

# **Simulation of Emission Related Faults on a Diesel Engine**

**Master's thesis**  
performed in **Vehicular Systems**

by  
**Magnus Adolfson**

Reg nr: LiTH-ISY-EX-3266-2002

6th December 2002



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**Dept. of Electrical Engineering**  
at **Linköpings universitet**

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| <b>Titel</b>   | Simulering av emissionsrelaterade fel på en diesel motor<br><br>Title Simulation of Emission Related Faults on a Diesel Engine  |   |
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| <b>Sammanfattning</b><br>Abstract  | <p>Today's legislation on exhaust gas emissions for heavy duty diesel (HDD) vehicles is more stringent than ever and will be even more tough in the future. More over, in a few years HDD vehicles have to be equipped with OBD (On-Board Diagnostics). This place very high demands on the manufacturers to develop better engines and strategies for OBD. As an aid in the process models can be used.</p> <p>This thesis presents extensions of an existing diesel engine model in Matlab/Simulink to be able to simulate emissions during standardized european test cycles. Faults in the sensor and actuator signals are implemented into the model to find out if there is an increase or decrease in the emissions. This is used to create a fault tree where it can be seen why predefined emission thresholds are exceeded. The tree is an aid when developing OBD.</p> <p>The results from the simulations showed that almost no faults made the emissions cross the thresholds. The only interesting faults were faults in the ambient temperature sensor and the injection angle actuator. This means that the OBD-system only needs to monitor a few components which implies a smaller system and less work.</p> |   |
| <b>Nyckelord</b><br>Keywords   | Diagnosis, OBD, engine modelling, emissions, fault tree   |   |



## Abstract

Today's legislation on exhaust gas emissions for heavy duty diesel (HDD) vehicles is more stringent than ever and will be even more tough in the future. More over, in a few years HDD vehicles have to be equipped with OBD (On-Board Diagnostics). This place very high demands on the manufacturers to develop better engines and strategies for OBD. As an aid in the process models can be used.

This thesis presents extensions of an existing diesel engine model in Matlab/Simulink to be able to simulate emissions during standardized european test cycles. Faults in the sensor and actuator signals are implemented into the model to find out if there is an increase or decrease in the emissions. This is used to create a fault tree where it can be seen why predefined emission thresholds are exceeded. The tree is an aid when developing OBD.

The results from the simulations showed that almost no faults made the emissions cross the thresholds. The only interesting faults were faults in the ambient temperature sensor and the injection angle actuator. This means that the OBD-system only needs to monitor a few components which implies a smaller system and less work.

**Keywords:** Diagnosis, OBD, engine modelling, emissions, fault tree

## Thesis Outline

**Chapter 1** Gives an introduction to the thesis and the objectives of it. Also some terms often used in the thesis are discussed, e.g. OBD and test cycles.

**Chapter 2** A very brief description of the original model that was the starting point. The extensions made to it to be able to reach the objectives are also presented.

**Chapter 3** Describes what faults are considered and how they are modelled. Also the results of the faults' effect on the emissions are presented with plots.

**Chapter 4** Further model improvements to make the model more accurate are presented. Only improvements of the extensions presented in Chapter 2 are discussed.

**Chapter 5** Conclusions.

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# Chapter 1

## Introduction

Today's legislation on Heavy Duty Diesel (HDD) vehicles have become more stringent and will be even tougher in the future. Each area has its own legislator regulating how much exhaust gas emissions the vehicles are allowed to emit. For Europe there is the EU, for the USA there is the EPA (Environmental Protection Agency) etc. While these laws help protect the environment, they exert pressure on the HDD vehicle manufacturers. To accommodate these new laws they have to develop better engines, control systems, Exhaust Gas Recirculation (EGR) and aftertreatment systems, e.g. particulate filter, Selective Catalytic Reduction (SCR). In the near future HDD vehicles will also have to be equipped with On-Board Diagnostics (OBD), see Section 1.2. As an aid and sometimes as a necessity in this development, models of the systems are used. Not only can this be more cost effective but it can also be easier to make certain changes to the system, no equipment other than a computer is necessary and simulation can be faster than real time.

Section 1.1 gives the objectives of this thesis. In Section 1.2 a description of what OBD is is presented and Section 1.3 describes two European test cycles used in this thesis work.

### 1.1 Objectives

This is a master thesis carried out at Scania CV AB under supervision of Vehicular systems, Dept. of Electrical Engineering at Linköpings universitet. The objectives of this thesis are to:

- Create a working model of a diesel engine with emissions, i.e. particulates and  $\text{NO}_x$ , and a testcell, to be able to simulate emissions during european test cycles;

- Develop a simulation aid to be able to explore which faults that would cause the emissions to exceed predefined thresholds regulated by law.

## 1.2 On-Board Diagnostics

OBD is already implemented in gasoline engines, light and medium duty diesels and has been for a few years, but the area is relatively new. Until recently there have been no laws regulating OBD for HDD vehicles, but by the year 2005, HDD vehicles have to be equipped with OBD.

OBD is a set of algorithms or strategies within the vehicles electronic system which monitor all components, that influence the emission levels, for faults. If there is a fault that causes an unacceptable increase in the vehicle's emissions, a lamp on the dashboard, or some other visual or audible indicator, must indicate the increase. An unacceptable increase is when the fault causes the emission level to exceed the OBD thresholds. The thresholds are applicable when executing an European Stationary Cycle (ESC), see Section 1.3, and are set to twice the basic limit for  $\text{NO}_x$  and five times the basic limit for particulates, see Table 1.1, for 2005. The emissions needed to be monitored are only  $\text{NO}_x$  and particulates since they are the most unhealthy and environmentally unsafe emissions from HDD vehicles. That is why those two emissions are the only ones considered in this thesis. For more information on OBD see [1, 2].

## 1.3 European Test Cycles

When certifying an engine for production it has to go through several tests which are defined by the government or the manufacturer. Some tests are to make sure the vehicle do not emit too much of the dangerous emissions. Two of these tests for measuring exhaust gas emissions in Europe are called ESC (European Stationary Cycle) and ETC (European Transient Cycle). After one of these tests the emission levels are calculated and compared to predefined limits, see Table 1.1. If the

Table 1.1: Basic emission limits for the ESC.

| Year | HC<br>(g/kWh) | CO<br>(g/kWh) | $\text{NO}_x$<br>(g/kWh) | Particulates<br>(g/kWh) |
|------|---------------|---------------|--------------------------|-------------------------|
| 2000 | 0.66          | 2.1           | 5.0                      | 0.10                    |
| 2005 | 0.46          | 1.5           | 3.5                      | 0.02                    |
| 2008 | 0.46          | 1.5           | 2.0                      | 0.02                    |

Table 1.2: The thirteen points of the ESC.

| Step | Engine Speed (rpm) | Load (%) | Weight Factor | Duration (min) |
|------|--------------------|----------|---------------|----------------|
| 1    | idle               | —        | 0.15          | 4              |
| 2    | A                  | 100      | 0.08          | 2              |
| 3    | B                  | 50       | 0.10          | 2              |
| 4    | B                  | 75       | 0.10          | 2              |
| 5    | A                  | 50       | 0.05          | 2              |
| 6    | A                  | 75       | 0.05          | 2              |
| 7    | A                  | 25       | 0.05          | 2              |
| 8    | B                  | 100      | 0.09          | 2              |
| 9    | B                  | 25       | 0.10          | 2              |
| 10   | C                  | 100      | 0.08          | 2              |
| 11   | C                  | 25       | 0.05          | 2              |
| 12   | C                  | 75       | 0.05          | 2              |
| 13   | C                  | 50       | 0.05          | 2              |

calculated values exceed the predefined limits the engine is not certified for production.

### 1.3.1 European Stationary Cycle

The ESC is a test cycle for measuring the engine's exhaust gas emissions during stationary operation. It consists of thirteen different points within the engine's domain of work, see Table 1.2. The points depend on the engines parameters such as power and torque curve. The following calculations decide which engine speeds that should be used,

$$A = n_{lo} + 0.25(n_{hi} - n_{lo}),$$

$$B = n_{lo} + 0.50(n_{hi} - n_{lo}),$$

$$C = n_{lo} + 0.75(n_{hi} - n_{lo}),$$

where,

$n_{lo}$  is the lowest engine speed at which 50% of maximum power is achieved,

$n_{hi}$  is the highest engine speed at which 70% of maximum power is achieved.

Maximum power is taken from the engine's power curve. At engine speed A 50% load means that the engine must produce a torque of 50% of its maximum torque at that particular speed. Each point or step has a weight factor which decide the importance of that step when calculating the emissions. The sum of the weight factors is one. For

gaseous emissions, e.g.  $\text{NO}_x$  and HC (Hydro Carbons, which is unburned fuel exiting the combustion chamber), the amount of emissions and power is measured during the last 30 seconds of each step and then the specific value in g/kWh is calculated, e.g. for  $\text{NO}_x$

$$\text{NO}_x = \frac{\sum_{i=1}^{13} \text{NO}_{x,i} * \text{WF}_i}{\sum_{i=1}^{13} P_i * \text{WF}_i},$$

where,

$\text{WF}_i$  is the weight factor for step  $i$ ,

$P_i$  is the engine power for step  $i$ .

For measuring of the particulates there is a filter downstream the engine where the particulates are collected from the exhaust gases. Before the filter there is an opening which is controllable. To include the weight factors in the calculations the size of the opening or the time it is open can be regulated. The limits for the ESC are shown in Table 1.1

### 1.3.2 European Transient Cycle

ETC is a test cycle where the engine is tested during transient operation. This cycle is more complicated than ESC. It consists of 1800 different points in the engine's domain of work dependent of its parameters, i.e. idle engine speed, maximum engine speed and maximum engine torque. As in ESC every point corresponds to an engine speed and load. The duration of the cycle is 1800 seconds which means a new point every second. The emissions are measured continuously during the entire cycle and then the specific values are calculated according to regulations, see [3]. The limits for EURO 4 for ETC are 3.5 g/kWh for  $\text{NO}_x$  and 0.03 g/kWh for particulates.

## Chapter 2

# Engine Model and Extensions

The Engine model is implemented in Matlab/Simulink. It is a phenomenological model, i.e. based on observations from real engines. Only a brief description of the original engine model is presented in Section 2.1, for more information see [4, 5]. The extensions described in Section 2.2 are the additions to the engine model to be able to reach the objectives.

### 2.1 Engine Model

The original model is a mean value engine model. The model can be described by state variables and flows. For a schematic overview of the system see Figure A.1. From the states (pressure and temperature) in control volume up, i.e. upstream, and down, i.e. downstream of a component, it is possible to calculate the flow through the component. The model is object oriented and components, e.g. compressor or turbine, can easily be replaced by newer and improved components with no or minor modifications to the model.

### 2.2 Extensions

To be able to simulate the engine's emissions during ESC and ETC a few things need to be added to the original engine model. The extensions are described below and are a small part of the software of a Scania ECU, a model of the emissions  $\text{NO}_x$  and smoke, a model of the engine torque and a model for testcell control.

### 2.2.1 Engine Control Unit

Because one of the objectives is to see how faults affect the emissions, there is a need to include in the model the variables, controlled by the ECU, that have a major impact on the engine's emissions. The variables are the injection angle  $\alpha$ , amount of injected fuel  $\delta$  and EGR valve opening controlling the amount of exhaust gas recirculated into the inlet manifold, see below for further information. One way is to integrate the wanted parts of the software of an ECU into the model. The ECU software discussed here is written in C-code.

In Simulink there is a built-in block called an S-function block that allows existing C-code to be incorporated into the Simulink model. A C-file needs to be written for that block which defines the block's parameters, i.e. the number of inputs, number of outputs, etc. From that C-file, interaction with any other C-files is possible, e.g. the ECU's files. Another choice is to use the ECU hardware, but that can lead to a lot of extra work.

The ECU software can consist of approximately 100 C-files and their corresponding header file. A C-file and its header file is called a module. Not all of them are needed to get the desired outputs. Also, if all of the software is included into the model the simulation time is increased.

It is desirable that no changes are made to the ECU software. There are more than one reason for this. If the C-files are out of date and have to be replaced by newer files the changes have to be done all over again. Altering the files also makes it easy to make mistakes, changing the function of the code in the files.

To avoid having to make changes to the software a C-file has to be written, which deals with the broken communication between the files used and the ones that are not used in the model. It also has to handle the fact that some sensor values are the outputs from the engine model and not the values from the usual module. For example, if one module handles the value from the engine speed sensor, every module that uses the engine speed has to be fed with the engine speed from the engine model instead. The module that handles the engine speed is now unnecessary and it can be excluded. This has to be done for every sensor value since there are no real sensors in the model. Some sensor values may not exist in the model and something else has to be done, e.g. the value may be set to a constant. The S-function block is fed with the appropriate inputs from the engine model and the outputs from the block are the calculated values by the ECU, see Figure 2.1.



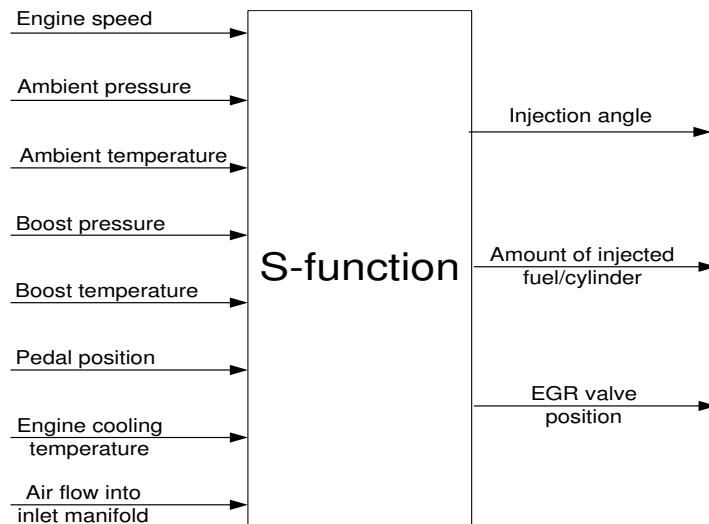


Figure 2.1: S-function block in Simulink with inputs and outputs.

### Injection Angle

Injecting the fuel earlier causes the formation of  $\text{NO}_x$  to increase due to higher temperature in the cylinder, but the amount of particulates decrease due to more oxidation time, see e.g. [6].

Only one module is needed to calculate the injection angle ( $\alpha$ ). This module consists of a number of look up tables. The inputs are interpolated in these tables and the logic of the module calculates  $\alpha$ . The injection angle calculated by the ECU is an average angle for all cylinders.

### Amount of Injected Fuel

The amount of fuel injected controls the entire engine. It is one of the most important parameters when developing engines.

There are a number of modules that calculate different amounts of injected fuel ( $\delta$ ). For example, one module calculates maximum  $\delta$  allowed to avoid smoke, one for controlling  $\delta$  at start up of the engine etc. The logic in a main module then decides which  $\delta$  is to be the correct one. Only a few of the modules are needed for testcell driving. One calculates  $\delta$  as a function of engine speed and the position of the accelerator pedal and one is used for fuel limiting, e.g. maximum allowed  $\delta$  to avoid smoke or breaking the engine. The amount of fuel injected calculated by the ECU is an average amount for all cylinders.

### EGR Valve

EGR lowers the combustion temperature and available oxygen therefor reducing the  $\text{NO}_x$  formation. Particulates oxidation is reduced because of the lower oxygen concentration, therefor, the amount of particulates in the exhaust gases increase, see e.g. [6]. EGR is one of the concepts Scania is investigating to be able to accommodate future emission levels.

Three modules are needed to calculate the position of the EGR valve. One calculates the amount of exhaust gas in the inlet manifold, one gives a reference value of the amount, depending on the state of the engine, and the last one controls the EGR valve to make the calculated amount equal to the reference value.

However, at this point EGR is not included in the engine model. No model of an EGR system is available.

### Validation of the ECU Model

The ECU model was validated with a PC program called Gredi which is made by Kleinknecht. The PC is connected via an interface to the ECU hardware. Through the program and the interface it is possible to read variable and parameter values from the ECU software. This was done in a test bench where it is possible to control the sensor values e.g. engine speed, boost pressure, pedal position etc. A number of different pedal positions and engine speeds were simulated with different sensor values in the test bench and the corresponding  $\delta$  and  $\alpha$  were recorded. The same test were then done in the Simulink model.

As expected the values agreed for the major part of the test points. If the engine cooling temperature is above a certain temperature the engine will shut down to avoid the engine overheating. At situations like this the model values and the test bench values differ for obvious reasons. No fault detection is included in the ECU model.

There is no EGR system in the model. Therefor, validating the EGR valve control signal is not possible.

### 2.2.2 Emissions

Modelling of the exhaust gas emissions is very difficult. Only approximate models can be found. This is true especially for particulates. That is why smoke was modelled instead of particulates. Particulate matter is approximately equal to smoke plus HC. There are some correlation between smoke and particulate emissions. For example they both decrease when the  $\text{NO}_x$  emissions increase, which is important to keep in mind when designing engines. The fact that when the  $\text{NO}_x$  emission decrease the particulate emission increase and vice versa is one of the main problems when optimizing the exhaust gas emissions.

### NO<sub>x</sub> and Smoke

A simple model for both smoke and NO<sub>x</sub> can be used,

$$Emission = a_0 + a_1\alpha + a_2\alpha^2, \quad (2.1)$$

where,

$Emission = NO_x$  or smoke

$a_i = a_i(M,N)$ , i.e. dependent of engine torque (M) and speed (N).

To get the model to apply for most of the engine's domain of work a number of different points with different  $\alpha$ :s have to be executed with the engine in a test bench and the corresponding emission value recorded. It is a good idea to choose the points of the ESC. One reason is because one of the objectives is to simulate the emissions during the ESC and therefor a valid model in those points is desirable. The result becomes a function,

$$\begin{aligned} NO_x &= f(\alpha, N, M), \\ smoke &= f(\alpha, N, M). \end{aligned}$$

The coefficients  $a_i$  are then fitted for each emission to give (2.1) for every point, see Figure 2.2 for NO<sub>x</sub> and Figure 2.3 for smoke, where the emission is shown as a function of injection angle for point 8 in the ESC, i.e. rpm B and 100 % load. A three dimensional look up table can be created from the equations with engine speed, torque and injection angle as inputs and the emission value as output.

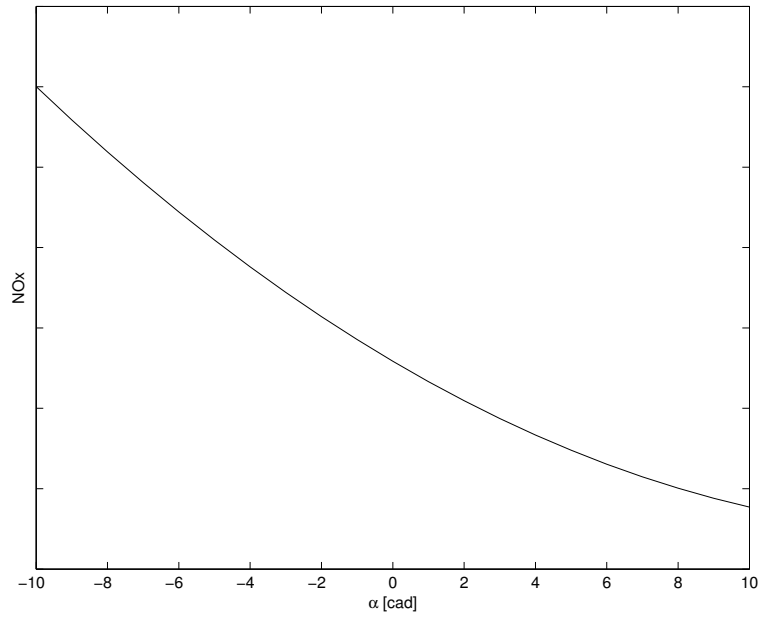
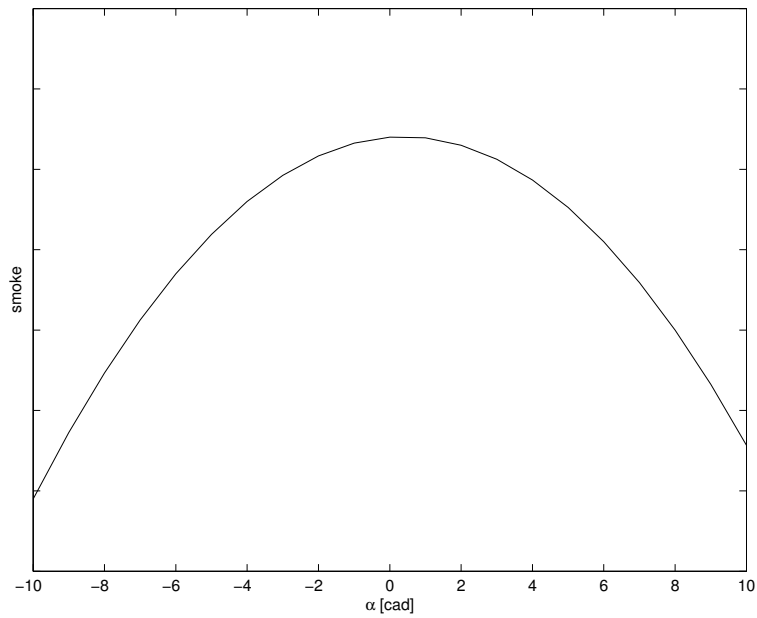
### Validation of the Emissions Model

For the area where the model is defined the model values are accurate. However, when faults are implemented the ECU is often outside the valid area. In these areas the model can only predict trends, i.e. if the emission is increased or decreased but not by how much. The results from the simulations must be compared with measured values before any decisions are made.

#### 2.2.3 Engine Torque

When executing one of the test cycles in a testcell, the engine torque is fed back to control the engine to the work points specified in the cycle. That is why a model of the torque is needed. Tests have shown that there is a strong linear dependency between  $\delta$  and the torque, see e.g. [7]. It was assumed that the torque could be modelled as

$$M = c_0 + c_1\delta + c_2N\delta, \quad (2.2)$$

Figure 2.2:  $\text{NO}_x$  as a function of  $\alpha$  for ESC step 8.Figure 2.3: Smoke as a function of  $\alpha$  for ESC step 8.

where  $c_i$  are constants. A number of measurements from different work points of the engine can be fitted with regression analysis to (2.2) to get the value of the constants.

### Validation of Engine Torque Model

The model was derived from one set of data resulting in,

$$M = -168 + 11.6\delta - 0.0016N\delta, \quad (2.3)$$

where  $\delta$  is in mg/stroke and  $N$  is in rpm. It was then validated against another set. An average error of 7 % was obtained. Where the average error  $E$  is calculated as,

$$E = \frac{1}{n} \sum_i \left| \frac{M_{Measured}(i) - M_{Estimated}(i)}{M_{Measured}(i)} \right| \quad i = 1..n,$$

where,

$M_{Measured}$  = measured torque,

$M_{Estimated}$  = estimated torque with Equation 2.3,

$n$  = number of measurements.

Figure 2.4 shows that the highest errors are reached at low  $\delta$ :s. This is because of the way the error  $E$  is calculated. Small  $\delta$ :s produce small torques. A difference between measured and estimated torque of 50 Nm has a bigger impact on  $E$  if the torque is 500 than if it is 1500. One more reason for this is because more measurements at high torques were used. Because most of the points of the ESC is at high torques it is more important to have an accurate model there.

### 2.2.4 Testcell Control

As mentioned above when executing a test cycle a desired torque and engine speed is specified, see e.g. Table 1.2 for ESC. Different methods are adopted, to govern the engine torque to follow the reference value, depending on the cycle to be executed. For the engine speed there is an electrical engine which is fed with the desired speed and, because it is connected via a shaft to the diesel engine, the diesel engine adapts and inherits the speed. The main focus is on designing a testcell model and its control for test cycles ESC and ETC.

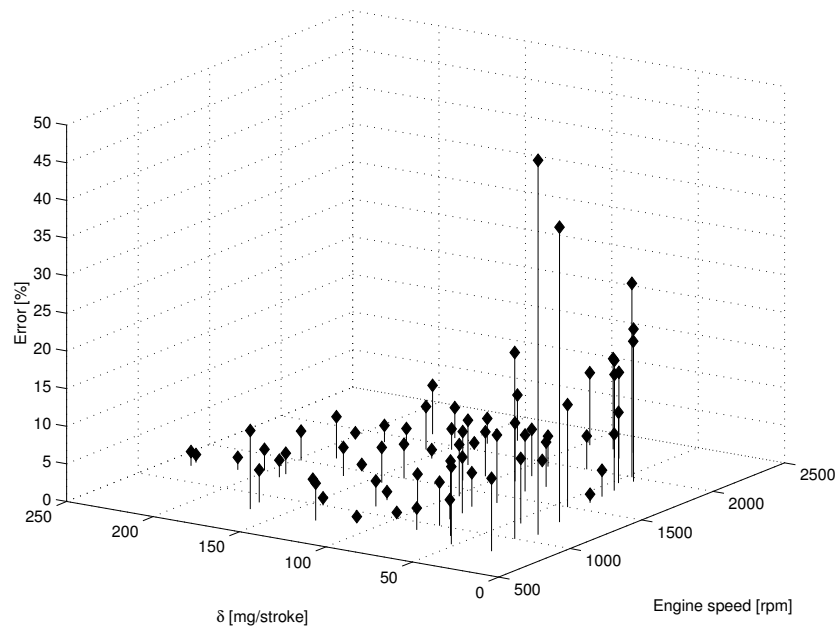


Figure 2.4: Error in percent between measured and estimated torque for each validation point.

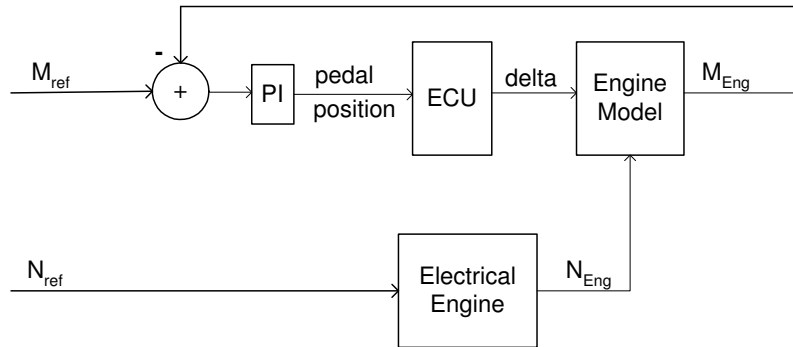


Figure 2.5: Testcell modelling for ESC.

### ESC Control

For ESC a simple PI-regulator is satisfactory to control the engine. The desired torque and engine speed are inputs to the model. The engine torque from the model is fed back and a pedal position is given, see Figure 2.5. Because the engine model stabilizes, i.e. the pressures and temperatures reach the final value, in the specified mode very fast, it is unnecessary to simulate in correct timescale, i.e. four minutes for the first step and two minutes for every else step.

### ETC Control

Because there are very fast transients in ETC a simple PI-regulator is not sufficient for controlling the engine. Instead a look up table can be used with engine torque and speed as inputs and an accelerator pedal position as output, see Figure 2.6. This is to get a fast enough control over the engine. No feedback of the engine's torque is necessary, although it has to be measured. When an ETC has been executed there are some statistical tests to validate the test cycle. Linear regression of the real values on the reference values shall be performed. Least square fit shall be used with the equation

$$y = mx + b,$$

where,

$y$  = feedback value of speed (rpm), torque (Nm) or power (kW),

$m$  = slope of the regression line,

$x$  = reference value of speed (rpm), torque (Nm) or power (kW),

$b$  = intercept of the regression line.

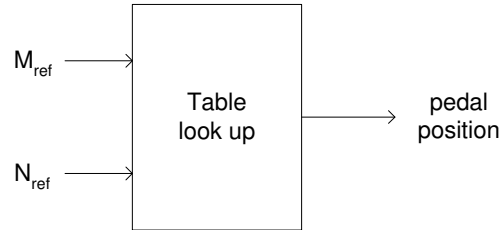


Figure 2.6: Testcell modelling for ETC.

For the ETC execution to be approved  $m$  and  $b$  must fulfill certain statistical requirements, see [3].

#### Validation of Testcell Models

An ESC was simulated and the model was able to follow the reference values. For ETC the above mentioned tests was executed after a simulated cycle and the statistical requirements were fulfilled. No check was done to see if the injection angle or amount of fuel injected during a simulation of these cycles was equal to measurements from a real ESC or ETC. The reason for this is that  $\alpha$  and  $\delta$  are dependent of what the sensors are showing. If the engine model is not accurate, resulting in the wrong boost pressure compared to a real engine during an ESC,  $\alpha$  and  $\delta$  will be different.



## Chapter 3

# Fault Modelling and Analysis

Here the results from the simulations with the different faults are presented. Only faults in sensor and actuator values are considered. The effort is to find out if any of them need to be monitored by the OBD system. Section 3.1 describes what type of sensor and actuator faults that are considered and how they can be modelled. In Section 3.2 the results from the simulations are presented with plots of the interesting faults from an OBD point of view. In Section 3.3 a fault analysis is made resulting in a fault tree.

### 3.1 Fault Modelling

The sensor values are the inputs to the ECU and the outputs of the engine. The actuator values are the outputs of the ECU and the inputs to the engine. The faults tested are gain faults, bias faults and sensors or actuators that get stuck in one position. This can be accomplished by multiplying the sensor or actuator values with a parameter  $\theta_G$  and adding a parameter  $\theta_B$  to them, i.e.

$$\begin{aligned}\bar{\mathbf{S}} &= \theta_{GS}\mathbf{S} + \theta_{BS}, \\ \bar{\mathbf{A}} &= \theta_{GA}\mathbf{A} + \theta_{BA},\end{aligned}$$

where  $\mathbf{S}$ ,  $\mathbf{A}$  are vectors with every sensor, actuator value, respectively,  $\theta_G$  is a vector with every gain fault which in the fault free case is  $\mathbf{1}$  and  $\theta_B$  is a vector with every bias fault which is  $\mathbf{0}$  in the fault free case. To simulate a gain fault in the first sensor  $\mathbf{S}(1)$ , e.g. the sensor shows

10% to much, simply set  $\theta_{BS} = \mathbf{0}$  and

$$\theta_{GS} = \begin{pmatrix} 1.1 \\ 1 \\ \vdots \\ 1 \end{pmatrix}.$$

To simulate a bias fault in  $\mathbf{A}(1)$ , set  $\theta_{GA} = \mathbf{1}$  and

$$\theta_{BA} = \begin{pmatrix} b \\ 0 \\ \vdots \\ 0 \end{pmatrix},$$

where  $b$  is a constant. To simulate that the same actuator gets stuck set

$$\theta_{GA} = \begin{pmatrix} 0 \\ 1 \\ \vdots \\ 1 \end{pmatrix}, \quad \theta_{BA} = \begin{pmatrix} b \\ 0 \\ \vdots \\ 0 \end{pmatrix}.$$

All kinds of different faults can now be modelled in sensors and actuators. Only single faults are implemented.

## 3.2 Fault Simulations

The sensors available in the model are:

- Ambient pressure;
- Ambient temperature;
- Engine speed;
- Engine cooling temperature;
- Intake manifold (boost) pressure;
- Intake manifold (boost) temperature;
- Accelerator pedal position;
- Air mass flow, located before inlet manifold.

The actuators available are:

- Amount of injected fuel  $\delta$ ;

- Injection angle  $\alpha$ ;
- EGR valve opening.

Since there is not any EGR system in the model the actuator controlling the EGR valve opening will not be considered. The value from the mass flow sensor is only used in the EGR modules and is therefor neither considered. The engine speed sensor is already monitored for safety purposes because a fault could cause serious damage to the vehicle. No fault is therefor implemented in the engine speed sensor.

Some faults make the engine unable to follow the reference torque during an ESC. An example is faults in the  $\delta$  actuator. At the 100% load points during the ESC the amount of fuel injected is close to the maximum allowed. A fault large enough would make the regulator unable to inject the necessary amount of fuel to produce the correct torque by pressing down the pedal further.

### 3.2.1 Gain Faults

Faults implemented as gain faults were varied between showing 90% less and 90% too much with respect to no fault. No gain fault made the emissions cross the thresholds.

### 3.2.2 Bias Faults

A number of bias fault values were implemented in each sensor and actuator. The bias value was chosen to a certain percent of the average value of the sensor or actuator during an ESC with no faults. The increase or decrease of the simulated emissions are of course dependent of how big the bias fault is chosen. In the figures the upper dotted line is the OBD threshold, i.e. 7.0 g/kWh for ESC and EURO 4 and the lower line is the regulated limit for ESC and EURO 4, i.e 3.5 g/kWh.

The only really interesting faults with respect to the OBD thresholds are faults in the ambient temperature sensor, see Figure 3.1 and the  $\alpha$  actuator, see Figure 3.2. These two plots show that when the fault is large enough (large negative bias fault) the  $\text{NO}_x$  level goes above or very close to the threshold. Left on the x-axis is a larger negative bias fault and right is a larger positive bias fault. If we compare the plots of  $\alpha$  between no fault and a certain negative bias fault, for the ambient temperature sensor, see Figure 3.3, it is clear why there is an increase in the emission level. When the fault is present the ECU believes it to be colder than it is. Colder ambient air leads to colder air into the combustion chamber which leads to lower  $\text{NO}_x$ . The ECU is now able to maintain the same level of  $\text{NO}_x$  by injecting earlier than when no fault is present and therefor decrease the fuel consumption. The air is

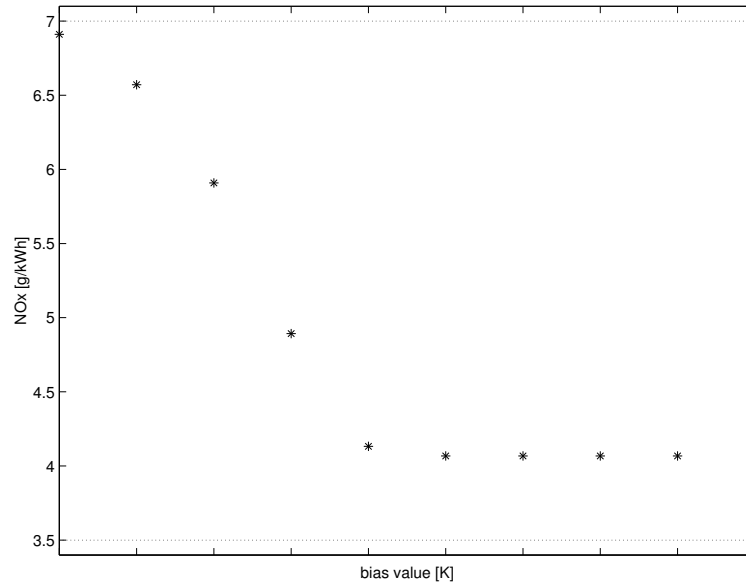


Figure 3.1:  $\text{NO}_x$  as a function of bias fault in ambient temperature sensor.

however not colder but the sensor is faulty and this will cause the  $\text{NO}_x$  to increase, as mentioned before.

### 3.2.3 Sensors or Actuators get Stuck

The engine cooling temperature is modelled as constant at  $80^\circ\text{C}$ . This is not at all inaccurate since during an ESC the temperature varies between  $78\text{--}86^\circ\text{C}$  and the ECU behaves the same in that interval. During the execution of an ESC the ambient pressure and temperature is constant. Therefore the results for these three are the same as in the previous section. For example a bias fault of  $-20^\circ\text{C}$  in the engine cooling temperature sensor is the same as that sensor is stuck showing  $60^\circ\text{C}$ . If the pedal position sensor or the  $\delta$  actuator get stuck the engine is not able to follow the reference torque and are therefore of no interest here. If the  $\alpha$  actuator gets stuck the impact on the emissions is significant as shown in Figure 3.4. As before the upper dotted line in the figure is the OBD threshold and the lower line is the regulated limit for ESC and EURO 4. Left on the x-axis corresponds to the actuator stuck in a position where it injects earlier and to the right is the opposite. If the actuator gets stuck at a position where it injects early enough through the entire cycle, which corresponds to the further most left point in the figure, the threshold will be exceeded.

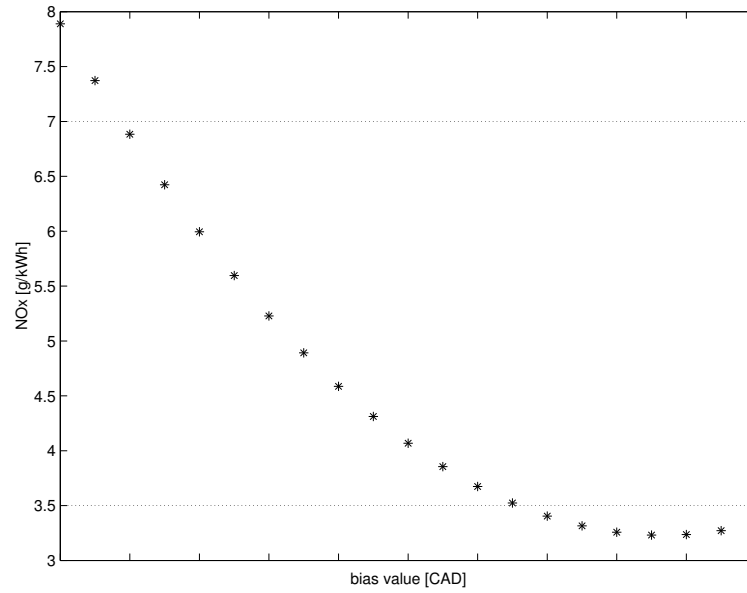


Figure 3.2:  $\text{NO}_x$  as a function of bias fault in  $\alpha$  actuator.

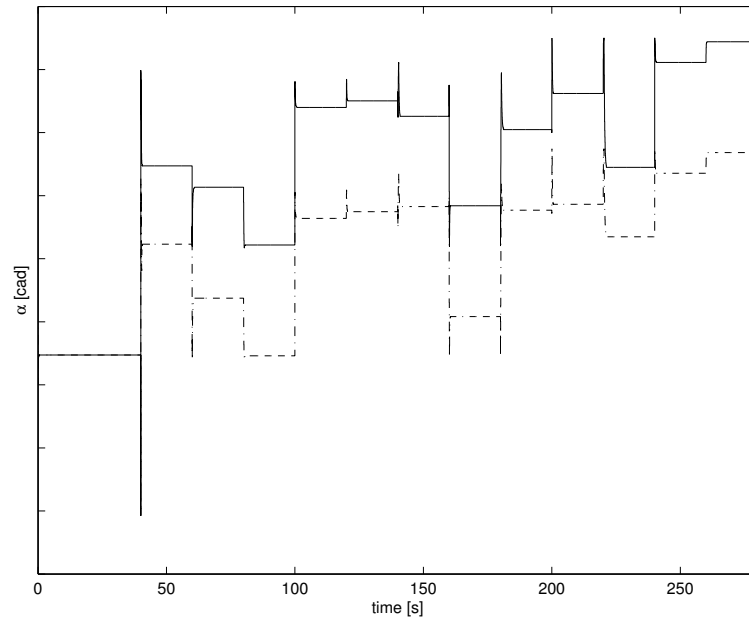


Figure 3.3: Injection angle for no fault (solid) and for ambient temperature sensor with a bias fault (dash-dotted).

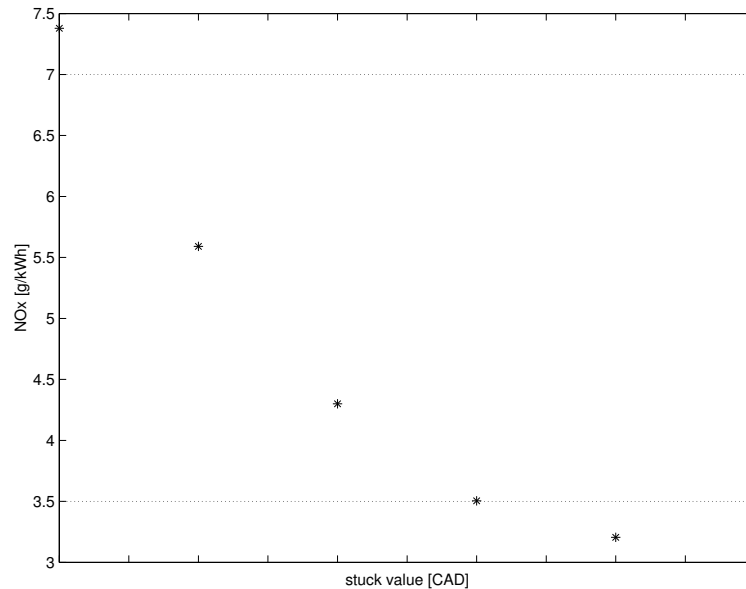


Figure 3.4: NO<sub>x</sub> as a function of the  $\alpha$  actuator being stuck.

### 3.2.4 Other Faults

Not only faults in sensors and actuators have an impact on the emissions. This was however the main focus in the thesis and the only ones simulated. Other faults that could be interesting to investigate are holes in the intercooler volume, since holes are often drilled to drain the volume of water that is gathered there. This can be modelled as an extra flow out of or in to the intercooler volume depending on the pressure outside and inside the volume. Leakage between components before inlet manifold could cause the boost pressure to decrease which would lead to more particulates. This could also be modelled as an extra flow in or out of inlet manifold volume. There are many more faults that would cause the emissions to increase, some could be modelled with ease and some not at all.

## 3.3 Fault Tree

A fault analysis means an analysis is made of which faults that can occur and how they effect the system considered. The result can be presented as a fault tree, see e.g. [8], which is used here. The interest is to see which faults made the simulated emissions exceed the OBD

thresholds. From the previous results a tree would look like,

0: OBD thresholds are exceeded

1: Too much  $\text{NO}_x$

2: Ambient temperature sensor is stuck

2: Ambient temperature sensor has a bias fault

2: Injection angle actuator is stuck

2: Injection angle actuator has a bias fault

1: Too much particulates

The tree should be interpreted as if the OBD thresholds are exceeded (0: occurs) it could be because of either one of the ones has occurred, i.e. too much particulates or too much  $\text{NO}_x$ . Both ones could be true if more than one fault is present but for now only single faults are considered. If the first one occurs, it could be because of any of the twos have occurred, e.g. ambient temperature sensor is stuck. The tree could also be more precise. It could say that only if the ambient temperature sensor has a gain fault of 20% or more the threshold would be exceeded. The tree could be extended with more levels, i.e. threes and fours, where it would say why for example the injection angle actuator is stuck. This could be of help when a fault has occurred but the reason for it, is unknown.

This tree is a very small one, but imagine analyzing all faults that can occur on an engine. Not all of them but some of them would cause the emissions to exceed the thresholds. Presenting the results in a fault tree is a good way to gain an overview of what needs to be done, i.e. what has to be monitored by the OBD system.

From the tree above it can be seen that only faults in the ambient temperature sensor and the injection angle actuator pushed the emissions above the OBD thresholds. The reason for this is explained in Sections 3.2.2 and 3.2.3. Therefor only these two need to be monitored.





## Chapter 4

# Further Model Improvements

The model is far from complete. Several things need to be modified or even replaced with better models. Of course the model cannot become perfect, but with improvements it can get adequate. Adequate means trends can be predicted with approximate values, i.e. the model will predict if the emissions will increase or decrease and give an approximate value of the size of the alteration. Only improvements of the extended model are considered. In Section 4.1 improvements of the emissions model is discussed and in Section 4.2 a more thorough model of the engine torque is presented.

### 4.1 Emissions

At this moment there is nothing in the model describing the effects of EGR on the emissions. It is a fact that EGR have a major impact on the reduction of  $\text{NO}_x$  and is therefor desirable to include in an emissions model. One way is to do the same as in Section 2.2.2 but with the polynomial,

$$\text{Emission} = a_0 + a_1\alpha + a_2\alpha^2 + a_3\text{EGR} + a_4\text{EGR}^2 + a_5\text{EGR}\alpha,$$

where  $\text{EGR}$  is the amount of exhaust gas, divided by the amount of air in the inlet manifold.

The most interesting emissions and the ones most dangerous for the environment and human health for a diesel vehicle are  $\text{NO}_x$  and particulates. Therefor, also a model of particulate emissions is wanted. A model of smoke can never replace a model of particulates although some correlation between them exist. One of the problems with particulate emission is that the particulates are hard to measure momentarily. No

knowledge of exactly when the particulates are formed is available. The emission model is only defined in a few work points for the engine, e.g. the points of the ESC. If faults are implemented during the execution of an ESC the engine will most likely find itself outside one of these points. A model that is defined over the entire engine's domain of work, i.e. all engine speeds and loads, is desirable. Driving the engine in the entire domain of work to make the model described in Section 2.2.2 valid for all points is not applicable, neither financially or with respect of time.

Better models of  $\text{NO}_x$  emissions exist. There are ones which use more of the chemistry behind the combustion process to model the  $\text{NO}_x$  formation. More advanced are the CFD (Computational Fluid Dynamic) models but they have not yet reached the level where they are practical to use in every day engineering. One of its drawbacks is that they are very time consuming to simulate.

## 4.2 Torque

The simple model described may be a good start but there are room for improvements. A more thorough investigation of the parameters that effect the engine torque has to be done. In [7], it is suggested that the following polynomial could be used for modelling the engine's mean torque,

$$\tilde{M} = H_l \delta (a_1 + a_2 N + a_3 N^2) (1 - a_4 \lambda^{a_5}),$$

where,

$H_l$  is the lower heating value of the fuel,

$\delta$  is the amount of fuel injected into one cylinder,

$N$  is the engine speed,

$\lambda$  is the air to fuel ratio,

$a_i$  are parameters to be fitted to the engine.

Important to remember when fitting the parameters  $a_i$  to the engine is to use measurements from the engine's entire domain of work. One parameter not included in the model above but has an effect on the torque is the injection angle or rather the ignition angle. There is a time delay between the fuel is injected and the torque is produced. According to [7] it can be modelled as,

$$M(t) = \tilde{M}(t - \tau), \quad \tau \approx \frac{2\pi \nu}{n\omega},$$

where,

$\nu$  is 1 for two-stroke and 2 for four-stroke engines,

$n$  is the number of cylinders.

## Chapter 5

# Conclusions

The objectives were reached with one modification. No model of particulates was incorporated into the simulation aid. There is a need for a model of particulate emission. However, the complexity of the particulate formation makes it hard to predict. Although some correlation exists between smoke and particulates no conclusions can be drawn from the results of the simulations.

Modelling vehicle emissions are overall not an easy task. The ones used in this thesis are based on measurements from real engines which means that if some emission related part of the engine are replaced, e.g. the piston, the models are not accurate anymore. New measurements are necessary every time changes are made and this is neither time nor cost effective. More advanced models exist which are based on the chemical reactions behind the combustion. These models can be very accurate but are yet to time consuming to be of use in everyday engineering.

Not many faults made the emissions exceed the OBD thresholds. If this is because the model lacks accuracy or if it is true also for real engines would be interesting to look into. A more thorough investigation has to be done with measurements in real testcells. In this thesis it has been found that only the ambient temperature sensor and the injection angle actuator have to be monitored by the OBD system. Monitored for the faults that made the emissions cross the OBD thresholds. This would make the OBD system much smaller and easier to implement in the ECU than if all sensor and actuators made the emissions cross the thresholds.

If this fault testing had to be done with real engines the amount of time required would be enormous. For each fault tested an ESC has to be run which would take approximately 30 minutes. In this thesis approximately 200 different faults were tested on different sensors and actuators. The faults were gain faults, bias faults and the sensor or

actuator getting stuck. This would take 100 hours to complete in a real testcell which has to be supervised by trained personnel. With the model done in this thesis this testing can be done over the weekend unsupervised on a PC.

# References

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# Notation

|                    |  |
|--------------------|--|
| $\alpha$           | Injection angle, the angle where the injection of the fuel starts in degrees before Top Dead Center.                                 |
| $\delta$           | Amount of injected fuel per cylinder.  |
| cad                | Crank Angle Degree.  |
| CO                 | Carbon monoxide.   |
| CFD                | Computational Fluid Dynamic.   |
| EGR                | Exhaust Gas Recirculation. A Method where exhaust gases are led from exhaust manifold to inlet manifold to reduce $\text{NO}_x$ .    |
| Emissions          | Everything in the exhaust gases regulated by law.  |
| EPA                | Environmental Protection Agency.   |
| ESC                | European Stationary Cycle.   |
| ETC                | European Transient Cycle.  |
| EURO 4             | Laws and regulations for regulating for example emission limits and OBD for Europe that come into effect in 2005.                    |
| HC                 | Hydro Carbons, unburned fuel from the combustion chamber.  |
| hPa                | hecto Pascal = 100 Pascal = 1 mbar.  |
| Load               | Actual engine torque divided by maximum torque (for that particular engine speed).   |
| M                  | Engine torque.   |
| N                  | Engine speed.  |
| OBD                | On-Board Diagnostics.  |
| Particulate Filter | Filter in the exhaust pipe where the particulates from the exhaust gases are collected to prevent them from entering the atmosphere. |
| SCR                | Selective Catalytic Reduction. An aftertreatment method where ammonia is used to reduce $\text{NO}_x$ .                              |





## Appendix A

# Original Engine Model

In this Appendix a schematic overview of the engine model with an EGR system is given see Figure A.1. The figure shows the path of the gas flowing through the engine. The air enters the engine via the filter. The air is then sucked further in by the compressor. The temperature of the air is increased because of the energy added by the compressor. To be able to increase the amount of air into the combustion chamber the density of the air is decreased by leading it through an intercooler lowering the temperature of the air. Before the combustion chamber the air is mixed with EGR in the inlet manifold. Fuel is injected into the combustion chamber and the combustion produces a torque which drives the engine. The hot gas then enters the exhaust manifold where some of it is led back to the inlet manifold via a cooler. The rest of the gas is pushed through the turbine where it loses some of its energy which drives the turbo. The gas then exit the engine to the surrounding through the exhaust system. In the figure,

$W$  is the mass flow through the component,

$\nu$  is the energy flow through the component,

$\chi$  is the amount of exhaust gas,

$n$  is either the speed of the engine or the turbine (rpm),

$M$  is torque,

$\delta$  is the amount of injected fuel.

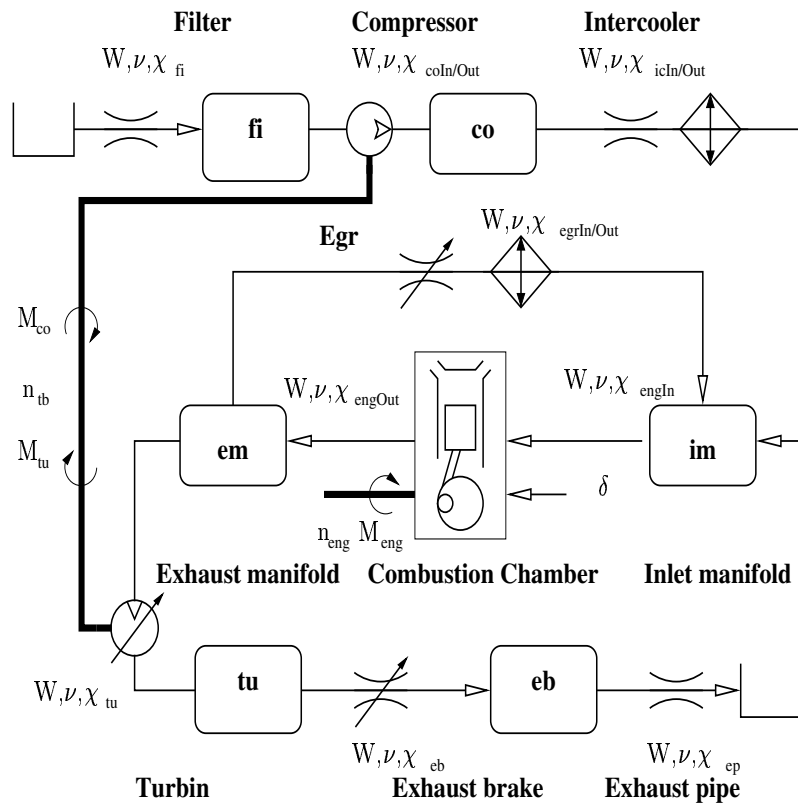


Figure A.1: Schematic overview of original engine model