# Project report
# Project 1 – TSFS09

Eric Moringe – erimo668@student.liu.se
David Wiman – davwi279@student.liu.se

February 15, 2023

# Contents

# Chapter 1

# Introduction

This project report deals primarily with a turbocharged engine. A mathematical model for the engine is to be developed and implemented, its model parameters identified from measured data, and the various models are validated. A controller in connected to the fuel injection system, which uses both feedforward and feedback from the discrete lambda sensor. Finally, the engine is coupled with a number of ready-made modules containing driver, clutch and driveline models. This is in order to perform simulations of the complete vehicle. A series of experiments are conducted with the aim to study the emission formation and consumption. The tool that is used for implementation is Matlab combined with Simulink.

Besides working on the engine model, the report addresses a series of studies, whose purpose is to illustrate how the energy stored in fuel is converted into a driving torque during the engine operating cycle, and the losses that may occur.

# Chapter 2

# Model description and experiment plan

In this chapter the engine is divided into a number of components, which are then modeled separately. For each component specified input and output signals, mathematical model which describes the behavior and the parameters are determined. It is then described how the model parameters will be identified. An overview of all input signals to the actuators and output signals from the sensors which should be included in project 1 is shown in Figure 2.1 where the red signals and components will be used in project 2 for a turbocharged engine.

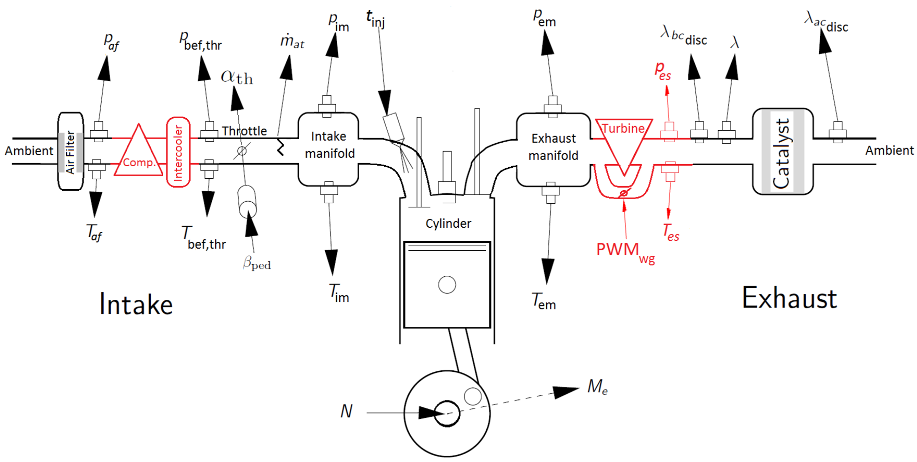


Figure 2.1: An overview of the air path with signals and components to be modeled in project 1 (shown in black) and project 2 (shown in red+black)

Mathematical models are going to be used for the modeling of following engine sub components:

- Accelerator pedal
- Throttle

- Intake manifold
- Fuel injector
- Cylinder
- Exhaust system with lambda sensor
- $\star$ Compressors wheel diameter (used in project 2)
- $\star$ Wastegate time constant (used in project 2)

Because the simulations should be done with both warm and cold engine, it is also explored how long it takes for the catalyst to become warm. Sensors that measure air mass flow and pressure in the intake manifold are assumed to have negligible dynamics, while only the delays at lambda measurement are taken into account and exhaust gas mixing dynamics in the exhaust manifold are neglected. The control signals which are the inputs to the engine model are:

- Accelerator pedal position ($\beta_{\text{ped}}$),
- Engine speed ($N$),
- Fuel injection time ($t_{\text{inj}}$),
- Wastegate control signal ($\text{PWM}_{\text{wg}}$).

**The control signals that are going to be mentioned in the experiment plans, must be selected only among these. During measurements in the lab, control signals are the ones which can be controlled from the control room.**

The entire engine model block in Simulink should produce the following output signals

- Engine torque ($M_e$),
- $\lambda$ measured by the discrete sensor ($\lambda_{\text{bc,disc}}$),
- Air mass flow past the throttle ($\dot{m}_{\text{at}}$)
- Intake manifold pressure ($p_{\text{im}}$).
- Exhaust manifold pressure ($p_{\text{em}}$).

## 2.1 Accelerator pedal

### 2.1.1 Model description

**Model input signal(s):** Accelerator pedal position ($\beta_{\text{ped}}$),

**Model output signal(s):** Throttle angle ($\alpha_{\text{th}}$)

**Model:** The throttle angle is calculated by the following differential equation:

$$\dot{\alpha}_{\text{th}} = \frac{1}{\tau_{\text{th}}}(\beta_{\text{ped}} - \alpha_{\text{th}}) \tag{2.1}$$

where $\beta_{\text{ped}}$ and $\alpha_{\text{th}}$ can changes continuously between 0 and 1.

**Parameter to find (via measurement):** Time constant of the throttle ($\tau_{\text{th}}$).

**Other parameters in the model: -**

### 2.1.2 Experiment plan

**Signal(s) to be measured:** Throttle angle ($\alpha_{\text{th}}$)

**Control signal(s):** Accelerator pedal position ($\beta_{\text{ped}}$)

**Type of experiment:** Dynamic.

**Measurement description:** While engine runs with a constant speed at an operating point many steps (up-down-up-down-...) are performed in accelerator pedal position. The times between steps are selected such that measured signals become stable before the next step is done.

**How to find the parameter(s):** Since it is assumed that the system has first order dynamics, the step response expressed in time domain is:

$$\alpha_{\text{th}}(t) = \left(1 - e^{-\frac{t-t_0}{\tau_{\text{th}}}}\right)(\beta_{\text{ped},\text{new}} - \beta_{\text{ped},\text{old}}) + \beta_{\text{ped},\text{old}} \tag{2.2}$$

where $t_0$ is the time point when the step happens. At time $t = \tau_{\text{th}} + t_0$ is

$$\left(1 - e^{-\frac{t-t_0}{\tau_{\text{th}}}}\right) = 1 - e^{-1} \approx 0.63 \tag{2.3}$$

Therefore the time constant is determined as the time interval between the instance when the first change in the signal is observed until throttle angle reaches 63% of its final values.

## 2.2 Throttle

The air mass flow past the throttle depends on throttle angle and ambient pressures and temperatures. In most of the engine operating points it is a significant pressure drop across the throttle which is well described by compressible flow models.

$$\dot{m}_{\text{at}} = \frac{p_{\text{us}}}{\sqrt{RT_{\text{us}}}} A_{\text{eff}}(\alpha_{\text{th}})\Psi(\Pi), \quad \Pi = \frac{p_{\text{ds}}}{p_{\text{us}}}$$

which is also found in the textbook along with the expression for $\Psi(\Pi)$. The only thing that is unknown is how the effective area $A_{\text{eff}}$ depends on throttle plate angle $\alpha_{\text{th}}$. Here we use a model using a quadratic polynomial in $\alpha_{\text{th}}$.

### 2.2.1 Model description

**Model input signal(s):** Throttle angle ($\alpha_{\text{th}}$), Pressure before throttle ($p_{\text{bef,thr}}$), Pressure after throttle (is equal to Intake manifold pressure $p_{\text{im}}$).

**Model output signal(s):** Air mass flow rate ($\dot{m}_{\text{at}}$)

**Model:** Air mass flow rate past the throttle is given by:

$$\dot{m}_{\text{at}} = \frac{p_{\text{bef,thr}}}{\sqrt{RT_{\text{bef,thr}}}} A_{\text{eff}}(\alpha_{\text{th}})\Psi(\Pi), \qquad \Pi = \frac{p_{\text{im}}}{p_{\text{bef,thr}}} \tag{2.4}$$

$$A_{\text{eff}}(\alpha_{\text{th}}) = a_0 + a_1\alpha_{\text{th}} + a_2\alpha_{\text{th}}^2 \tag{2.5}$$

$$\Psi = \sqrt{\frac{2\gamma}{\gamma-1}\left(\Pi_{lim}^{\frac{2}{\gamma}} - \Pi_{lim}^{\frac{\gamma+1}{\gamma}}\right)}, \qquad \Pi_{lim} = max\left(\Pi, \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}\right) \tag{2.6}$$

**Parameter to find:** Parameters $a_0, a_1$ and $a_2$ in the effective area ($A_{\text{eff}}$) model, temperature before throttle ($T_{\text{bef,thr}}$).

**Other parameters in the model:** Gas constant ($R$) and ratio between specific heat capacities, $\gamma = c_{\text{p}}/c_{\text{v}}$.

### 2.2.2 Experiment plan

**Signal(s) to be measured:** Throttle angle ($\alpha_{\text{th}}$), Air mass flow ($\dot{m}_{\text{at}}$), Intake manifold pressure ($p_{\text{im}}$), Pressure before throttle ($p_{\text{bef,thr}}$), Temperature before throttel ($T_{\text{bef,thr}}$)

**Control signal(s):** Accelerator pedal position ($\beta_{\text{ped}}$)

**Type of experiment:** Static.

**Measurement description:** While engine is running with a constant speed at an operating point, the accelerator is depressed. We then measure Air mass flow ($\dot{m}_{\text{at}}$), Intake manifold pressure ($p_{\text{im}}$), Pressure before throttle ($p_{\text{bef,thr}}$) using sensors in the engine.

**How to find parameters:** $\frac{\dot{m}_{\mathrm{at}}\sqrt{RT_{\mathrm{bef,thr}}}}{p_{\mathrm{bef,thr}}\Psi(\Pi)} = a_0 + a_1\alpha_{\mathrm{th}} + a_2\alpha_{\mathrm{th}}^2$

Since it is important that the model is well suited when there is a significant pressure drop across the throttle plate only points with $\Pi < 0.73$ are used in the parameter estimation. With $\Pi > 0.73$ the pressure difference is too small and the air is traveling to slow.

## 2.3 Intake manifold

Pressure dynamics in intake manifold.

### 2.3.1 Model description

**Model input signal(s):** Air mass flow rate ($\dot{m}_{\text{at}}$), Intake Manifold Temperature ($T_{\text{im}}$), Engine Speed ($N$), Intake Manifold Pressure ($p_{\text{im}}$).

**Model output signal(s):** , Intake manifold pressure ($p_{\text{im}}$).

**Model:** $\frac{dp_{\text{im}}}{dt} = \frac{RT_{\text{im}}}{V_{im}}(\dot{m}_{\text{at}} - \dot{m}_{ac})$
$\dot{m}_{ac} = \eta_{vol} \frac{p_{\text{im}} V_{\text{d}} n_{\text{cyl}} N}{RT_{\text{im}} n_r}$
$\eta_{vol} = c_0 + c_1 \sqrt{p_{\text{im}}} + c_2 \sqrt{N}$

**Parameter to find:** $c_0, c_1$ and $c_2$

**Other parameters in the model:** $V_{im}, V_{\text{d}}, n_{\text{cyl}}, R, n_r$.

### 2.3.2 Experiment plan

**Signal(s) to be measured:** Intake Manifold pressure ($p_{\text{im}}$), Air mass flow rate ($\dot{m}_{\text{at}}$), Intake Manifold Temperature ($T_{\text{im}}$),

**Control signal(s):** Engine Speed ($N$)

**Type of experiment:** Static

**Measurement description:** Run engine static and measure $\dot{m}_{\text{at}}, T_{\text{im}}, p_{\text{im}}$

**How to find parameters:** $\frac{\dot{m}_{ac} R T_{im} n_r}{p_{\text{im}} V_{\text{d}} n_{\text{cyl}} N} = c_0 + c_1 \sqrt{p_{\text{im}}} + c_2 \sqrt{N}$
Static experiment results in $\dot{m}_{ac} = \dot{m}_{\text{at}}$.

## 2.4 Fuel injector

### 2.4.1 Model description

**Model input signal(s):** Engine Speed ($N$), Injection Time ($t_{\text{inj}}$), $\lambda$

**Model output signal(s):** Fuel Mass flow rate ($\dot{m}_{fi}$).

**Model:** $\dot{m}_{fi} = \frac{N n_{\text{cyl}}}{n_r} m_{fi}$

$m_{fi} = c_{fi}(t_{\text{inj}} - t_0)$

$\dot{m}_{fi} = \frac{\dot{m}_{\text{at}}}{\lambda(\frac{A}{F})_s}$

**Parameter to find:** $c_{fi}, t_0$

**Other parameters in the model:** $n_{\text{cyl}}$, $\mathrm{n}_r$,$\mathrm{t}_0$,$(\frac{A}{F})_s$.

### 2.4.2 Experiment plan

**Signal(s) to be measured:** $\lambda, \dot{m}_{\text{at}}$

**Control signal(s):** Engine Speed ($N$), Injection Time ($t_{\text{inj}}$)

**Type of experiment:** Static

**Measurement description:** Run engine static and measure $\lambda$ and $\dot{m}_{\text{at}}$.

**How to find parameters:** $\frac{\dot{m}_{\text{at}} n_r}{\lambda(\frac{A}{F})_s N n_{\text{cyl}}} = c_{fi} t_{\text{inj}} - c_{fi} t_0$

Least square method.

## 2.5 Cylinder

### 2.5.1 Model description

**Model input signal(s):** $m_f, \lambda_c, p_{\text{em}}, p_{\text{im}}, N, \dot{m}_{exh}$

**Model output signal(s):** $M_e, T_e$

**Model:** $M_e = \frac{W_{i,g} - W_{i,p} - W_{fr}}{2 n_r \pi}$

$W_{i,g} = m_f q_{LHV} (1 - \frac{1}{r_c^{\gamma - 1}}) \min(1, \lambda_c) \eta_{ign}(\theta_{ign}) \eta_{ig,ch}(\omega_e, V_{\text{d}})$

$\eta_{ign} = 1$ (perfect timing)

$\eta_{ig,ch} \in [0.8, 0.85]$

$W_{i,p} = V_D (p_{\text{em}} - p_{\text{im}})$

$W_{fr} = V_D \text{FMEP}$

FMEP$= C_{fr,0} + C_{fr,1} N + C_{fr,2} N^2$

$T_e = T_0 + k \sqrt{\dot{m}_{exh}}$

**Parameter to find:** $C_{fr,0}, C_{fr,1}, C_{fr,2}, k$

**Other parameters in the model:** $q_{LHV}, r_c, \gamma, \eta_{ig,ch}, T_0$

### 2.5.2 Experiment plan

**Signal(s) to be measured:** $\lambda_c, m_f, p_{\text{im}}, p_{\text{em}}$

**Control signal(s):** $N$

**Type of experiment:** Static

**Measurement description:** Run the engine static and measure said signals.

**How to find parameters:** $\frac{W_{i,g} - W_{i,p} - 2 M_e n_r \pi}{V_D} = C_{fr,0} + C_{fr,1} \frac{60N}{1000} + C_{fr,2} (\frac{60N}{1000})^2$

$T_e = T_0 + k \sqrt{\dot{m}_{\text{at}} + \dot{m}_{fi}}$
As mentioned previously, a static experiment results in $\dot{m}_{ac} = \dot{m}_{\text{at}}$ which also applies here.

## 2.6 Exhaust manifold

### 2.6.1 Model description

**Model input signal(s):** $T_{em}, V_{em}, \dot{m}_{at}, \dot{m}_{fi}$

**Model output signal(s):** $p_{em}$

**Model:** $\frac{dp_{em}}{dt} = \frac{RT_{em}}{V_{em}}(\dot{m}_{cyl} - \dot{m}_{es})$
$\dot{m}_{cyl} = \dot{m}_{\text{at}} + \dot{m}_{fi}$

**Parameter to find:** -

**Other parameters in the model:** -

### 2.6.2 Experiment plan

**Signal(s) to be measured:** $p_{es}, p_{amb}, T_{em}, \dot{m}_{ac}, \dot{m}_{fi}$

**Control signal(s):** $N, t_{\text{inj}}, \alpha_{\text{th}}$

**Type of experiment:** Static.

**Measurement description:** Run the engine static and take necessary measurements.

**How to find parameters:** $C_3 = \frac{p_{es}^2 - p_{es}p_{amb}}{RT_{em}\dot{m}_{es}^2}$

## 2.7 Exhaust flow

### 2.7.1 Model description

**Model input signal(s):** $p_{amb}, p_{es}, T_{es}$

**Model output signal(s):** $\dot{m}_{exh}$

**Model:** $\dot{m}_{exh} = C_2\sqrt{\frac{p_{es}}{RT_{es}}(p_{es} - p_{amb})}$

**Parameter to find:** $C_2$

**Other parameters in the model:** $R$

### 2.7.2 Experiment plan

**Signal(s) to be measured:** $\dot{m}_{\text{at}}, \dot{m}_{fi}, T_{amb}, p_{amb}, p_{ds}$

**Control signal(s):** $\alpha_{\text{th}}, t_{\text{inj}}$

**Type of experiment:** Static

**Measurement description:** Run engine static at operating point.

**How to find parameters:** $\frac{(\dot{m}_{\text{at}}+\dot{m}_{fi})RT_{amb}}{p_{amb}(p_{amb}-p_{ds})} = C_2$

## 2.8 Lambda sensor

### 2.8.1 Model description

**Model input signal(s):** $\dot{m}_{\text{at}}, \dot{m}_{fi}$

**Model output signal(s):** $\lambda_{exh}, \lambda_{disc}$

**Model:** $\lambda_c = \frac{\dot{m}_{\text{at}}}{\dot{m}_{fi}(\frac{A}{F})_s}$

$\frac{d}{dt}\lambda_{exh} = \frac{1}{\tau_{mix}}(\lambda_c(t - \tau_d) - \lambda_{exh})$

$\lambda_{disc} = 1$, if $\lambda_{exh} \geq 1$ $\lambda_{disc} = -1$, if $\lambda_{exh} < 1$

**Parameter to find:** $\tau_d$,$\tau_{mix}$

**Other parameters in the model:**

### 2.8.2 Experiment plan

**Signal(s) to be measured:** $\lambda_{exh}$

**Control signal(s):** $\alpha_{\text{th}}, t_{\text{inj}}$

**Type of experiment:** Dynamic

**Measurement description:** Increase fuel amount in step and measure time until $\lambda_{exh}$ reaches a maximum.

**How to find parameter(s):** $\tau_{mix} + \tau_d = \tau_\lambda$ is 63% of the time it takes $\lambda_{exh}$ to reach its maximum.

## 2.9 Catalyst light-off

### 2.9.1 Model description

**Model input signal(s):** $\alpha_{\mathrm{th}}, \dot{m}_{fi}$

**Model output signal(s):** $\lambda_{ac}$

**Model: -**

**Parameter to find: -**

**Other parameters in the model: -**

### 2.9.2 Experiment plan

**Signal(s) to be measured:** $\lambda_{ac}$

**Control signal(s):** $\alpha_{\mathrm{th}}, \dot{m}_{fi}$

**Type of experiment:** Dynamic

**Measurement description:** Measure time until $\lambda_{ac}$ stabilizes.

**How to find parameters:** Measure time.

## 2.10 ⋆ Compressor- and turbine impeller diameters

As part of the compressor model for Project 2, the outer wheel diameter of compressor impeller ($d_{C2}$) is needed. This can most easily be measured by using calipers. In the same way, the turbine inlet diameter ($d_{T1}$) should be measured with calipers.

**Parameter to find:** Outer diameter of compressor wheel $d_{C2}$ and outer diameter of turbine wheel $d_{T1}$.

## 2.11 ⋆ Wastegate

Wastegate position of a turbocharged engine is normally controlled by the pressure on one side of a membrane. Pressure on other side of the membrane is normal ambient pressure. The pressure is controlled by using a mixing valve, where two sources with different pressure alternately are connected to the pressure chamber of the wastegate. This mixing valve is controlled by a PWM signal. An overview of the various components included in the wastegate controller on the turbocharged engine lab is shown in Figure 2.2.

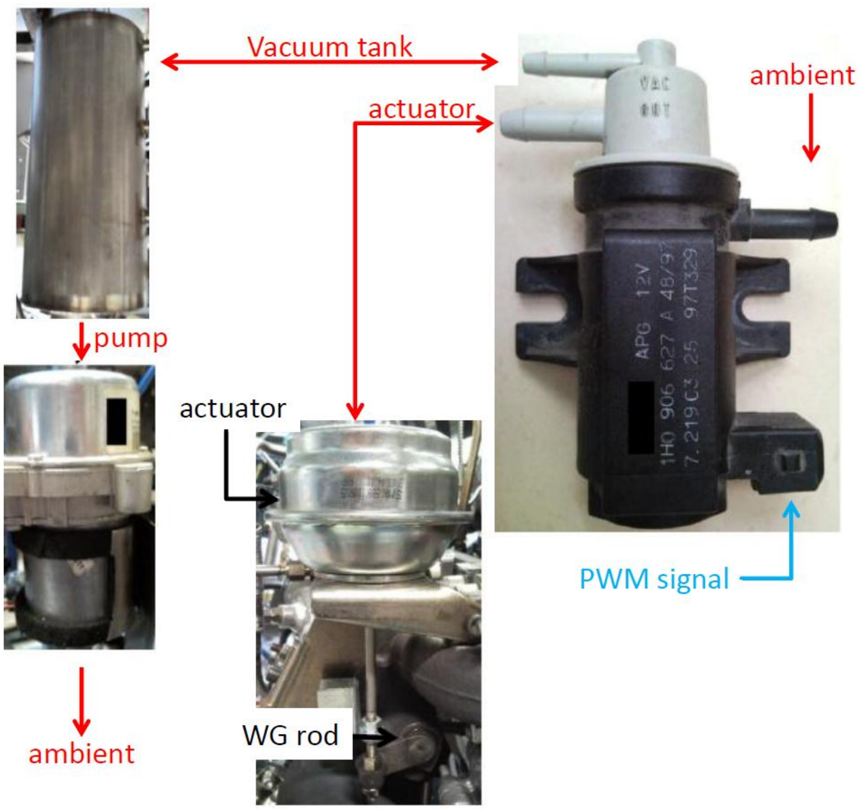


Figure 2.2: Snapshot of the wastegate actuation system. A PWM signal controls the pressure in an actuator chamber, by alternately (and quickly), connecting the chamber to two different pressure sources. The pressure in actuator chamber then actuates a membrane that controls actuation lever. A return spring also serves on the actuator chamber which is why a greater pressure difference between the membrane different sides is required for larger change in position of the arm.

The PWM signal alternates between +5 V and ground, and the relative length difference between the +5 V level and ground-level controls the valve behavior. The frequency of the PWM signal is so high that an almost continuous signal is obtained (ie change between +5 V and ground occurs with the order of hundred Hz, because wastegate system frequency is significantly lower). The position of the wastegate arm can be measured in lab, and the PWM signal to the mixing valve can be controlled if wanted. A first order behavior, as for throttle angle, is assumed here. Model description and experiment plan for the wastegate will therefore largely follow the accelerator pedal.

### 2.11.1 Model description

**Model input signal(s):** PWM signal for wastegate valve ($\mathrm{PWM}_{\mathrm{wg}}$)

**Model output signal(s):** Position of the wastegate ($pos_{\mathrm{wg}}$)

**Model:** Similar to the accelerator pedal model the wastegate position can be calculated by $\dot{pos}_{wg} = \frac{1}{\tau_{wg}}(PWM_{wg} - pos_{wg})$

**Parameter to find:** $\tau_{wg}$

**Other parameters in the model:** -

### 2.11.2 Experiment plan

**Signal(s) to be measured:** $pos_{wg}$

**Control signal(s):** $PWM_{wg}$

**Type of experiment:** Dynamic

**Measurement description:** While engine runs with a constant speed at an operating point many steps (up-down-up-down-...) are performed in $PWM_{wg}$ signal. The times between steps are selected such that measured signals become stable before the next step is done.

**How to find parameters:** The time constant is determined as the time interval between the instance when the first change in the output signal is observed until $pos_{wg}$ reaches 63% of its final values.

## 2.12 Complete engine

Now that models are described and input-output-control signals are defined for all components, the block diagram of entire engine model can be illustrated as shown in Figure 2.3.

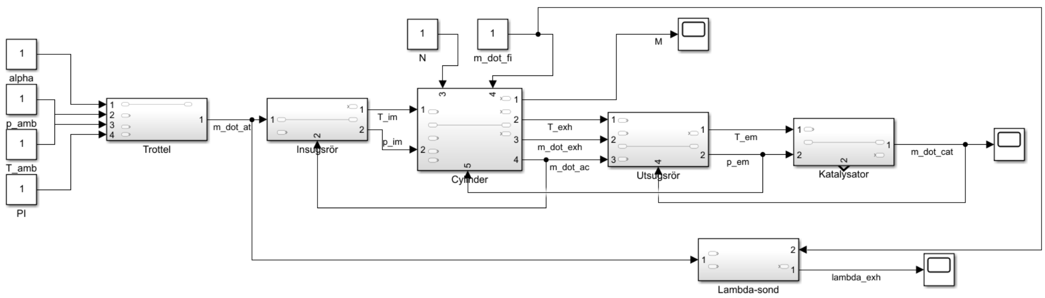


Figure 2.3: Block diagram of complete engine.

# Chapter 3

# Stationary analysis and model validation

This chapter outlines and discusses the results of projects 1B. The aim in projects 1B is to show how engine torque can be produced from chemically stored energy, and where losses can occur. Approach is described by presenting the utilized equations and the name of the used data file(s). The results of parameter estimations in models of different engine components are also reported and the models are validated against measurements.

## 3.1 In-cylinder analysis

### 3.1.1 pV diagram

The difference is that pCylHigh reaches a much higher pressure, close to 60 bar instead of roughly 12 bar as for pCylLow.

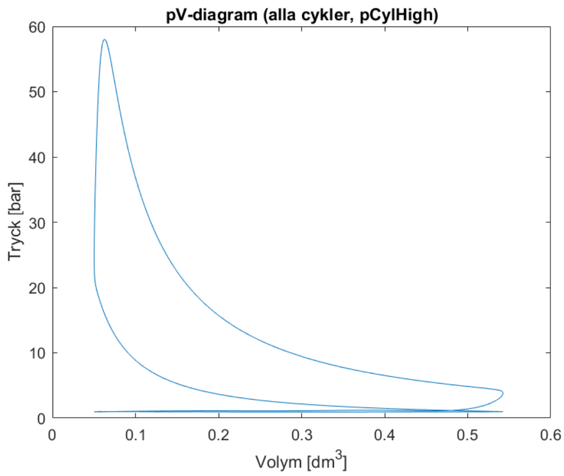


Figure 3.1: pV diagram, pCylHigh

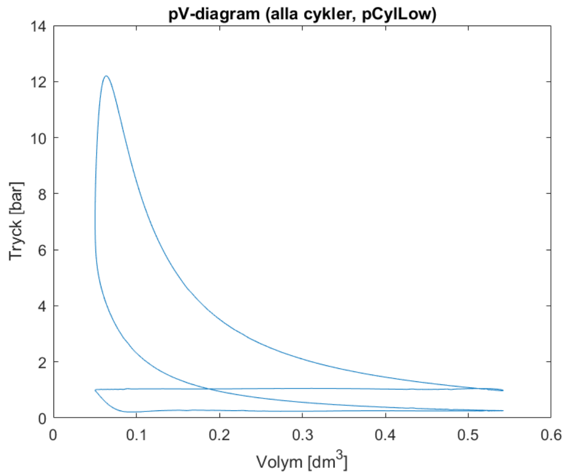


Figure 3.2: pV diagram, pCylLow

pCylHigh: The work performed by one cylinder during one cycle was 551 J which means the calculated torque from all four cylinders during one cycle was 175 Nm. The measured torque was 158 Nm. These two numbers are different since we do not take friction into consideration.

### 3.1.2 Otto cycle

The peak pressure in the measured cycle is much higher than the ideal one. Otherwise are they roughly the same shape. The peak pressure in the ideal cycle is about 6 bar while the measured cycle reaches about 12 bar while using pCylLow.

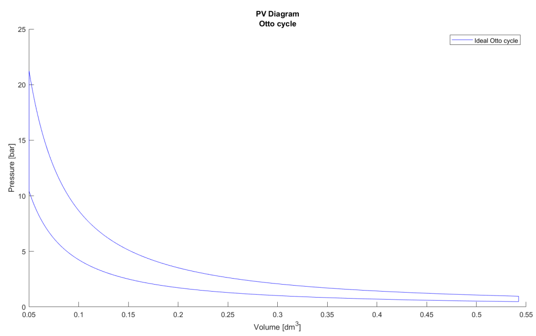


Figure 3.3: Ideal Otto cycle, pCylHigh

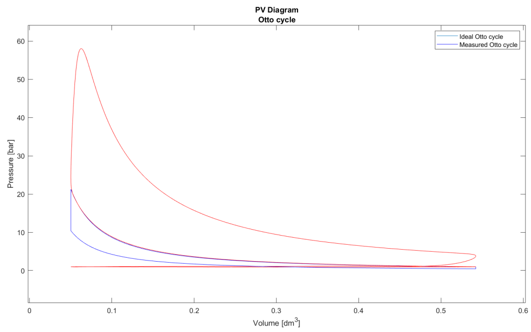


Figure 3.4: Ideal and measured Otto cycle, pCylHigh

### 3.1.3 Specific fuel consumption

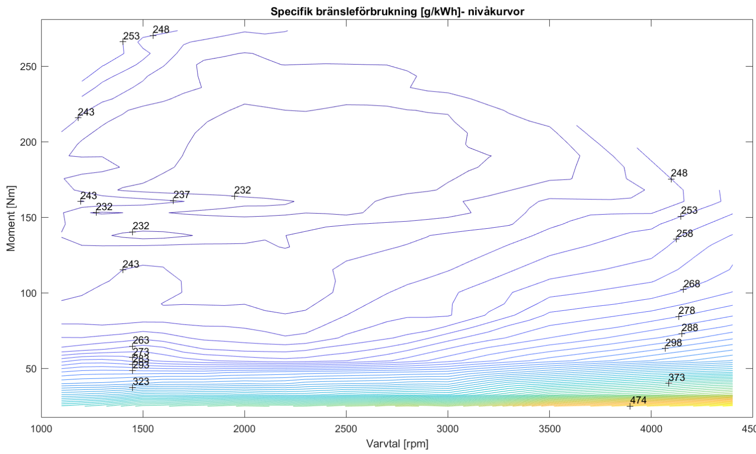


Figure 3.5: SFC Map

Best performance is at 2000 RPM and 200 Nm.

## 3.2 Model validation

In this section, the models developed in previous chapter are compared against the measurement data.

### 3.2.1 Accelerator pedal

The accelerator pedal takes pedal position ($\beta_{\text{ped}}$) as input and provides throttle angle ($\alpha_{\text{th}}$) as output. The model is described by the equation:

$$\dot{\alpha}_{th} = \frac{1}{\tau_{\text{th}}}(\beta_{\text{ped}} - \alpha_{\text{th}}) \tag{3.1}$$

**Parameter(s) value:** Time constant for the throttle $\tau_{\text{th}}$ in (3.1) is estimated to be 0.04 sec.

**Measurement file:** airstep.mat

**Method:** The time constant is estimated as the time that it takes for the step to reach 63% of the final value as explained in the experiment plan 2.1.2.

**Validation:** In Figure 3.6 we see that the model fits the measured step response. The rise time certainly depends on how big of a step is made but this will not have any significant impact on experiments done in this project.

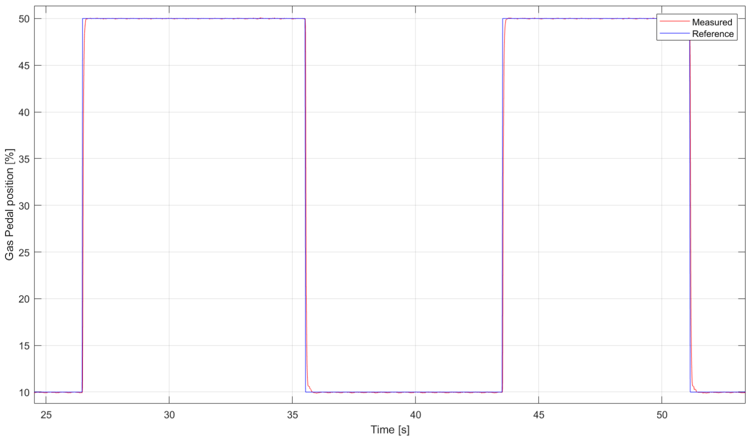


Figure 3.6: Estimation of time constant for throttle.

The measured and reference time constant for the throttle looks noticeably alike according to figure 3.5.

### 3.2.2 Throttle

The model of the throttle determines the air mass flow rate into the intake manifold based on throttle angle. Model equation presented in Section 2.2, is repeated here

$$\dot{m}_{\text{at}} = \frac{p_{\text{bef,thr}}}{\sqrt{RT_{\text{bef,thr}}}} A_{\text{eff}}(\alpha_{\text{th}})\Psi(\Pi), \qquad \Pi = \frac{p_{\text{im}}}{p_{\text{bef,thr}}} \tag{3.2}$$

$$A_{\text{eff}}(\alpha_{\text{th}}) = a_0 + a_1\alpha_{\text{th}} + a_2\alpha_{\text{th}}^2 \tag{3.3}$$

$$\Psi = \sqrt{\frac{2\gamma}{\gamma-1}\left(\Pi_{lim}^{\frac{2}{\gamma}} - \Pi_{lim}^{\frac{\gamma+1}{\gamma}}\right)}, \qquad \Pi_{lim} = max\left(\Pi, \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}\right) \tag{3.4}$$

What needs to be determined is the parameters of the polynomial for the effective area.

**Parameter(s) value:** $a_0 = 0.00000971$, $a_1 = 0.00017133$, $a_2 = 0.00261896$

**Measurement file:** EngineMapTSFS09.mat

**Method:** For each measurement point the effective throttle area is calculated, then the parameters are adjusted with least squares method to the measured data.

**Validation:** The model and measurements are compared in Figure 3.7. The figure shows that the modelled and measured values are in a good agreement.

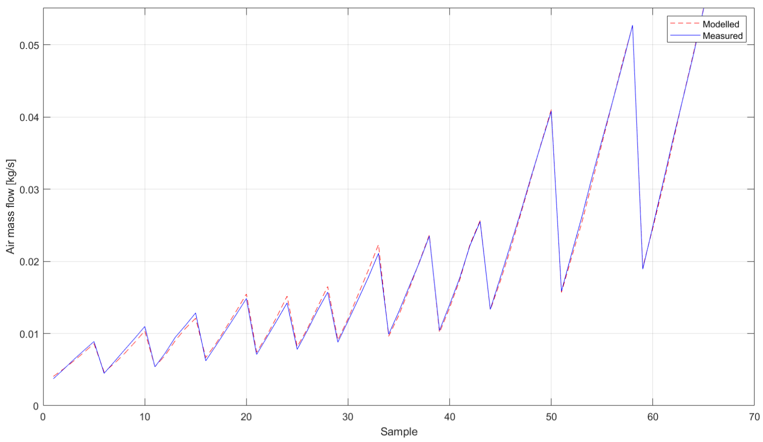


Figure 3.7: Throttle

In figure 3.6 we can see that the modelled air mass flow at the throttle follows the general measured flow fairly good. The differences we can see are mainly that the highs and the lows are larger than the measured flow.

### 3.2.3 Intake manifold

**Parameter(s) value:** $c_0 = 0.2720, c_1 = 0.0014, c_2 = 0.0177$

**Measurement file:** EngineMapTSFS09.mat

**Method:** Static

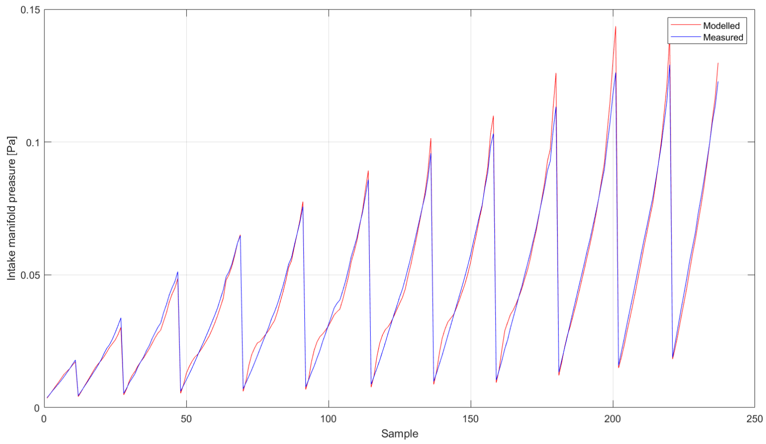


Figure 3.8: Intake Manifold Pressure

**Validation:**

Figure 3.7 shows a very similar behaviour of the measured and modelled pressure.

### 3.2.4 Fuel injector

**Parameter(s) value:** $c_{fi} = 0.0169, t_0 = 0.0007\ [s]$

**Measurement file:** EngineMapTSFS09.mat

**Method:** Static

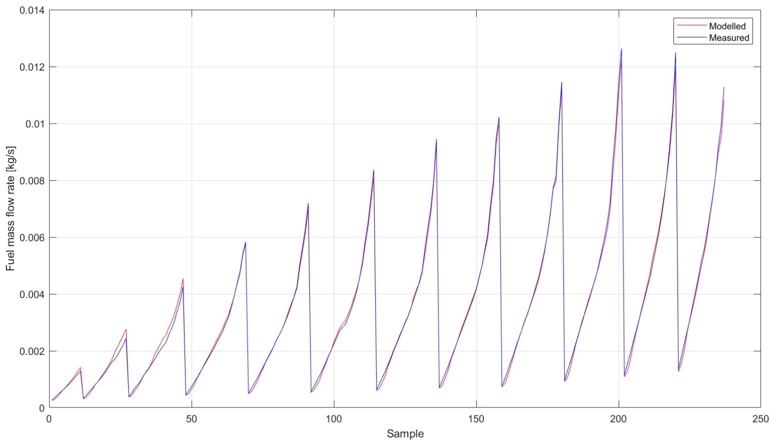


Figure 3.9: Fuel mass flow rate

**Validation:**

In the figure 3.8 we can clearly see that the modelled fuel mass flow rate follows the measured very closely.

### 3.2.5 Cylinder

**Parameter(s) value:** $C_{fr,0} = 48922.4, C_{fr,1} = -3272, C_{fr,2} = 9293, k = 1613, T_0 = 738\ [K]$

**Measurement file:** EngineMapTSFS09.mat

**Method:** Static

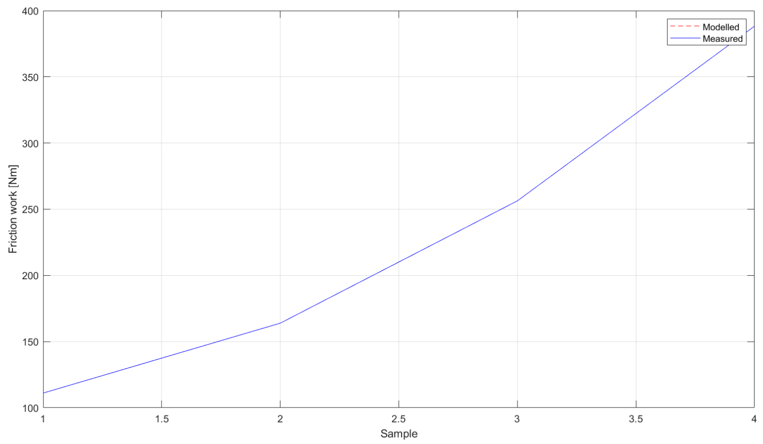


Figure 3.10: Cylinder friction work

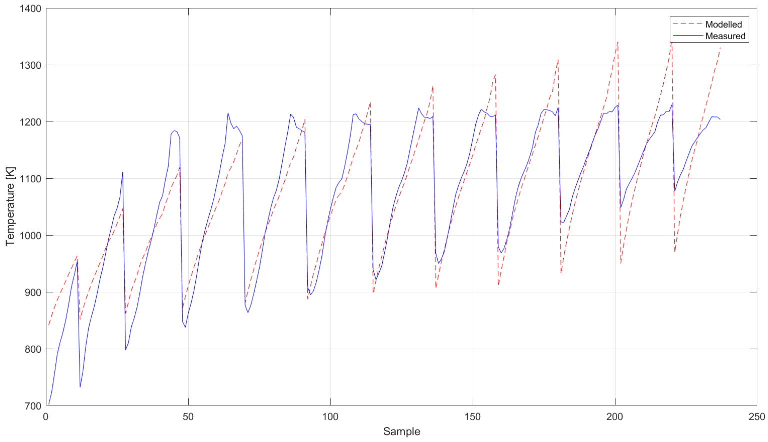


Figure 3.11: Cylinder Temperature

**Validation:** In figure 3.9 and 3.10 we can see that the modelled data follows the measured data very well. The fit is slightly worse in 3.10 but follows the general shape .

### 3.2.6 Exhaust manifold

**Parameter(s) value:** -

**Measurement file:**

**Method:** Static

**Validation:**

### 3.2.7 Exhaust flow

**Parameter(s) value:** $C_2 = -6.2605 \cdot 10^{-6}$

**Measurement file:** EngineMapTSFS09.mat

**Method:** Static

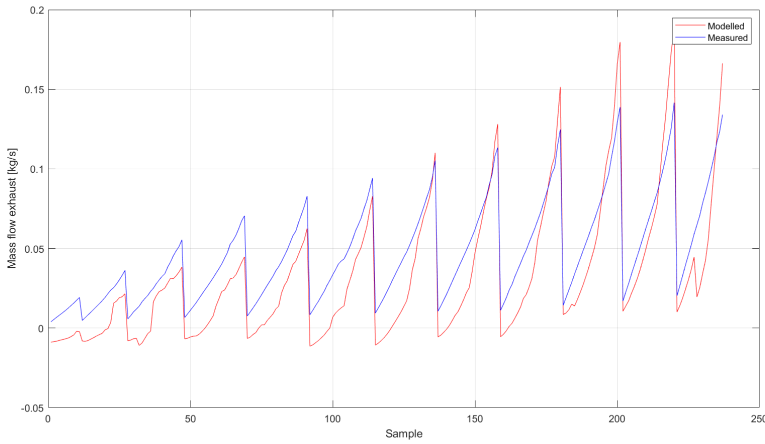


Figure 3.12: Air mass flow rate in exhaust system

**Validation:** The air mass flow rate in the exhaust system showed in figure 3.12 shows a similar shape between the measured and modelled flow rate but the modelled has larger extremes, in the beginning lower lows and later on higher highs.

### 3.2.8 Lambda sensor

**Parameter(s) value:** $\tau_d = 0.069\ [s], \tau_{mix} = 0.089\ [s]$

**Measurement file:** fuelstep.mat

**Method:** Dynamic

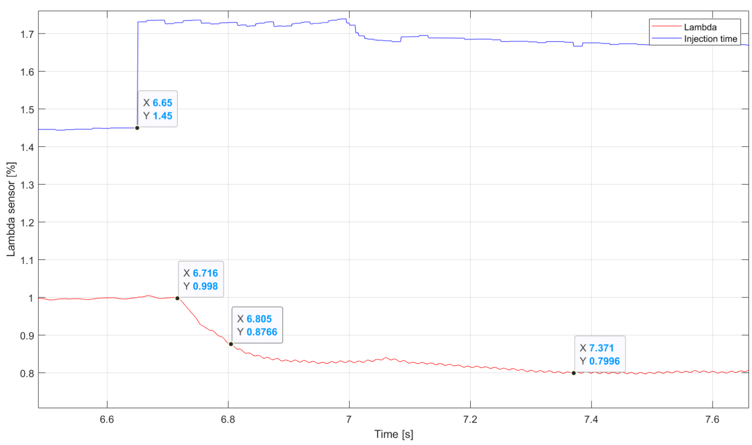


Figure 3.13: Lambda sensor

**Validation:** In figure 3.13 we can see that there is a delay from the point we increase fuel flow until we see a change in the lambda sensor and another delay until the lambda sensor maxes out.

### 3.2.9 Catalyst light-off

**Parameter(s) value:** 37.83 [s]

**Measurement file:** lightOff.mat

**Method:** Dynamic

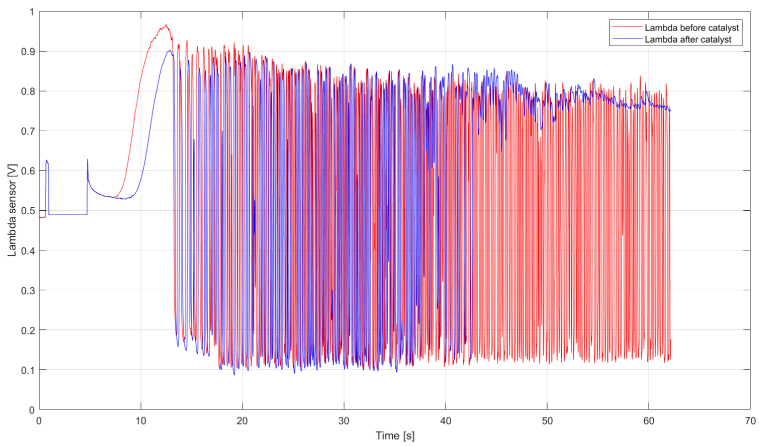


Figure 3.14: Catalyst lightoff

**Validation:** The lambda value after the catalyst stabilizes after roughly 37.8 seconds in figure 3.14.

## 3.3 Table of Parameters

All estimated parameters in the different engine sub models are summarized in table 3.1.

Table 3.1: Estimated parameters in engine sub models

| Component | Parameter | Value |
|---|---|---|
| Accelerator pedal | $\tau_{\mathrm{th}}$ | 0.04 [sec] |
| Throttle | $a_0$ | 0.00000971 |
| | $a_1$ | 0.00017133 |
| | $a_2$ | 0.00261896 |
| | $T_{bef,thr}$ | 307.62 |
| Intake manifold | $c_0$ | 0.2720 |
| | $c_1$ | 0.0014 |
| | $c_2$ | 0.0177 |
| Fuel injector | $c_{fi}$ | 0.0169 |
| | $t_0$ | 0.0007 |
| Cylinder | $\eta_{ig,ch}$ | 0.825 |
| | $C_{fr,0}$ | 48922 |
| | $C_{fr,1}$ | $-3272.4$ |
| | $C_{fr,2}$ | 9893 |
| | $k$ | 1613 |
| | $T_0$ | 738 |
| Exhaust manifold | - | - |
| Exhaust flow | $C_2$ | 0.00121323 |
| Lambda sensor | $\tau_d$ | 0.069 |
| | $\tau_{mix}$ | 0.089 |
| Catalyst light-off | $\tau_c$ | 37.83 |

# Chapter 4

# Implementation of engine model

## 4.1 Accelerator pedal

**Implementation:** In Figure 4.1 the implementation of accelerator pedal model in Simulink is shown.

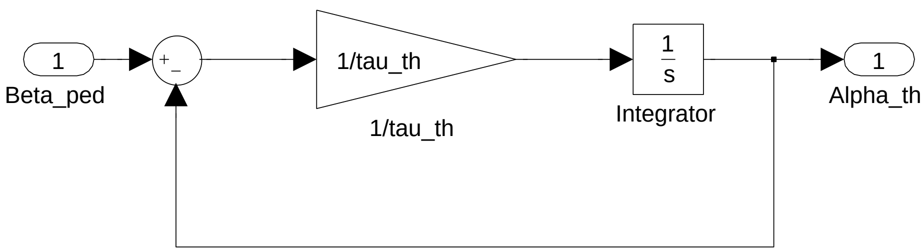


Figure 4.1: Simulink model of the implemented throttle.

## 4.2 Throttle

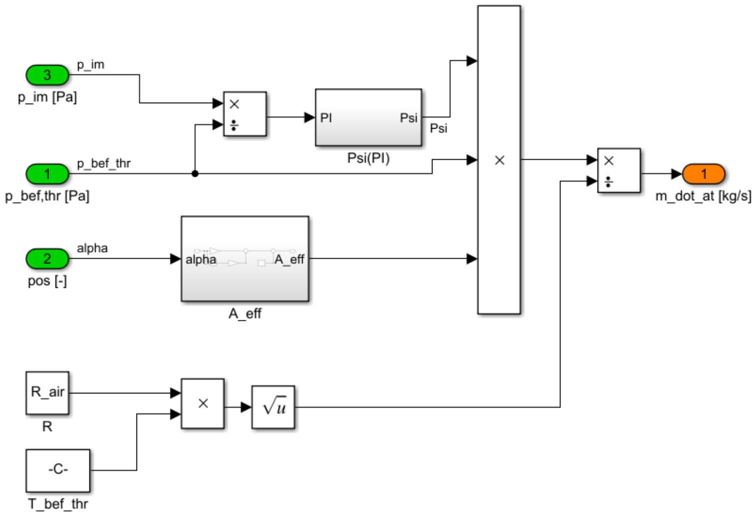


Figure 4.2: Throttle model

**Implementation:**

## 4.3 Intake manifold

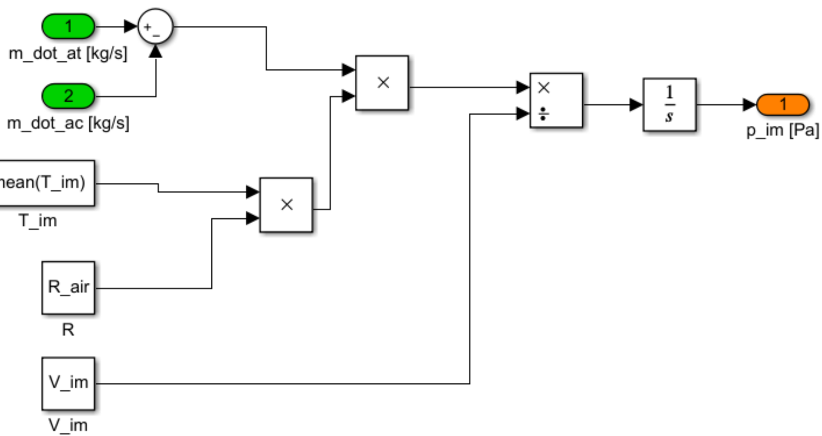


Figure 4.3: Intake manifold model

**Implementation:**

## 4.4 Fuel injector

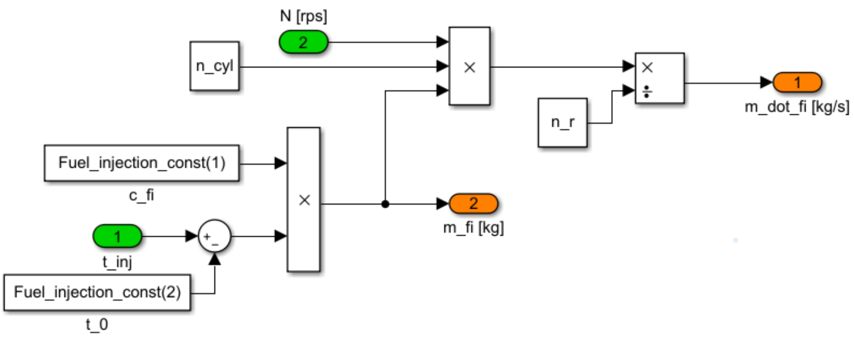


Figure 4.4: Fuel injector model

**Implementation:**

## 4.5 Cylinder

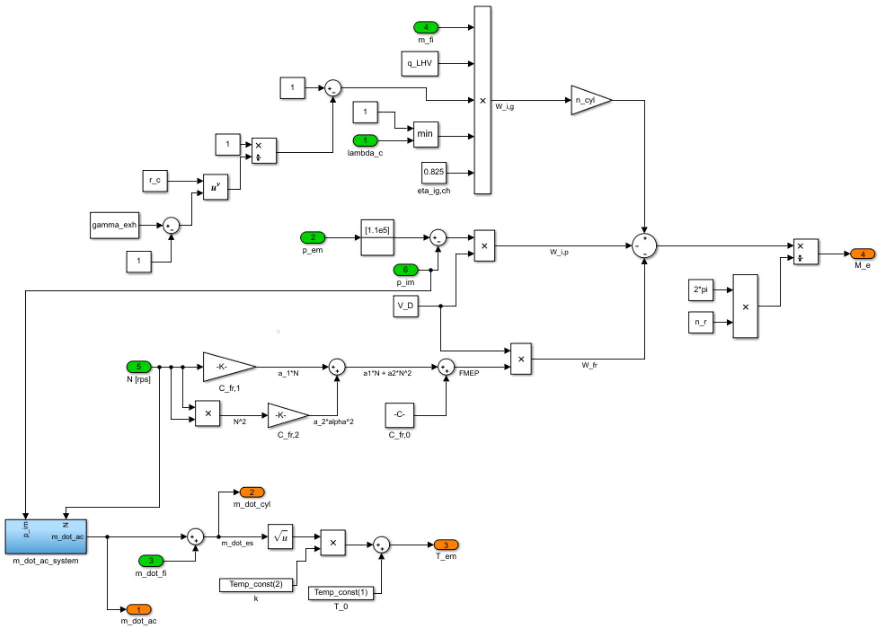


Figure 4.5: Cylinder model

**Implementation:**

## 4.6 Exhaust manifold

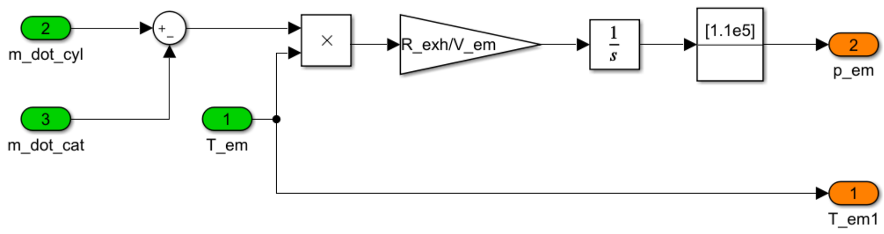


Figure 4.6: Exhaust manifold model

**Implementation:**

## 4.7 Exhaust flow

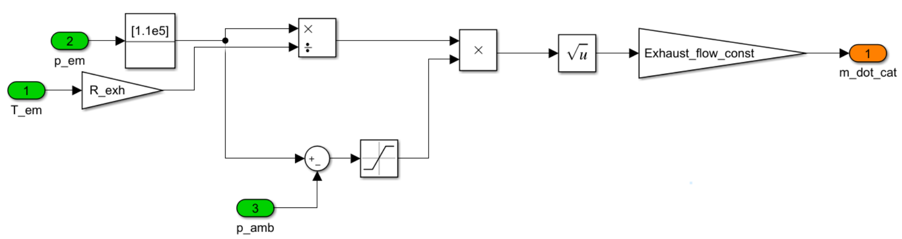


Figure 4.7: Exhaust flow model

**Implementation:**

## 4.8 Lambda sensor

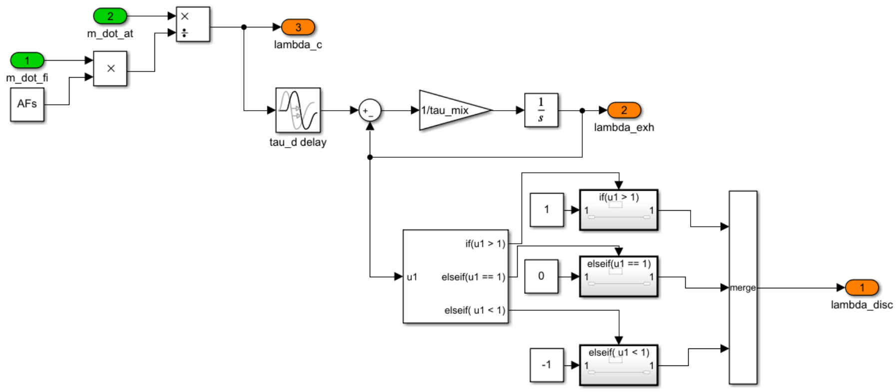


Figure 4.8: Lambda sensor model

**Implementation:**

## 4.9 Complete engine model

**Implementation:** Figure 4.9 shows the entire engine model implemented in Simulink which is in agreement with the initial design in Figure 2.3.

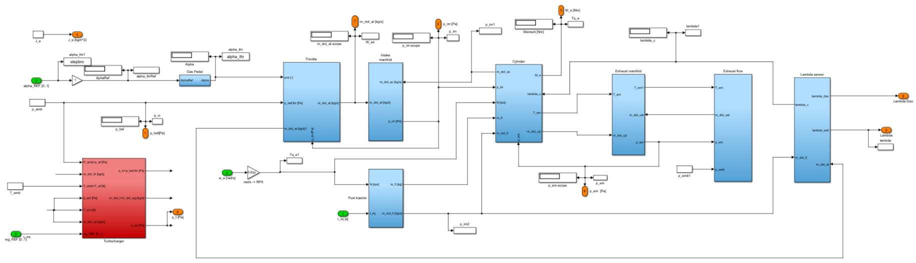

Figure 4.9: Complete engine model

# Chapter 5

# Controller

A fuel controller is connected to the engine fuel injection system. In this chapter, the design of the controller, the way we went about it to determine the controller parameters, and figures showing that we have succeeded are presented. A step in accelerator position is implemented, and the plausibility of the results is assessed.

**Implementation:**

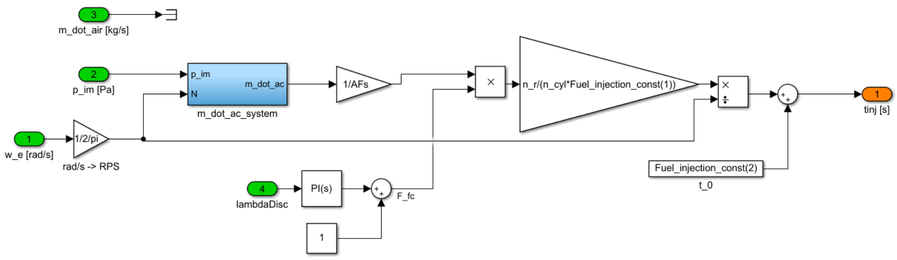


Figure 5.1: Fuel controller model

The constants in the PI-controller were chosen to be $K_I = 0.1$ and $K_P = \tau_d \frac{K_I}{2}$ after some trial and error. The relationship between $K_I$ and $K_P$ was given in the course book. This controller gives good enough results.

# Chapter 6

# Experiments

This chapter first presents the results of a number of experiments specified in the project compendium. The results are discussed and the plausibility is assessed.

## 6.1 Acceleration test

The time it took for the torque to reach 67 % of its maximum took 26 ms which can be seen in Figure 6.1.

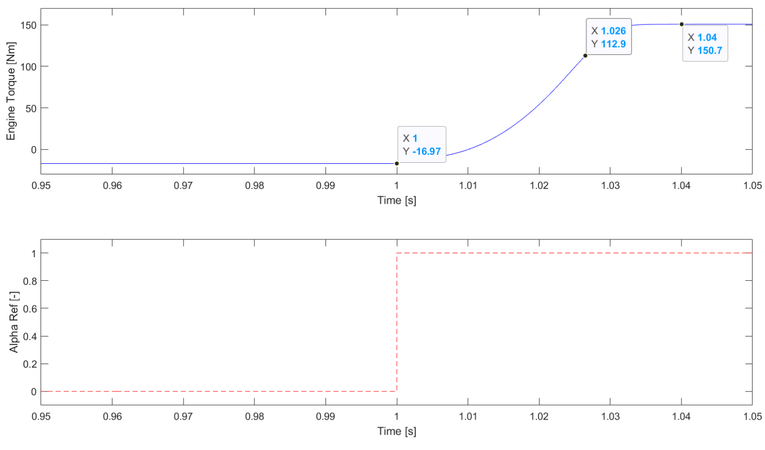


Figure 6.1: Graph of the step response of the torque.

The time it took for the vehicle to accelerate from 70 km/h to 110 km/h was 8.743 s which can be seen in the Figure 6.2.

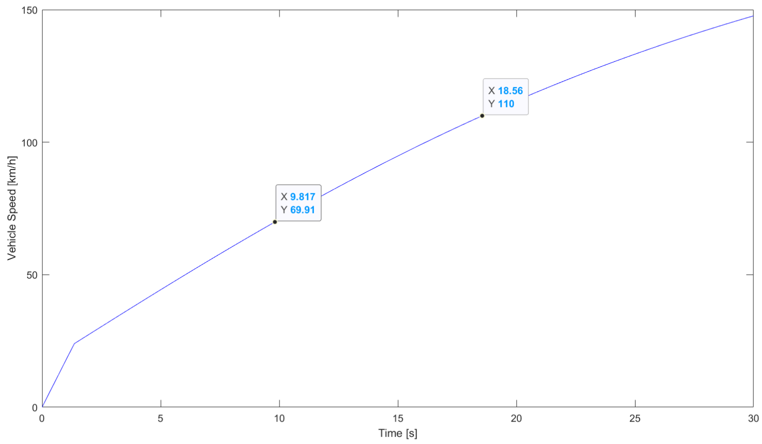


Figure 6.2: Graph of the acceleration of the vehicle.

## 6.2 Test run on part of drive cycle

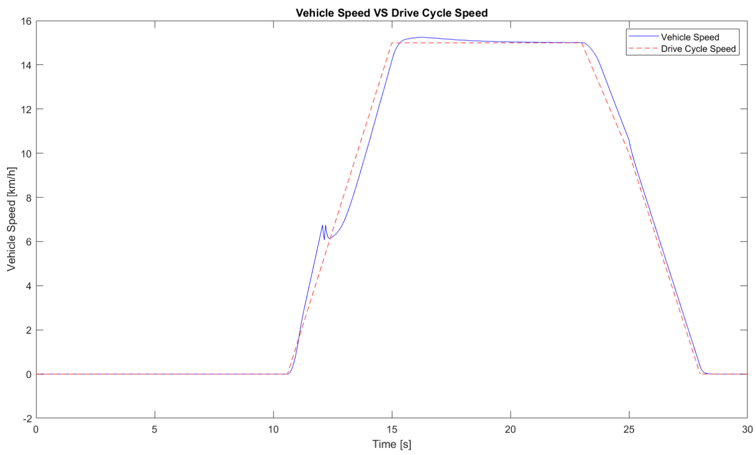


Figure 6.3: Vehicle speed vs drive cycle speed during part of a full cycle.

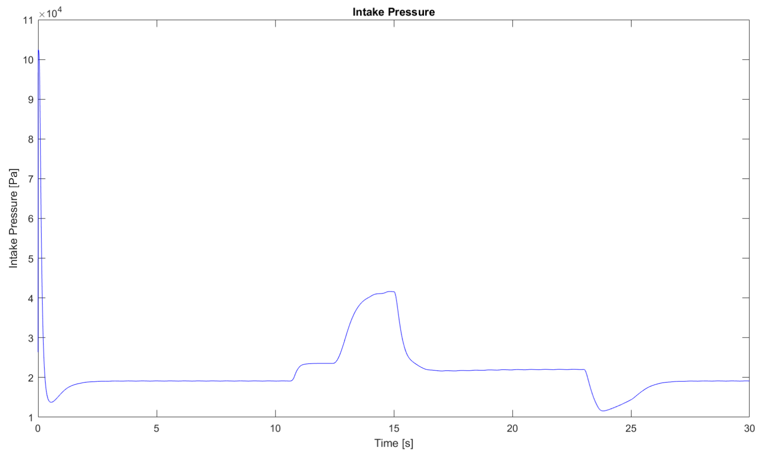


Figure 6.4: Intake pressure during part of a full cycle.

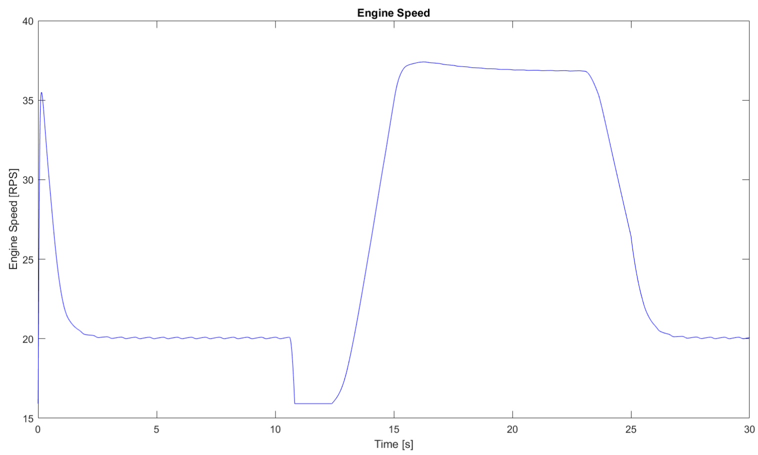


Figure 6.5: Engine speed during part of a full cycle.

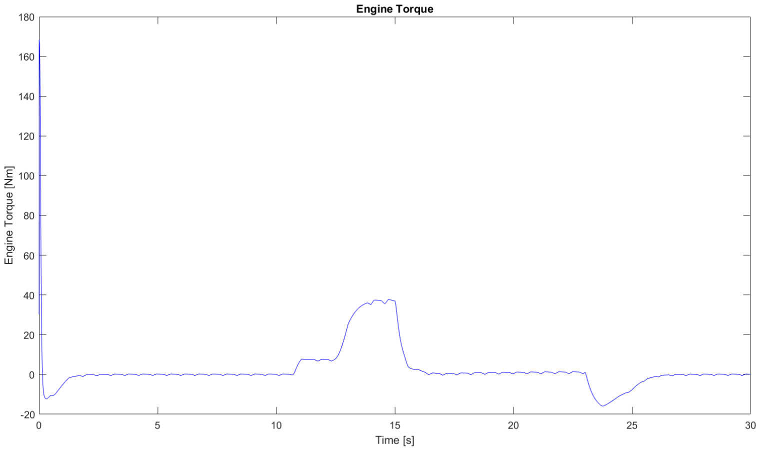


Figure 6.6: Engine torque during part of a full cycle.

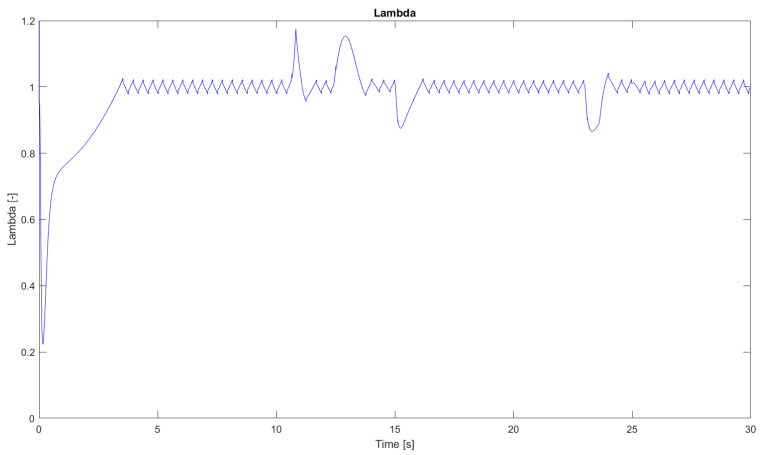


Figure 6.7: Lambda during part of a full cycle.

## 6.3 Simulation of complete drive cycle

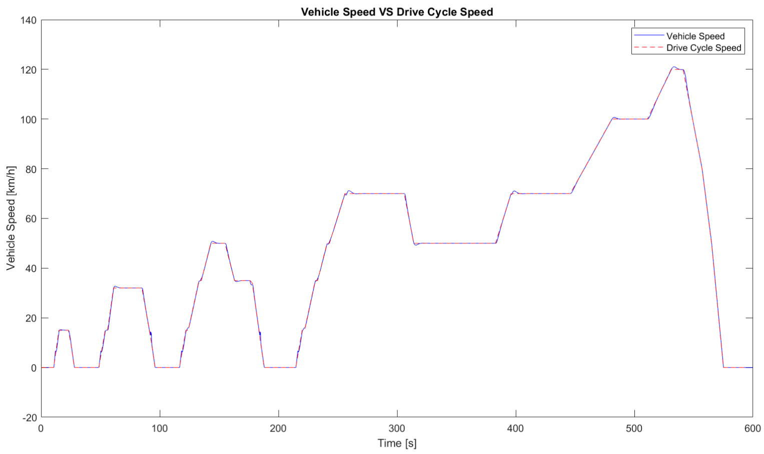


Figure 6.8: Vehicle speed vs drive cycle speed during a full cycle.

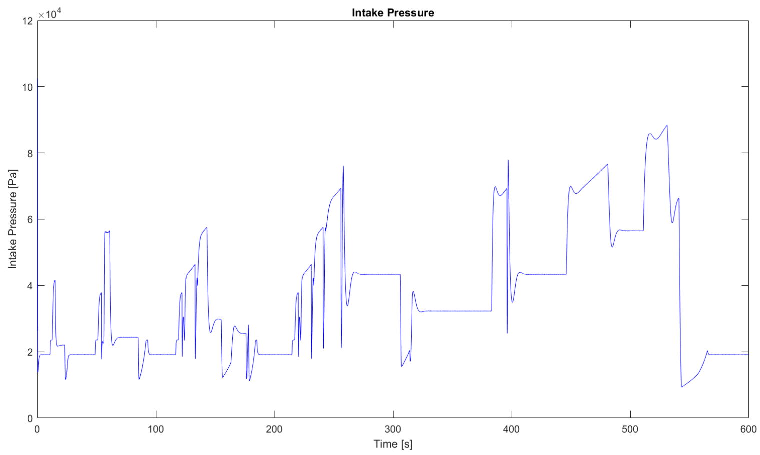


Figure 6.9: Intake pressure during a full cycle.

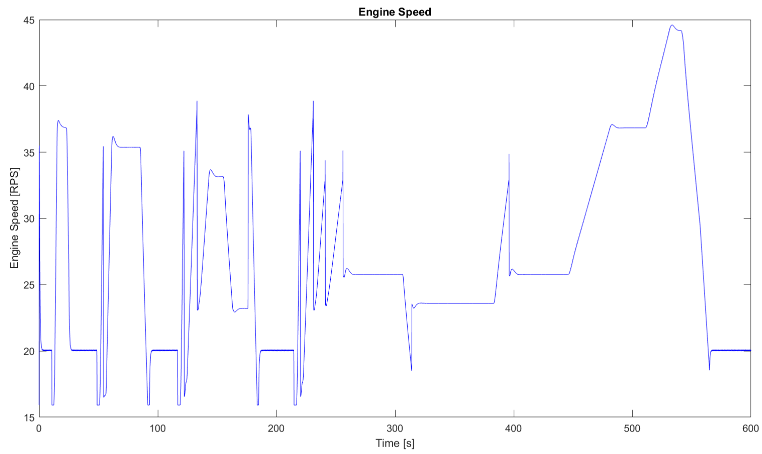


Figure 6.10: Engine speed during a full cycle.

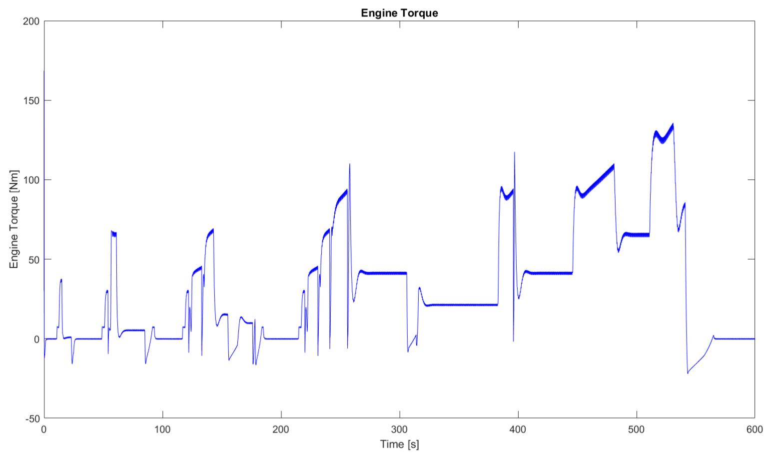


Figure 6.11: Engine torque a during full cycle.

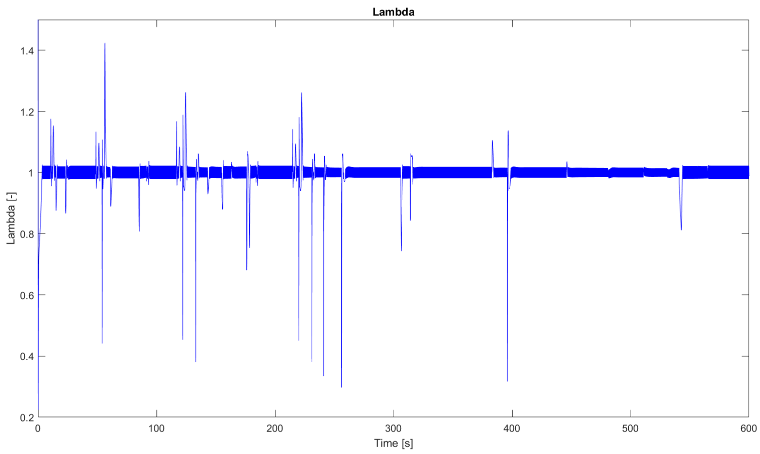


Figure 6.12: Lambda during a full cycle.

## 6.4 Emissions

### 6.4.1 Cold Engine

CO : 1.19 [g/km] Limit EURO 3 : 2.3 [g/km] EURO 4 : 1.0 [g/km]
HC : 0.09 [g/km] Limit EURO 3 : 0.20 [g/km] EURO 4 : 0.10 [g/km]
NOx : 0.08 [g/km] Limit EURO 3 : 0.15 [g/km] EURO 4 : 0.08 [g/km]

### 6.4.2 Hot Engine

CO : 0.91 [g/km] Limit EURO 3 : 2.3 [g/km] EURO 4 : 1.0 [g/km]
HC : 0.07 [g/km] Limit EURO 3 : 0.20 [g/km] EURO 4 : 0.10 [g/km]
NOx : 0.04 [g/km] Limit EURO 3 : 0.15 [g/km] EURO 4 : 0.08 [g/km]

If the catalyst ignites instantly from the start, the emissions drop below the EURO 4 threshold.

We use the lambda value in the exhaust system right before the catalyst for the calculations. This is the last measuring point we have and the value will not change anymore before the catalyst.

## 6.5 Fuel consumption

The fuel consumption was $5.78l/100km$. This is very reasonable.

# Chapter 7

# Conclusions

## 7.1 Different size

When we decrease the vehicle's weight by 25%, it has no problem following the drive cycle which can be seen in Figure 7.1. Also, is has low emissions, staying under the EURO 4 limits,

CO : 0.98 [g/km] Limits EURO 3 : 2.3 [g/km] EURO 4 : 1.0 [g/km]
HC : 0.08 [g/km] Limits EURO 3 : 0.20 [g/km] EURO 4 : 0.10 [g/km]
NOx : 0.08 [g/km] Limits EURO 3 : 0.15 [g/km] EURO 4 : 0.08 [g/km]

The fuel consumption was 5.1 $l/100km$.

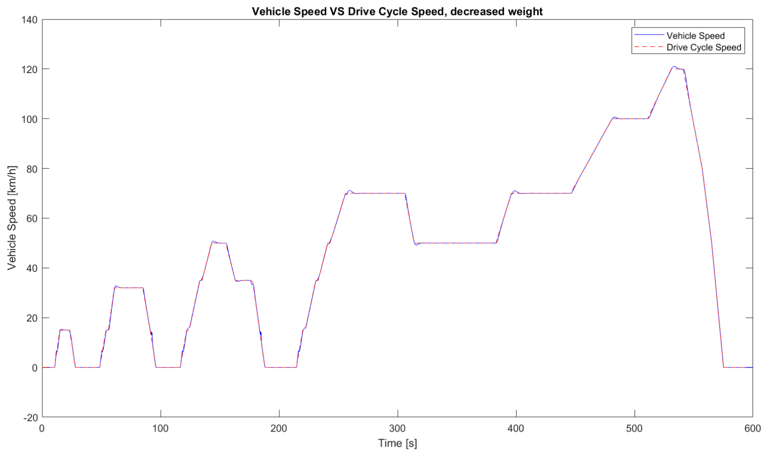


Figure 7.1: Vehicle speed vs drive cycle speed with decreased vehicle weight.

When we decrease the vehicle's area by 20%, it has no problem following the drive cycle which can be seen in Figure 7.2. Also, it has fairly low emissions and is just barely staying over the EURO 4 limits,

CO : 1.06 [g/km] Limits EURO 3 : 2.3 [g/km] EURO 4 : 1.0 [g/km]
HC : 0.08 [g/km] Limits EURO 3 : 0.20 [g/km] EURO 4 : 0.10 [g/km]
NOx : 0.08 [g/km] Limits EURO 3 : 0.15 [g/km] EURO 4 : 0.08 [g/km]

The fuel consumption was 5.78 $l/100km$, the same as before the change.

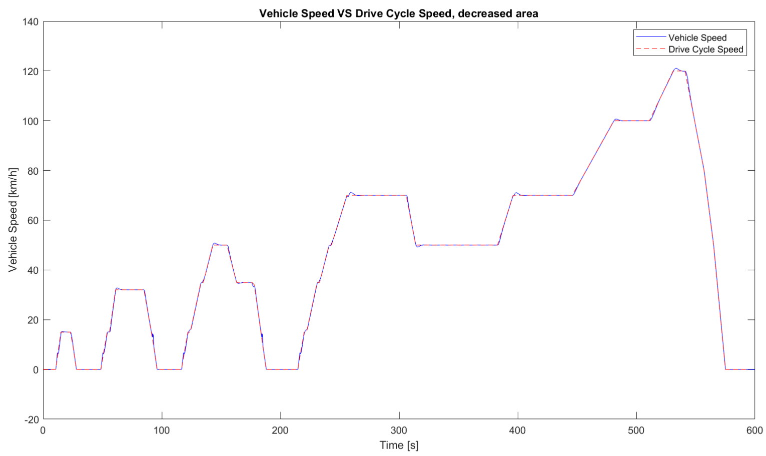


Figure 7.2: Vehicle speed vs drive cycle speed with decreased vehicle area.

When we decrease the vehicle's engine size by 50%, it has no problem following the drive cycle which can be seen in Figure 7.3. Also, it has low emissions and is just barely staying under the EURO 4 limits,

CO : 0.99 [g/km] Limits EURO 3 : 2.3 [g/km] EURO 4 : 1.0 [g/km]
HC : 0.08 [g/km] Limits EURO 3 : 0.20 [g/km] EURO 4 : 0.10 [g/km]
NOx : 0.07 [g/km] Limits EURO 3 : 0.15 [g/km] EURO 4 : 0.08 [g/km]

The fuel consumption was 5.48 $l/100km$.

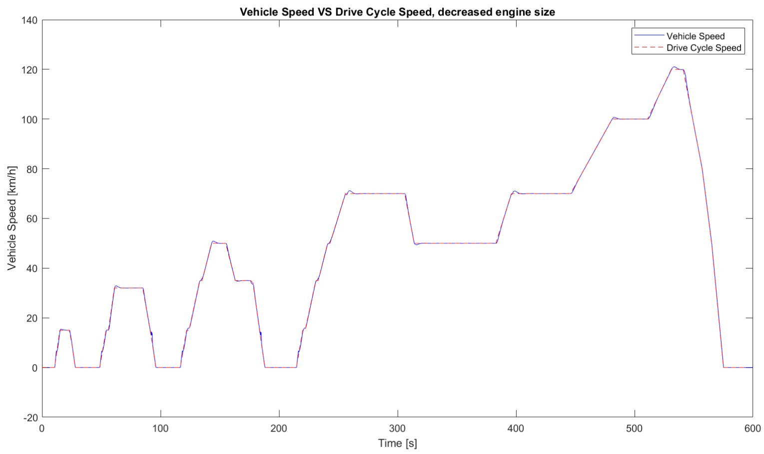


Figure 7.3: Vehicle speed vs drive cycle speed with decreased engine size.

When we decrease the vehicle's mass by 25%, area by 20% and engine size by 50%, it has no problem following the drive cycle which can be seen in Figure 7.4. Also, it has low emissions and is staying under the EURO 4 limits,

CO : 0.94 [g/km] Limits EURO 3 : 2.3 [g/km] EURO 4 : 1.0 [g/km]
HC : 0.08 [g/km] Limits EURO 3 : 0.20 [g/km] EURO 4 : 0.10 [g/km]
NOx : 0.07 [g/km] Limits EURO 3 : 0.15 [g/km] EURO 4 : 0.08 [g/km]

The fuel consumption was 5.20 $l/100km$.

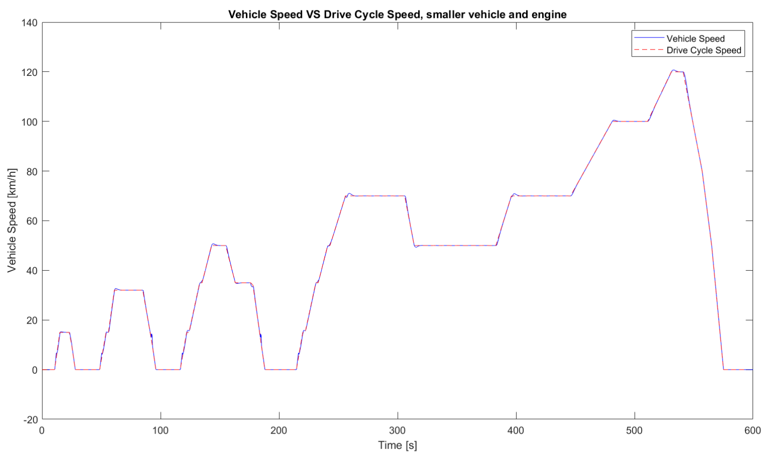


Figure 7.4: Vehicle speed vs drive cycle speed with decreased vehicle weight, area and engine size.

As we can see, decreasing vehicle and engine size can effect the emission of a vehicle. In our testing, decreasing the vehicle weight and engine size showed to be the most potent tools in decreasing emissions. The area of the vehicle didn't effect the emission as much.

## 7.2 Different fuel

When we fill the tank of the vehicle with a different fuel, i.e. change AFs to 15.5, the emissions of CO and HC are horrible, but NOx is way below the limits when running without the feedback loop.

CO : 61.06 [g/km] Limits EURO 3 : 2.3 [g/km] EURO 4 : 1.0 [g/km]
HC : 1.15 [g/km] Limits EURO 3 : 0.20 [g/km] EURO 4 : 0.10 [g/km]
NOx : 0.01 [g/km] Limits EURO 3 : 0.15 [g/km] EURO 4 : 0.08 [g/km]

The fuel consumption was 6.82 $l/100km$.

When we running with the feedback loop, the emission got a lot better,

CO : 1.07 [g/km] Limits EURO 3 : 2.3 [g/km] EURO 4 : 1.0 [g/km]
HC : 0.09 [g/km] Limits EURO 3 : 0.20 [g/km] EURO 4 : 0.10 [g/km]
NOx : 0.09 [g/km] Limits EURO 3 : 0.15 [g/km] EURO 4 : 0.08 [g/km]

The fuel consumption was 5.69 $l/100km$.

This shows that our engine model can handle different fuels very well when using feedback.

# Chapter 8

# Components in the turbocharged engine

## 8.1 Theory

1. The main components of a turbo are the compressor and the turbine. The turbine takes energy from the exhaust gases and delivers it to the intake air via the compressor. The limitations in the operating region comes from either temperature or high air pressure. If the pressure is to high, the turbine is bypassed through the waste gate.

2. A compressor map is made by plotting the pressure ratio over the compressor as well as the compressor efficiency as functions of the corrected air mass flow through the compressor.
   The turbo map is made by plotting the turbine flow parameter (TFP) as a function of the inverse of the turbine pressure ratio and separately plot the turbine efficiency as a function of the blade speed ratio (BSR).
   Corrected quantities is data that has been made independent of surrounding conditions and we use them to be able to calculate the compressor and turbine performance for any surrounding conditions, not just the once we have measured.
   The reference point for the compressor is 293.15 K and 101.3 kPa. For the turbine, the pressure reference is the same but the temperature reference is 873.15 K.

3. A larger engine can output more power but is less efficient than a smaller engine. It is also heavier, which means it takes more energy to move it. If we add a turbo to a smaller engine, we can regain the power lost from down sizing but we also introduce more pump work since the pressure in the exhaust system is increased.

4. We add an actuator to open and close the waste gate to control how much of the exhaust gases we let through the turbine.

5. (a) $T_{02} = T_{01}\left(1 + \frac{\Pi_c^{\frac{\gamma_{air}-1}{\gamma_{air}}} - 1}{\eta_c}\right)$

(b) $\dot{W}_c = \dot{m}_c c_{p,c} \Delta T_c$

(c) $T_{q_c} = \frac{P_c}{\omega_{tc}}$

6. (a) $T_{04} = T_{03}\left(1 - \eta_t\left(1 - \Pi_t^{\frac{\gamma_{exh}-1}{\gamma_{exh}}}\right)\right)$

   (b) $\dot{W}_t = \dot{m}_t c_{p,t} \Delta T_t$

   (c) $T_{q_t} = \frac{P_t}{\omega_{tc}}$

7. (a) For maximum performance, the waste gate should be closed as much as possible to achieve the highest possible air mass flow into the engine. We only open the waste gate when the pressure gets dangerously high.

   (b) For best fuel efficiency, the waste gate should be as open as possible to reduce the pump work the engine has to perform.

8. If we want a low pressure drop over the throttle, the more open the waste gate is, the more open the throttle should be.

   (a) Compared to the most fuel efficient strategy, the new strategy consumes more fuel but has better response time.

   (b) Compared to the maximum performance strategy, the new strategy has better fuel consumption but worse response time.

## 8.2 Turbocharger parameter estimation and model validation

### 8.2.1 Compressor mass flow model

We used a non linear least square method for estimating the parameters $\Psi_{max}$ and $\dot{m}_{c,corr,max}$ in the model:

$$\Pi_{c,max} = \left(\frac{u_2^2 \Psi_{max}}{2c_p T_{af}} + 1\right)^{\frac{\gamma}{\gamma-1}}, \tag{8.1}$$

$$u_2 = r_c \omega_{tc}, \tag{8.2}$$

$$\dot{m}_{c,corr} = \dot{m}_{c,corr,max}\sqrt{1 - \left(\frac{\Pi_c}{\Pi_{c,max}}\right)^2}. \tag{8.3}$$

The parameters were estimated to be:

$$\Psi_{max} = 1.0016, \text{ and } \dot{m}_{c,corr,max} = 0.1805. \tag{8.4}$$

The validation plot can be seen in Figure 8.1.

### 8.2.2 Compressor efficiency model

We used a non linear least square method for estimating the parameters $\eta_{c,max}$, $\dot{m}_{c,corr@\eta_{c,max}}$, $\Pi_{c@\eta_{c,max}}$, $Q_{11}$, $Q_{12}$ and $Q_{22}$ in the model:

$$\eta_c = \eta_{c,max} - \chi^T Q_\eta \chi \tag{8.5}$$

$$Q_{\eta_t} = \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{12} & Q_{22} \end{bmatrix}, \ \chi = \begin{bmatrix} \dot{m}_{c,corr} - \dot{m}_{c,corr@\eta_{c,max}} \\ \sqrt{\Pi_c - 1} - (\Pi_{c@\eta_{c,max}} - 1) \end{bmatrix} \tag{8.6}$$

The parameters were estimated to be:

$$\eta_{c,max} = 0.8206 \tag{8.7}$$
$$\dot{m}_{c,corr@\eta_{c,max}} = 0.0842 \tag{8.8}$$
$$\Pi_{c@\eta_{c,max}} = 1.9778 \tag{8.9}$$
$$Q_{11} = 90.5045 \tag{8.10}$$
$$Q_{12} = -6.4116 \tag{8.11}$$
$$Q_{22} = 0.8223 \tag{8.12}$$

The validation plot can be seen in Figure 8.1.

### 8.2.3 Turbine flow model

We used a non linear least square method for estimating the parameters $k_0$ and $k_1$ in the model:

$$TFP_{model} = k_0 \sqrt{1 - \Pi_t^{k_1}}, \ \Pi_t = \frac{p_{04}}{p_{03}} = \frac{p_{es}}{p_{em}} \tag{8.13}$$

$$\dot{m}_t = \frac{p_{em}}{\sqrt{T_{em}}} TFP_{model} \tag{8.14}$$

The parameters were estimated to be:

$$k_0 = 0.0054, \text{ and } k_1 = 1.4503. \tag{8.15}$$

The validation plot can be seen in Figure 8.1.

### 8.2.4 Turbine efficiency model

We used a non linear least square method for estimating the parameters $\eta_{t,max}$ and $BSR_{max}$ in the model:

$$BSR = \frac{\omega_{tc} r_t}{\sqrt{2 c_{p,exh} T_{em} \left(1 - \Pi_t^{\frac{\gamma_{exh}-1}{\gamma_{exh}}}\right)}} \tag{8.16}$$

$$\eta_t(BSR) = \eta_{t,max} \left(1 - \left(\frac{BSR - BSR_{max}}{BSR_{max}}\right)^2\right) \tag{8.17}$$

The parameters were estimated to be:

$$\eta_{t,max} = 0.8073, \text{ and } BSR_{max} = 0.6790. \tag{8.18}$$

The validation plot can be seen in Figure 8.1.

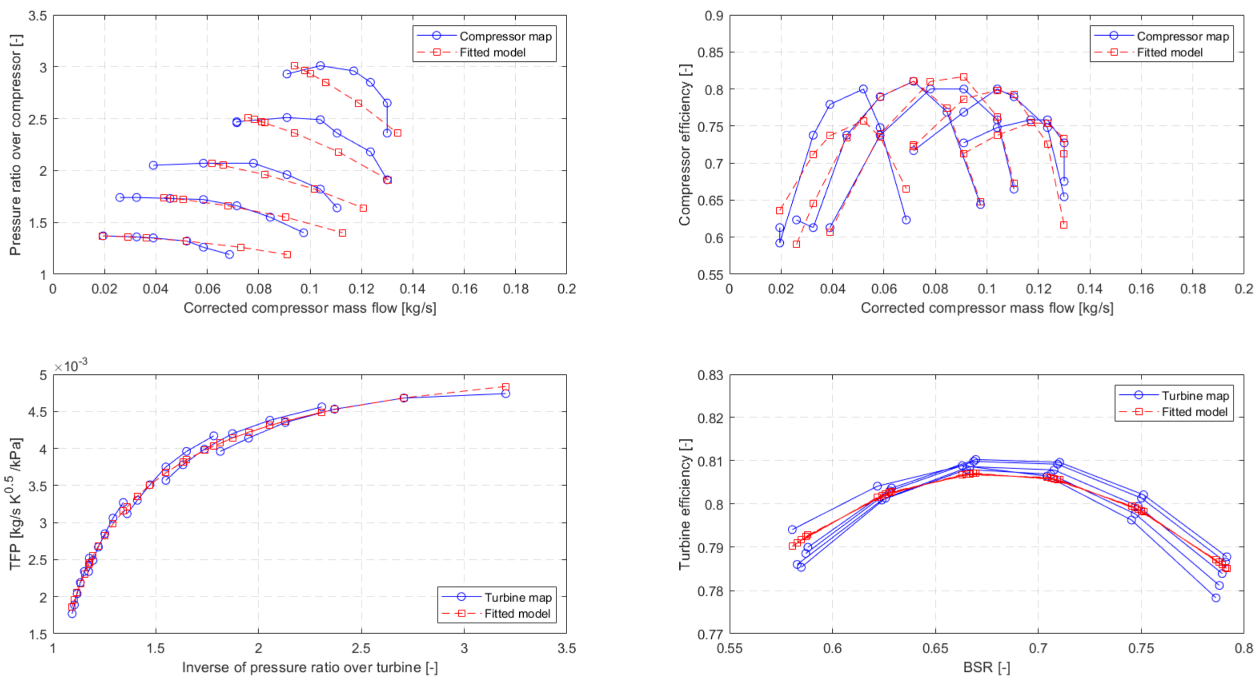


Figure 8.1: Compressor and turbine model validation.

All the validation plots confirm that the models are in good enough agreement with the compressor and turbine maps. Our plots look very similar to the ones given in the project instruction.

### 8.2.5 BMEP model

We used a least square method for estimating the parameters $C_{P0}$ and $C_{P1}$ in the model:

$$bmep_{model} = -C_{P0} + C_{P1} \cdot p_{im} \tag{8.19}$$

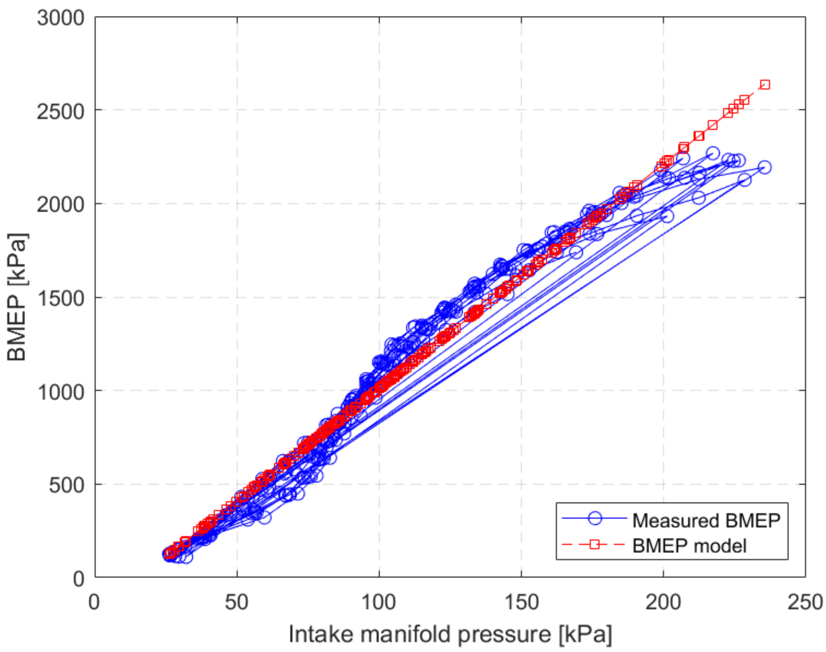


Figure 8.2: BMEP model validation.

The validation plot shows that our BMEP model captures the behaviour seen in the measured data.

## 8.3 Table of Parameters

All estimated parameters in the compressor and turbine models as well as the BMEP model are summarized in table 9.2.

Table 8.1: Estimated parameters in the compressor and turbine models as well as the BMEP model.

| Model | Parameter | Value |
|---|---|---|
| Compressor mass flow | $\Psi_{max}$ | 1.0016 |
| | $\dot{m}_{c,corr,max}$ | 0.1805 |
| Compressor efficiency model | $\eta_{c,max}$ | 0.8206 |
| | $\dot{m}_{c,corr@\eta_{c,max}}$ | 0.0842 |
| | $\Pi_{c@\eta_{c,max}}$ | 1.9778 |
| | $Q_{11}$ | 90.5045 |
| | $Q_{12}$ | $-6.4116$ |
| | $Q_{22}$ | 0.8223 |
| Turbine mass flow | $k_0$ | 0.0054 |
| | $k_1$ | 1.4503 |
| Turbine efficiency model | $\eta_{t,max}$ | 0.8073 |
| | $BSR_{max}$ | 0.6790 |
| BMEP | $C_{P0}$ | 189890 |
| | $C_{P1}$ | 12.0093 |

# Chapter 9

# Implementation and validation

## 9.1 Exercise 1

Table 9.1: Validation of the simulink compressor model.

| Compressor speed [RPM] | Source | Compressor mass flow [kg/s] | Efficiency [-] |
|---|---|---|---|
| 110910 | Compressor map | 0.0445 | 0.7376 |
| | Matlab model | 0.0460 | 0.7337 |
| | Simulink model | 0.0460 | 0.7418 |
| 131070 | Compressor map | 0.1018 | 0.7584 |
| | Matlab model | 0.0996 | 0.7626 |
| | Simulink model | 0.0996 | 0.7722 |
| 171400 | Compressor map | 0.1018 | 0.7480 |
| | Matlab model | 0.0919 | 0.7377 |
| | Simulink model | 0.0919 | 0.7074 |

## 9.2 Exercise 2

Table 9.2: Validation of the simulink turbine model.

| Turbine speed [RPM]<br>Exhaust manifold pressure [Pa] | Source | Turbine mass flow [kg/s] | Efficiency [-] |
|---|---|---|---|
| 80012<br>122010 | Turbine map<br>Matlab model<br>Simulink model | 0.0110<br>0.0111<br>0.0111 | 0.8092<br>0.8057<br>0.8057 |
| 130000<br>205440 | Turbine map<br>Matlab model<br>Simulink model | 0.0305<br>0.0300<br>0.0300 | 0.8009<br>0.8020<br>0.8020 |
| 150010<br>181360 | Turbine map<br>Matlab model<br>Simulink model | 0.0243<br>0.0250<br>0.0250 | 0.7783<br>0.7871<br>0.7871 |

The turbine torque were within reasonable values during these tests staying between 0 and 1 Nm.

## 9.3 Exercise 4

(a) The $K_p$ value was set to 0.000001 and $K_i$ was set to 0.4.

(b) When using both feedback and feedforward, the intake manifold pressure follows the reference quite well. There is some overshoot and but the pressure reaches a steady state in reasonable time. The fade out from the overshoot is smooth.

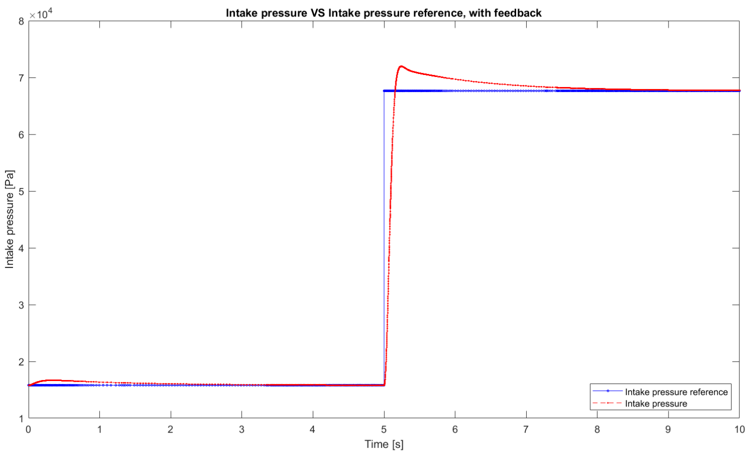


Figure 9.1: Intake pressure VS reference, with feedback.

(c) When only using the feedforward part of the controller, the intake pressure does not follow the reference as well as when also using the feedback part. When the feedback is not used, the system is also slower and has a static error. However, there was no overshoot and the pressure reached steady state faster.

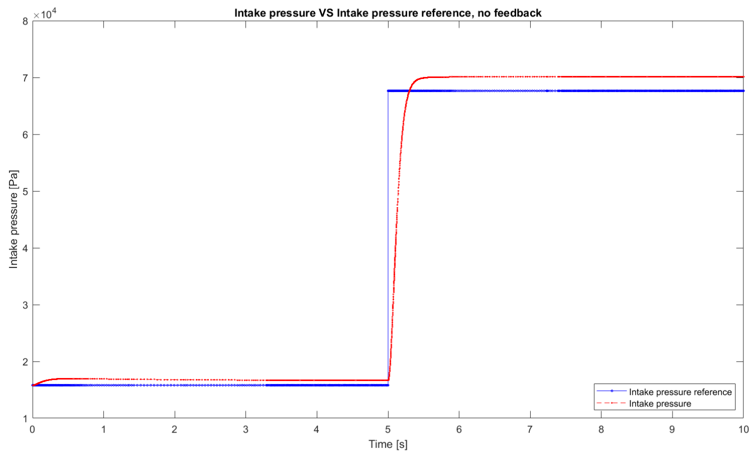


Figure 9.2: Intake pressure VS reference, no feedback.

(d) The feedforward part is not good enough on its own since it is based on a model of the real world and the model is not perfect, it has many small imperfections. A feedback part will correct these small errors.

## 9.4 Exercise 5

The $K_p$ value was set to 0.000005 and $K_i$ was set to 7. This made both the intake pressure and the boost pressure follow their respective references fairly well. Both have some overshoot but the fade out is smooth.

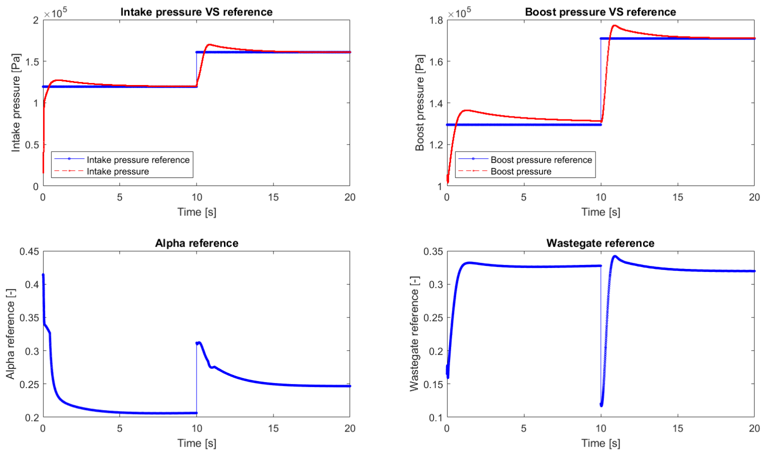


Figure 9.3: Intake pressure VS reference, boost pressure VS reference.

A fully open wastegate minimizes pump work for the engine and makes is more efficient. Therefore, it is desirable to have the wastegate open when we do not need the extra power the turbo would give us.

## 9.5 Exercise 6

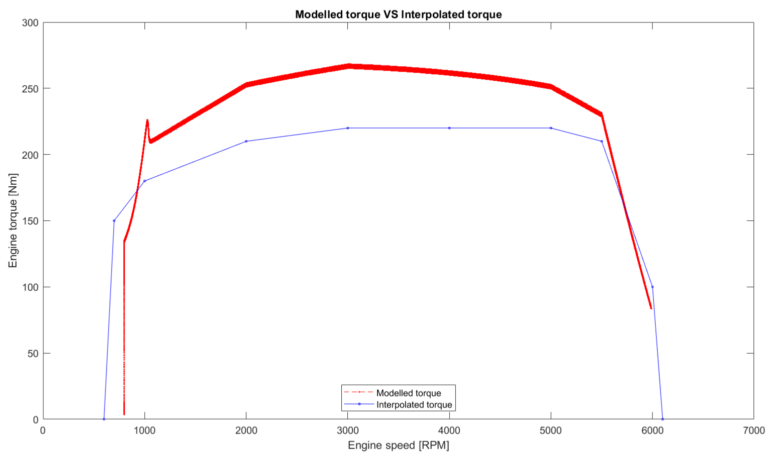


Figure 9.4: Modelled VS interpolated torque.

(a)

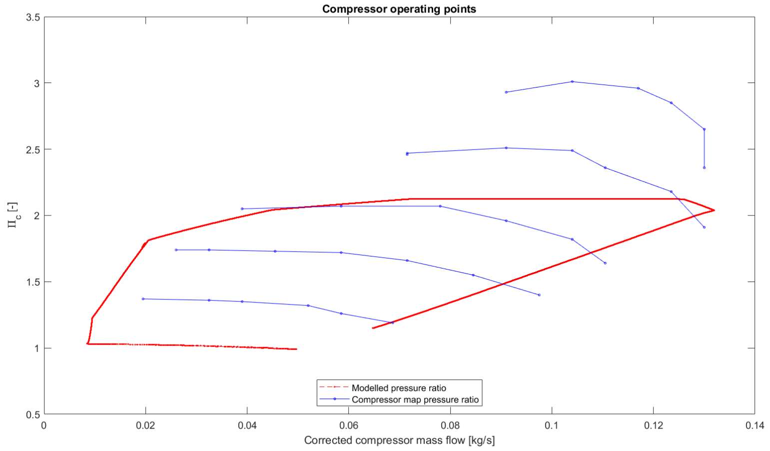


Figure 9.5: Compressor operating points.

(b) The compressor operating region has $\Pi_c$ between 1 and 2 and corrected compressor mass flow between 0.01 and 0.13.

## 9.6 Exercise 7

(a) The time it took for the vehicle to accelerate from 70 km/h to 110 km/h was 4.3 seconds. This is a lot faster than without the turbo.

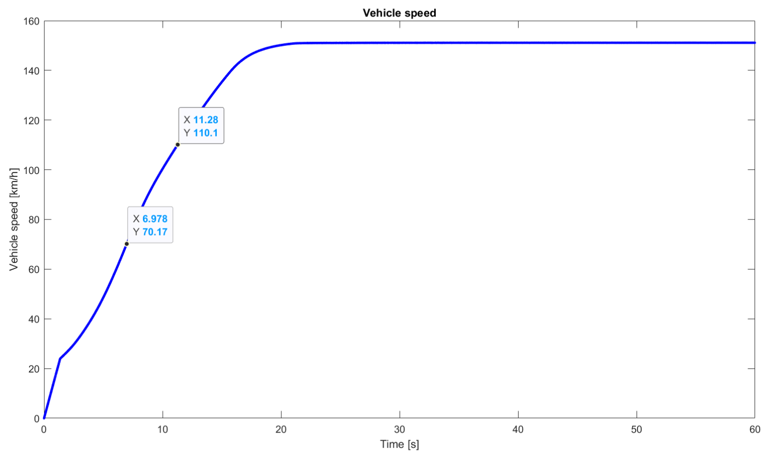


Figure 9.6: Acceleration test, 70-110 km/h.

(b) The emission for the turbo charged engine are lower than the EURO 3 limits. The CO and NOx emissions surpass the EURO 4 limits. The fuel consumption was calculated to be 5.09 $l/100km$

The emission are comparable to the ones from the naturally aspirated engine with some emissions being higher and some lower. The fuel consumption for the turbo charged engine was lower than for the naturally aspirated engine.

CO : 1.22 [g/km] Limits EURO 3 : 2.3 [g/km] EURO 4 : 1.0 [g/km]
HC : 0.08 [g/km] Limits EURO 3 : 0.20 [g/km] EURO 4 : 0.10 [g/km]
NOx : 0.09 [g/km] Limits EURO 3 : 0.15 [g/km] EURO 4 : 0.08 [g/km]

## 9.7 Exercise 8

The maximum torque output was 278 Nm. The torque increases fast in the beginning when it does not need the turbo but then slows down as the turbo is not up to speed yet. Once the turbo is up to speed, the torque can reach its maximum output.

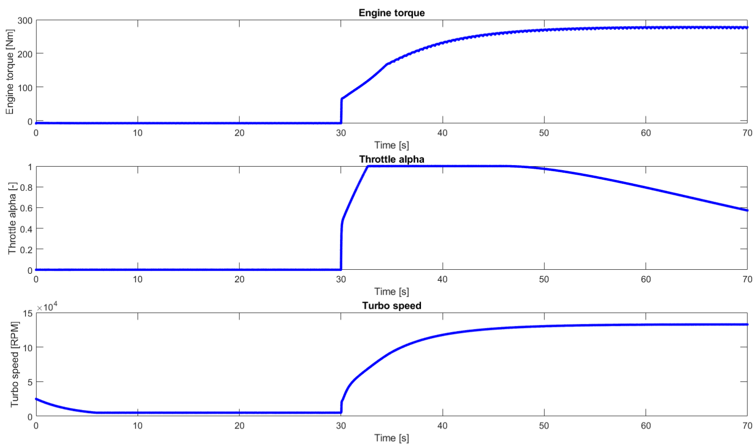


Figure 9.7: Engine torque, alpha throttle, turbo speed

# Chapter 10

# Driveline component model, prerequisites

## 10.1 Component models

### 10.1.1 Engine

$$\left(J_m + \frac{J_t}{i_g^2} + \frac{J_f}{i_g^2 i_f^2}\right)\dot{\omega}_e = M_e - M_t \tag{10.1}$$

$$\dot{M}_e = \frac{1}{\tau_e}(M_{e,ref} - M_e) \tag{10.2}$$

### 10.1.2 Gearbox

$$\omega_e = i_g \omega_t \tag{10.3}$$

$$M_t i_g = M_f \tag{10.4}$$

### 10.1.3 Final drive

$$\omega_t = i_f \omega_f \tag{10.5}$$

$$M_f i_f = M_{shaft} \tag{10.6}$$

### 10.1.4 Drive shaft

$$M_{shaft} = k(\theta_f - \theta_w) + c(\omega_f - \omega_w) \tag{10.7}$$

### 10.1.5 Wheel

$$(J_w + m r_w^2)\dot{\omega}_w = M_{shaft} - F_w r_w \tag{10.8}$$

$$r_w \omega_w = v \tag{10.9}$$

### 10.1.6 Vehicle

$$m\dot{v} = F_w - mgc_r \tag{10.10}$$

## 10.2 States

$$x_1 = \theta_f - \theta_w = \frac{\theta_e}{i_g i_f} - \theta_w \tag{10.11}$$

$$x_2 = \omega_e \tag{10.12}$$

$$x_3 = \omega_w \tag{10.13}$$

$$x_4 = M_e \tag{10.14}$$

## 10.3 Differentiation of states

$$\dot{x}_1 = \frac{1}{i_g i_f} x_2 - x_3 \tag{10.15}$$

$$\dot{x}_2 = \frac{1}{(J_m + \frac{J_t}{i_g^2} + \frac{J_f}{i_g^2 i_f^2})}\left( - \frac{k}{i_g i_f} x_1 - \left(\frac{b_t}{i_g^2} + \frac{b_f + c}{i_g^2 i_f^2}\right) x_2 + \frac{c}{i_g i_f} x_3 + x_4 \right) \tag{10.16}$$

$$\dot{x}_3 = \frac{k}{mr_w^2 + J_w} x_1 + \frac{c}{(mr_w^2 + J_w) i_g i_f} x_2 - \frac{c}{mr_w^2 + J_w} x_3 - \frac{r_w mgc_r}{mr_w^2 + J_w} \tag{10.17}$$

$$\dot{x}_4 = \frac{1}{\tau_e}(\dot{M}_{e,ref} - x_4) \tag{10.18}$$

## 10.4 Linear state space form

Consider the system

$$\begin{aligned} \dot{x} &= Ax + Bu + Hl \\ y &= Cx \end{aligned}$$

where

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

and

$$
A = \begin{bmatrix} 0 & \frac{1}{i_g i_f} & -1 & 0 \\ -\frac{k}{(J_m + \frac{J_t}{i_g^2} + \frac{J_f}{i_g^2 i_f^2}) i_g i_f} & -\frac{\frac{b_t}{i_g^2} + \frac{b_f + c}{i_g^2 i_f^2}}{J_m + \frac{J_t}{i_g^2} + \frac{J_f}{i_g^2 i_f^2}} & \frac{c}{(J_m + \frac{J_t}{i_g^2} + \frac{J_f}{i_g^2 i_f^2}) i_g i_f} & \frac{1}{(J_m + \frac{J_t}{i_g^2} + \frac{J_f}{i_g^2 i_f^2})} \\ \frac{k}{m r_w^2 + J_w} & \frac{c}{(m r_w^2 + J_w) i_g i_f} & -\frac{c}{m r_w^2 + J_w} & 0 \\ 0 & 0 & 0 & -\frac{1}{\tau_e} \end{bmatrix} \tag{10.19}
$$

$$
B = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{\tau_e} \end{bmatrix} \tag{10.20}
$$

$$
H = \begin{bmatrix} 0 \\ 0 \\ -\frac{r_w m g c_r}{m r_w^2 + J_w} \\ 0 \end{bmatrix} \tag{10.21}
$$

$$
l = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix} \tag{10.22}
$$

$$
C = \begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix} \tag{10.23}
$$

## 10.5 Block scheme

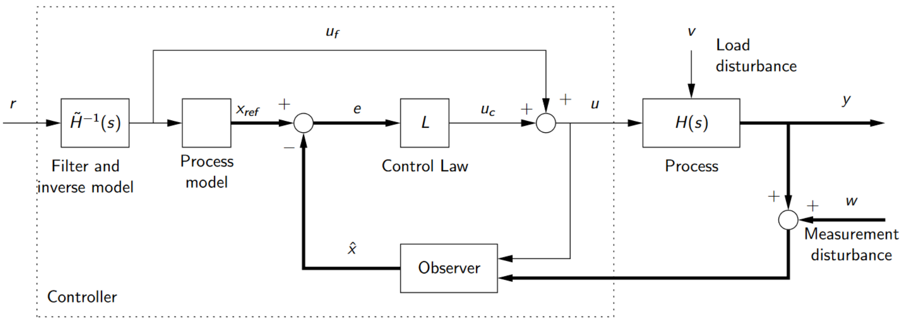


Figure 10.1: Controller block scheme

## 10.6 Observer of the drive line model

$$
\dot{\hat{x}} = A\hat{x} + Bu + K_f(y - C\hat{x}) \tag{10.24}
$$

$$
\hat{y} = C\hat{x} \tag{10.25}
$$

## 10.7 Observer in state space form

Consider the form

$$\dot{\hat{x}} = A_{obs}\hat{x} + B_{obs}u_{obs}$$

$$y_{obs} = C_{obs}\hat{x}$$

where

$$A_{obs} = A - K_f C \tag{10.26}$$

$$B_{obs} = \begin{bmatrix} B & K_f & H \end{bmatrix} \tag{10.27}$$

$$C_{obs} = I_{4\times4} \tag{10.28}$$

$$u_{obs} = \begin{bmatrix} u \\ y \\ l \end{bmatrix} \tag{10.29}$$

$$y_{obs} = \hat{x} \tag{10.30}$$

## 10.8 Observer gain

The observer gain should be choose such that $A - K_f C$ has good pole placement. We want the poles to be far away from from the origin in the left half of the complex plane and close to the real axis.

## 10.9 Equations for a state feedback controller

The control signal is

$$u = l_0 r - K_c\hat{x} \tag{10.31}$$

where $\hat{x}$ is observed data and $r$ is reference signals. $l_0$ is the reference signal gain and $K_c$ is the feedback gain.

## 10.10 Feedback gain

The feedback gain can be computed in many ways, for example through LQ design.

# Chapter 11

# Driveline component model, validation

1. A figure showing the complete simulink driveline model.

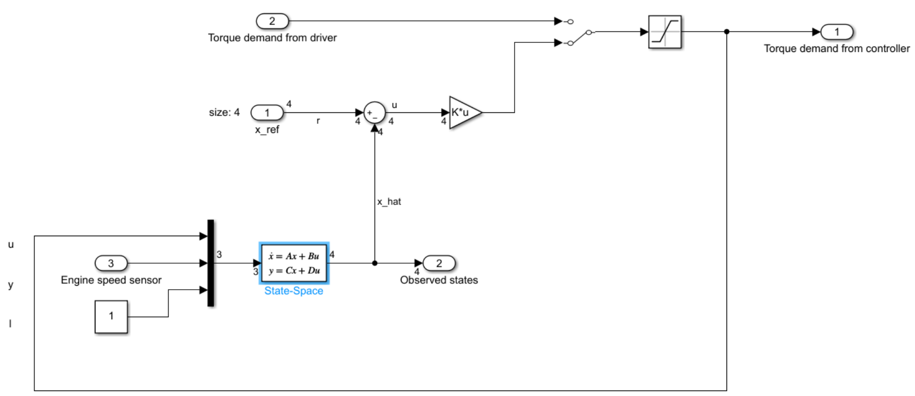


Figure 11.1: Simulink drivelink model.

2. Plots of the observed and the real drive line variables with the observer gain set to zero.

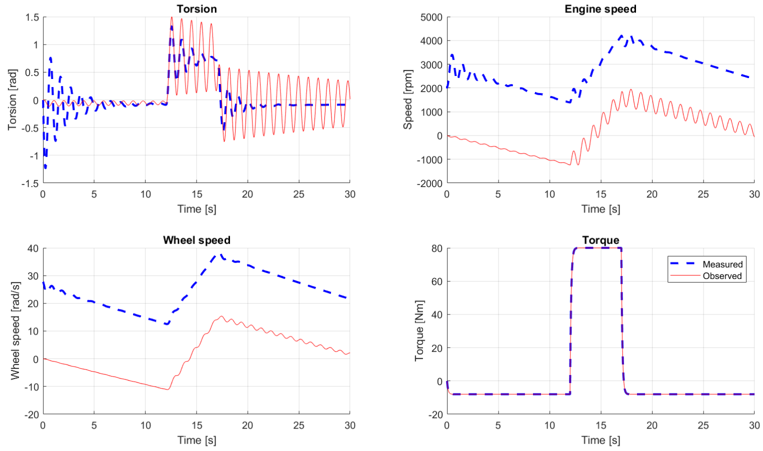


Figure 11.2: Observed and real drive line variables, zero observer gain.

3. Plots of the observed and the real drive line variables with the calculated observer gain.

   It is clear to see that the result is much better than with zero observer gain. There is no torsion, the engine and wheel speeds are accurately captured and the torque is still good.

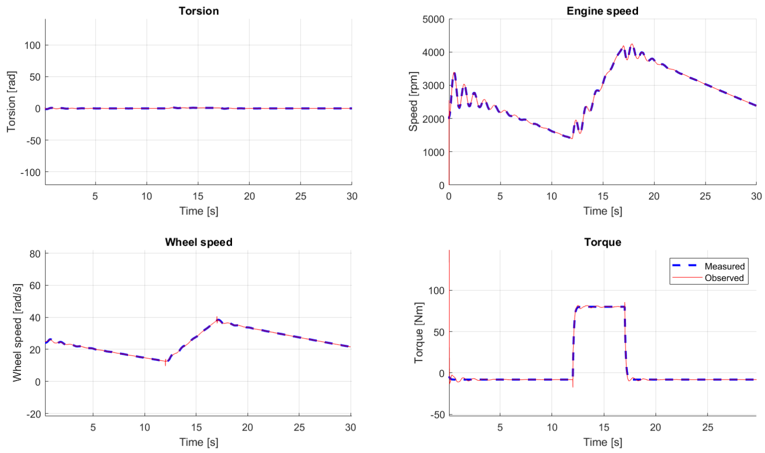


Figure 11.3: Observed and real drive line variables, calculated observer gain.

4. -

5. (a) The demanded torque and vehicle acceleration plot without the state feedback:

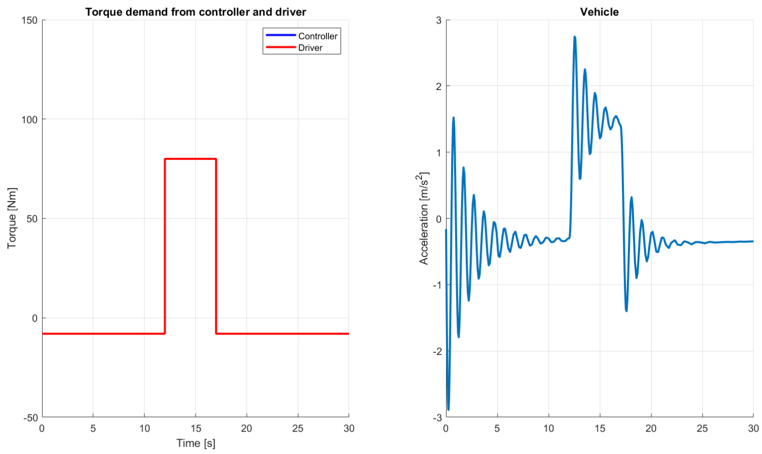


Figure 11.4: Demanded torque and vehicle acceleration without state feedback.

The demanded torque and vehicle acceleration plot with the state feedback:

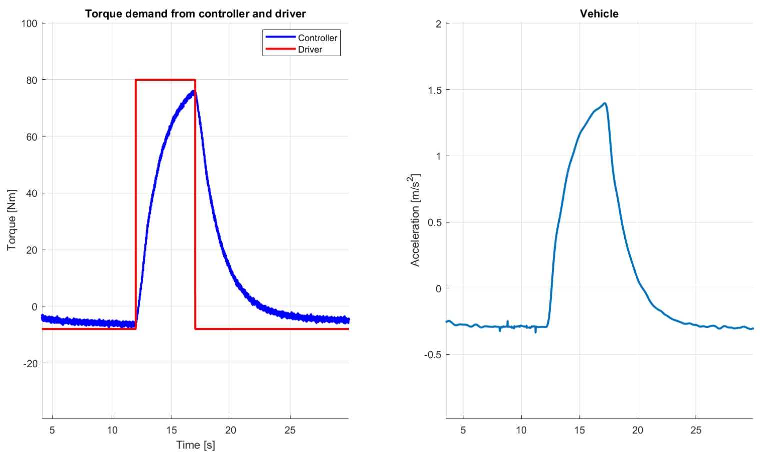


Figure 11.5: Demanded torque and vehicle acceleration with state feedback.

With the state feedback, the behaviour is much better. The rise time is quick and there is no overshoot. Also, the vehicle acceleration with the controller is almost 1.5 $m/s^2$, which was the target.

(b) Below, there are plots of the drive line variables both in damped and undamped mode, beginning with the undamped.

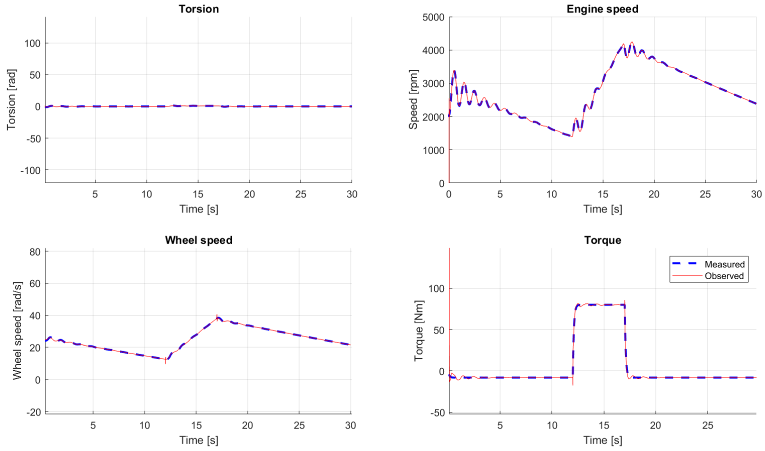


Figure 11.6: Driveline variables, undamped.

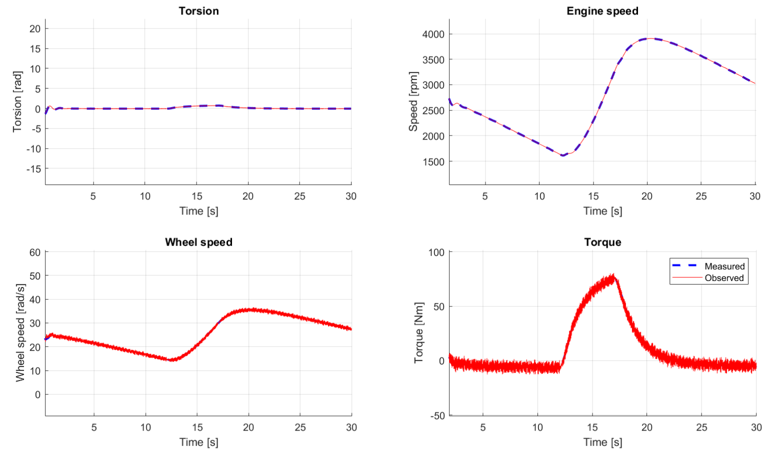


Figure 11.7: Driveline variables, damped.

In the damped mode, all variables behave a lot smoother. This will be more pleasant for the driver and reduce wear and tear on the engine.

There is a high frequency oscillation in the observed torque and wheel speed. This can be reduced or even removed with finer tuning of the state feedback controller.