

On-Board Particulate Filter Failure Prevention and Failure Diagnostics Using Radio Frequency Sensing

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ABSTRACT

The increasing use of diesel and gasoline particulate filters requires advanced on-board diagnostics (OBD) to prevent and detect filter failures and malfunctions. Early detection of upstream (engine-out) malfunctions is paramount to preventing irreversible damage to downstream aftertreatment system components. Such early detection can mitigate the failure of the particulate filter resulting in the escape of emissions exceeding permissible limits and extend the component life. However, despite best efforts at early detection and filter failure prevention, the OBD system must also be able to detect filter failures when they occur. In this study, radio frequency (RF) sensors were used to directly monitor the particulate filter state of health for both gasoline particulate filter (GPF) and diesel particulate filter (DPF) applications. The testing included controlled engine dynamometer evaluations, which characterized soot slip from various filter failure modes, as well as on-road fleet vehicle tests. The results show a high sensitivity to detect conditions resulting in soot leakage from the particulate filter, as well as potential for direct detection of structural failures including internal cracks and melted regions within the filter media itself. Furthermore, the measurements demonstrate, for the first time, the capability to employ a direct and continuous monitor of particulate filter diagnostics to both prevent and detect potential failure conditions in the field.

CITATION: Sappok, A., Ragaller, P., Herman, A., Bromberg, L. et al., "On-Board Particulate Filter Failure Prevention and Failure Diagnostics Using Radio Frequency Sensing," *SAE Int. J. Engines* 10(4):2017, doi:10.4271/2017-01-0950.

INTRODUCTION

Particulate matter (PM) emissions from diesel and gasoline engines have come under increasing regulatory scrutiny over the past decade. PM emissions from on-road diesel engines are limited to no more than 0.01 g/hp-hr (0.013 g/kW-hr) in the United States and 0.01 g/kW-hr in the European Union, which also imposes a particle number limit [1, 2]. The Euro 6 standards limit particle number emissions to no more than 6.0×10^{11} particles/km by 2018 [3] which impacts both diesel and gasoline engines.

Efforts to meet these regulations have converged on the use of particulate filter technologies, primarily cellular ceramic filters for diesel engines (DPF) and are increasingly being applied to reduce PM emissions from gasoline direct injection engines (GPF) in some applications. Standards similar to those mandated by the U.S. and E.U. are being phased in around the world (to varying degrees), and include off-road, mobile and stationary engines as well.

Properly functioning (healthy) particulate filters are extremely effective at trapping and reducing engine-out PM emissions, and may achieve trapping efficiencies of 99% or more in some cases [4-5].

However, actual in-use conditions may exist which can compromise filter operation. Ensuring proper particulate filter operation and detection of malfunctions of the system on the vehicle is critical in order to meet additional on-board diagnostics (OBD) requirements. OBD requires the detection of filter failures or malfunctions on the vehicle, which could lead to tailpipe PM levels exceeding some predefined multiple of the emissions limit [6-7]. These OBD requirements have further motivated the development of physical and virtual (model-based) sensors and algorithms to detect particulate filter failure conditions. Nonetheless, accurate detection of filter failures to meet OBD limits is a challenge.

In addition to filter diagnostics, accurate determination of the particulate filter loading state is important for safe and efficient operation of the engine and aftertreatment system. The accumulation of PM in the filter results in increased exhaust flow restriction with a direct impact on engine efficiency. The accumulated PM may be removed from the filter through active or passive oxidation processes to maintain exhaust backpressure at acceptable levels. Active soot

oxidation (regeneration) requires the consumption of additional fuel in order to increase exhaust temperatures to initiate and sustain soot oxidation in the particulate filter [8].

In order to protect the filter, it is important to ensure the PM does not accumulate above an acceptable level, defined as the soot mass limit, in order to avoid excessively high temperatures during regeneration which may result in filter failures due to melting or cracking [9]. Indeed, the majority of filter failures are typically the result of either an upstream failure or malfunction of the engine such as a malfunction of the EGR, turbo-charger, injection system, or similar sub-system resulting in high engine-out PM, or a failure of the sensing and control system to accurately determine the filter loading level. The result of both of these malfunctions to either the engine or aftertreatment sensing or control system is often manifested as an uncontrolled regeneration event, resulting in physical damage to the filter and a potential loss in filtration efficiency [10]. Typical failure modes due to these sources include the formation of radial cracks (so-called “ring-off cracks”), melt regions in the filter, or the fracture of the material and loss of channel end-plugs in some cases [10]. In all cases the aim of the combined engine and aftertreatment control system is to avoid these types of failures under all conditions. However, should such a failure occur, the OBD system must detect conditions which may result in PM emissions above acceptable levels.

Conventional Approaches

Current methods for managing particulate filter operation rely on an indirect approach utilizing filter pressure drop measurements, so called delta-P sensors, to deduce the filter soot load from the exhaust flow restriction due to the accumulated soot. A schematic of the system is shown in Figure 1. The accuracy of this approach depends heavily on the flow conditions at the time of the measurements and there are a number of operating conditions over which accurate pressure drop measurements are not possible, including: (i) low flow rate such as idle, and (ii) highly transient operation with large fluctuations in flow and pressure drop.

In other cases, including during regeneration, the dynamics of the soot oxidation (whether occurring in the pores or on the filter cake layer) also introduce considerable variability in the pressure drop measurements, including well-known hysteresis effects [11]. Such effects occur in both active and passively regenerated systems. In one example, studies at Oak Ridge National Laboratory reported pressure drop levels returning to nearly clean levels with over half of the soot remaining in the filter during regeneration [12]. The use of predictive models, in addition to pressure measurements, can improve the overall accuracy of the pressure-based estimates in some cases, however without direct feedback these approaches are not able to adapt to conditions outside the bounds of the initial model calibration.

Following regeneration, a small amount of incombustible material or ash is left behind. The ash, primarily composed of inorganic metallic components derived from engine oil additives, including detergents and anti-wear additives also accumulates in the filter over time [13]. Ash accumulation further restricts exhaust flow through the filter and contributes to an increase in pressure drop, which further

complicates pressure-based control systems. Depending on the location of the ash deposits, the ash may also enhance the filtration efficiency (particle capture) by serving as an added filtering medium along the channel walls [14].

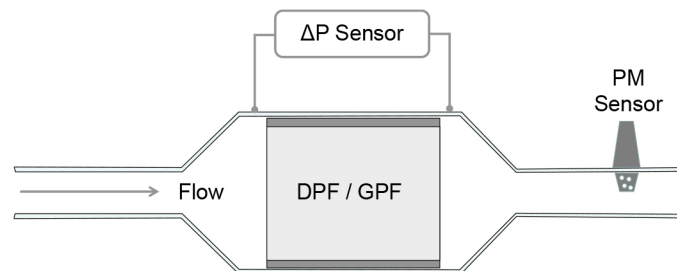


Figure 1. Conventional particulate filter monitoring configuration consisting of a differential pressure sensor and downstream PM sensor.

For many of the reasons outlined above, OBD requirements are challenging for pressure- and model-based approaches. As a result, soot sensors have been developed to detect soot which may pass through the particulate filter. Various types of sensors exist but can be broadly defined by two categories: (i) accumulating electrode sensors, and (ii) electric charge-based sensors [15]. Accumulating electrode type sensors function in a similar manner to the particulate filter, by monitoring a change in the electrical properties (typically resistance) on an electrode due to soot deposition. The electrode is periodically heated to regenerate (oxidize) any accumulated soot. In this manner accumulating electrode type sensors do not provide a real-time measurement of exhaust soot levels, but rather a time averaged measurement between sensor regeneration events [16].

Charge-based sensors, on the other hand, operate by inducing a charge on the incoming soot particles and monitoring that charge to determine the soot emissions rate [17]. The placement of these sensors in the exhaust stream requires additional optimization relative to exhaust flow, as both of these kinds of sensors require physical interaction with a sample of the exhaust stream. In either approach, the current state-of-the-art for particulate filter control and OBD relies on the use of indirect estimates of the filter loading state from pressure-drop measurements and predictive models, along with downstream soot sensors to detect soot leakage from the particulate filter only after the filter has failed via a small sample of the overall exhaust flow. Recent work has also indicated the inability of resistive approaches to accurately monitor tailpipe soot emissions from gasoline engines [18].

Radio Frequency Sensing

In contrast to current approaches, this work utilized radio frequencies (RF) to directly interrogate and monitor the state of the particulate filter. The operation of the system for directly monitoring soot and ash levels on the filter has been described in detail in previous publications [19, 20, 21]. The measurements rely on the use of the metallic filter housing as an RF resonant cavity. Accumulation of particulate matter on the filter alters the dielectric properties of the resonant cavity and enables direct measurement of the particulate filter soot loading level, provided the filter media is non-conducting (transparent to RF). Similar RF-based approaches have also been

applied to catalyst systems including selective catalytic reduction (SCR) and three-way catalysts (TWC) to monitor ammonia loading and oxygen storage, respectively [22-23]. Figure 2 provides an illustration of the RF system configuration used in this study where two probes are used to transmit and receive an RF signal in the filter housing. The RF signal propagates through the ceramic filter thereby providing a direct measurement of the filter's state.

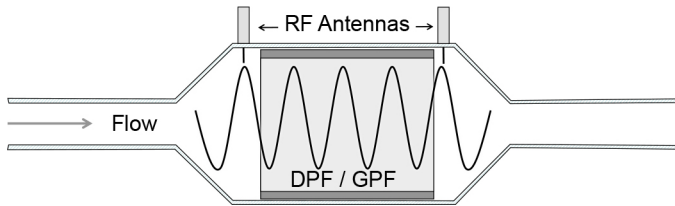


Figure 2. RF measurement system configuration showing two antenna probes used to transmit and receive the RF signal as well as the signal propagating through the ceramic filter media within the housing.

Other configurations of the system shown in Figure 2 are possible, including the use of only a single antenna, where the same antenna is used to transmit and receive the RF signal. A benchmarking study using a single antenna RF system to control DPF regeneration relative to the stock pressure- and model-based controls was previously reported to result in 15% to 30% shorter regenerations due to direct feedback of the soot oxidation during regeneration from the RF sensor [21]. Results of fleet durability testing of RF measurements systems with several Volvo/Mack vehicles also showed similar results [20].

Transmitting an RF signal over a broad frequency range within a metallic filter housing results in the resonance response shown in Figure 3. The peaks in the curves correspond to specific resonant modes, characteristic of the cavity, which are influenced by the dielectric properties of the material residing therein (filter, soot, ash). The figure shows a clear and distinct difference between an empty filter housing and one that contains a filter, which results in a shift of the resonances to lower frequencies. In this manner the presence (or absence) of the filter from the housing is readily detected. The same approach is applicable to catalysts.

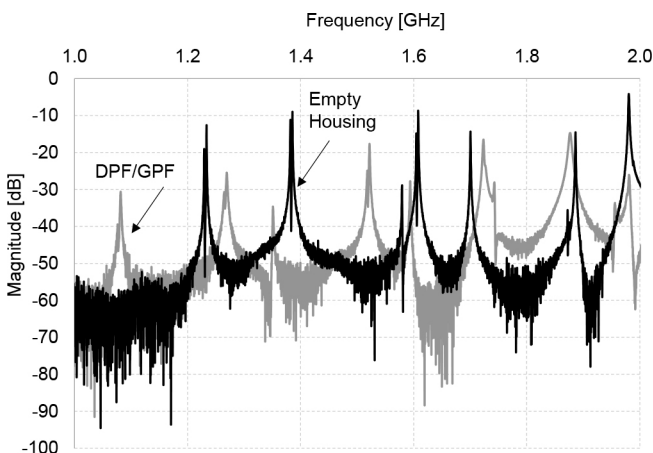


Figure 3. RF response for empty filter housing (black curve) and filter housing containing ceramic filter element (DPF/GPF).

The measurements corresponding to the results in Figure 3 were conducted with no flow through the system (engine off). In contrast to current approaches using pressure or temperature sensors to detect the presence of the filter or catalyst, which requires the engine be on and generating sufficient exhaust flow for a measurement, the RF measurements may be carried out at any time over the course of the drive cycle, including with the engine off.

Previous work has described the impact of soot and ash accumulation in the filter on the RF signal response, which serves to reduce the amplitude of the resonances (due to the high dielectric loss of the soot) and impacts the resonance frequency (in the case of ash) [19, 20, 21, 24]. In all cases the presence or absence of the filter, shown in Figure 3, exerts a change in the RF signal far greater than normal soot or ash loading, and can thus be readily distinguished from normal filter operation.

Examples of the impact of various intentionally induced filter failure modes on the RF signal response are shown in Figures 4, 5, 6, 7. A series of successively deeper cuts (in the radial direction) to the back surface of the filter is shown in Figure 4, which had the effect of removing an increasing number of ceramic end-plugs from the back of the filter. The corresponding RF measurements are shown in Figure 5 for one particular resonant mode. As can be seen from the measurements, the removal of ceramic material from the filter, such as the removal of end-plugs, results in a shift to higher resonant frequencies. The shift to higher frequencies with the removal of filter material from the housing is further consistent with the results in Figure 3, which show a large shift to lower frequencies as the filter was added to the cavity, relative to the empty cavity measurements.

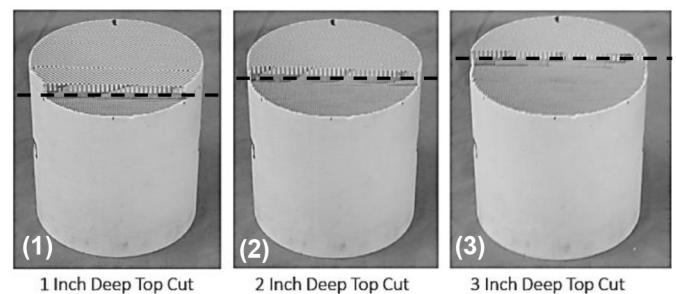


Figure 4. Defects introduced to new cordierite filter by cutting an increasing number of ceramic end plugs off of the back face of the filter.

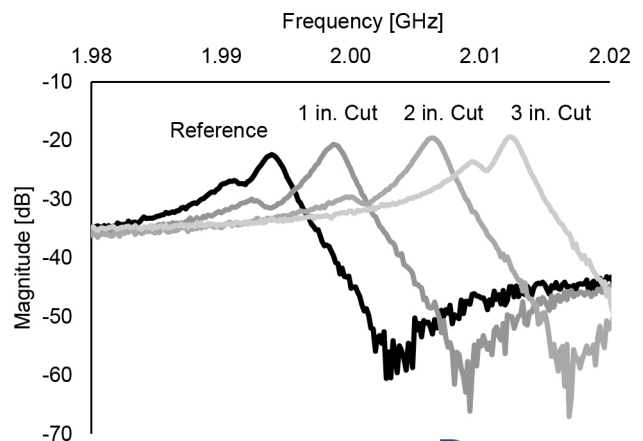


Figure 5. RF response of new filter and impact of increasing severity of defect introduced to back face of ceramic filter on RF signal.

Similar experiments were conducted, as shown in Figure 6, where a radial cut was made near the center of the DPF, with increasing thickness (depth of cut). The corresponding RF measurements are shown in Figure 7 for another resonant mode. Similar to the results in Figure 5, the removal of ceramic material from the filter results in a shift in the resonances to higher frequencies.

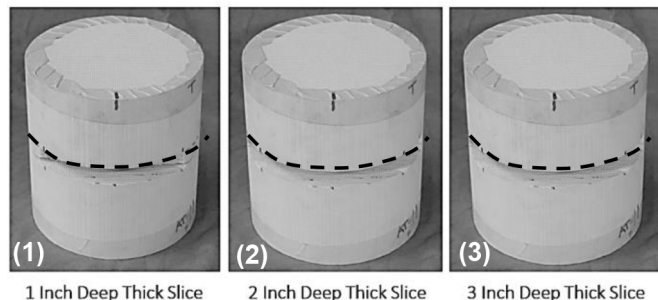


Figure 6. Defects introduced to new cordierite filter by cutting a slice from the center of the filter of increasing depth from 1 to 3 inches.

The sensitivity of a particular resonant mode to a specific local defect is dependent on the local electric field strength of that particular mode. Each resonant mode is associated with a specific electric field distribution in the filter, and monitoring multiple modes enables different regions of the filter to be interrogated spatially. The results of experiments and simulations evaluating the electric field distribution within the filter housing for a particular configuration are reported in [25]. Figure A-1 of the Appendix presents several examples of the simulation results showing the electric field distribution for different resonant modes, corresponding to a cordierite gasoline particulate filter application.

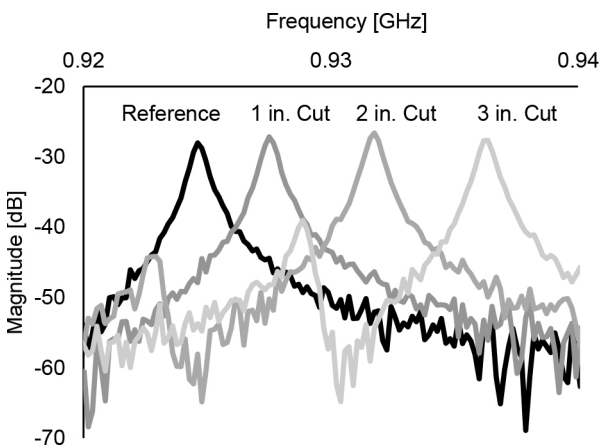


Figure 7. RF response of new filter and impact of increasing severity of defect introduced to center of ceramic filter on RF signal.

Figures 3, 5, and 7, thus indicate the potential to not only detect the presence or absence of the filter (or other ceramic substrate) within the exhaust aftertreatment system, but also indicate the sensitivity of the RF measurements to local defects. The measurements may further be carried out during normal operation, or even with the engine off (no exhaust flow) as shown in the figures.

EXPERIMENTAL APPROACH

Given this discussion on the background and fundamental operating principles of the RF measurements, the remainder of this work is focused on evaluating specific diagnostic applications of the RF sensing technology. It was the aim of this study to first detect signs of upstream (of the DPF/GPF) malfunctions in order to provide early warning/prevent catastrophic filter failure, and second to evaluate the accuracy of the RF measurements to detect a reduction in filter trapping efficiency should damage to the filter have occurred. The experimental results span heavy-duty vehicle tests as part of a three-year field trial as well as laboratory dynamometer evaluations on diesel and gasoline engine applications conducted at Oak Ridge National Laboratory's Fuels, Engines and Emissions Research Center.

RF Sensor

The RF sensor utilized in this study consists of a sensor control unit and a measurement probe, shown in Figure 8. The measurement probe, a stainless steel rod-type antenna, is a passive component used to transmit and receive the radio-frequency signals in the filter housing. The antenna is of similar size and form factor to conventional temperature sensors used in exhaust systems. The control unit contains the RF electronics as well as an embedded micro-controller. A wiring harness, connected to the unit, provides additional inputs from exhaust temperature sensors for temperature compensation of the RF signal. The measurement output is broadcast via the CAN network.



Figure 8. RF measurement system including sensor control unit and measurement probe.

The RF sensor, shown in Figure 8 provides fast response, less than 1 second, measurements of filter soot levels, enabling near real-time filter management. Unlike conventional pressure sensors, the RF sensor is unaffected by exhaust flow rate [19], but does require temperature compensation, as the dielectric properties of the PM do vary with temperature. The sensor is capable of accurately measuring soot in the DPF over the full range of engine operating conditions spanning idle to high temperature active regeneration events, including drop-to-idle, as previously reported [24].

Results of RF sensor evaluations on a 1.9L GM turbo-diesel engine at Oak Ridge Laboratory are presented in Figure 9. The evaluations explored sensor response time relative to AVL Microsoot Sensor (MSS) measurements of engine-out soot. Figure 9(a) shows the RF sensor derivative response to soot accumulation on the DPF for two pedal tip-in events along with the AVL measurements [26].

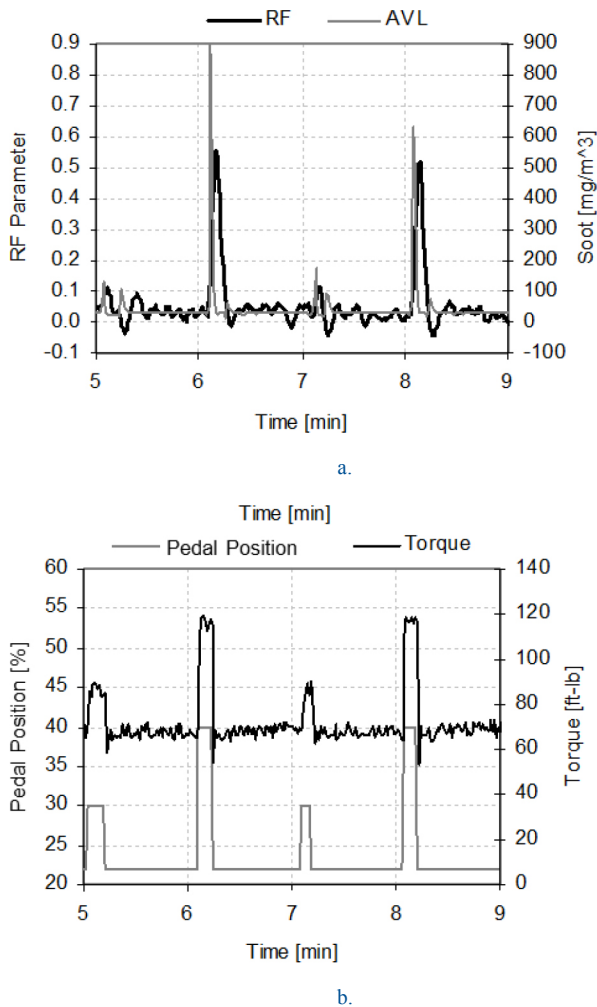


Figure 9. AVL MSS response and derivative of the RF measured DPF soot load (a) for short-duration pedal tip-in events at elevated load (b). Images from SAE 2016-01-0918.

The RF sensor derivative response in Figure 9 is determined from the instantaneous soot accumulation levels measured on the DPF. Figure A-2 of the Appendix includes the raw RF measurements of the filter soot loading levels, as well as the derivative response computed from those measurements. In this manner, the fast-response RF sensor measurements of the filter loading state (2.5 Hz in this study) may serve as an indication of engine-out soot levels, with the particulate filter itself essentially serving as an accumulation soot sensor. While the previous work [26] characterized RF sensor response with a fully-intact (healthy) DPF, this study builds on the previous work by exploring the effect of specific filter failure modes on the RF sensor response over a range of operating conditions.

Fleet Vehicle Evaluations

A three year fleet vehicle test was conducted with MY 2009 and 2010 Volvo/Mack trucks operated by the New York City Department of Sanitation (DSNY). The vehicles were equipped with six-cylinder, 11 L,

direct injection, Mack MP-7 diesel engines. Depending on calibration, the engine is rated from 325 to 405 Hp (242- 302 kW) at 2,100 rpm and 1,200 to 1,480 lb-ft (1,626 - 2,005 N-m) at 1,200 rpm. All testing was conducted with the engine operating from the stock calibration and control system, with the RF sensor passively monitoring the state of the particulate filter. Results from the first year of fleet testing were reported by the authors in a previous publication [20].

The DPF system for the test vehicles consisted of an un-catalyzed cordierite particulate filter, measuring 12 inches (30.28 cm) in diameter and 12 inches (30.48 cm) in length, for a total filter volume of 22.24L. A thermal regenerator (burner system) installed in the exhaust near the filter inlet was used for active DPF regeneration, given the low-temperature, urban drive cycles over which these vehicles are routinely operated. Figure 10(a) shows the RF sensor installed on the exhaust stack next to the DPF, and Figure 10(b) shows the vertical aftertreatment system configuration on one of the fleet test vehicles.

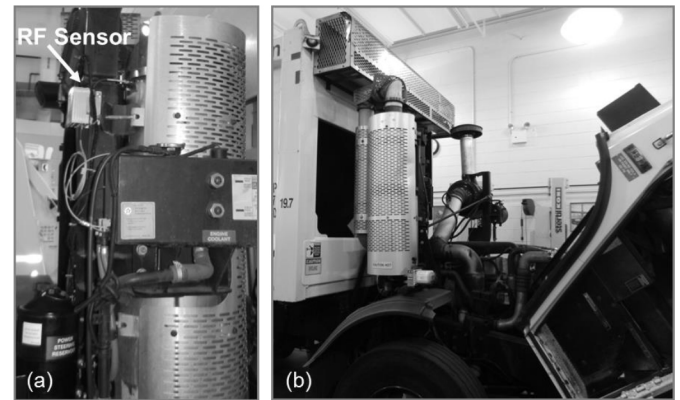


Figure 10. RF sensor installed on exhaust stack of Mack test vehicle (a) and diesel particulate filter configuration and test vehicle (b).

Diesel Engine and Instrumentation

Laboratory testing was also conducted with the RF sensor installed on a 1.9-liter, four-cylinder General Motors (GM) common rail diesel engine coupled to a motoring direct current dynamometer. The engine has a rated power of 110 kW (148 hp) at 4000 rpm and a rated torque of 315 N-m (232 ft-lb) at 2000 rpm. The engine is equipped with a high-pressure common rail fuel injection system, variable geometry turbocharger, swirl actuation, and cooled exhaust gas recirculation (EGR). All experiments were carried out with the engine operating on ultra-low-sulfur certification diesel fuel (Haltermann Solutions).

The RF sensor was installed on a catalyzed cordierite diesel particulate filter, with a 200/12 channel geometry (200 cells per square inch / 0.012 inch wall thickness). The total particulate filter volume was 2.47L. A diesel oxidation catalyst (DOC) was located upstream of the catalyzed DPF. Figure 11 presents a schematic layout of the engine, exhaust system, and RF sensor configuration.