

# Evaluation of Non-Contiguous PM Measurements with a Resistive Particulate Matter Sensor

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## ABSTRACT

The resistive particulate matter sensor (PMS) is rapidly becoming ubiquitous on diesel vehicles as a means to diagnose particulate filter (DPF) leaks. By design the device provides an integrated measure of the amount of PM to which it has been exposed during a defined measurement period within a drive cycle. The state of the art resistive PMS has a large deadband before any valid output related to the accumulated PM is realized. As a result, most DPF monitors that use the PMS consider its output only as an indicator that a threshold quantity of PM has amassed rather than a real-time measure of concentration. This measurement paradigm has the unfortunate side effect that as the PM OBD threshold decreases, or the PMS is used on a vehicle with a larger exhaust volume flow, a longer measurement is required to reach the same PM sensor output. Longer PMS measurement times lead to long particulate filter monitoring durations that may reduce filter monitor completion frequency.

This work investigates a way to improve the completion frequency of a filter monitor by allowing PMS measurements to be interrupted and later resumed, for example from one drive cycle to the next. The experimental results presented show the effect of stopping a PMS measurement and resuming it after delays of various lengths and initiated at various levels of PM sensor soot loading. In most cases the measurement variability increased by 50% or more and the overall sensitivity for the same cumulative conditions decreased by as much as 20%. Observations of the PM dendrite behavior before and after an interruption in the sensor electrode bias voltage using an optical access PMS are included to provide some explanation for the increased variability.

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## INTRODUCTION

Most modern diesel fuelled vehicles use a diesel particulate filter (DPF) to trap and store particulate emissions. In the past, filter leaks were detected by comparing pressure drop across the filter as a function of flow rate to a threshold [1]; however, such monitors struggle to detect the small leaks that can yield emissions above the OBD threshold on vehicles certifying to recent PM standards [2]. The availability of a low cost onboard particulate matter (PM) sensor has shifted the filter OBD paradigm to the direct measurement of post-DPF particulates. The PM sensor detects the presence of particulate matter, composed primarily of black carbon soot, in the exhaust gas downstream of the filter. At the time of writing, the state-of-the-art PM sensor is a resistive type that works by measuring the conductivity of material accumulated on a ceramic element over time. References [3] and [4] contain details on the function and design of two examples of such a sensor. The sensor supplied by Bosch is widely used by several OEMs including Ford, GM, FCA, Volkswagen and several others in vehicles ranging from passenger cars to heavy trucks.

The resistive sensor consists of a pair of electrodes at opposing electrical potential separated by an insulating gap. As particulate matter accumulates on the sensor, it bridges the gap and provides a conductive path. A fixed bias voltage is applied to the electrodes, so the amount of current that can flow is related to the amount of PM that has deposited. Because the gap between the electrodes is on the order of tens of micrometers and the size of the PM particles from diesel exhaust is on the order of tens of nanometers[5], there is a minimum amount of soot that must deposit before a complete conductive path is formed across the gap. During this initial PM build-up, the sensor is in a deadband region where there is no change in current related to PM deposits. Once a bridge is formed, the sensor current increases exponentially as more PM accumulates. [Figure 1](#) shows sensor current normalized to the maximum current at the end of a measurement during a sample accumulation at steady state engine conditions and constant PM concentration. The deadband region accounts for over half of the total measurement time. Once current begins to flow, it rapidly increases to the current threshold, which is typically specified by the sensor supplier and varies with sensor design.

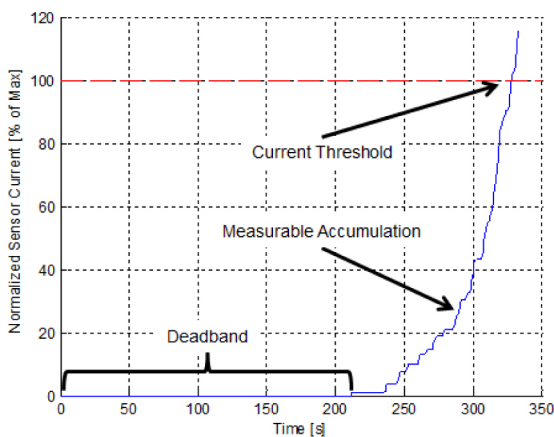


Figure 1. Sample resistive PM sensor current during steady state engine conditions.

The highly non-linear current versus accumulated PM relationship of the PM sensor makes it difficult to derive a metric relating sensor response to real-time PM concentration or mass flow. Also, for roughly half of the measurement cycle the sensor provides no output at all. Some initial studies of resistive sensor signals raised issues of signal noise due to individual large particles and showed that in some cases PM can blow off the sensor resulting in a temporary decrease in current [6]. For these reasons, the sensor output is typically interpreted as the time required to reach a current threshold. This time is inversely related to the measured PM concentration. During an entire measurement cycle, the effects of local noises on the overall time to reach the current threshold are small and are essentially averaged out of the measurement, improving measurement-to-measurement repeatability.

As an accumulating device, the resistive PM sensor is sensitive to low average PM concentrations that are significantly less than would be observed leaking through an OBD threshold DPF. However, the time required to accumulate enough PM to form the initial bridge between the electrodes and eventually reach the current threshold that signals the end of a measurement, varies inversely with the average concentration measured. This means that as regulated emissions and OBD thresholds drop, measurements take longer. The increase in measurement time is problematic for future OBD regulations with lower thresholds. A three-fold decrease in the OBD threshold roughly translates into a three times longer DPF monitor duration. Very long monitor durations can cause low completion frequency, which risks not meeting in-use completion frequency requirements dictated by California Air Resources Board. To improve the completion frequency, the sensitivity of the PM sensor must be increased or the availability of measurement must be improved.

This work investigates ways to increase measurement availability of a resistive PM sensor. The accumulating nature of the device is exploited by retaining material captured in one measurement segment for use in another that follows some sort of interruption in the electrode bias. The interruption can occur due to a drive cycle ending or an engine stop event within a drive cycle for a vehicle with automatic stop/start functionality. Experimental data shows the effect

of this interruption on the latent PM maintained from one measurement segment to the next. Testing was conducted in vehicle and in dynamometer.

## USE OF THE PM SENSOR IN A DPF MONITOR

Delphi, Bosch and other sensor makers indicate that any measurement made with resistive PM sensors should be preceded by sensor regeneration at high temperature [3][4][7]. This serves to clean off any accumulated material and ensures measurements begin at a known zero PM load. Resistive PM sensors include a heater to regenerate the device on demand. Regeneration takes between 30 and 120 seconds. For a cold engine start condition, an additional delay is required prior to heating to ensure all exhaust condensate upstream of the sensor is evaporated to avoid damage from the thermal shock of a droplet impact. The time required to complete a DPF monitoring session with a PM sensor includes the heating delay for dew point and the regeneration event, as well as the active PM measurement time. An overview of the operation of a typical PM sensor based DPF monitor is shown in Figure 2 and is based on monitor concepts presented in [4] and [7]. Alternatives to this concept are the primary subject of this report.

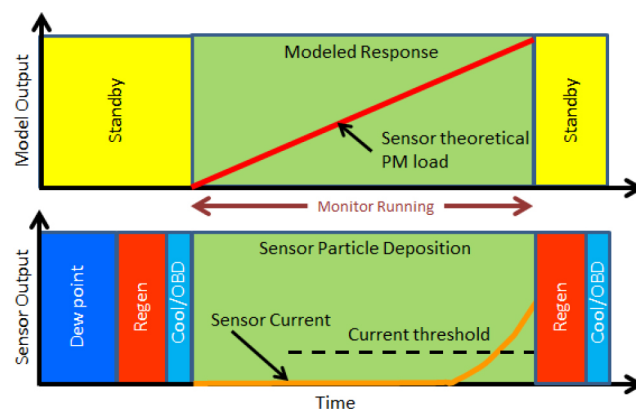


Figure 2. PM sensor based DPF monitor strategy.

In the diagnostic concept in Figure 2, the PM sensor output is compared to a model of the sensor response. This modeled response, or theoretical PM load (TPL), provides an estimate of the fraction of the total accumulation capacity of the sensor that has been filled as a function of the time since measurement start. In vehicle, the TPL is computed from the exhaust conditions the sensor is predicted to see for an OBD threshold DPF. The DPF diagnostic assesses whether the measured PM sensor current has reached the current threshold by the time the TPL indicates a full sensor. For a faulty DPF, the PM sensor current would exceed the sensor threshold before the TPL computed for an OBD threshold DPF reaches its maximum.

The sensor capacity used to compute TPL is defined as the time required for the sensor to reach the threshold current,  $\tau_{PM}$ . This response time is derived from a model of the sensor and a model of the PM concentration expected from an OBD limit DPF. A simplified formulation of the sensor model is shown in equation (1), where  $\bar{c}_{PM}$

is the average modeled PM concentration in  $\text{mg}/\text{m}^3$ ,  $K_s$  is the sensitivity factor for the PM sensor in  $\text{m}^3/(\text{g}\cdot\text{s})$ ,  $\overline{v_{gas}}$  is the average exhaust gas velocity in  $\text{m}/\text{s}$  and  $\overline{T_{gas}}$  is the average exhaust gas temperature in  $^{\circ}\text{C}$ . The average for each quantity is computed over the entire sensor measurement period.

$$\tau_{PMS} = \frac{1}{\overline{c_{PM}} K_s} \times f(\overline{v_{gas}}, \overline{T_{gas}}) \quad (1)$$

The response time is primarily a function of the PM concentration  $\overline{c_{PM}}$  and the sensitivity of the PM sensor,  $K_s$ . It is a weaker function of the exhaust gas flow and gas temperature. The exact formulation of the sensor model is proprietary to the sensor supplier, and each sensor design has a different model that accounts for the mechanisms by which PM deposits on the sensor, and the way bulk exhaust flow relates to flow through the sensor. The key input to the sensor model is the concentration. In a vehicle, this is usually derived from an engine-out soot model in series with a model of the PM leakage through an OBD threshold DPF.

In the testing for this study, the sensor model of eq. (1) is inverted to calculate the variation in PM sensor sensitivity,  $K_s$ , for the conditions tested. The sensor response time, PM concentration, gas speed and temperature are all measured, so the corrected sensitivity can be calculated in units of inverse of concentration times time, or  $\text{m}^3/(\text{g}\cdot\text{s})$ . The shift and variability in calculated sensitivity is used as the metric to compare different sensor operating strategies in this report.

## METHOD FOR VEHICLE TESTING

The first series of tests was designed to evaluate the effect of measurements that span multiple drive cycles on overall variability in PM sensor response. This testing was conducted on a vehicle with a single PM sensor mounted after an OBD threshold DPF. The vehicle was a Ford F-350 pick-up truck with 6.7L diesel engine and exhaust system with DOC, DPF and SCR. The threshold DPF leak was simulated by milling out sufficient end plugs in the substrate to achieve PM emissions of  $60 \pm 15 \text{ mg}/\text{mi}$  on the FTP75 cycle. On-road PM emissions were measured in real-time using a Pegasor MI3 analyzer sampling through a post-DPF probe and heated line. A Bosch resistive particulate matter sensor from a MY15 Ford F-series truck was installed after the DPF, and the manufacturer supplied control module for the PM sensor was replaced with a rapid prototype controller that facilitated non-standard transitions between measurement (bias voltage on) and regeneration (bias off, heater on) states. The sensor sensitivity was calculated with [equation 1](#) using the total active measurement time required to reach the current threshold, the average PM concentration, average gas velocity and average gas temperature. This setup supported investigation of two alternatives to the regenerate-then-measure paradigm in arbitrary real-world drives.

The first alternative measurement scheme considered the effect of regeneration and PM accumulation events that occur in different drive cycles. The sensor was regenerated as soon as the engine stopped at the end of one drive cycle and transitioned directly to

measurement after dew point in the next drive. This strategy is outlined in [Figure 3](#). The benefit of such an operating strategy was that the regeneration, which takes as much as two minutes depending on sensor design, was confined to periods where the engine was not running and did not divert time away from measurement in the subsequent drive. This procedure was used to evaluate the effect of the engine off period and exposure to exhaust condensate below dew point in the subsequent drive on the sensor response. The engine-off soak period varied from two to twelve hours.

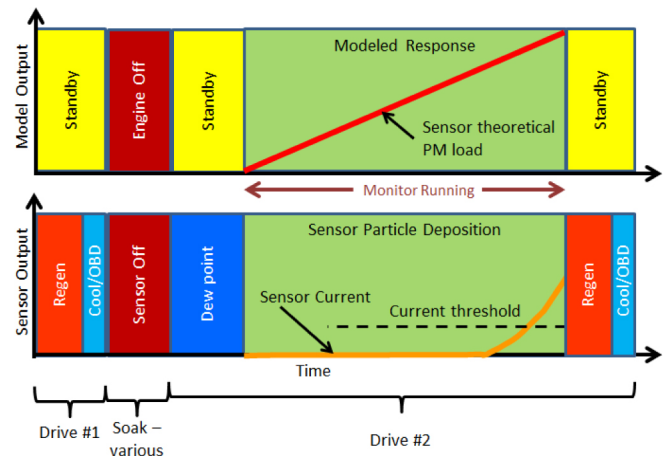


Figure 3. PM sensor measurement relying on regeneration at end of a prior drive.

The second test conducted on vehicle was designed to evaluate the effect of measurement interruptions on overall PM sensor variability. Such interruptions arise during the hot soak period of the FTP75 emissions cycle or on a vehicle equipped with an engine auto-stop, or stop-start feature, if the PM sensor cannot remain in the measurement state during the stop. A simple stop-start strategy was implemented on the same F-350 vehicle used for the testing described above. The strategy shut down the engine when the exhaust system reached normal operating temperature, dew point was exceeded at the PM sensor, and the vehicle was stopped with brake pedal pressed. During the stop, the PM sensor either maintained or shut down the voltage to the electrodes. When the brake pedal was released, the engine was restarted and voltage restored to the electrodes. A third test case was also investigated in which the voltage to the sensor electrodes was off only during the engine crank of the restart event.

To compare the alternative measurement schemes, the calculated sensitivity of the PM sensor over a complete measurement was used. As described above, the calculated sensitivity, in units of  $\text{m}^3/(\text{g}\cdot\text{s})$ , is the inverse of the measured response time multiplied by the measured soot concentration. It is derived from [equation \(1\)](#) by solving for  $K_s$  and includes corrections for temperature and exhaust gas velocity. A larger number for this metric is desirable and indicates a higher sensitivity and a faster sensor response. During the measurement interruption, the PM concentration is assumed to be zero so the time spent with engine stopped is properly considered in the calculation of [equation \(1\)](#).