

Uncertainty Analysis of Model Based Diesel Particulate Filter Diagnostics

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ABSTRACT

This paper analyzes the potential benefit of a model based DPF leakage monitor over a conventional DPF leakage monitor that checks pressure drop after a complete regeneration. We analyze the most important noise factors involved in both approaches and demonstrate that the model based leakage monitor does not improve on the conventional leakage monitor in accuracy. It does improve on completion frequency, but at the expense of a great modeling effort.

1. INTRODUCTION

Diesel Particulate Filters (DPFs) have found wide spread application in European and US diesel powertrains after introduction of emissions thresholds for particulate matter that could not be met without filters. In the US, the 2007 emissions threshold for PM for heavy duty applications was decreased from 100 mg/bhphr to 10 mg/bhphr. In Europe, the Euro IV emissions threshold was decreased to 10 mg/km which only light passenger vehicles could meet without DPF. While European monitoring requirements were de facto limited to detecting complete removal of the DPF, the ARB OBD regulations required detection of a partially damaged DPF to a threshold level of PM leaking out the tail pipe. For heavy duty diesel dyno certified applications this threshold is set to 0.09 g/bhphr from 2004 to 2009, which is lowered to 0.05 g/bhphr for the 2010-2012 time frame [8].

Title 13 section 1968.2 for light duty OBD II published by the California Air Resources Board lists several monitoring requirements for Diesel Particulate Filters. In addition to the requirement to monitor the filtration performance ("leakage monitoring"), the following functions require monitoring in 2010:

1. the ability to achieve conditions appropriate for regeneration (which is really a monitor on the DOC),
2. the regeneration frequency,
3. the proper functioning of external or intrusive exhaust injection (if present),
4. incomplete regeneration,
5. a missing substrate,
6. NMHC conversion (due to a catalytic washcoat),
7. closed loop feedback control.

This paper will focus on monitoring the most important function of the DPF, which is the removal of soot from the exhaust. The corresponding monitor is termed the leakage monitor.

We analyze the capability of the different monitoring approaches by their robustness against noise factors. The term "noise factors" is borrowed from the vocabulary of robust systems engineering, where it designates factors that affect the ideal response of a system (here the ability of monitor to distinguish a leaking DPF from an intact DPF) but are outside its control and not known to the system.

2. DIAGNOSTICS FOR DIESEL PARTICULATE FILTERS

The only technology available to meet the DPF leakage monitoring requirement in 2007 was a pressure sensor in combination with a flow measurement, which was generally found to be of limited capability [1], because of the high tolerance caused by the relevant sensors, due to noise factors not measured by the engine control system, and due to the driving conditions under which monitoring could take place.

It is understood that ultimately the only technology that will be able to meet ARB's monitoring requirements is a tail pipe soot sensor [6]. Soot sensors are currently not

available at a price point and durability class that makes them applicable to large scale automotive applications. Such sensors are not expected to be available for series production before 2013.

Until 2013 we are then faced with the challenge to improve upon the pressure based leakage monitor, without having more capable sensors available. ARB's initial statement of reason claims that: "*A comprehensive and accurate soot-loading model is necessary for successful monitoring of the PM filter. The proposed monitoring requirements are feasible with further development of the PM filter soot-loading model to make it sufficiently accurate to detect when the actual filter loading inferred from the pressure sensor does not agree with the predicted loading from the soot loading model. (...) Therefore, a cracked or missing filter can be detected if the backpressure fails to increase at the rate projected by the soot-loading model.*"

It is thus suggested by ARB in their initial statement of reason that model based techniques may offer relief and result in a more capable monitor than a purely pressure based monitor alone. This paper investigates the ability of model based DPF leakage monitors to improve upon the pressure based DPF leakage monitor. The theoretical background for model based monitoring is provided, the noise factors entering the relevant models are presented and explained, and a numerical evaluation is presented that evaluates the capability of the model based leakage monitor under typical values of the noise factors. Necessary conditions are outlined for the model based DPF leakage monitor to be a viable approach for 2010 diesel applications.

3. CONVENTIONAL PRESSURE BASED MONITORING

Most DPF leakage monitors currently used in production are based on pressure drop. For a DPF with constant soot loading, the pressure drop Δp roughly follows the Darcy-Forchheimer equation for pressure drop through a porous medium, as a function of volumetric flow F [2,3,4,5]:

Δp = c0 + c1 · ν · F + c2 · ρ · F² (3.1)

Where ν is the kinematic viscosity of the fluid (here exhaust gas) and ρ is its density. For a DPF loaded with soot, this equation takes the form:

Δp = c0 + c1 · R(soot) · ν · F + c2 · ρ · F² (3.2)

where R is the restriction (which is normalized, hence unitless), which is a function of soot. There are several discrepancies between the Darcy-Forchheimer equation and reality. Most importantly, the equation holds when the fluid and the porous medium have homogeneous properties, such as temperature and pressure. During transient driving conditions, the temperature and

pressure are rarely constant across the DPF, but rather fluctuate, where the fluctuations become larger with DPF volume. Another departure from reality in the Darcy-Forchheimer equation is the assumption of pure inertial diffusion. Lastly, the coefficients c0, c1, c2 are estimated from experimental data, taken with imperfect measurement equipment, resulting in errors in the values for these coefficients.

To take the error due to the DPF soot load out of the equation, the monitor is most reliable when it runs right after a complete regeneration, and the pressure drop follows Eqn (3.1). This goes to the detriment of the completion of the DPF leakage monitor, which runs at best once every 300 to 500 miles, depending on the regeneration frequency of the application, and depending on how often a complete regeneration can be achieved. The monitor detects a leaking DPF when the pressure drop Δp is much lower than the right hand side of Eqn (3.1) predicts. Note that this threshold depends on temperature and exhaust flow.

To avoid false detection of a leaking DPF, the pressure drop must be compared against a threshold that is low enough to account for the tolerance stackup of the variables involved in the Darcy-Forchheimer Equation. The pressure drop is a function of volumetric flow, which depends on pre-DPF temperature and pressure, the latter in itself depending on the pressure drop over the DPF, the pressure drop over the post-DPF exhaust system (possible including another catalyst such as an SCR, a muffler, and a resonator) and the ambient pressure. The noise factors thus include:

1	Tolerance of the DPF pressure sensor
2	Tolerance of the mass air flow sensor
3	Tolerance of the temperature sensor(s)
4	Tolerance of the ambient pressure sensor
5	Tolerance of the pressure drop and its estimate over the post DPF exhaust system, including muffler, resonator, and possible further catalysts.
6	Uncertainty due to transient driving conditions and inhomogeneous pressure and temperature
7	Tolerance of the pressure drop over a clean DPF substrate
8	Uncertainty due to incomplete regeneration. Regenerations removing more than 80% of the soot are rare, since the amount of energy spent removing the last 20% of soot is large and usually not worth the benefit of the lower pressure drop.
9	Uncertainty due to the fact that the monitor needs some time for averaging, during which soot is accumulated in the DPF, increasing the pressure drop

Table 1: noise factors for a pressure based leakage monitor

The actual values of these noise factors are application dependent. Since the noise factors usually don't act all simultaneously in the same directions, their effects are added in a statistical sense (e.g. the square root of the

sum of the squares). A typical value for the cumulative effect is on the order of 50%.

The effect of ash loading on the DPF pressure drop is a noise factor sometimes mentioned in the context of estimating soot load from pressure. We have found that for moderate soot loads, the ash does not add appreciably to the pressure drop, and we will neglect this factor in this paper.

Most of the noise factors above work in a multiplicative fashion, so that their effect scales mostly linearly with flow and soot load. The tolerance of the pressure sensor however, is expressed as a percentage of full scale reading, and is constant with flow. This implies that the same pressure sensor becomes more accurate in a relative sense as the flow increases, and as the soot load increases. This causes the leakage monitor to be more accurate at high flow conditions. It also causes the lower bound of the expected pressure drop to become negative at low flows and low soot loads.

If we are to derive soot load from pressure drop under conditions other than shortly after regeneration, the noise factors 8 and 9 in Table 1, "uncertainty due to incomplete regeneration" and "uncertainty for averaging" can be ignored, but another noise factor "correlation between pressure drop and soot load" needs to be added. This latter noise factor accounts for the fact that pressure drop and soot load do not maintain a 1-1 relation due to differences in soot morphology and packing geometry that are beyond the understanding of current soot accumulation models. This latter factor alone adds around 25-30% uncertainty to the relation between soot and pressure drop, for a total of around 50%, depending on flow.

4. MODEL BASED DPF LEAKAGE MONITORING

In their final statement of reason, the California Air Resources Board suggested that accurate monitoring of diesel particulate filters may be achieved by comparing a model of the soot balance in the DPF to a soot estimate derived from the pressure drop over the DPF. The soot accumulation balance over the DPF consists of soot going into the DPF S_{in} reduced by soot regenerated in the DPF outside of actively commanded regeneration, S_{rgn} .

$$S_{bal} = \int S_{in} - S_{rgn} dt \quad (4.1)$$

S_{in} in turn is the soot produced by the engine minus the soot oxidized over the diesel oxidation catalyst (DOC):

$$S_{in} = S_{fg} - S_{doc} \quad (4.2)$$

Note that the DOC mostly takes out the soluble organic fraction (SOF) of the soot, which can amount to around 30% of the soot mass. The quantity S_{bal} is compared to the soot estimate derived from the normalized pressure

drop, as described in the previous section (Equation 3.2), which we call S_{dp} . If S_{dp} is much smaller than S_{bal} , one can conclude that the pressure drop over the DPF is lower than what would be expected from the soot accumulation model, and that the soot deficit has passed through the DPF to the tailpipe. Conversely, if S_{dp} is much higher than S_{bal} , the engine or the DOC is operating outside of normal operating conditions (generating more soot than) where the soot model was fitted. This can happen for example when the engine operates with excessive EGR, or when the DOC has lost its oxidizing function.

As with pressure based leakage monitoring, the difference between S_{bal} and S_{dp} above which a DPF leakage error is set must be chosen such that it is robust with respect to the uncertainties involved in both estimates, i.e. the uncertainty in the feed gas soot model, the oxidation of soot over the DOC and the regeneration of soot in the DPF.

It is important to realize that most of the noise factors present in the conventional pressure based leakage monitor, as tabulated in Table 1, are present in the soot estimate S_{dp} . Only noise factors 8 and 9 in Table 1 do not play a role in S_{dp} , but as observed above, another important noise factor enters in the model based monitor, namely the correlation between pressure drop and soot load. It then becomes clear that any improvement in the model based leakage monitor can only come from the relative magnitude of the stackup of noise factors 8 and 9 in Table 1 on the one hand, compared to the stackup of the correlation between pressure drop and soot, and the FG soot model accuracy and passive regeneration accuracy on the other hand.

5. TOLERANCE STACKUP OF FEED GAS PARTICULATE MODEL

Soot formation in the combustion chamber of a diesel engine is a highly complex process, that is mostly determined by fuel type, and temperatures and local oxygen availability during the combustion. Among the main factors determining these in-cylinder conditions are the air-to-fuel ratio, the fuel pressure and the injection timing. Since an exhaustive study of the determining factors for soot formation is beyond the scope of this paper, we limit ourselves to some of the key factors, as displayed in Table 2. This table lists 3 important noise factors determining in-cylinder conditions during combustion, and a factor that is completely outside of the control of the engine control system, namely biodiesel content of the fuel.

We do not intend to derive a feedgas particulate model in this paper. Many papers have been written on this subject and it is outside of the scope of this paper. Rather we take a model independent view, by considering noise factors that affect the feedgas soot and are not known to the engine control unit, so that any soot model will be subject to these uncertainties.