4.2 Max Acceleration

The previous tests were designed to test the static performance of the powertrain model. To evaluate the dynamic performance of the model, a dynamic test with fully pressed accelerator pedal was conducted for gear three and higher. Figure 5.6 shows six sets of curves, where the first two are for gear three, the third and fourth are for gear four and the last two sets are for gear five. The figure shows vehicle speed along with measured and modeled torque at the wheels and throttle position.

First, the output from the old model with the friction loss model was plotted. The results from this model are the blue lines in Figure 5.6. As can be seen, the modeled torque has only 38.2% fit to the references data. To find the reason for the poor results, output from two different versions of the model and throttle position are shown in the figure. By excluding the friction losses the purple lines with 45% fit are obtained and by using measured throttle as input to the engine map, the yellow, dashed lines with 43.7% fit are obtained.

By compiling these results, it can be ruled out that the poor data fit is due to the throttle map nor to the friction loss model. The reason for this is that the modeled throttle position had 78.7% data fit and the performance of the powertrain model only increased slightly without the loss model.

The poor results from the dynamic test can explained by studying Figure 5.7. The figure shows data that was used to create the throttle and engine map. Pedal and throttle position, torque and lambda value are presented when the engine speed is held constant at 4000 RPM. At $t = 565$ s it is clearly seen that the pedal position and the torque increases. However, the throttle position is unchanged. This is accomplished by lowering the lambda value, thus making the fuel mixture rich. That is, an engine map with throttle position as input cannot be used to model the engine with a fully pressed accelerator pedal.

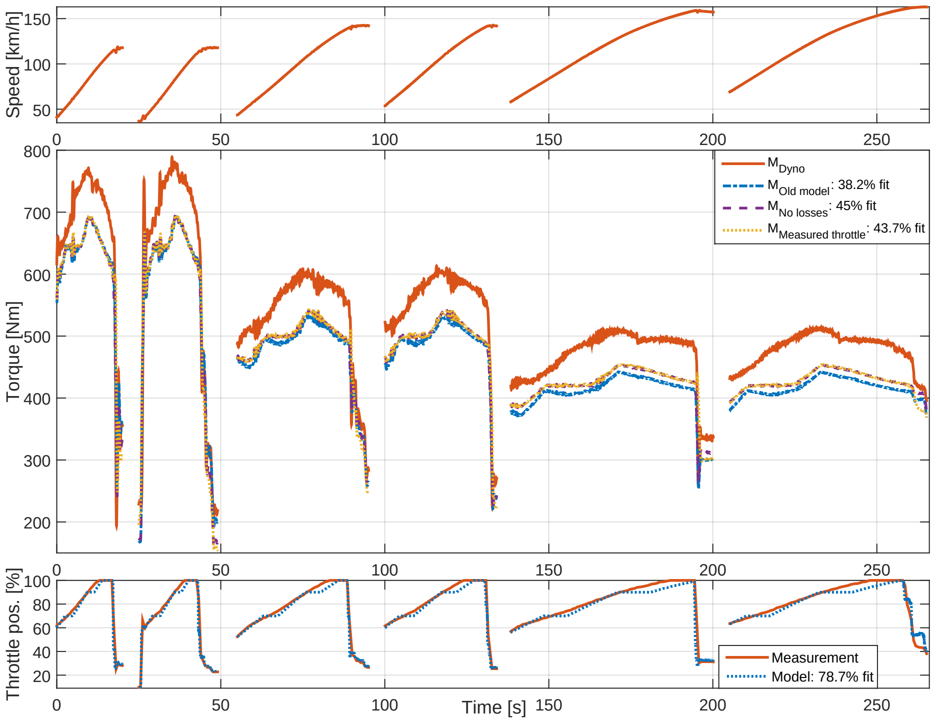

Figure 5.6: *Dynamic test with maximum accelerator pedal position for third, fourth and fifth gear.*

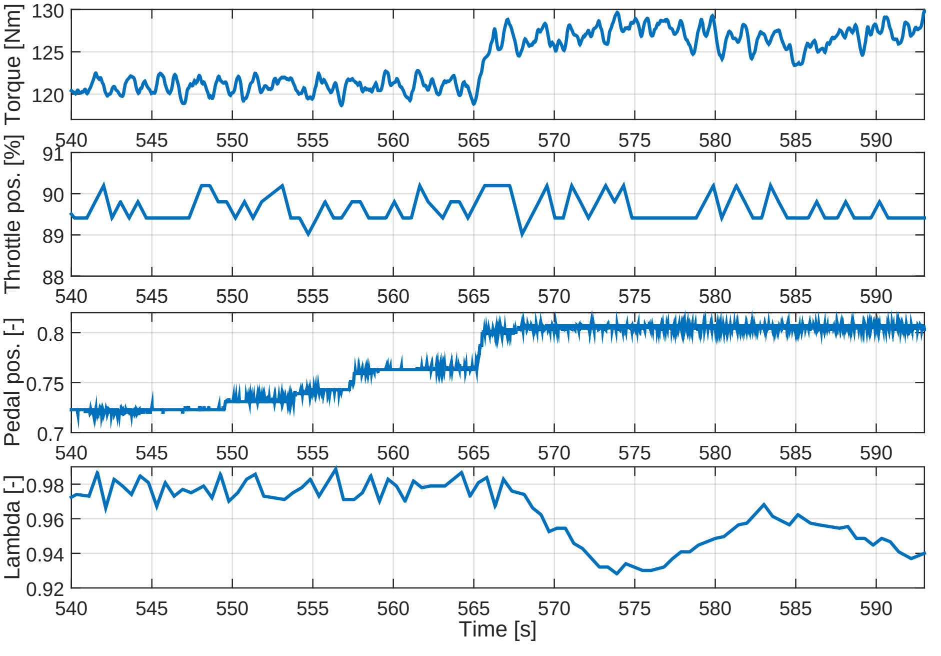

Figure 5.7: *Extracted from data that was used to make the throttle and engine map. The engine speed is held constant at 4000 RPM.*

5.4.3 Driveline Dynamics

Figure 5.8 shows a comparison between engine speed and wheel speed during a step in accelerator pedal position. The engine speed is measured through the CAN-bus and the wheel speed from the chassis dynamometers. To compare the two signals, the wheel speed is scaled with the combined gear and final drive ratio for the first gear. The two curves overlap each other and there are no signs of any driveline dynamics that are not explained by the rigid driveline model.

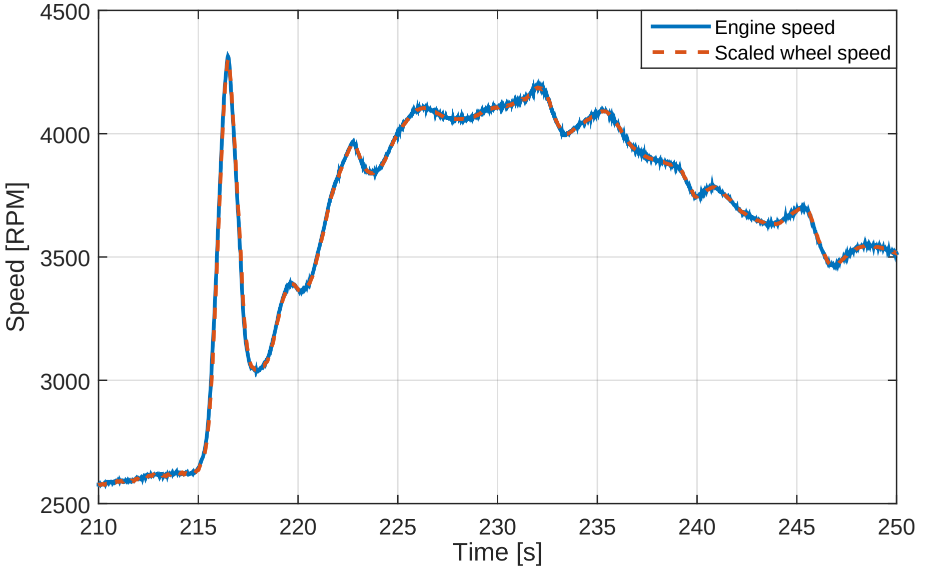

Figure 5.8: *Comparison between engine speed and wheel speed. The wheel speed is the mean value of the two driven wheels, scaled with the combined gear and final drive ratio for the first gear.*

5.5 Summary

In this chapter the engine and driveline model developed in [11] have been evaluated with real data from both static and dynamic experiments. From the results it can be concluded that the throttle map performs fairly well during both static and dynamic conditions and even for lower gears. The engine map, on the other hand, does not work well for the lower gears. It is also shown that an engine map with throttle position and engine speed as input cannot capture the behaviour of the engine during maximum acceleration. The powertrain model gives acceptable output that fit to reference data, while driving with constant speed and gear three and higher.

The driveline model complexity has also been examined and there are no signs of any dynamic behaviour that is not captured by rigid driveline model. The output torque from the powertrain model is almost always lower than reference data, this implies that friction loss model will not improve the performance of the model. This is also concluded in [11].

6 Improved Powertrain Model

This chapter presents how the powertrain model is improved, using the results and conclusions from chapter 5.

6.1 Powertrain Model

In the previous chapter it is concluded that the former powertrain model does not perform well for the first two gears. During maximum acceleration, the output is too low and the friction loss model does not improve the performance of model. In [11] the throttle signal from the OBD-tool is utilized to make two separate performance maps. However, it is not justified to have two consecutive maps and the reason is that two mappings have to be done with respective measurement errors. Also the throttle position cannot capture the behaviour of maximum acceleration and the throttle position is not used anywhere else in the vehicle model.

Instead of using two separate performance maps, a single 3 dimensional map is developed. The map takes pedal position, engine speed and gear as input. Gear one and two are treated separately and the higher gears use the same map, since the behaviour of the higher gears does not differ too much.

Since there are no dynamics in driveline that is not explained by rigid driveline model from [8], this driveline model is used. The only parameter in this model is the engine inertia, which was estimated in [11]. Since the friction loss model does not improve the performance, it is not included in the driveline model.

6.2 Data Acquisition

To create the engine map, the same data that was used to create the old maps is used for the higher gears. The purpose of this is to exclude the possibility that bad measurements are the reason behind the poor results. However, the data sets lack data for fully pressed accelerator pedal position, so the sets have to be complemented with measurements done during fully pressed pedal.

The chassis dynamometers are used to gather data necessary to create the maps. Constant speed is used with engine speed ranging from 1500 to 6000 RPM in steps of 500 RPM. Lower engine speeds cannot be measured since the wheel speed is too low for dynamometers and higher engine speeds are both harmful for the engine and are not necessary to make a useful model. For each engine speed, the accelerator pedal position is held constant while the torque reach a steady-state condition. Since the engine speed is held constant, the torque at the wheels can be considered to be the same as the engine torque but scaled with the combined final drive and transmission ratio.

This method of data acquisition is suitable for gear two and higher. However, for the first gear it becomes rather problematic. This is illustrated in Figure 6.1. The figure shows torque, pedal position and engine speed measured during constant speed mode with the first gear. As seen in the figure, the engine speed is far from constant and the torque oscillates greatly. For engine speeds of 4000 and 4500 RPM, it is not even possible to complete the measurements for all pedal positions.

6.2.1 Max torque

Signals to be measured: Pedal position, Engine speed, Wheel torque.

Control signal(s): Pedal position, Engine speed.

Test mode: Constant speed.

Measurement description: The accelerator pedal is fully pressed and the wheel torque is measured. This is repeated for all engine speeds from 1500 to 6000 RPM using the third gear.

6.2.2 Torque mapping

Signals to be measured: Pedal position, Engine speed, Wheel torque.

Control signal(s): Pedal position, Engine speed.

Test mode: Constant speed.

Measurement description: The accelerator pedal is held constant at different levels while the torque settles to a constant value. This is performed on the first two gears and engine speeds ranging from 1500 to 6000 RPM with steps of 500 RPM.

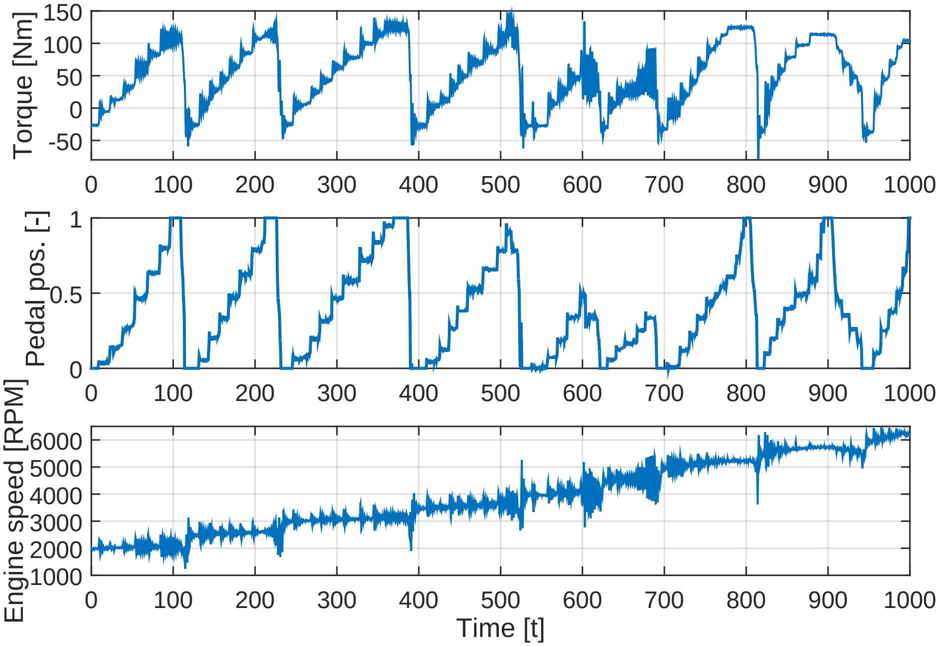

Figure 6.1: *Data gathered using constant speed mode and gear 1.*

6.3 Results

Instead of using pre-defined values for the pedal position, which was done in [11], the actual measured pedal position and torque from each operating point is used. Then by using the Matlab function `interp1`, the values are interpolated to a pedal vector with a length of 100 values. Thus creating a finer data grid and reducing the need of interpolation when the model is used.

The engine model is implemented in Simulink, which is illustrated in Figure 6.2 and replaces the old model in the vehicle model. Figure 6.3 shows a 3D contour of the developed performance maps. The lowest possible engine speed when performing experiments with the chassis dynamometers and constant speed mode is 1500 RPM. The dynamometers are not capable to rotate the driveline for lower speeds. However, during driving it is possible to reach lower engine speeds than 1500 RPM e.g. during idling. To handle this and eliminating the need to extrapolate outside the map, an extra tier of data is added to the engine map. The extra data is at 800 RPM and the pedal and torque values are the same as for 1500 RPM. The lower pedal position values are slightly adjusted. This results in an engine map that can handle lower engine speeds than 1500 RPM and the bad extrapolation, that can be seen for gear two and three at the beginning of Figure 5.4, is avoided.

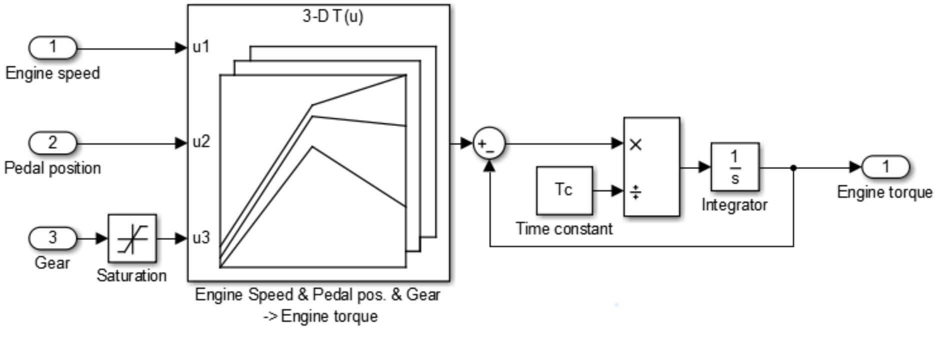

Figure 6.2: *Simulink scheme of the three dimensional engine map. Pedal position, engine speed and gear are taken as input to the map. The gear signal is saturated between 1 and 3, since the higher gears use the same map. The output then passes through a first order lag element with time constant 0.21.*

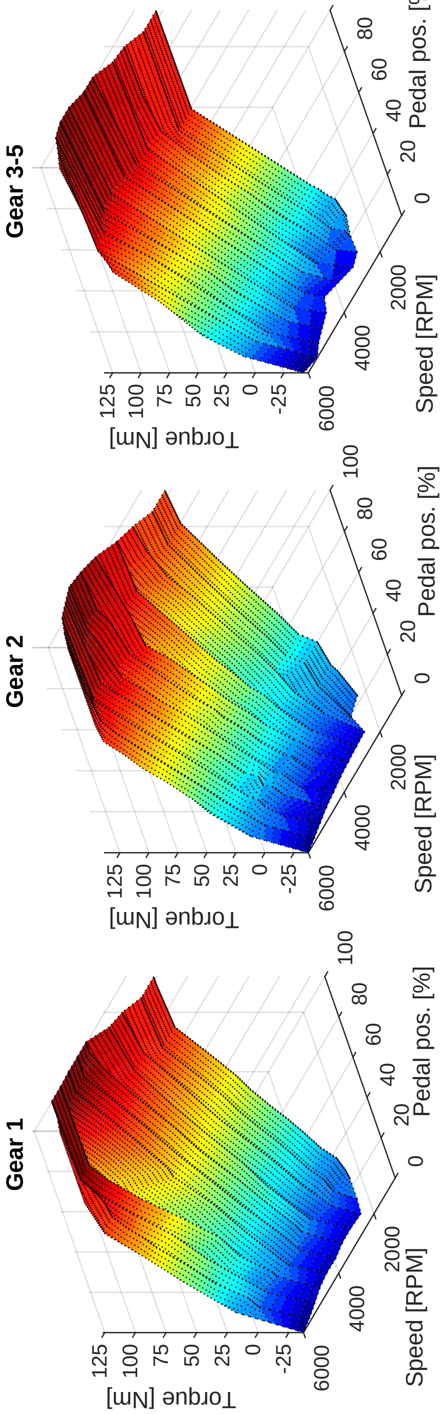

Figure 6.3: *3D contour of the three engine maps.*

7 Model Validation

In this chapter the improved powertrain model is validated and compared to the former model and measurements. The validation data consists of both data that resembles the driving task classes from Chapter 4 and data used to evaluate the former model in Chapter 5.

7.1 Constant Speed

The first test is performed on each gear separately and the purpose of the test is to see how the model performs at different constant levels of accelerator pedal position and vehicle speed. This test is similar to constant speed test performed in Chapter 5.

Figure 7.1-7.5 shows the performance of the improved powertrain model compared to the former model without the driveline losses and measured torque. To be able to compare the performance between the different gears, the torque has been scaled with the combined final drive and transmission ratio.

The improved model has a better data fit for all gears and it is more apparent for the first two gears. For gear one and two the data fit is positive for the improved model, whereas for the former model the fit is negative. Meaning that it is no better than a straight line with mean value of the references data. For the higher gears the data fit is only marginally better, only improving the fit with some percentage points.

The oscillations in the torque in Figure 7.1 comes from the problematic behaviour of measuring the torque and wheel speed on the first gear. The torque becomes to high for the chassis dynamometers to handle and the control system cannot dampen the oscillations. The reason that the modeled torque also oscillates is due to the wheel speed being used as input to the performance maps.

Experiment plan

Signals to be measured: Pedal position, Engine speed, Wheel speed, Wheel torque.

Control signal(s): Accelerator pedal position, Gear.

Test mode: Road resistance.

Measurement description: The accelerator pedal is held constant at different levels while the engine speed is brought to steady state. This is done for all gears.

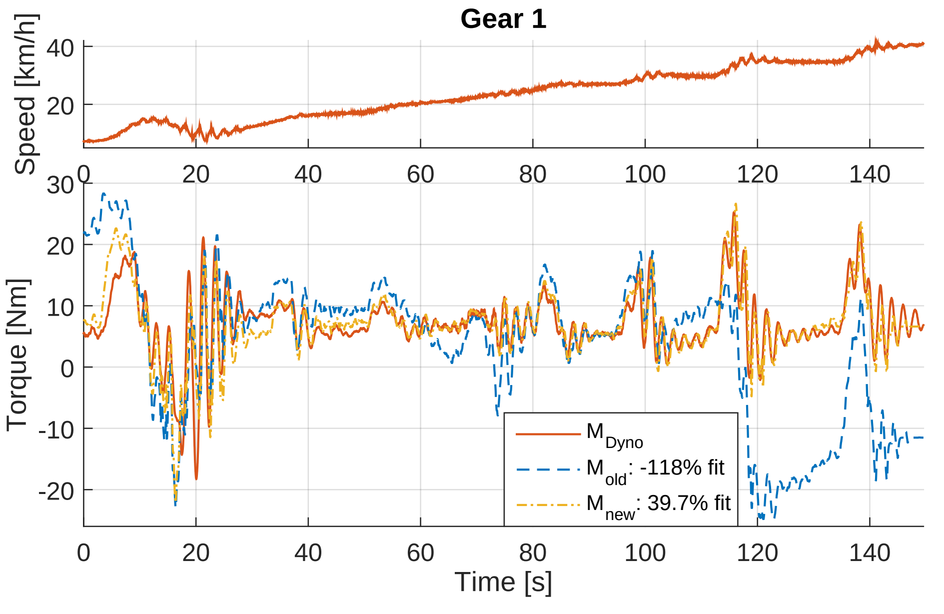

Figure 7.1: *Powertrain model validation for the first gear.*

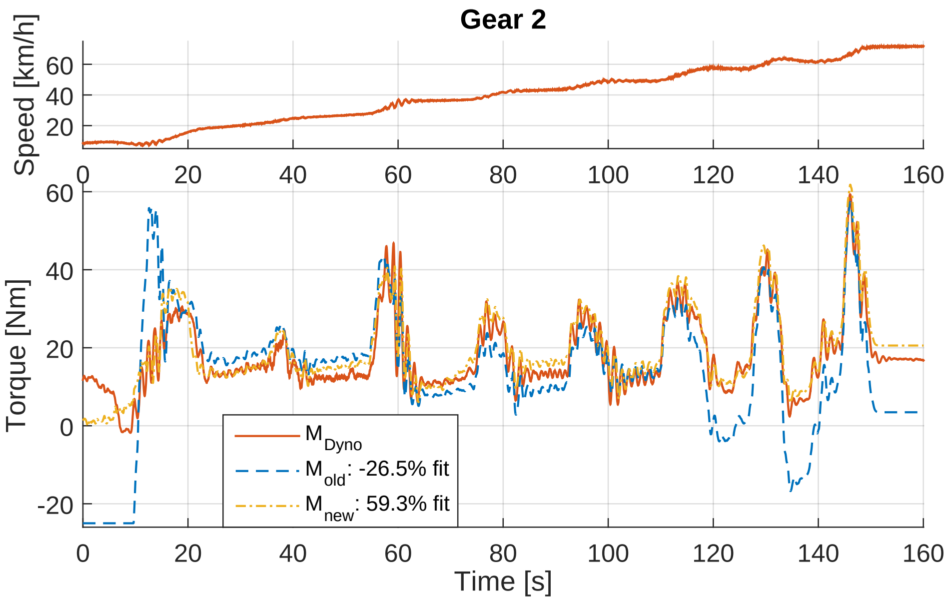

Figure 7.2: Powertrain model validation for the second gear.

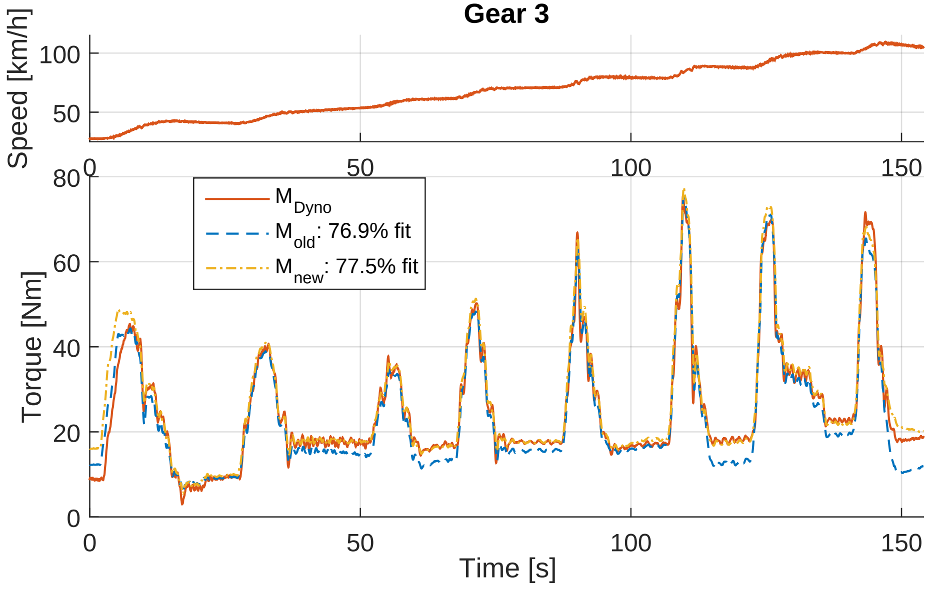

Figure 7.3: Powertrain model validation for the third gear.

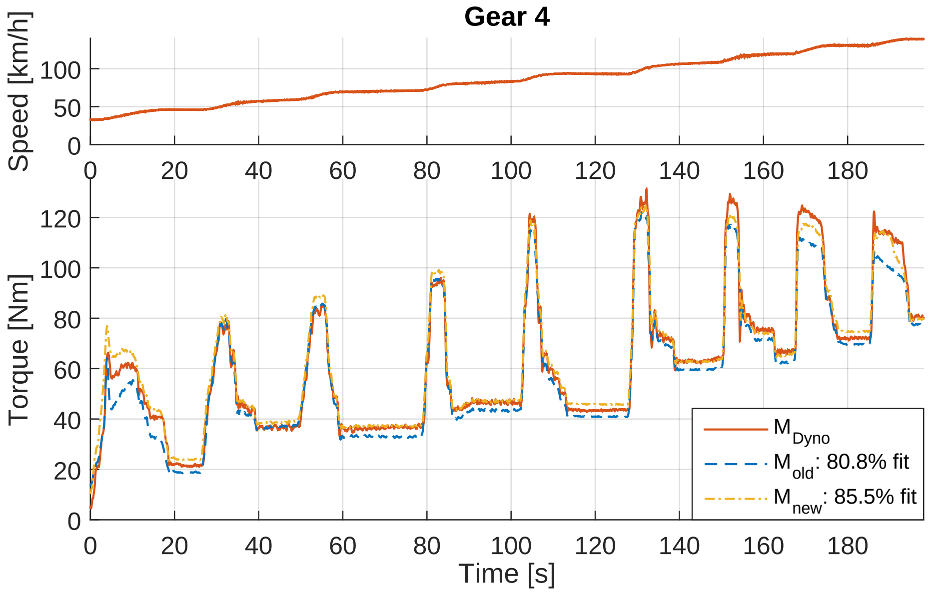

Figure 7.4: *Powertrain model validation for the fourth gear.*

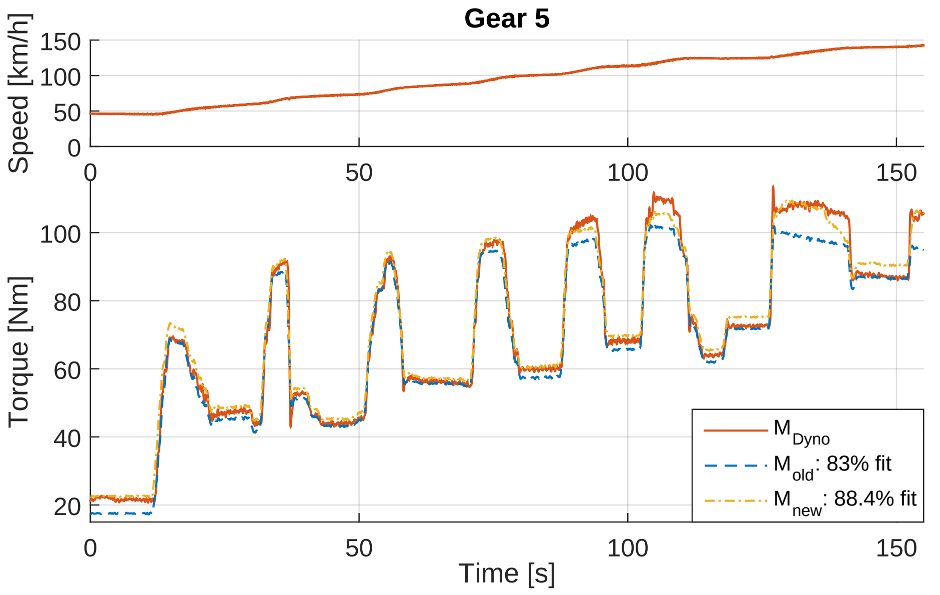

Figure 7.5: *Powertrain model validation for the fifth gear.*

7.2 High Constant Velocity

Since the most common driving task in the Sim III simulator is the *"High Constant Velocity"*-task, it is advisable to perform a test that resembles this driving task. This is done by following the speed of the Artemis Motorway 130 drive cycle.

Figure 7.6 shows vehicle speed and wheel torque from the performed test. Since the original drive cycle is over 16 minutes long, only a smaller part of the drive cycle has been plotted. The used data resembles real world driving that can be classified as *"High Constant Velocity"*. As can be seen in the figure, the improved model has improved the data fit with over 20 percentage points.

Experiment plan

Signals to be measured: Pedal position, Clutch, Engine speed, Wheel speed, Wheel torque.

Control signal(s): Pedal position, Clutch, Gear.

Test mode: Road resistance.

Measurement description: The velocity from the Artemis Motorway 130 drive cycle is followed during the test.

7.3 Max Acceleration

In Chapter 5, it is concluded that the former powertrain do not perform well during maximum acceleration. To validate that the improved model can handle this driving behaviour, the same data from the max acceleration test is used.

Figure 7.7 shows six acceleration steps, performed twice on each of three highest gears. The improved model performs much better than the former model and is actually close to follow the measured torque. The data fit has improved with over 30 percentage points and it is clearly shown that the improved engine model can handle full acceleration.

Experiment plan

Signals to be measured: Pedal position, Engine speed, Wheel speed, Wheel torque.

Control signal(s): Accelerator pedal position, Gear.

Test mode: Road resistance.

Measurement description: The accelerator pedal is fully pressed and it is performed for gear three and higher due to limitations in the dynamometers. Two accelerations is performed on each gear.

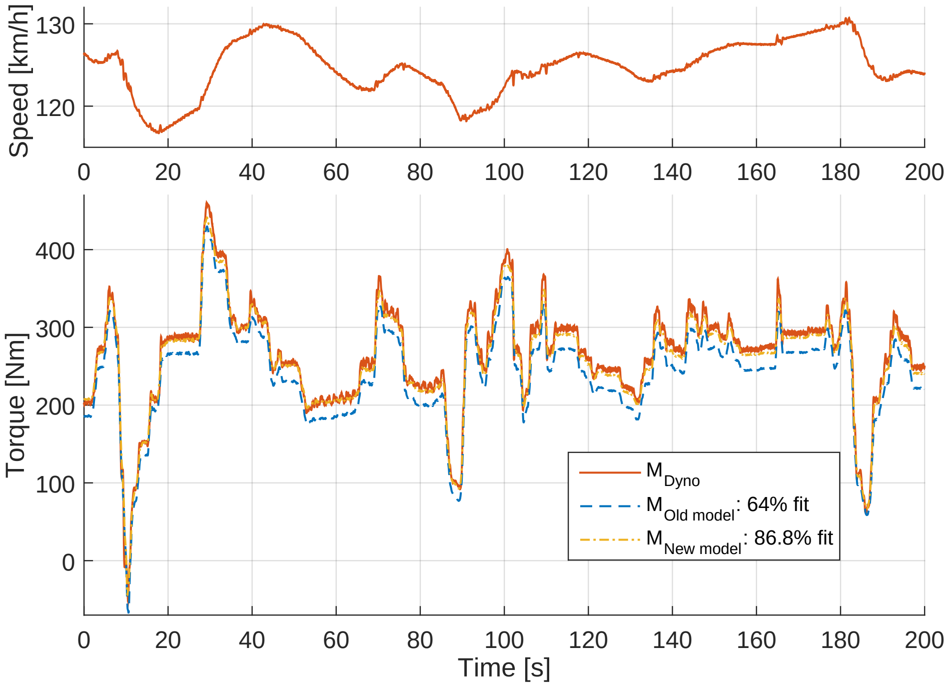

Figure 7.6: *Comparison between measured and modeled wheel torque using a smaller data segment from data that resembles the Artemis Motorway 130 drive cycle.*

7.4 Low Speed Dynamic

Finally, the models are validated against low speed dynamic data. The data is gathered when the vehicle is moving slowly on the first three gears. This case is similar to the low speed parts of the *"Mixed Driving"*-class from Chapter 4.

Figure 7.8 shows the results from the low speed dynamic test. Vehicle speed, torque, engine speed, gear and clutch signal is presented in the figure. When the clutch pedal is pressed, the engine speed is calculated from the engine torque according to the following equation

$$\dot{\theta}_e = \int \frac{M_e}{J_e} \, \mathrm{d}t \tag{7.1}$$

since the torque at the clutch is assumed to be zero. With a data fit of only around 40%, neither the former nor the improved model perform well during the test.

Unlike the previous validation test, gear shift are performed during this test. The model can handle this but it need a continuous clutch signal to give reliable re-

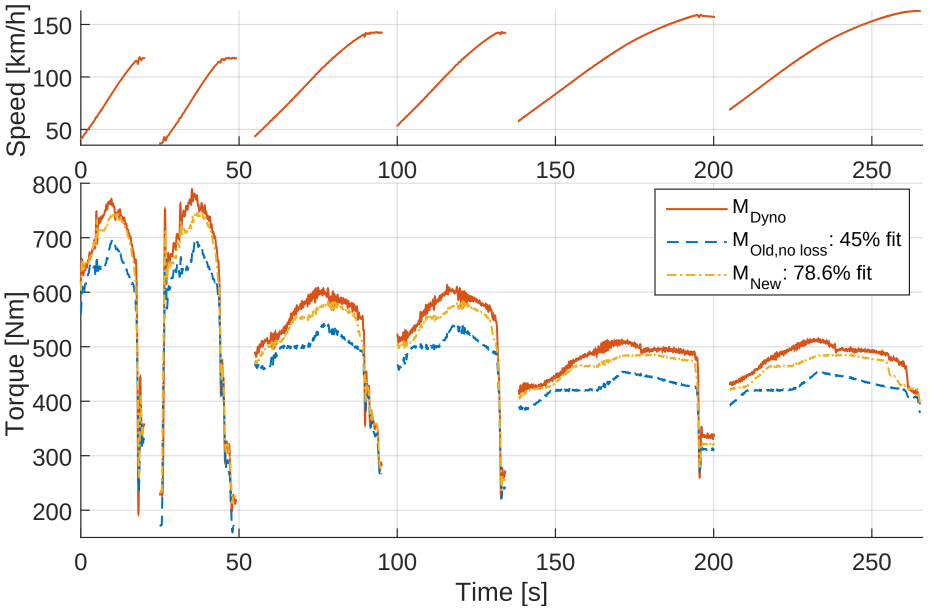

Figure 7.7: *Comparison between measured and modeled torque. The accelerator pedal is fully pressed during the test and each gear from three and higher is tested twice.*

sults during the gear shift. However, the CAN-bus only logs a discrete value of the clutch position. This can explain the irregular behaviour of the engine speed and torque when the clutch pedal is pressed and released. The spikes in the torque signal, which for an example can be seen at $t = 4$ in Figure 7.8 are due to the driveline model. The wheel torque is calculated according to

$$M_w = i_t i_f (M_e - J_e \ddot{\theta}_e) \tag{7.2}$$

and when the clutch pedal is released the engine speed drops quickly resulting in the derivative of the engine speed ($\ddot{\theta}_e$) becomes large negative. This in turn results in the spikes in the torque signal.

Experiment plan

Signals to be measured: Pedal position, Clutch, Engine speed, Wheel speed, Wheel torque.

Control signal(s): Pedal position, Clutch, Gear.

Test mode: Road resistance.

Measurement description: The test is performed by running the vehicle on low speeds and gears. During the test, the vehicle is brought to rest and then starting again.

7.5 Summary

In this chapter, the improved powertrain model has been validated with realistic driving cases. The improved model has been compared to the former model and measurements to show its enhanced performance. Table 7.1 shows a data fit compilation of validation tests performed in this chapter. As can be seen in the table, the largest improvements has been for the lower gears and during high speeds and accelerations. The performance of the higher gears has only improved slightly and this also applies for driving with low speeds and gears.

Table 7.1: *Data fit compilation of all test performed in this chapter.*

Test	Former Model	Improved Model	Diff
Constant Speed Gear 1	-118%	37.7%	155.7%
Constant Speed Gear 2	-25.6%	59.3%	84.9%
Constant Speed Gear 3	76.9%	77.5%	0.6%
Constant Speed Gear 4	80.8%	85.5%	5.0%
Constant Speed Gear 5	83.0%	88.4%	5.4%
High Constant Velocity	64.0%	86.8%	22.8%
Max Acceleration	45.0%	78.6%	33.6%
Low Speed Dynamic	39.8%	41.5%	1.7%

The improved model has been compared to the former model and measurements to show its enhancement and performance.

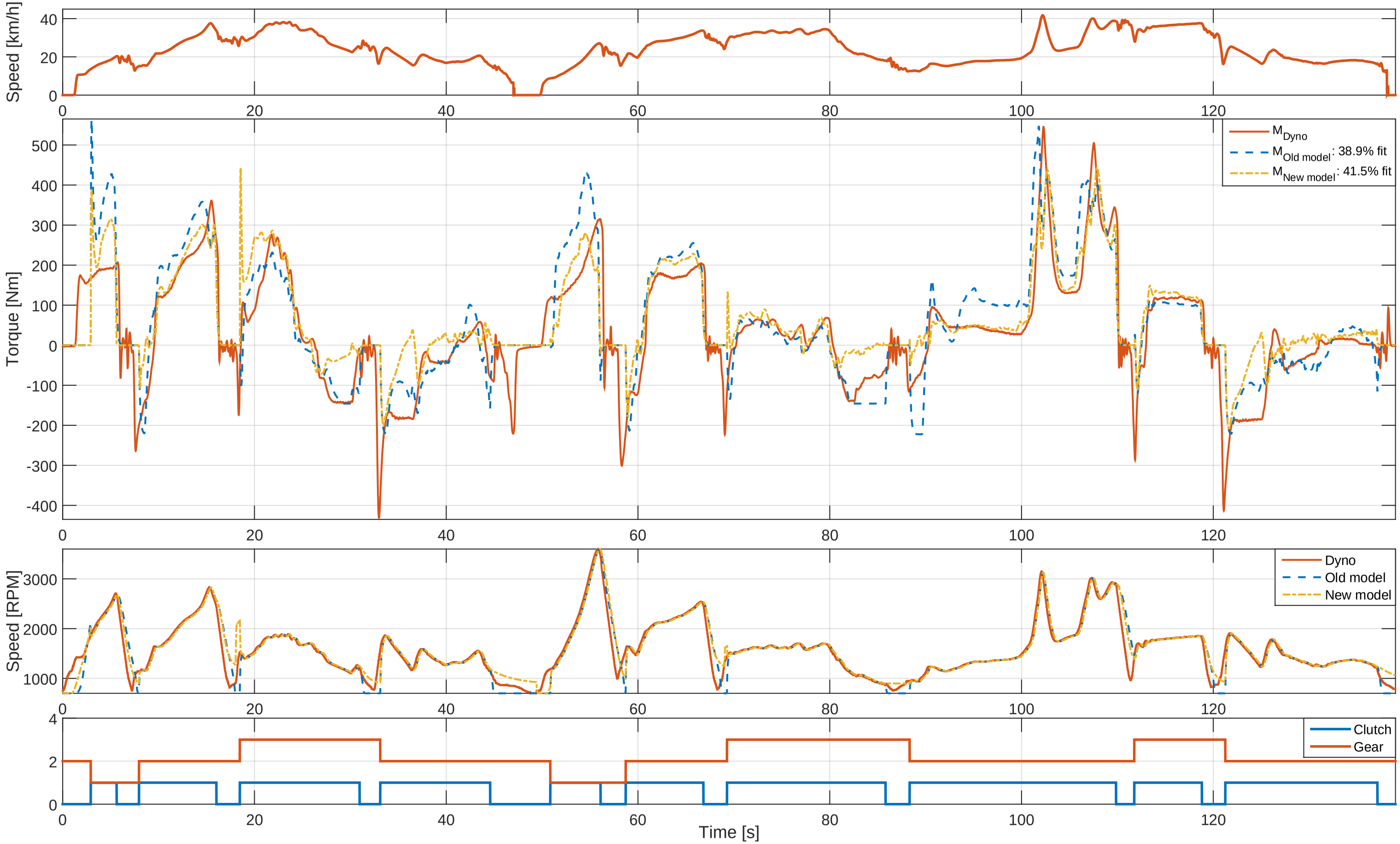

Figure 7.8: *Comparison between modeled and measured torque during a low speed dynamic test. The third figure shows engine speed, when the clutch pedal is pressed the engine speed is calculated from the engine torque. The clutch signal in the fourth figure is zero when the clutch pedal is fully pressed and one when it is released.*

8
Discussion and Conclusions

This chapter contains a discussion of the performed work in this thesis. The methodology and results of each chapter is discussed and analyzed. Finally, conclusions that can be drawn from the results are presented along with possible future work.

8.1 Discussion

Driving Task Classification The driving task classification was performed on simulator studies using statistical parameters. The three drivings tasks were expected considering the number of studies analyzed. More driving task can be identified if more studies with greater variety are examined. When the classification in this thesis was performed, the studies in Table 4.1 were the only available. The classification was done with mean values of statistical parameters used to describe driving patterns in drive cycles [6, 7, 15]. Mean values are used to reduce the influence of outliers. In Table 4.4, the simulator data is compared to real driving data where the velocity is higher than 80 km/h. It is not entirely correct to compare the different data sets in this manner since the conditions are different. However, it is interesting that the cruising time differs so much between simulator data and real driving. Many of the analyzed studies have large negative accelerations that is not present in the real world driving data. This is probably due to test persons were intructed to fully pressing the brake pedal.

Evaluation of Former Powertrain Model Although the former model was validated in [11], a new evaluation of the former model was performed in this thesis. The difference between the performed tests, is that in this thesis the test corresponds to actual driving and more realistic driving behaviour. In [11] it was concluded that the bad performance of the model came from the throttle map. However, in this thesis it is shown that the throttle map performs quite well. It is remarkable that the conclusions are directly opposite to each other and it shows the importance of carefully choosing validation data. The former model consist of two performance maps, however the decision to have two maps is not sufficiently motivated, since the throttle position is not used anywhere else in the model. In Figure 5.7 it is even shown that the throttle position cannot capture the behaviour of the engine during full acceleration. This is due to the λ–control described in Chapter 3.

Improved Powertrain Model The powertrain model was improved using the conclusions drawn from the evaluation in Chapter 5. The major improvement was done with the engine model. Instead of using two performance maps, a single 3D map was estimated. To ensure that the improvement came from a better model, the same data that was used to estimate the former engine maps was used for the higher gears. This excludes the possibility that the bad performance of the former model was due to bad measurements. Since the former model was created using mostly the third gears, new measurements had to be done to create the map for gear one and two. The mapping procedure was carried out in the same manner as for the higher gears, i.e. the accelerator pedal was held constant at as many levels as possible while the torque was brought to steady state. This procedure requires the engine speed to be constant for Equation 7.2 to hold. This is possible for gear two and higher but for gear one it becomes problematic, which can be seen in Figure 6.1. The engine speed is oscillating violently and it is really hard to get good measurements. It is possible to create an engine map from this data, but particularly good results cannot be obtained. This is shown in the validation of the engine map in Chapter 7.

Model Validation The new powertrain model was validated with measurements that was supposed to resemble actual driving and simulator scenarios. This ensures that the model is validated in the area where it will be used. The choice of validation data was also based on the driving task classification done in Chapter 4. The new and former model were compared to the measurements using data fit. The biggest change in performance is for constant speed and the first two gears. This is expected since the new engine map is gear dependant and handles the first two gears separately. There is a smaller change in performance for the higher gears and this is due to the two maps being estimated using the same data. However, during maximum acceleration the performance of the new model has significantly increased due to not considering the throttle position. Figure 7.8 shows the most complex driving test and the performance of both the new and former model is around 40%. Despite the new gear dependant engine map the new model does not perform well. This is most likely due to the clutch being used in this test. When the clutch is pressed, the engine speed is calculated from the engine torque and then fed back to the engine map. Furthermore, the clutch model expect a continuous clutch signal, but this signal is only available when using a pedal robot. When studying the measured torque in Figure 7.8 effects from the dynamometers can be seen. The large negative torque arises when the clutch pedal is pressed and the engine is disconnected from the driveline.

8.2 Conclusions

The first goal of this master thesis was to classify different driving tasks, by statistically examine simulator studies performed in the Sim III simulator. Using statistical parameters commonly used when analyzing drive cycles, the studies can be divided into three driving tasks: "High constant velocity", "High velocity with evasive maneuver" and "Mixed driving". Where the first one is the most common and consist mainly of motorway driving with none to little traffic. The second is a special case of the first one where the driver has to perform an evasive maneuver, such as braking or performing a lane change. The last driving task is the most complex and consist of city driving, driving at low speeds and performing gear shifts.

The second goal was to improve the performance of a former powertrain model and validate the model with measurements. A new engine map has been developed and consists of a single map instead of two. The new map is a 3D performance map that takes engine speed, accelerator pedal position and gear as input to calculate the engine torque. The reason that a single map is used is that a torque map that takes throttle position and engine speed as input cannot capture the behaviour of the engine during maximum acceleration. The driveline is modeled as rigid without any friction losses, since the loss model does not improve the performance of the powertrain model.

The new powertrain model has been validated using realistic data measured with chassis dynamometers. The performance of the new model has significantly increased when driving with high constant velocity and during maximum acceleration. However, when driving with low gears and speeds the performance of the model has only slightly increased, despite the new gear dependant engine map.

8.2.1 Future Work

Clutch model The powertrain model does not perform well when the clutch is pressed and the engine speed is calculated from the engine torque. To provide credible results the model needs further investigation. However, it is not advisable to perform this in the chassis dynamometers laboratory, since the the engine torque cannot be measured when the clutch pedal is fully pressed.

Vehicle model parameter investigation The powertrain is a smaller subsystem of a larger vehicle model in the Sim III simulator. To run the full model, several vehicle dependent parameters must be determined to get accurate results e.g. aerodynamic, wheel and suspension parameters. Furthermore, a methodology to validate the vehicle model must be developed. However, this is not a trivial task since there is a human driving the simulator. This means that the exact same driving behavior must be conducted in both the simulator and on the road/lab to be able to draw proper conclusions of the model performance.

Appendix

A

Statistical Parameters

This appendix describes how the statistical parameters used in Chapter 4 are defined and how they are calculated. A total of 17 different parameters were used and each parameter belong to one of the following three categories: velocity, acceleration or driving characteristics.

For data from the simulator studies, the velocity and acceleration were given. However, for the real driving data, the acceleration had to be calculated from the velocity. In each sample i, the acceleration is given by

$$a_i = \frac{v_{i+1} - v_i}{3.6 \cdot T_s}, \ i = 1, ..., N - 1$$

where v is the velocity, T_s is the sample time and N the number of samples. The unit for the velocity is km/h and for the acceleration it is m/s^2. The statistical parameters in this appendix are in the same order as in Table 4.2 and 4.3.

A.1 Velocity

Average velocity is defined as

$$\overline{v} = \frac{1}{N} \sum_{i=1}^{N} v_i \tag{A.1}$$

Average running velocity is the average velocity of the vehicle when it is moving. It is defined as

$$\overline{v}_{\text{pos}} = \frac{1}{N_{v>0}} \sum_i v_i, \quad v_i > 0 \tag{A.2}$$

Standard deviation of velocity is defined as

$$\sigma_v = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (v_i - \overline{v})^2} \tag{A.3}$$

where $\overline{v}$ is the average velocity.

A.2 Acceleration acceleration

Average acceleration is defined as

$$\overline{a} = \frac{1}{N} \sum_{i=1}^{N} a_i \tag{A.4}$$

Average positive acceleration is defined as

$$\overline{a}_{\text{pos}} = \frac{1}{N_{a>0}} \sum_i a_i, \quad a_i > 0 \tag{A.5}$$

where $N_{a>0}$ is the number of samples where $a > 0$.

Average negative acceleration is defined as

$$\overline{a}_{\text{neg}} = \frac{1}{N_{a<0}} \sum_i a_i, \quad a_i < 0 \tag{A.6}$$

where $N_{a<0}$ is the number of samples where $a < 0$.

Maximum positive acceleration is defined as

$$a_{max} = \max\{a_i\}, \quad i = 1, \dots, N \tag{A.7}$$

Maximum negative acceleration is defined as

$$a_{min} = \min\{a_i\}, \quad i = 1, \dots, N \tag{A.8}$$

95th percentile maximum acceleration is a limit where 95% of the values are lower than this limit.

95th percentile minimum acceleration is a limit where 95% of the values are higher than this limit.

Standard deviation of acceleration is defined as

$$\sigma_a = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(a_i - \overline{a})^2} \tag{A.9}$$

A.3 Driving Characteristics

The limits used to define the different driving characteristics are commonly used limits when comparing drive cycles. The velocity is measured in km/h and the acceleration in m/s^2.

Percentage of time idling is defined as

$$\text{time}_{\text{pct,idling}} = \frac{N_{v=0}}{N} \tag{A.10}$$

where $N_{v=0}$ is the number of samples where the vehicle is stationary.

Percentage of time creeping is defined as

$$\text{time}_{\text{pct,creeping}} = \frac{N_{|a|\leq 0.1,\ 0<v\leq 18}}{N} \tag{A.11}$$

where $N_{|a|\leq 0.1,\ 0<v\leq 18}$ is the number of samples where the vehicle is moving forward slowly.

Percentage of time cruising is defined as

$$\text{time}_{\text{pct,cruising}} = \frac{N_{|a|\leq 0.1,\ v>18}}{N} \tag{A.12}$$

where $N_{|a|\leq 0.1,\ v>18}$ is the number of samples where the vehicle is assumed to move at constant speed.

Percentage of time accelerating is defined as

$$\text{time}_{\text{pct,accelerating}} = \frac{N_{a>0.1}}{N} \tag{A.13}$$

where $N_{a>0.1}$ is the number of samples where the vehicle is accelerating.

Percentage of time decelerating is defined as

$$\text{time}_{\text{pct,decelerating}} = \frac{N_{a<-0.1}}{N} \tag{A.14}$$

where $N_{a<-0.1}$ is the number of samples where the vehicle is decelerating.

Percentage of time on each gear is defined as

$$\text{time}_{\text{pct,gear }i} = \frac{N_{\text{gear}=i}}{N},\ i = 0, \ldots, 5 \tag{A.15}$$

where $N_{\text{gear}=i}$ is the number of samples for each gear i.

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