

Diagnostics Development for Cost-Effective Temperature Sensor based Particulate Matter OBD Method

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ABSTRACT

A particulate matter On-Board Diagnostics method based on temperature sensing is demonstrated. The concept applies a detection filter downstream of the main particulate filter and a flow diversion pipe. A small fraction of the main exhaust flow is diverted through the detection filter. In case the main soot filter has some leakage, soot will collect on the detection filter where it reduces the filter's permeability. As a result the diverted flow is reduced. This effect is sensed by a temperature sensor placed downstream of the detection filter because the change of diverted mass flow results in a change of heating rate. This principle allows particulate filter diagnostics based on cost-effective and readily available sensing technology.

Comprehensive diagnostics software is developed to interpret and assess the temperature signal. The developed diagnostics software detects particulate filter filtration inefficiency and performs plausibility checks. The concept is demonstrated using an instrumented test vehicle with purposely damaged particulate filter. The diagnostics prove successful in detecting a filtration inefficiency fault that leads to particulate matter emissions close to the 12 mg/km 2017 Euro 6 OBD Threshold Limit.

CITATION: Cloudt, R., "Diagnostics Development for Cost-Effective Temperature Sensor based Particulate Matter OBD Method," *SAE Int. J. Passeng. Cars – Electron. Electr. Syst.* 7(2):2014, doi:10.4271/2014-01-1550.

INTRODUCTION

The recent past has seen the application of particulate filters on diesel passenger cars. This development has been driven by progressing emission legislation. [Figure 1](#) summarises the evolution of passenger car Particulate Matter (PM) emission limits for Europe and the US. Heavy-duty emission legislation shows similar trends. Besides a limit on particulate mass emission, a limit on Particulate Number (PN) has been imposed in Europe. This effectively enforces the use of wall flow type particulate filter. The particulate number limit will also affect Gasoline Direct Injection (GDI) engines, albeit that a higher PN limit is initially allowed. Because of this PN limit the future may show particulate filters applied to GDI engines.

On-Board particulate filter monitoring is required to ensure proper real-life functioning of the particulate filter. A particulate filter issue needs to be detected by the On-Board Diagnostics (OBD) system if the resulting PM emissions exceed the OBD Threshold Limit (OTL). The evolution of the OTL is strongly linked to the available sensing technology. Up till recently the only viable particulate filter monitoring strategy was based on (differential) pressure sensing. This approach has limited sensitivity though. This has led to a large difference between the PM limit for type approval and the OTL, as shown in [Figure](#)

1. However, the recent emergence of new sensing techniques results in a narrowing gap between the PM type approval limit and OTL in the near future.

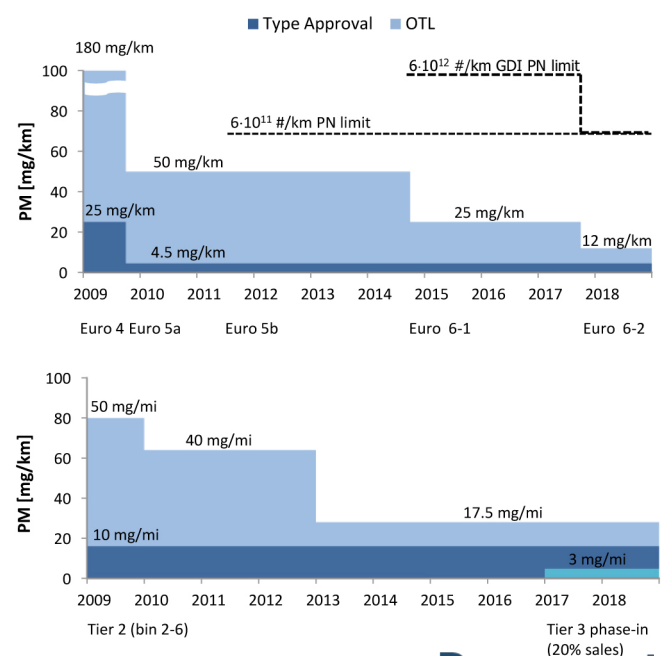


Figure 1. Passenger car PM emission legislation for Europe and US

STATE OF PM OBD SENSING TECHNOLOGY

Many PM sensors have been presented during the past years. Most of them are accumulating resistive type sensors that collect soot on an electrode pattern and sense the change in impedance (e.g. [1, 2]). These sensors are periodically regenerated by an integrated heating element and the time between regenerations is a measure for PM emission. There are few other initiatives that allow real-time PM sensing based on particle charge and electrostatic principles [3, 4].

Ideally a PM OBD sensor should exhibit a deterministic repeatable response that allows reliable judgement within a few test cycles. It should be accurate enough to at least detect a failure that results in exceedance of 12 mg/km PM emission, the lowest OTL on the current horizon. The sensor should be able to perform self-diagnostics and plausibility checks on a frequent basis. In order to arrive at a sound judgement on OTL exceedance, the PM sensor signal should be processed and interpreted by diagnostics algorithms running in the engine control unit. In-field demonstration and validation is furthermore highly desirable.

At present stage it appears that no sensor has convincingly proven all desiderata [5, 7]. There are serious concerns about the effect of soot composition variation on the sensor response. Specifically for the resistive type sensors: the effect of even low concentration contaminants affecting the conductivity of the soot deposited on the sensing electrode [6]. Frequent sensor self-diagnostics can be an issue too [7]. Some sensor faults may not be easily distinguishable from other potential failure modes.

Immaturity of current PM sensing technology is reflected by the late changes in PM OBD rule making for the 2013-2015 period:

- US Californian Air Resources Board (CARB) light-duty OBD: Specific exemptions related to PM sensor monitoring are allowed in the 2013-2014 time frame [7, 8].
- Europe light-duty OBD: Final OTL review scheduled in September 2014 [9].
- US CARB heavy-duty OBD: sales volume based PM sensor phase-in schedule for 2014-2015 [10].
- Europe heavy-duty OBD: technology gap to meet 0.025 g/kWh OTL recognised. Specific requirements for 2014/2015 differential pressure based monitoring instead [11].

All current OBD legislations have furthermore adopted a specific In-Use Performance Ratio (IUPR) provision for particulate filter related monitors. The provision states that the IUPR denominator for particulate filter related monitors should be incremented after 800 km (or a similar engine operation time). In-Use Performance Ratio requirements impose a lower bound on the expected frequency of monitor events. The

additional provision relaxes monitoring requirements to a large extent as for many applications an active particulate filter regeneration is likely to occur within few 800 km stretches.

ALTERNATIVE: TEMPERATURE SENSOR BASED PM OBD

An alternative approach for Particulate Matter On-Board Diagnostics is offered by the arrangement proposed in Figure 2. The principle schematized in Figure 2 relies on diverting a small portion of the main exhaust flow downstream of the (diesel) particulate filter into a secondary diversion pipe. A small detection filter is installed in the diversion pipe followed by a temperature sensor. There are obviously many other ways to construct the secondary diversion exhaust line and to install this detection filter and the concept shown in Figure 2 is only one of them.

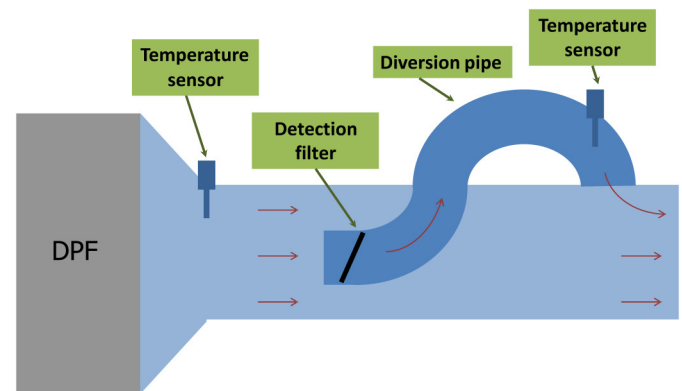


Figure 2. Proposed arrangement for temperature sensor based PM OBD

As soon as the particulate filter starts leaking, the detection filter will progressively clog, its permeability will progressively decrease and this will cause progressive reduction of the diverted exhaust flow. Since the diversion pipe is located externally to the main exhaust line, a reduction of the diverted mass flow will also cause a reduction of the diversion pipe outlet gas temperature. The evolution of this temperature over time will depend on the evolution of the derived mass flow rate which in turn depends on the detection filter clogging level due to possible soot leakages from the main particulate filter. Consequently monitoring the diversion pipe outlet temperature will allow determination of the amount of soot leaking from the main particulate filter.

The proposed arrangement has no means of self-regeneration of the detection filter. It relies on the regeneration of the upstream particulate filter. Location of the detection filter inside the main exhaust line assures quick and proper detection filter regeneration when exposed to high temperatures during active regeneration of the main particulate filter.

There are several material candidates for constructing the detection filter. One good candidate is a metal fleece filter material that is also used in some metallic particulate filters. The temperature sensors are standard resistive exhaust temperature sensors.

The proposed concept allows particulate filter monitoring based on a simple cost-effective concept using proven sensor technology and materials. Assuming a temperature sensor is already present at the particulate filter outlet, only one additional temperature sensor is required. No complicated or additional electronics are required for this sensing concept. The temperature sensor can be interfaced with existing control units.

The principle has been proven before [12] and this concept has also been evaluated in a project on the state of PM sensing technology executed for the European Commission [13]. Up to now the associating diagnostic algorithms and software have been missing. These have recently been developed and tested.

DIAGNOSTICS DEVELOPMENT

A diagnostics algorithm for the proposed temperature sensor based PM OBD method has been developed in a model-based development setting. First a simulation model of the diversion pipe arrangement was developed. This model allows computer simulation of situations and eases algorithm development to a large extend.

The basis of developed diagnostics algorithm is illustrated in Figure 3. The algorithm is based on comparing the measured diversion pipe outlet gas temperature to predictions from a thermal model of the diversion pipe. The thermal model predicts the diversion out temperature for a reference condition; typically a clean detection filter. Leaking particulate filters are expected to show a temperature difference with the modelled temperature that grows over time. This means that a severely and a marginally leaking filter can show the same temperature difference but at a different point in time. To assess the leakage level, the temperature difference needs to be combined with information on the driving pattern and expected soot emission history. A qualitative soot model is implemented for this purpose. The model provides a qualitative index estimate of the detection filter soot load for a marginally leaking filter. This provides a reference for assessing the model-measurement temperature difference. A significantly leaking particulate filter will show a certain temperature difference at a low detection filter soot load index whereas a mildly leaking filter shows similar temperature difference at a much higher detection filter soot load index. Long term tracking of the detection filter soot load is difficult and prone to accumulation of errors. To enhance reliability, detection of particulate filter filtration inefficiency is limited to a limited detection filter soot load window after a regeneration event.

The developed diagnostics software comprises the following modules:

- Diversion thermal & flow model
- Detection filter soot load model
- Comprehensive component monitoring
- Diversion flow monitor
- Detection filter permeability compensation
- On-Board Diagnostics executive

Together these functions make up a diagnostics framework that meets all the requirements for a modern PM OBD system. Each module will be briefly described subsequently.

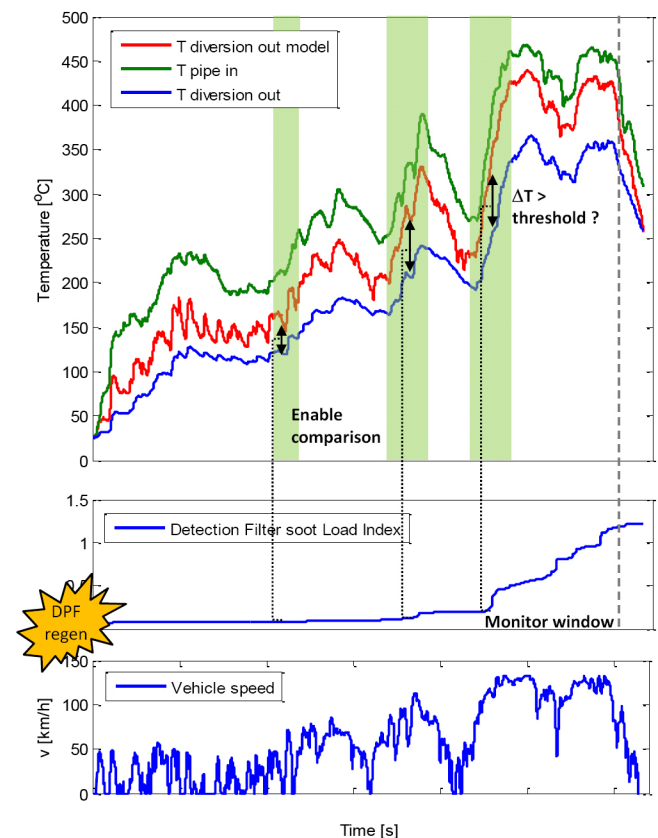


Figure 3. Illustration of PM OBD diagnostics concept

Diversion Thermal & Flow Model

The diversion thermal & flow model is the centrepiece of the diagnostics strategy. Judgements are based on comparison of model predictions against sensed diversion outlet gas temperature. The diversion flow is obtained through equating the driving dynamic pressure with the detection filter and diversion pipe pressure drops and solving for mass flow. Energy balance equations constitute the thermal models for the main and diversion pipe. Standard heat transfer correlations for pipe flow are used for the internal heat transfer coefficients. Coefficients for external heat transfer are tuned. A model for the temperature sensor response is included too. As the flow in the diversion pipe is low, limited heat transfer to the sensor's actual sensing element will cause a difference