

Air Mass-Flow Measurement and Estimation in Diesel Engines Equipped with EGR and VGT

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ABSTRACT

With stricter emission legislations and customer demands on low fuel consumption, good control strategies are necessary. This may involve control of variables that are hard, or even impossible, to measure with real physical sensors. By applying estimators or observers, these variables can be made available. The quality of a real sensor is determined by e.g. accuracy, drift and aging, but assessing the quality of an estimator is a more subtle task. An estimator is the result of a design work and hence, connected to factors like application, model, control error and robustness.

The air mass-flow in a diesel engine is a very important quantity that has a direct impact on many control and diagnosis functions. The quality of the air mass-flow sensor in a diesel engine is analyzed with respect to day-to-day variations, aging, and differences in engine configurations. The investigation highlights the necessity of continuous monitoring and adaption of the air mass-flow. One way to do this is to use an estimator. Nine estimators are designed for estimation of the air mass-flow with the aim of assessing different quality measures. In the study of the estimators and quality measures it is evident that model accuracy is important and that special care has to be taken, regarding what quality measure to use, when the estimator performance is evaluated.

INTRODUCTION

Stricter emission legislations and customer demands on low fuel consumption drive the technical development of engines and new solutions are introduced, like e.g. Exhaust Gas Recirculation (EGR) and Variable Geometry Turbo (VGT) systems on diesel engines. This increases the system complexity and the demands on the control systems, that in its turn must handle both the increased complexity and the tighter tolerances for the controlled quantities like e.g. λ and EGR-fraction. To be able to fulfill these stricter demands it is necessary to analyze and sometimes also improve the information that is available for the controllers in the engine control systems. This may introduce new variables that are hard, or even impossible, to measure with real physical sensors. By applying filters, observers and estimators (sometimes referred to as virtual sensors [1]) these new

variables can be made available or the quality of the available sensor can be improved.

A central quantity that is used in the control systems is the air mass-flow into the intake system. It is used for many purposes and influences both the engine performance and emissions and it is essential to have an air mass-flow measurement of good quality. This sensor signal, on a diesel engine with EGR and VGT, is studied in detail in this paper and there are two issues that are addressed. The first deals with variations in the sensor characteristics, i.e. how accurate is the air mass-flow sensor, while the second studies how the quality of a sensor can be improved, by for example an estimator, and also how the quality can be assessed.

All measurements and data used have been collected jointly with Scania CV and the measurements have been performed in the engine test cells at Scania in Södertälje, Sweden.

Air mass-flow sensor variations

The first problem that is addressed is the air mass-flow sensor quality. One important issue is the sensors long term stability and variation. Two questions are asked: How does the sensor characteristic vary with time? and how does it vary between engine configurations?

To answer these questions, systematic engine test cell measurements have been conducted on a limited range of air mass-flow sensors over the span of several weeks. A central piece of information is a calibration curve that has been recorded and stored for all days and all tests. The data is stored and analyzed with respect to day-to-day variations, aging, changes between configurations etc, and all these changes are quantified using experimental data.

Methods for measuring and improving sensor signals

Next, methods for improving sensor signals is studied, e.g. by applying an estimator or observer. Due to factors like system aging and different operating conditions caused by geographical location, for example pressure, temperature, humidity etc. of the surrounding air, the air mass-flow sensor signal is in need of continuous adaptation. Several approaches to cope with

this adaptation are investigated including ad hoc mapping and Kalman filtering. This investigation highlights questions regarding model quality and robustness. The quality of a physical sensor is determined by, e.g. accuracy, drift and aging, but the quality of an estimator is a more subtle task. An estimator or observer is the result of a design work and hence connected to factors like application, model, control error and robustness. It is of great interest to have these estimated signals available both in transients and stationary conditions.

The air mass-flow is used to estimate EGR-fraction and λ , two different applications that, in some sense, demand different quality properties of the signal. Therefore a discussion on appropriate quality measures is conducted in Section 5. For example, if the signal is used to estimate the amount of EGR fed through the engine it is suitable to use an absolute measure, but if it is used to estimate a concentration, e.g. λ , it might be better to choose a relative measure. In some applications a bias is not crucial and it is better to use a signal noise based measure.

Outline

This paper is organized as follows. Sections 1 and 2 address variations in the sensor characteristics. In Sections 3 to 7 sensor quality improvement is studied, and finally, Section 8 presents the conclusions.

1 AIR MASS-FLOW SENSOR VARIATIONS

The air mass-flow signal is needed for computations of λ and EGR-fraction, which both are important quantities that greatly affects the emissions. In a diesel engine λ , defined as

$$\lambda = \frac{W_{\text{air}}}{W_{\text{fuel}}},$$

can not be allowed below a certain limit, $\lambda_{\text{smoke lim}}$, to avoid generating smoke. Normally in a diesel engine, when λ is greater than $\lambda_{\text{smoke lim}}$, W_{fuel} is decided by the desired torque. However when the desired torque forces λ towards $\lambda_{\text{smoke lim}}$ and when λ reaches $\lambda_{\text{smoke lim}}$, the control law enters a mode where W_{fuel} is proportional to W_{air} [2]. This is particularly important during transients where the torque demand is high, i.e. during acceleration. In these cases, an error in the air mass-flow signal results in either creation of smoke or reduced torque output. The other important quantity, the EGR-fraction

$$EGR_{\text{frac}} = \frac{W_{\text{tot}} - W_{\text{air}}}{W_{\text{tot}}},$$

where W_{tot} is the total gas mass-flow into the engine and W_{air} is the air mass-flow into the engine, is used to control the NO_x emissions. Both these quantities are important for the emissions and they rely heavily on the air mass-flow W_{air} . Hence, it is important to have a good measurement or estimation of the air mass-flow. Note that the EGR-fraction also depends on W_{tot} , which is computed using the volumetric efficiency of the engine and is, by experience, considered to be accurate.

The calibration curve used in the air mass-flow sensor variation analysis is developed from a long series of engine measurements. The production air mass-flow sensor, W_{raw} , has been compared to a reference, W_{ref} , and the difference has been

stored in a calibration curve that is implemented as a lookup-table consisting of 12 support points. These calibration curves have been recorded over several weeks to enable the study of day-to-day variations. The calibration curve is computed according to

$$r(W_{\text{raw}}) = \frac{W_{\text{ref}}}{W_{\text{raw}}} - 1, \quad (1)$$

The reference sensor is mounted on a straight pipe in the test cell, where the air mass-flow is laminar, and is considered to give very accurate measurements of the air mass-flow. Some more details concerning the reference sensor W_{ref} is given in Section 6.

2 ADAPTATION MAP EVALUATION

Adaptation maps from two diesel engines, one straight six cylinder and one V8, are gathered from test runs in an engine test cell. The maps are collected for a total time of about two weeks for the six cylinder engine and four weeks for the V8 engine. Figure 1 presents the typical appearance of an adaptation map, the upper for a 6 cylinder engine and the lower for a V8 engine. These adaptation maps, that are collected over a period of several weeks and come from the two engine configurations, are used to analyze the quality of the air mass-flow sensor.

The change between engine configurations can be seen by comparing the upper and lower plots in Figure 1 and 2, where Figure 1 presents the day-to-day variations and Figure 2 presents the trend of four representative support points in the adaptation map. Figure 1 shows that the day-to-day variations are quite large, especially for the V8 engine where the standard deviation varies between 2–3 percentage units. For the 6 cylinder engine the variations are not that large. Another difference between the two engine configurations is the appearance of the adaption line. For the 6 cylinder engine the line starts at approximately 5 %, has a slightly positive slope, and ends at approximately 10 %. For the V8 engine the line is quite different, it starts at about 1 %, varies quite a bit, and ends at -1 %.

The 6 cylinder engine data indicates that the air mass-flow into the engine has to be continuously monitored. The following small example gives a rough estimate of the consequence of incorrect air mass-flow measurement.

Example 1. Assume a true EGR-fraction of 20 % and that the air mass-flow sensor signal is not corrected and reads $W_{\text{air}}/1.1$, which is approximately the worst case according to Figure 1. Then, the computed EGR-fraction would become

$$EGR_{\text{frac}} = \frac{W_{\text{tot}} - \overbrace{(0.8 W_{\text{tot}})/1.1}^{W_{\text{raw}}}}{W_{\text{tot}}} \approx 27.3 \%$$

which would have a significant effect on the NO_x emissions. $\diamond$

Analogous computations can be made for λ close to $\lambda_{\text{smoke lim}}$ which further supports the statement that the air mass-flow is important.

The large spread among the adaptation maps for the V8 engine plot indicates that an ad hoc approach for compensating the sensor signal using only an adaptation map might not be enough. An increase in quality that reduces the spread is also needed. These observations together with the importance of the estimates of λ and EGR-fractions necessitate an accurate estimate of the air mass-flow. This is one of the motives for the discussion in Sections 3 to 7.



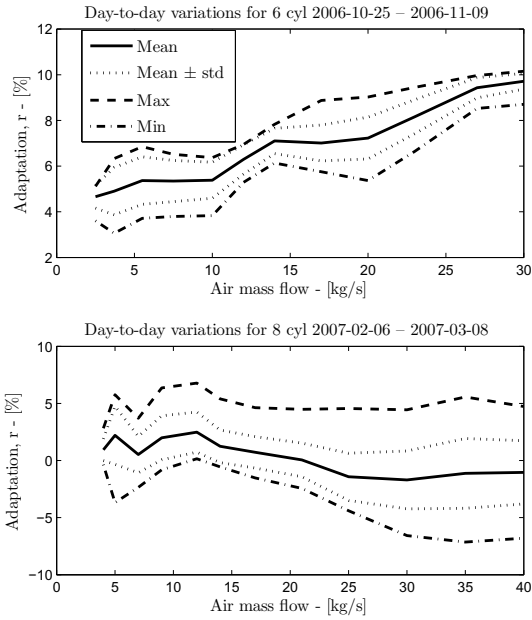


Figure 1: Min, max, mean, and the standard deviation over all collected adaptation maps are presented for a 6 cylinder engine (upper plot) and a V8 engine (lower plot). It can be seen that the variation is quite large for both engine configurations, especially for the V8 engine.

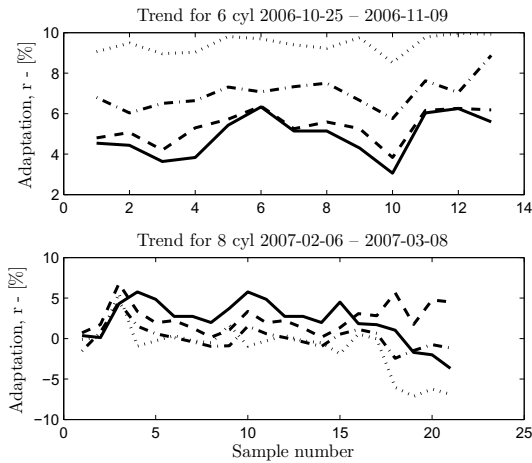


Figure 2: In this figure the trend of 4 support points are presented for a 6 cylinder engine (upper plot) and a V8 engine (lower plot). It shows that there is no particular trend in either of the engine configurations. Note that the samples are not equidistant.

As Figure 2 shows there are no obvious trends in the data over time. However, due to the relatively short time span over which data is collected, it is hard to draw any conclusions regarding long term aging of the air mass-flow sensors.

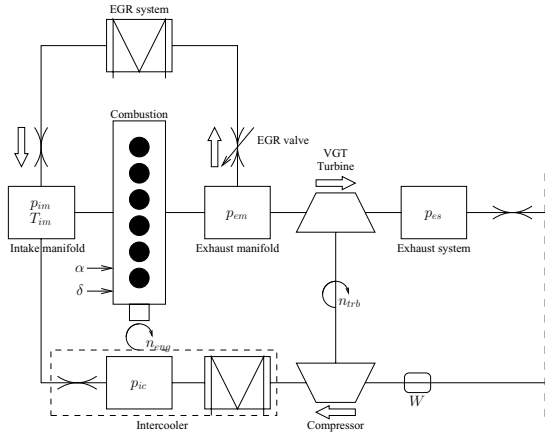


Figure 3: The model structure of the diesel engine. It has four control inputs, and six states related to the engine, see Table 1. In addition, it has one external parameterization input, n_{eng} , and one extra state for sensor dynamics.

3 ENGINE MODEL

Section 2 indicated that some sort of adaptive scheme is needed to improve the air mass-flow sensor signal and the sections to come present some different methods for improving the air mass-flow sensor signal. Several of these are model-based and the Mean Value Engine Model (MVEM) [3] that they rely upon is summarized here.

An MVEM describes the average behavior of the engine, which means that the signals, parameters and variables considered are averaged over one or several engine cycles. MVEMs are used to describe gas flow components such as compressor, intercooler, intake manifold, engine flows, exhaust manifold, EGR-system, VGT and exhaust system. A system overview is presented in Figure 3. The MVEM used is described in [4]. The model inputs, states and outputs, are presented in Table 1.

The model has five inputs where four are control inputs, presented in Table 1. The fifth input, the engine speed, is an external parameterization input. Further, all model outputs are measured in the vehicle.

The focus in this model is on the gas flow and the model is used for construction of estimators evaluated in an engine test cell. The engine operation is often defined by the engine speed, n_{eng} , for example given as an input from a drive cycle. Therefore, it is natural to parameterize the model using n_{eng} [2].

The model states are presented in Table 1, where the first six states originate from the engine dynamics. The last, $\tau_{T_{im, sens}}$, arises from sensor dynamics. The model is a non-linear state-space model and can, with the signals defined above, be written in the form

$$\dot{x}(t) = F(x(t), u(t)) + w_1(t) \quad (2a)$$

$$y(t) = H(x(t), u(t)) + w_2(t) \quad (2b)$$

Where, $y(t)$ represents the measurements and $x(t)$ is the state vector of the system at time t and w_1 and w_2 are the process noise and measurement noise respectively. For further details concerning the model see [4].