

Real-time Sensing of Particulate Matter in a Vehicle Exhaust System

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ABSTRACT

Onboard diagnostic regulations require performance monitoring of diesel particulate filters used in vehicle aftertreatment systems. Delphi has developed a particulate matter (PM) sensor to perform this function. The objective of this sensor is to monitor the soot (PM) concentration in the exhaust downstream of the diesel particulate filter which provides a means to calculate filter efficiency. The particulate matter sensor monitors the deposition of soot on its internal sensing element by measuring the resistance of the deposit. Correlations are established between the soot resistance and soot mass deposited on the sensing element. Currently, the sensor provides the time interval between sensor regeneration cycles, which, with the knowledge of the exhaust gas flow parameters, is correlated to the average soot concentration. Recent advancements in the filtering and processing of the PM Sensor output signal now allow for translation of the sensor resistance signal into real time instantaneous soot mass flow, soot flux, and soot concentration which are available throughout the active zone of the sensor cycle. Additional algorithms provide cumulative soot mass, average flux and average concentration during the sensor cycle and also for the duration of the vehicle drive cycle. This paper describes the recent advances in the PM Sensor signal processing algorithms along with their implementation on a real-time PM Sensor Development Controller. A summary of algorithm performance in comparison to laboratory instrumentation is provided. Finally, an evaluation of the potential benefits of the new technology is presented along with planned next steps.

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INTRODUCTION

Particulate filters are now commonplace throughout the world for emissions control in automotive, light, and heavy duty diesel vehicle applications for the reduction of particulate matter (PM) in the vehicle exhaust. Global regulations have continued to tighten the allowable PM emissions as shown in Figure 1, while simultaneously broadening the scope of the regulation to include gasoline fuelled vehicles. Tier 3 regulations which phase in from 2017 to 2025 allow only a small fraction of the PM and NO_x emissions allowed by the Tier 2 standards. Simultaneous reductions in engine-out emissions and improvements in aftertreatment performance are required to meet the new regulations.

As with other vehicle emissions-related devices, diagnosis of the particulate filter is typically required. The diagnostic threshold limits continue to be reduced making diagnosis accuracy, repeatability, and sensitivity increasingly important. Figure 2 illustrates how the On-Board Diagnostic (OBD) thresholds are decreasing thereby necessitating an increase in the required diesel particulate filter (DPF) efficiency of a threshold filter, making the pass/fail diagnostic window narrower.

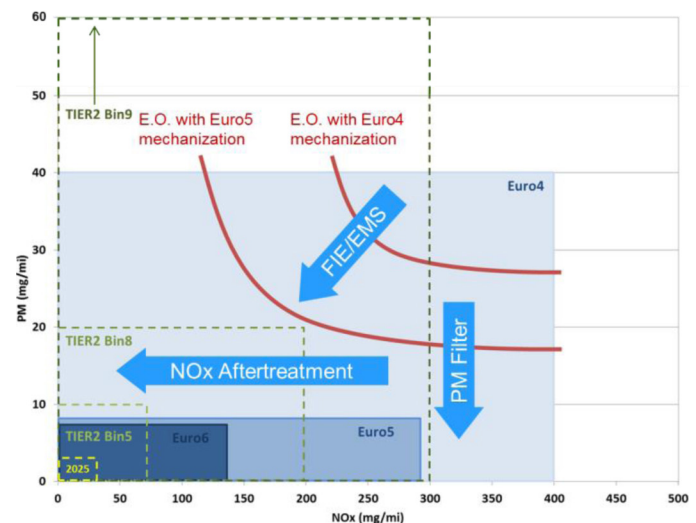


Figure 1. Tightening worldwide emissions standards for PM and NO_x achieved via reductions in engine-out (E.O.) emissions using improved fuel injection equipment and engine management systems with the remainder of the emissions reduction via aftertreatment. [1]

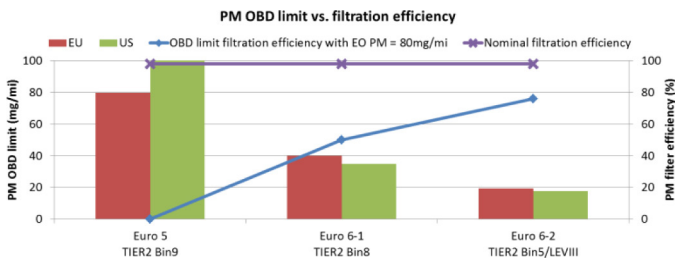


Figure 2. On-Board Diagnostic threshold limit reductions and corresponding required DPF efficiency increases are narrowing the pass/fail diagnostic window. [1]

Several different techniques or methods of diagnosing DPF's have been developed, each with its own unique characteristics and capabilities [2]. One such method of diagnosing the particulate filter is through the use of a PM sensor that is placed downstream of the filter and detects PM that has passed through the DPF. PM emissions that are higher than the normal range would be indicative of a failed or malfunctioning particulate filter or engine system. PM sensor designs are typically either an accumulating style sensor (in which soot accumulates on an internal pair of electrodes) or are based on measuring the flow of charged particles. A general description, principle of operation and performance summary of various styles of PM sensors is provided by Khalek et. al. in [3].

The focus of this paper is on the development of improved algorithms for interpreting and controlling the output of an accumulating type, resistive style PM sensor as shown in Figure 3. The electrodes for this style sensor are closely spaced on a non-conductive substrate. The carbonaceous PM particles are conductive and cause the resistance between the electrodes to decrease as the particles deposit onto the electrode surface. The equivalent electrical circuit for the sensor is shown in Figure 4. The sensing element includes a bias resistor (which is in parallel with the substrate and soot resistance), an integrated heater near the sensing electrodes, and integrated resistive temperature device (RTD) element sensing the temperature of the sensor/soot deposit.

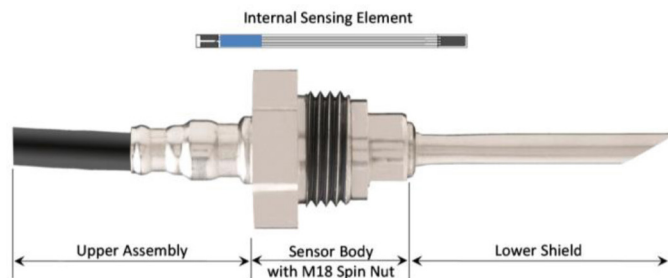


Figure 3. PM Sensor assembly and sensing element construction.

Control electronics monitor this resistance and periodically trigger a sensor regeneration event based on reaching a pre-defined resistance threshold. Sensor regeneration is achieved by heating the PM deposit to a temperature above its oxidation point using an electric heater contained within the sensor element. The time between regenerations is termed the “cycle time” or “response time” and is correlated to the average soot flux occurring in the exhaust pipe during that time

period. For a detailed description of this specific sensor construction, principle of operation, control electronics and performance characteristics please see Husted et. al [4].

OBD regulations specify that the diagnostic methods used for verifying DPF efficiency are capable of detecting a failed or degraded filter which causes the vehicle to exceed a threshold value during a defined test cycle. Summary information regarding emissions and OBD requirements for passenger cars, light duty, heavy duty and off-highway vehicles is available on the Delphi website [5, 6]. This threshold PM emissions level is correlated to the response time of the PM sensor such that a response time less than a minimum value is interpreted as an underperforming filter. Varying driving conditions will naturally cause changes in the amount of particulate matter generated by the engine and subsequently emitted at the tailpipe. A model of engine-out soot flux, minimum DPF efficiency and corresponding tailpipe soot flux can be used to generate an expected PM Sensor response time for the varying driving conditions, and thus a threshold response time for the diagnostic. Alternative strategies are also being developed using a virtual pre-DPF PM sensor in conjunction with a conventional post-DPF PM sensor [1].

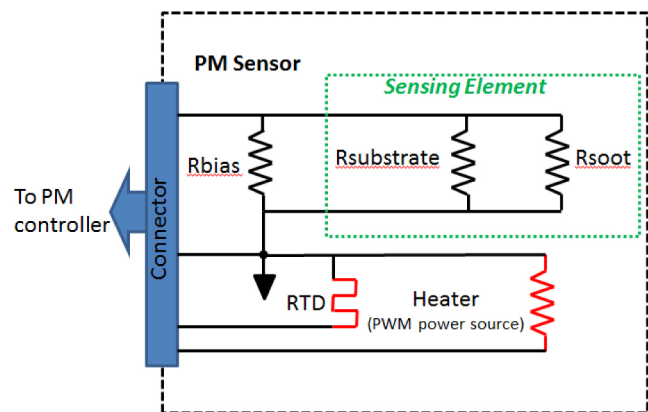


Figure 4. Sensor equivalent electrical circuit.

OVERVIEW OF PM SENSOR OPERATION AND DESCRIPTION OF NEW ALGORITHMS FOR INTERPRETING SENSOR SIGNAL

In the absence of soot, there is a very high electrical resistance between the electrodes of sensing element (see Fig. 5). As soot accumulates on the surface of the sensor between the electrodes, the soot particles begin to overlap and bridge the gap between the electrodes (kerf). Because the soot particles are electrically conductive, the resistance between the electrodes decreases, as does the effective sensor resistance, and is measured by the control electronics. The authors have found that it is beneficial to analyze and interpret the sensor signal in the conductance domain rather than the resistance domain to simplify computations (example will be provided later in the paper). Equivalent sensor conductance can be expressed by eq. (1):

$$G_{\text{sensor}} = G_{\text{bias}} + G_{\text{substrate}} + G_{\text{soot}}$$

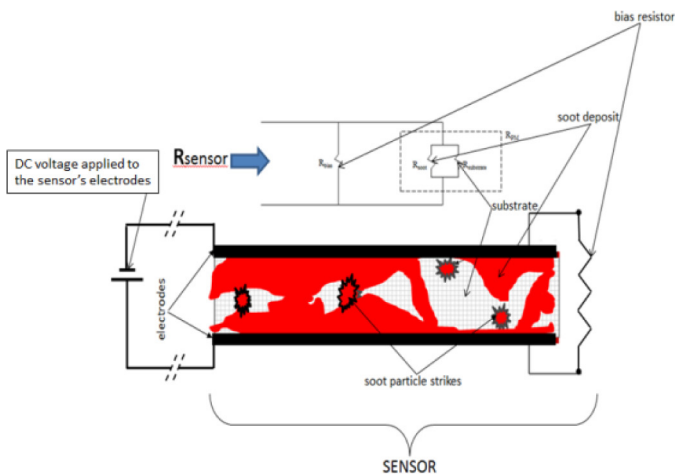


Figure 5. Illustration of sensing element showing gradual accumulation of the soot deposit on the initially non-conductive surface of the substrate.

The sensor's operational cycle consists of two parts:

- Collection and detection of particulate matter during the sensing time period.
- Sensor "regeneration" in which the collected soot is oxidized at high temperature and thus removed from the sensing portion of the sensor.

During the sensing time period, there are two distinct phases of the sensor's electrical conductance behavior: a "deadband" phase when the sensor's conductance does not noticeably change even though the sensor surface is collecting soot, and an "active" phase when the sensor's conductance increases noticeably in response to increasing soot loading. The remainder of the time which defines a single complete "cycle" is the regeneration time in which the soot deposit is removed from the sensing element. Definition of a single cycle is depicted in Figure 6. The sensor's conductance reading representing the conclusion of the deadband is chosen at a point where the conductance trace clearly is responding to soot accumulation. The conclusion of the cycle and onset of regeneration is limited only by the amount of soot the regeneration process is able to handle.

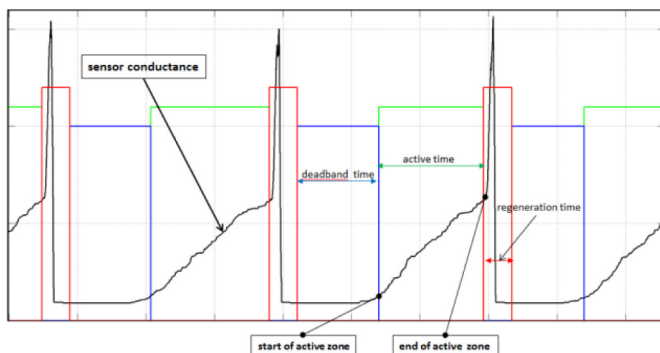


Figure 6. Definition of individual zones within the sensor's operational cycle. Sensor conductance and logic gates plotted versus time.

It is worthwhile to notice that, to-date, "cycle time" (also referred to as "response time" or "sensing time"), i.e., time interval between regenerations (or strictly the combined time of deadband and active zones) is used for the DPF diagnostic, since the "cycle time" clearly correlates with the soot flux rate in the exhaust pipe (see e.g., [7]). For the purposes of this paper, "cycle time" excludes the sensor regeneration time as a matter of convenience.

In order to more fully understand the behavior of the sensor, simulations of sensor response to particle deposition were conducted [3]. Figure 7 represents the sensor response (G_s) to various rates of particle deposition, representing corresponding exhaust system soot flux rates. For each deposition rate, 20 identical sensors were simulated, and the results combined into one plot. Clearly, even in the absence of ever-present changes in the exhaust gas temperature, velocity, etc., there is variation in the sensor response. In particular, neither the conclusion of the deadband nor the onset of regeneration is uniquely identified within a single particle deposition rate selected for simulation. This is due to the randomness of the deposition of individual soot particles on the sensing element, which, in turn, generates variation in the sensor conductance as the particles unite to form conductance paths across the sensor electrodes.

In addition, as has been observed by others (e.g., [8]), the sensor's output signal can be corrupted by soot re-entries into the exhaust stream (blow-offs), and sudden signal jumps associated with unusually large particles strikes. Also, it has been observed that deposit instabilities can exist that cause intermittent fluctuations in sensor conductance. Consequently, the unprocessed "raw" sensor conductance provides, in practice, the "cycle time" upon which a potentially less reliable estimate of soot flux is correlated. In short, further improvement in the data processing and interpretation of the sensor output signal, in the light of more stringent regulations, is highly desirable.

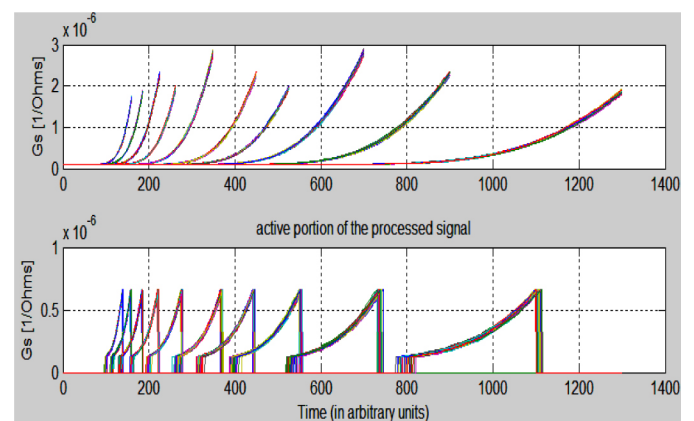


Figure 7. Simulation of sensing element response to ten different soot concentrations over an extended period of time. The upper row depicts sensors electric conductance. The bottom row depicts evolution of sensor conductance within the active zone ("active time") defined in Fig. 6. Note that simulation depicted in the upper plot was run beyond the cumulative soot deposit representing the end of a cycle.

The first, clearly desired improvement, is to remove parasitic soot blow-offs and sudden, large particle signal steps corrupting the conductance trace. This substantially improves reliability of cycle time-based diagnostic whenever these anomalies occur. Moreover, it pre-conditions the signal for subsequent real-time soot concentration estimate and possibly would allow for implementation of PM sensor-based diagnostics assessing transient engine-out particulate emissions. The technique, which quite successfully handles the sensor's conductance signal anomalies associated with large particle strikes, blow-offs, and soot deposit instabilities is presented next, and thereafter the newly developed PM-controller algorithms and their performance is discussed.

Anomalies Filter and Large Particle Sizer

Study of large particle impacts on the shape of the sensor conductance trace indicates that only particles of a size on the order of the distance between sensing electrodes have a substantial impact on the sensor conductance. Depicted in Figure 8 are the sensor resistance traces (upper plot) and corresponding conductance traces (lower plot) which represent a simulation of periodic random deposition of a large particle (with size as listed in the legend of the figure) during the baseline random deposit of normal size particles, plus simulation of only normal-size particles (with no large particle strikes). The sensor resistance plot illustrates the dramatically different effect that identically sized large particle strikes create in the resistance domain. When the same data is plotted in the conductance domain, the steps caused by the large particles are substantially equal, regardless of the status (conductance) of the sensor. This illustrates the reasoning behind the authors' decision to process the sensor signal in the conductance domain. Clearly, the simulation indicates that large particles representing sizes of up to 50% of kerf width do not substantially corrupt sensor traces as the sensor response is practically identical to those calculated in the absence of large particles. Furthermore, the simulated analysis of soot deposition progress, in the presence of periodic but occasional large particle strikes, indicates that the volume of all particles accumulated at the sensor surface at the onset of regeneration remains nearly constant if large particles are not greater than approximately 80% of kerf width (see Fig. 9). This suggests that larger than normal particles, as long as they do not approach the size of the kerf, induce an effective increase in the sensor conductance representing true incremental growth of the soot deposit. When the large particle dimension approaches the size of the kerf, an individual large particle strike can create a step-like change in sensor response that is not proportional to the increase in the mass of the deposit, and thus corrupt the process of translating cycle time into the soot flux estimate.

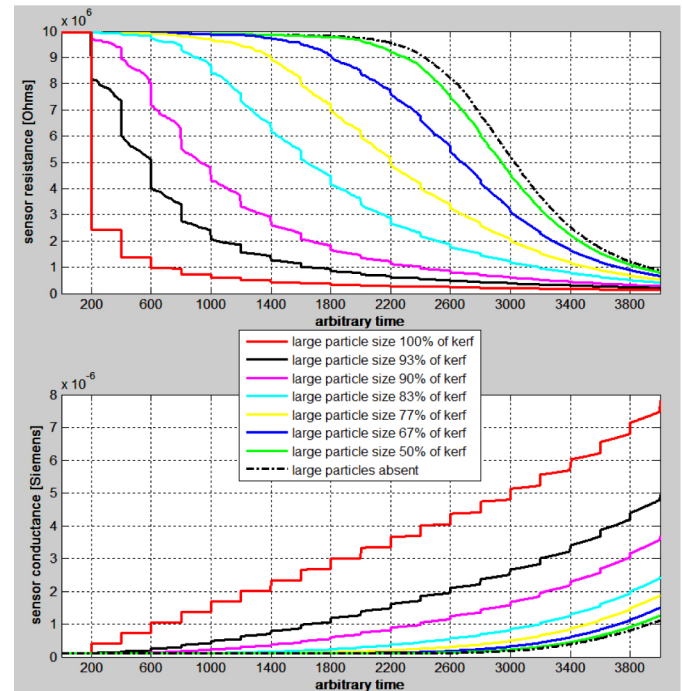


Figure 8. Simulation of large particle strikes every 200-time units on PM sensor response.

Substantial statistical separation of what is considered to be normal soot accumulation versus large particle strikes, allows for identification of the critical threshold in the conductance time differential indicative of large particle strike events (see [9]). The filter's logic is based on the assumption that the differential between two subsequent readings of the sensor conductance signal cannot be larger than a certain pre-defined level if compared to the previous differential, or if compared to a mean (or median) of some arbitrary selected number of previous readings; otherwise it is flagged as being an anomaly. Once the violation of a certain calibrated threshold level is detected, the large particle mass is estimated based on the magnitude of the differential, and stored in the event accumulator, available for the calculation of PM mass for the duration of the vehicle drive cycle. The amount of error introduced by large particle strikes is dependent not only on the size of the particle, but also the position into the overall cycle at which the particle strikes. If it strikes near the end of an otherwise normal cycle, the effect is minimal; but if it strikes during the deadband or initial portion of the active zone it is much more pronounced. The example shown in Figure 9 indicates over 50% error for particles approaching the size of the kerf (see the diving slope of the data points representing volume of all particles). The large particle filter algorithm reduces this error to less than 15% under the same conditions.

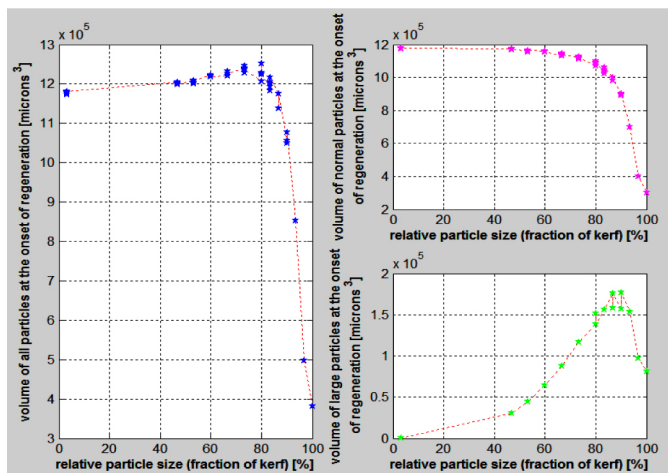


Figure 9. Result of simulation of the increase of the volume of the soot deposit in the presence of periodic large particle strikes. The model, for simplicity, assumes normal particles to be 1 μm in size, and illustrates how the total volume of the soot deposit which triggers the sensor regeneration is affected by the size of occasional strikes of large particles.

A particle blow-off condition accounts for another anomaly causing an error effect, one in which a step-like decrease of the measured sensor conductance occurs due to particles becoming dislodged from the sensor surface. While large particle strikes are expected to be rare, unusual events, it is expected that small blow-offs are a part of almost every monitoring cycle. Kinetics of the soot particle impacts and the tangential component of the exhaust gas velocity can be expected to, at least occasionally, lead to soot re-entry into the exhaust stream with the rate most likely affected by the adhesion of the newly-settled soot particles to the substrate. However, if all negative differentials of the conductance were “flagged-out” as blow-offs, electronic noise would be misinterpreted as minute blow-offs and, therefore, create erroneous corrections. Consequently, a threshold value defining a single blow-off event must be established with the consideration of the presence of electronic noise (see [9]).

The action of the large particle / blow-off conductance corrector algorithm was captured during dyno experiments and is shown in Figure 10, where the raw sensor conductance represented by the blue trace is depicted together with the filter-corrected purple trace. The corrected (reconstructed) conductance trace is subsequently used to extract soot flux information and also used to trigger the conclusion of the deadband and onset of the regeneration. Note that the cycle without large particle strike or discernable blow-offs remains unaltered.

For some not yet fully identified reasons, the impact of a large particle is sometimes followed by a subsequent partial separation. Alternatively, vibration of a delaminated “flake” is recorded as alternating strikes of large particle and blow-off events. These types of events lead to an oscillating conductance trace that can corrupt the extraction of soot accumulation information. Nearly coincidental detection of blow-offs and large particle strikes of similar severity, however, can potentially be used as a warning signal to initiate the sensor regeneration procedure (cycle abort).

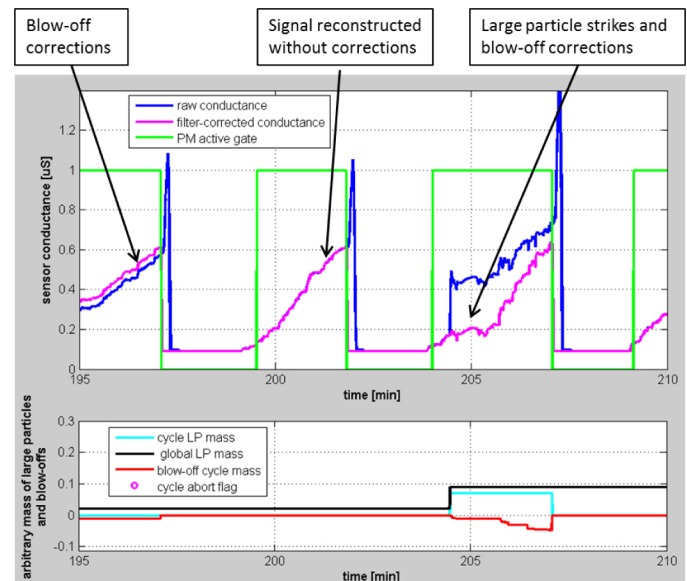


Figure 10. Example of Large Particle Strike and Blow-off filter performance. Upper plot depicts conductivity and reconstructed conductivity traces. Bottom plot depicts cycle blow-off mass, cycle large particle mass and cumulative large particle mass for engine run cycle. Note that the corrected sensor conductance (purple trace in the upper row) compensates for large particle strikes and blow-offs, but may also conclude in a cycle abort since correct signal interpretation becomes very unlikely. Note also, that legend marker “cycle abort flag” is not used since the sensor abort procedure was not activated in the given example.

In the summary, filtering large particles and blow-offs provides the following functionality:

- Detection of large particle strikes
- Large particle mass sizer and accumulator
- Correction of errors in sensor conductance caused by large particles
- Detection of PM blow-offs from sensor
- Correction of errors in sensor conductance caused by blow-offs
- Detection of simultaneous large particle and blow-off events signaling instability of sensor output which may initiate, if necessary, the sensor cycle abort procedure

At the filter output, the corrected conductance trace provides much improved information (when these anomalies exist in the signal) for the core algorithms which then extract soot flux information from the evolving soot deposit as described in the following section.

Basis for Estimation of PM Mass, Flux and Concentration

As a result of the algorithm described in the previous section, the filtered and corrected conductance signal now carries higher quality information regarding the soot flux (mass per unit area per unit time) in the exhaust system. New algorithms which have been developed and embedded in the PM Sensor Development Controller consist of several independent segments, each of which supports the estimation of the soot mass (or mass flow rate) and soot concentration from various portions of the sensor cycle. This is in contrast to existing