TSFS09 1A

September 12, 2025

1 Description of the research laboratory

The Vehicular Systems Research Laboratory consists of an engine test cell and a control room. In the engine test cell, there are two engines and two electric brakes. The brakes are often used to generate a loading torque, but they can also do the reverse, i.e. drive engines. The engines, brakes and sensors are controlled and monitored from the control room.

An introduction to the lab is given below.

1.1 Engine test cell

At present, the engine test cell includes two turbocharged engines, coupled to one brake respectively. The brakes are big, controllable, electric machines, which make it possible to perform repeated tests with great accuracy. Brakes are normally controlled so that they (and therefore the engine) keep a constant speed, while the engines are controlled to maintain a constant throttle opening.

Since the engines are in an engine test cell, it is possible to send control signals which a regular control system normally does not produce. It is for example possible to make the amount of injected fuel vary independent of air mass flow. We can also change the throttle position without affecting the engine speed.

1.2 Control room

In the control room, there are computers, measurement instruments, and control devices for the brakes. One of the computers is connected to the engine control system, through which it can read the measurement signals and send control signals to the engine. Another computer controls a high-speed measurement system, and the brakes (when necessary).

Measurement data collection is handled via Matlab. Matlab takes in measured data and saves it in a .mat file. Manual readings of measurements can in some cases be appropriate.

The measurements performed in the lab can be divided into three different types:

- Stationary (engine map)
- Dynamic
- Crankshaft based

The three categories of measurements can be briefly described as follows:

Stationary The engine is controlled to a desired operating point, where it is given time to stabilize, i.e. the dynamics will have time to subside. Thereafter, data collection is performed for some time (usually a couple of seconds). What is returned is the average value over this period. The result is then one measurement per operating point and sensor.

Usually, various operating points are measured in series after each other. Going from a working point to the next, allowing the engine to stabilize, measuring, moving on to the next, allowing the engine to stabilize, and so on. This is called making an **engine map**.

Dynamic Data collection is performed in continuous time, both the signal values and time are recorded. The result is thus a vector of time-resolved data for each signal that is recorded.

Crankshaft based Crankshaft measurement is used when you want to see what happens during a cycle. An ordinary resolution is 1 sample/degree.

2 Suggested Models for Some Components

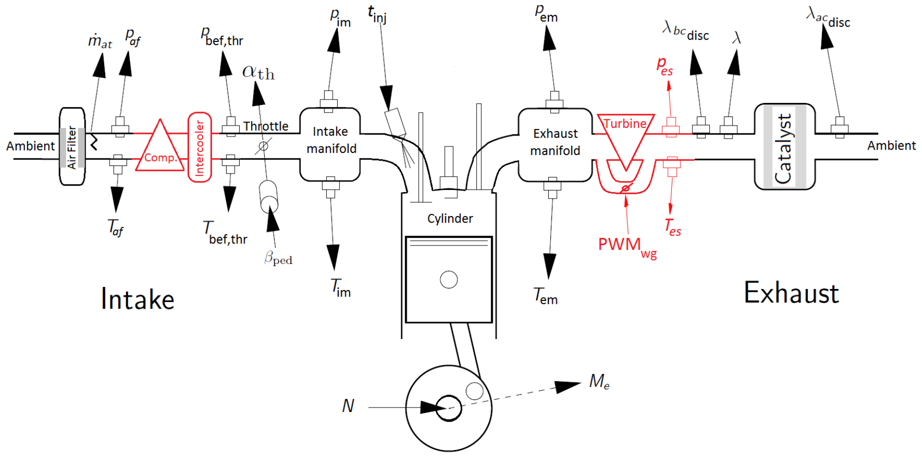

Figure 1: An overview of the air path with signals and components to be modeled in Project 1 (shown in black) and Project 2 (shown in red+black)

In Figure 1 an overview of the air path and engine components is shown. The measurements available for the estimation of model parameters in the supplied static engine map are:

- Pressure after the air filter (before the compressor) (p_{af}),
- Pressure before the throttle ($p_{bef,thr}$),
- Intake manifold pressure (p_{im}),
- Exhaust manifold pressure (p_{em}),
- Pressure before the catalyst (after the turbine) (p_{es}),
- Temperature after the air filter (before the compressor) (T_{af}),
- Temperature before the throttle ($T_{bef,thr}$),
- Intake manifold temperature (T_{im}),
- Exhaust manifold temperature (T_{em}),
- Temperature before the catalyst (after the turbine) (T_{es}),
- Engine speed (N),
- Dynamometer brake torque (M_e),
- Throttle position (α),

- Air mass flow after the air filter (before compressor) ($\dot{m}_{at}$),
- Fuel injector injection time (t_{inj}),
- Lambda sensor value (λ)

2.1 Throttle response model

The accelerator pedal is not connected directly to the throttle, but its position is translated in the control system into a reference angle for the throttle. A controller makes the throttle angle follow the reference. The details of the throttle control will not be included in this project, but assume there is a working controller. If we see the pedal position as the reference angle, the dynamics of the throttle angle, including the controller, can be approximated by a first-order system according to

$$\dot{\alpha} = \frac{1}{\tau_t}(\beta - \alpha) \tag{1}$$

2.2 Throttle airflow model

Components with significant pressure drop and a small flow area, such as the throttle in most operating points, can often be described well by the equations for compressible flow. These are given by

$$\dot{m}_{at} = \frac{p_{\text{bef,thr}}}{\sqrt{R T_{\text{bef,thr}}}} \, A_{\text{eff}} \; \Psi(\Pi), \qquad \Pi = \frac{p_{im}}{p_{\text{bef,thr}}}$$

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

in which $A_{\text{eff}} = A(\alpha)\, C_d$ describes the effective flow area as a function of throttle angle. This can be parameterized in different ways, but here we suggest a second-degree polynomial in α according to

$$A_{\text{eff}}(\alpha) = a_0 + a_1 \, \alpha + a_2 \, \alpha^2 \tag{2}$$

Note: This model gives a good description of the mass flow rate for pressure ratios that are not too close to 1, so do only use points with $\Pi < 0.8$ in the estimation of these model parameters.

Hint: In Matlab, use conditional indexing to select vector elements for which $\Pi < 0.8$. For example. If $x = [0.7,\ 0.9]$, then

$$x(\Psi > 0.8) = [\,]$$

removes the unwanted elements resulting in $x = 0.7$.

2.3 Intake Manifold

The intake manifold pressure is modelled as a volume where the pressure dynamic behaviour is calculated from the inflow and outflow:

$$\dot{p}_{im} = \frac{RT}{V_{im}} \left(\dot{m}_{at} - \dot{m}_{ac}\right)$$

2.4 Volumetric Efficiency

The proposed model for volumetric efficiency includes not only the intake pressure and engine speed, but also the effective valve opening angles for intake (θ_{ivo}) and exhaust (θ_{evo}):

$$\eta_{\text{vol}} = c_0 + c_1\ p_{im} + c_2\ N \cdot p_{im} + c_3\ N + c_4\ \sqrt{p_{im}} + c_5\ \theta_{\text{eff,ivo}} + c_6\ \theta_{\text{eff,evo}}, \quad (3)$$

where

$$\begin{aligned} \theta_{\text{eff,ivo}} &= \max(\theta_{\text{ivo}}) - \theta_{\text{ivo}} \\ \theta_{\text{eff,evo}} &= \max(\theta_{\text{evo}}) - \theta_{\text{evo}} \end{aligned}$$

See lectures for additional information on variable valve timing.

Hint:

- $c_0 \approx 0.3566$
- $c_5 \approx 0.0012$

2.5 Torque model

The engine output torque can be modelled in many different ways. Equation (7.55) in the course book is recommended for torque modelling and is based on efficiency, since this may be the most physical model. Read chapter 7.9. before doing this part. Assume that the ignition is optimal i.e. $\eta_{ign} = 1$. For friction modelling use the Heywood model on page 191 (Correct parameters will be given in the template Matlab code).

2.6 Exhaust temperature (out of the cylinder)

Temperatures on the **intake side** of the engine can be assumed constant in each part and estimated as the mean of the corresponding temperature in the engine map. The ambient temperature is set equal to the temperature after the air filter.

Note: You should only use these mean values when using the model, when you estimate other parameters in the model you should use the entire map including measured temperatures.

The temperature in the exhaust manifold is assumed to be equal to the cylinder out temperature which is mainly a function of the mass flow. Hence, this temperature can be modeled as a linear function of the square root of mass flow out of the engine

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

where T_0 and k are model parameters.

Note: The exhaust mass flow out of the cylinder is equal to the air flow in to the cylinder plus the injected fuel.

2.7 Exhaust Manifold

The exhaust manifold pressure is modeled as a volume where the pressure dynamic behavior is calculated from the inflow and outflow, just as the intake manifold.

2.8 Exhaust System Flow

The exhaust system is comprised of a model for the mass flow through the exhaust system which includes the catalyst. The mass flow through the exhaust system can be modelled as an incompressible turbulent restriction, see chapter 7.2 in the book

$$\dot{m}_{es} = C\ \sqrt{\frac{p_{us}}{R\ T_{us}}}\ \sqrt{\Delta p}$$

Note: Considering Figure 1, the fact that the engine map data is obtained from a turbocharged engine and that a naturally aspirated engine is going to be modelled, which one of p_{em} or p_{es} signals in the engine map should be used in this task and why? This is an important question so you should make sure that you understand it.

2.9 Fuel injectors

When modeling the fuel injectors, use the equation for injected mass per stroke as the base model for parameter estimation and validation,

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

Note: There are multiple ways to model the injector. You can choose to model the injected fuel in kilograms per cycle per cylinder, m_{fi}, or the injected fuel flow in kilograms per second, $\dot{m}_{fi}$. Either way works, but you must be consistent when using the model. Mixing m_{fi} and $\dot{m}_{fi}$ is a common error.

2.10 Lambda sensor

It is suggested to assume that the time delay, τ_d, to the lambda sensor is constant over the whole engine operating region. In addition to the pure time delay, the exhaust manifold and sensor add a certain dynamic. Assume that this can be described by a first-order system, with time-constant, τ_s that should be estimated.

Note: In class we used a second order system for the gas mixing and sensor dynamics. In the project, we simplify and use a first order system, combining the two time constants to one.