On-Board Engine Exhaust Particulate Matter Sensor for HCCI and Conventional Diesel Engines

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Technical Development Partners:
Cummins Engine Company
EmiSense, Inc.

Commercialization Partner:
EmiSense, Inc.

Final Report

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The goal of the research was to refine and complete development of an on-board particulate matter (PM) sensor for diesel, DISI, and HCCI engines, bringing it to a point where it could be commercialized and marketed. The work was performed through a joint effort between the University of Texas at Austin and the Cummins Engine Company in cooperation with our commercialization partner EmiSense Inc.

The project start-date was October 1, 2006 with an original completion-date of December 31, 2009. Subsequent no-cost extensions were granted carrying the project through September 30, 2011. The primary reason for the requested extensions was to allow Cummins Engine Company enough time to perform tests of the sensor in their facilities to complete fulfillment of their cost-share obligation. Cummins was a vital contributor to the project. They provided UT with a 6.7 liter diesel engine and engine control software for sensor development along with a diesel oxidation catalyst (DOC) and diesel particulate matter filter (DPF). In addition, they provided considerable technical help over the duration of the project in the form of Engineer and Technician time allowing us to keep the UT development facility operational. The testing of the sensors at Cummins did not occur, however. As a result we submitted a request to DOE to substitute cost share from EmiSense for that of Cummins. This request was approved.

According to the original proposal the in-house Cummins testing was to constitute the majority of their cost-share to the project. The original cost-share to be contributed by Cummins was \$99,000 which was in addition to the \$282,001 in cost-share contributed by UT. This gave an original cost-share percentage for the project of 42% for Phase 1 (Year 1) and 50% for Phase 2 (Years 1 and 2).

As part of the Phase II tasks Cummins was to evaluate the sensor on both a heavy-duty diesel engine and an HCCI engine that they planned to develop. The main problem that we ran into during Phase II was that we had still not developed the sensor to the point where it could be reliably and accurately tested by Cummins within the original time

frame, despite our best efforts. Through continued development the problems were largely solved by the end of the project through the cooperative research between UT and our commercialization partner EmiSense, but further development continues.

The project was initiated to support the development of a PM sensor concept discovered at the University of Texas at Austin. It was discovered that soot particles passing through the electric field between two electrodes having a 1000 VDC potential difference across them could interact with these electrodes, depositing electric charge on them. The resulting current or charge could be detected with a charge or current amplifier and related to the concentration of the carbonaceous PM in the flow.

The focus of Phase 1 was the development of a PM sensor system that would account for the velocity dependence of the sensor; other tasks were to quantify the sensitivity and dynamic range of the sensor. Phase 1 of the project was completed during the first budget period with most of the work done at UT. Two concepts were examined for accounting for velocity sensitivity. In the first, a pitot tube was used in the exhaust to measure the exhaust velocity. This velocity was to be used as a parameter in an empirically derived correlation to determine the PM concentration. The second concept was to have a separate flow circuit for the PM sensor. Instead of inserting the sensor directly into the exhaust system, a by-pass flow circuit would be attached at this point, with a small downstream blower used to create a fixed volumetric flow rate of exhaust gases past the sensor that is independent of engine operating conditions.

Eight tasks comprised the first budget period. The first three tasks are given below.

Task 1.1. Assemble new PM sensors and sensor electronics and configure data acquisition.

Task 1.2. Design external flow channel, order parts and materials, and order pitot tube system.

Task 1.3. Complete set-up and instrumentation of existing single-cylinder diesel engine test stand.

- For Task 1, a new, compact, design for the PM sensor electronics was created and tested.
- For Task 2, a new exhaust manifold system was designed, built, and installed in the single cylinder Yanmar diesel engine that we used for testing prior to commissioning the Cummins engine. This system allowed access to the exhaust for the PM sensor at several locations and included an isokinetic sample port for gravimetric PM concentration measurements.
- For Task 3, the single-cylinder diesel engine and its dynamometer were relocated and set up in another dyno-lab offering better security. The engine fuel supply system was installed. The engine and dynamometer was tested by running the engine over a range of speeds and loads, and the computer interfacing to the dynamometer was completed. This allowed a continuous readout of engine

speed, torque, and power. A new filter-based particulate matter sampling system was designed and built. This system was tested by taking repeated measurements at the same operating condition to assess reproducibility of the filter measurements.

In the second quarter of the research additional progress was made toward completing Tasks 1.1-1.3 and progress was made on Task 1.4, given below.

Task 1.4. Build external by-pass flow channel and test different blower/evacuation configurations with the single-cylinder diesel engine.

The idea behind Task 1.4 was to put the sensor in a separate exhaust gas flow channel in which the velocity of the gasses could be kept constant to eliminate any sensitivities due to velocity changes. This, ultimately, was not successful. It was difficult to maintain a steady flow in the pulsating exhaust using a blower and it added complication to the system.

Also in the second quarter, an opportunity arose to work closely with a possible commercialization partner. This was Task 2.1 of the project (given below).

Task 2.1. Identify qualified sensor commercialization partner.

This was not scheduled to occur until the second budget period, but we felt this task should be pursued early to take advantage of the opportunity presented to us since we feel it would speed both the development and commercialization of the sensor system.

- The possible commercialization partner was Emisense, Inc., located in Salt Lake City, Utah. They expressed interest in commercializing the sensor for use as a detector of particulate filter failure in diesel engines. They designed and built two sensors which they sent to us for testing. These initial designs were very different from ours. They consisted of epitaxially deposited electrons on flat ceramic substrates incorporating integrated heating element to keep the sensor clean. We tested the sensors and found that while this design worked, the sensor became dirty and the signal deteriorated quickly. The important observation from these measurements; however was that their heater was excellent at keeping the heated part of the sensor clean.
- Following this and related to Task 1.1, we just started, once again, making new sensors of our own. We built them to incorporate a heating element similar in concept to the sensors provided by Emisense. In a short engine test this heater also did a good job keeping the sensor clean, however, we discovered that this first sensor did not provide enough electrical isolation, so the sensor part of it did not work.

In the third and fourth quarters progress was made on tasks 1.5 and 1.6.

Task 1.5. Evaluate the performance of the pitot tube velocity measurement system in the single-cylinder diesel engine.

We discovered that a pitot tube did not have sufficient response-time to follow the rapid changes in velocity associate with the pulsating flow of a single-cylinder engine. Fortunately we found other methods of evaluating the effects of flow velocity on sensor response. These are mentioned below as part of the work we did toward completion of Task 1.6.

Task 1.6. Measure and document time-response, sensitivity, dynamic range, and durability of the best PM sensor system (from Tasks 1.4 and 1.5) in the exhaust of a single-cylinder engine, evaluating different sensor designs

Figure 1 Simultaneous measurements with two PM sensors during two short and one long engine transient, along with engine speed.

Figure 1 is an example of sensor response. It shows simultaneous measurements from two PM sensors located in the exhaust. The sensors show their response to momentary increases in fuel delivery known as tip-in events. The interesting aspect is the correlation between the outputs of the two sensors. Measurements were often done using two sensors because by observing two sensors it was much easier to distinguish between actual changes in PM concentration and noise artifacts in the signal. The strong correlation between the features in the signals is clear.

The analyses of these tip-in events were found important to quantifying sensor response and effects of exhaust velocity. Figure 2 shows the responses of two sensors to a pair of typical tip-in events. While the responses of the two sensors were qualitatively similar, features of the responses raised many interesting questions.

- The sensor response to the transient had a curious double hump; the signal envelope first rose and then decreased before rising again and finally falling to the baseline level.
- Pronounced spikes in the signal were evident which were especially large in the first hump.

Figure 2. Response of sensors PM1 and PM2 to a double tip-in event.

The spikes seen in Fig. 2 have a period of 70-80 ms, equal to the duration of one engine cycle. An especially curious aspect is that the first hump appeared to occur simultaneously in the two signals, but there is a time lag between the second humps of the two sensors.

We measured the time-resolved exhaust gas opacity while simultaneously measuring the PM sensor signal. The two signals were recorded on the oscilloscope for the same type tip-in events as above. An example of one set of results for a pair of tip-in events is shown in Figure 3.

Figure 3. Response of sensor PM1 and opacity sensor to a pair of tip-in events.

These results were especially elucidating. The upper trace is the PM sensor output while the lower trace is the opacity signal. The opacity signal decreases as the light intensity reaching the detector drops due to attenuation by soot particles in the optical path.

- The most important observation is that the opacity signal begins to fall at the same moment the PM sensor signal begins its rise at the beginning of the tip-in. This demonstrates that the first hump in the PM sensor signal was indeed a reaction to the presence of particulate matter and not a spurious signal.
- The second important observation was that the high PM concentration flow reached the two measurement locations very fast, on the order of 10 ms. At an engine speed of 1500 rpm the duration of the exhaust stroke from BDC to TDC was 20 ms.

The data suggested that the first three engine or four cycles during a tip-in event receive large amounts of fuel and have very strong blow-down events. These blow-down events were strong enough to eject a portion of the cylinder contents more than 2 meters downstream of the exhaust port in a time shorter than the duration of the exhaust stroke. The PM in the second hump moved through the exhaust at a velocity close to the time-averaged exhaust flow velocity.

In the 5th quarter from October 2007 through December 2007 we achieved the following accomplishments:

- A particulate filter measurements system was designed and assembled to allow the sensors to be calibrated for non-volatile mass emissions of particulate matter. Using this system the engine's PM emissions were determined as a function of engine operating condition.
- New sensor designs were developed, tested, and calibrated. A new air purged sensor design was created and evaluated. This design led to much improved sensor durability. The lifetime of the first sensor of this type was in excess of 15 hours of operation, over an order of magnitude improvement over earlier designs. An hour-long test showed no change in sensor sensitivity. This concept was eventually abandoned, however, since the use of active air purging would be undesirable in a commercial sensor.
- The response of the sensor to PM emissions created during engine transients was assessed. The response time of the sensor was found to be less than 20 ms.
- We formalized the relationship with our industrial partner to commercialize our PM sensor technology. The company, as mentioned above is Emisense, Inc. a division of Ceramatec, Inc.

In the quarter from January 2008 through March 2008 we completed Phase 1 of the project and began Phase 2. The focus of Phase 2 was further refinement of the sensor for production engine use, the pursuit of commercialization, further understanding of sensor fundamentals of operation, and application of the sensor to a Cummins 6.7 liter engine.

The tasks for Year 2 of the project are given below.

Task 2.2. Identify qualified sensor commercialization partner.

Task 2.3. Complete set up of the 6.7 L Cummins light-duty engine on a dynamometer test stand.

Task 2.2.1. Couple 6.7 L Cummins engine to dynamometer

Task 2.2.2. Install fuel delivery system and instrumented exhaust system for pressure and temperature measurements, and gas extraction.

Task 2.2.3. Install engine electronic control unit and adapt dynamometer actuators to control engine operating parameters

Task 2.2.4. Break-in engine and test over appropriate speed and load range.

Task 2.2.5. Adapt exhaust PM filter system to engine exhaust.

Task 2.2.6. Configure sensor data acquisition system and sensor elements for engine.

Task 2.4. Measure and document sensitivity, time response, and durability of the best PM sensor in the exhaust of the 6.7 L Cummins engine.

Task 2.2.1. Identify speed and load range of interest by observing sensor signal levels and measured levels of PM mass on filters.

Task 2.2.2. Acquire sensor data to confirm transient response time over the range of speeds and loads of interest.

Task 2.2.3. The engine will be run for extended periods of time over many hour and days to assess sensor durability, quantifying in terms of both sensor failure, electronics failure and signal degradation

Task 2.2.4. Regimes of engine operation will be identified in terms of speed and load, and EGR level, and transient operation to maximize the variations of PM mass emission levels to quantify the sensor's dynamic range and low-end sensitivity

Our progress on the Phase 2 tasks was initially slowed because of delays in Cummins' ability to supply us with the 6.7 liter engine. In the mean time we made several important fundamental breakthroughs in the design of the sensor, and a licensing agreement between the University of Texas and Ceramtec was signed in early February 2008.

Figure 4 Three PM sensor designs. From top to bottom: (a) air purged sensor, (b) brass housing sensor with ceramic tube electrode shields, (c) brass housing foil-electrode sensor with external heater coil.

- The air purges sensors gave way to two new sensor designs that greatly increased sensor durability and ease of manufacture. A new sensor design having a metal housing rather than the previous cold weld housing was developed. This sensor had its electrodes seated deeply within ceramic tubes. The result was that particulate fouling of the electrodes was reduced since the exhaust particulate flows had a hard time flowing into the ceramic tubes. The old cold-weld design can be seen in Figure 4 (Design a), with the next generation sensor also shown in Figure 4 (Design b). The construction of the sensors was also simplified by this construction. While sensor durability was improved the sensor did still become fouled during operation with very heavy soot loading in the exhaust. Another problem was that the new sensor electrodes were greatly cantilevered. This resulted in vibration of the electrodes and a new noise contribution.
- Design (c) followed. This design eliminated the use of solid metal electrodes in favor of thin metal foil electrodes that were bonded to ceramic tubes. Design (c) incorporated a resistive heater to burn PM from the tube surface preventing a conductive path from being created. This design was demonstrated to have several advantages. We have found it more sensitive to PM than the other sensors. The heater on the sensor electrode did a reasonably good job of keeping the sensor free of fouling and we demonstrated the sensors operation for durations of one hour in the single-cylinder engine without fouling. In addition, since the electrodes of the sensor were mounted on two rigid ceramic posts, the vibration noise of the sensor was dramatically reduced.

- We tested the sensor in flows of volatile organic compounds, for example, condensed-phase aerosols generated by the impingement of oil on a hot plate and found the sensor completely unresponsive to these volatile compounds.
- At this point in the project we began work on a steady-state rig in which to test the sensors. The advantage being eliminating the pulsating flow of the engine exhaust which allowed us to focus on the fundamentals of sensor operation such as the fundamental principle/s of operation and refinement of the velocity effect on sensor output.

In the quarter from April 2008 through June 2008 we had to redirect the research because of the continuing delay in obtaining the 6.7 liter engine from Cummins. We were told in late May 2008 that we could expect the engine within a week or two, but within that time heavy rains in the Midwest led to flooding that flooded the underground storage area of the Cummins Technical Center where the engine was stored. The flooding shut-down their operations and ruined the engine they had picked out for us. This led to additional delay.

At this point our DOE Program Manager contacted Cummins, on our behalf, and facilitated an accelerated search for a new engine.

In the mean time we concentrated our efforts on four areas.

1. Finishing the setup of our steady-state test-rig, and using it for PM sensor development, testing, and evaluation.
2. Preparing for on-board vehicle testing of the PM sensors.
3. Refinement of sensor design
4. Commercialization of the PM sensor technology

Steady-Flow-Rig.

The steady-flow-rig consisted of a vertically oriented flow tube constructed of PVC plastic (Figure 5). The tube necked down twice in the direction of flow so that three different flow velocities were present in the tube simultaneously at different locations. Particulate matter was generated using a steady-state diffusion flame.

Figure 5 Steady-flow-rig for testing PM sensors.

The purpose of the steady-flow-rig was to allow us to gain a better understanding of the physical principles governing sensor operation and performance.

From prior research we knew that the sensor's sensitivity was a function of the flow velocity in addition to the particulate mass concentration. The steady-flow-rig was to allow us to explore this dependence without the complications created by the inherent pulsating flow of the engine exhaust.

We finished the construction and testing of the steady-flow-rig in this quarter and began testing PM sensors using it. This testing led to very important insights about the principal of operation of the sensor. Before discussing that further, however, some other issues shall be mentioned.

In the early PM sensor testing with the steady-flow-rig we found it difficult to maintain a steady base-line signal with the PM sensors we were using. The output signals tended to drift upward with time in a manner we had not seen in the exhaust of our single-cylinder test engine. We eventually concluded that the drift was due to the sensors becoming dirty with carbon soot. We were using the same heated sensors which tend to keep the sensors relatively clean in the engine exhaust. By probing the soot accumulated on the sensor surface we determined that the soot was more "fluffy" than PM deposits in the engine. The soot could be easily blown or wiped away much more easily than deposits from

engine operation. We hypothesize that the soot did not “wet” the surface as the diesel exhaust did which has greater VOC content. We think this resulted in very poor thermal contact between the soot and the heated sensor surface making it hard to burn off.

The soot was created using a diffusion flame burning acetylene. Thinking the phenomenon might have something to do with the type of fuel, we modified the rig to run on a diffusion flame burning diesel fuel. This required modifying the rig to operate on a liquid fuel which took some effort. The results with diesel fuel soot were similar, however, so we concluded that it was not the type of fuel, but rather the difference between burning the fuel in a burner versus the engine where apparently more VOCs are present.

An important discovery about the PM sensor principal of operation came while testing the sensors in the steady-flow-rig. Our results in the engine showed an increase in sensor sensitivity to PM with increasing flow velocity, but this trend was reversed in the steady-flow-rig. Our prior hypothesis was that we were detecting the naturally charged particles in the diesel exhaust. We then introduce carbon particles into the steady-flow-rig flow in the form of activated carbon and graphite powder. To our surprise we measured a strong signal from the PM sensor. At the time we concluded that we were not detecting only particles naturally charged through combustion. Later bench-top testing (to be described later) found that tribologic charging of the particles was the likely source of the signal.

We are currently working on how to use this new knowledge to our advantage.

Vehicle Testing

Since the Cummins engine was still unavailable to us, we decided to start testing the sensor in a vehicle. To this end we began the process of adapting the sensor system to our Chevy Equinox equipped with a 1.9 liter Fiat/Opel turbo-diesel engine. The exhaust was without a diesel particulate filter. An access hole for the sensor was made in the exhaust about mid-way between the engine and muffler and the wiring and installation of the power electronics was completed. An opacity meter was designed that fit to the end of the vehicle’s tailpipe and allowed us to compare the PM sensor output with measurements of opacity. The vehicle was instrumented to simultaneously record the PM sensor output, the signal from the opacity meter, vehicle speed, engine speed, pedal position, and engine load.

By the end of the quarter (Sept. 31 2008) we had still not received the 6.7 liter test engine from Cummins. The engine finally arrived in early October 2008 at which time we began the process of installing the engine on one of our test cell dynamometers. The efforts in this quarter were aimed at gaining a better understanding of the fundamentals of sensor operation, creating new PM sensor designs for enhanced durability, and vehicle testing of the sensor.

Figure 6– Five minute drive cycle from Equinox showing PM sensor output, opacity meter output, engine speed (rpm divided by 1000), vehicle speed (km/hr divided by 10), and pedal position (% of max.).

The vehicle testing was done on city streets around the University. Five minutes of driving data are shown in Fig. 6 to provide an overview of the behavior of the various parameters. For these data the PM sensor was mounted at the mid-point position in the exhaust. The figure shows the PM sensor output voltage, opacity meter output voltage, vehicle speed in km/hr divided by 10, engine speed in rpm divided by 1000, and pedal position.

As seen in Fig. 7, the baseline opacity meter signal decreases with time, particularly following large transient PM emissions; this was caused by soot fouling the photodetector. Because of this the photodetector required frequent cleaning. No change in the baseline signal was observed for the PM sensor during the vehicle tests. For some of the transients seen in Fig. 7, the PM sensor signal did not come down to the baseline value immediately following the peak. It was not clear why this behavior was more evident in the PM sensor signal than in the opacity meter signal.

Figure 7 Approximately one minute portion of drive cycle from Equinox showing PM sensor output and opacity meter output.

Figure 7 shows a one minute period from the drive cycle of Fig. 6, presenting only PM sensor output and opacity meter output. There is reasonably good qualitative agreement between the two; the short duration peaks are well correlated. For two engine transients near the 2 s time mark, the PM concentrations were great enough to saturate the PM sensor, sending its output off scale (beyond 5 V). The time-response of the sensor is evident through its rapid recovery time from the transient puffs. The PM sensor response time was limited by a low-pass filter set to approximately 0.9 Hz. This was considered adequate to resolve the transients since its signal durations were comparable to those of the opacity meter which had a detector time-response in the sub-millisecond range. The sensor used for the above measurements showed good durability over several hours of driving.

The tasks for Year 3 of the project are given below.

- Task 3.1. Examine PM sensor suitability as an on-board diagnostic for regeneration of a diesel particulate filter and detection of filter failure.**
- Task 3.2. Optimize electronics package.**
- Task 3.3. Assist commercialization partner with design of production version of PM sensor system, and assist with licensing agreements.**
- Task 3.4. Document sensitivity, time response, suitability, and durability for application to a heavy-duty diesel HCCI engine - in HCCI mode.**
- Task 3.5. Document sensitivity, time response, suitability, and durability for application to a heavy-duty diesel HCCI engine - in transition (mode-switching) mode.**
- Task 3.6. Examine PM sensor installation in HCCI exhaust manifold for suitability for individual cylinder control.**
- Task 3.7. Optimize electronics package (note, redundant with Task 3.2).**
- Task 3.8. Identify most commercially-viable design for PM sensor and electronics.**

The efforts in the first two quarters of Year 3 from October 1 2008 through March 31 2009 proceeded on two fronts.

1. Commissioning of the Cummins 6.7 liter engine
2. Further development of the PM sensor design and application to a vehicle

The previous tasks of Year-2 of the project were modified to adjust for the late arrival of the Cummins 6.7 liter engine at UT. Because of its late arrival we proceeded on to testing of the PM sensor in a vehicle. This work has continued into the 3rd year of the project. We are continued the vehicle testing in parallel with the Cummins engine testing.

We finally received the 6.7 liter engine from Cummins is October 2008. The engine was quickly installed on an engine dynamometer and the necessary ancillary parts were fitted to complete its setup. A Cummins technician spend one week in early March 2009 helping us get the engine operational. At that time we were still waiting for Cummins to provide us with a diesel particulate filter (DPF) for the engine. The DPF was considered critical for the further development of the sensor. While we have made preliminary PM sensor measurements in the untreated exhaust of the Cummins engine the DPF was needed to obtain the ultra-low levels of PM concentration for the development of the PM sensors for such low PM levels. During this time we were actively working with our commercialization partner EmiSense on sensor development and were testing their prototype commercial sensors. Work continued to improve the sensor design for improved durability. New heater designs and electrode support geometries resulted in a great improvement in sensor durability. This was illustrated by the long duration vehicle testing that was done.

Continuation of Light-Duty Vehicle Testing

The purpose of the vehicle testing was two-fold: to evaluate the sensor behavior on an actual vehicle and to characterize the PM emissions behavior of the vehicle. For the sensor, we were primarily interested in its time-response, its sensitivity to PM, its noise characteristics, particularly with respect to vibration, and its durability.

Figure 8 shows the output of the PM sensor compared with the output of the opacity meter for 11 minutes of urban driving. While PM emissions are relatively low for most of the drive-cycle several very high PM concentration events were recorded. As seen in the figure, the PM concentrations were exceeding 1000 mg/m³.

Figure 8 Calibrated PM sensor output (sensitivity = $200 \text{ mg/m}^3 \text{ V}$) compared with opacity meter output for 12 minute drive.

The PM sensor signal was recorded as a voltage proportional to the dry PM mass. We used gravimetric filter measurements to quantify the PM concentration of the exhaust (mg/m^3) and relate these measurements to the PM sensor signal for calibration.

During the quarter of April 1 through June 30 2009 the Cummins engine was adapted for PM sensor measurements. The exhaust pipe was fitted with bosses for the installation of PM sensors at various downstream locations, as well as, thermocouples. The Cummins 6.7 liter engine was tested over its full range of speeds and to mid-load torque levels. Previously, we had not tested the engine beyond low torque conditions because of the relatively light-duty transfer shaft between the engine crankshaft and the dynamometer input drive. In early June a higher torque rated transfer shaft was installed to allow high torque testing. The resistive torque developed by the dynamometer was speed dependent and had a maximum of 500 ft-lbs; thus, the full load range of the engine could not be reached.

An exhaust sampling system was installed and we made extensive gravimetric measurements of PM mass concentrations over a range of speeds from 700 to 2200 rpm and torques levels of up to 50% of maximum. The PM emissions behavior of the Cummins was very different from the single-cylinder Yanmar engine we had been using. The engine-out PM mass concentration emissions of the Cummins were significantly lower than from the Yanmar. The lowest emissions from the Yanmar occurred for idle conditions and were in the range of $15\text{-}30 \text{ mg/m}^3$. These concentrations increased dramatically with increasing load.

The Cummins engine had non-volatile PM mass emissions concentrations in the range of about $15\text{-}20 \text{ mg/m}^3$ at idle and they tended to decrease as load increased. At 1800 rpm and 300 ft-lb torque emissions are in the range of about $5\text{-}10 \text{ mg/m}^3$. To our surprise, the

sensor output voltage was greater for higher torque operation at the same engine speed, for which lower PM mass concentrations were measured gravimetrically. This behavior was very different from what we saw with the Yanmar engine. We theorized that it was due to a change in the size distribution of the particles with load. We further theorized that the particles were smaller and more numerous at the higher load conditions contributing to the increased signal. Since we didn't have particle sizing instrumentation we were not able to verify this

We ran several tests to ensure that the sensor was not changing its response as its temperature increased at higher torque levels. We verified that the temperature of the sensor was not affecting the measurements. We did this by changing load very quickly, over a time scale short relative to the time for the sensor temperature to change. The signal changed immediately with a change in torque, faster than the sensor temperature could change significantly. It may be noted that the most recent designs from EmiSense show a significant influence of temperature on sensor sensitivity, a consequence of the newer single electrode designs.

Another unexpected observation was the sensor response to increasing amounts of EGR at fixed speed and load. EGR levels were varied from 0 to 20%. Gravimetric measurements showed a slight increase in PM mass concentration with increased EGR while sensor output voltage decreased as EGR was increased. The filters were visibly much blacker with higher EGR, consistent with the gravimetric measurements. This is further evidence suggesting to us that a changing particle size distribution may be playing a role in PM sensor sensitivity. It may be that at higher EGR levels the particle number concentrations are smaller, but the particles are larger leading to similar or higher mass concentrations. This trend is also reversed for the newest EmiSense sensors which consistently show increasing output voltage with increases in EGR.

Another important observation from the Cummins engine measurements was that the PM sensors had a higher sensitivity to particulate mass-concentration than in the Yanmar engine. Observed sensitivities varied with operating condition, particularly engine speed, with sensitivity increasing with an increase in engine speed. At 1800 rpm PM sensor sensitivities were approximately 1 V/mg/m^3 . This was very near the level needed to measure DPF failure with a downstream sensor. We did more work with EmiSense to improve the design of their sensors. This involved studying different electrode geometries and sensor packaging.

The rest of 2009 was mostly spent testing new designs of EmiSense manufactured prototype sensors

Sensor Design Evolution in Cooperation with EmiSense

The sensor design evolved greatly over the period from October 2009 through March 2010. Figure 9 shows a prototype commercial sensor built by Emisense. Most of our Year-3 work was done with these pre-production sensors (Figure 9).

Figure 9 - Typical EmiSense electronic soot sensor with electrode and shrouds on the left, M18 threads, and sensor body on the right.

The engine was fitted with a combined DOC/DPF unit installed in the exhaust system to enable full testing of the OBD function of the sensor. Plumbing was installed to allow part or all of the exhaust gas to flow around the DOC/DPF. In this way, a DPF failure could be simulated by allowing unfiltered exhaust to reach a sensor installed downstream of the DPF. Valves were installed at the DPF inlet and in the bypass to provide no-partial- or full-diversion of exhaust gas through the bypass. A schematic diagram of the DPF-bypass arrangement is shown in Figure 10.

Figure 10 - Arrangement of the diesel particulate filter and bypass loop.

Simulation of DPF Failure

To simulate the failure of a DPF by leakage of unfiltered exhaust gas, sensors were installed in the upstream and downstream ports. The engine was warmed up and brought to thermal equilibrium. Initially, all of the exhaust flow was directed through the DPF. At a specified time, the valve to the bypass loop was slowly opened. After 20 seconds, the valve to the DPF was closed, thus diverting all of the flow through the bypass. Then after 20 seconds, the process was reversed, first by opening the valve to the DPF, and then by closing the valve to the bypass. Steady-state averages were calculated for the initial state, the intermediate state, and the full bypass state. Figure 11a shows the signal history from one such test at a high-speed, low load condition at 2200 RPM. The signal from the upstream sensor is shown for comparison.

Figure 11 - (a) Simulation of DPF leak at 2200 RPM at light load, (b) increase in PM sensor output during DPF leak event at various fueling rates

Several such tests were conducted ranging from idle condition (where the sensor has the least sensitivity) to partial load (50%, 1800 RPM) to assess the ability of the sensor to detect leakage of unfiltered exhaust gas through the DPF. At each condition, the mean value of the sensor signal was calculated for the initial, DPF-filtered state, and for the partial and full bypass states. A percent increase in the signal over the initial, post-DPF baseline condition ($V_{\text{mean,DPF}}$) could then be calculated for the partial and full bypass conditions as follows

$$\%increase = \frac{V_{\text{mean}} - V_{\text{mean,DPF}}}{V_{\text{mean,DPF}}}$$

These percentage increases are shown plotted against fueling rate in injection mass per second in Figure 11b. Note that the increase for the partial bypass condition is about half the increase for the full bypass. In the case with the greatest sensitivity, the full-bypass produces a signal increase of 620% over the baseline condition. In the least sensitive case, at 700RPM idle, the increase was 88% for full bypass.

By the second quarter of 2010 the project was largely completed. The UT efforts during the 6 months of the first two no-cost extensions were mainly focused on providing technical support to EmiSense in their commercialization efforts. The most important steps toward commercialization was to compare the sensor response against commercial laboratory grade PM mass measurement instruments and perform testing of the sensor in a heavy-duty diesel engine. The heavy-duty engine testing was to take place at Cummins, as expressed in Tasks 3.4-3.6. Because of the delays in sensor development and the lack of these scientific-grade PM instruments at UT, the heavy-duty engine testing was done at the University of California-Riverside under contract with EmiSense. The HCCI mode testing was not successful so the sensor was tested in diesel mode only. The sensor was tested on-road in the exhaust of a 2009 MY Peterbilt tractor having a 2008 Cummins ISX-485 diesel engine. The EmiSense sensor response was compared with an AVL MSS-483. The AVL instrument provides a time-resolved measurement of PM mass concentration. In the tests during the first no-cost extension only one or two sensors were tested as a time. During the second 3-month no-cost extension, EmiSense went back to UC-Riverside and tested 12 sensors simultaneously.

Figure 12 - Major Systems within UCR's Mobile Emission Lab (MEL)

Figure 13 - Twelve PMTrac sensors were installed in the exhaust pipe prior to the MEL.

UCR's unique heavy-duty diesel mobile emissions laboratory (MEL) is designed and operated to meet stringent specifications. MEL is a complex laboratory and a schematic of the major operating subsystems for MEL are shown in Figure 12. The accuracy of MEL's measurements has been checked/verification against ARB's and Southwest Research Institute's heavy-duty diesel laboratories. MEL routinely measures a wide

range of speciated and PM emissions from diesel engines.

Figure 14 – Comparison of temperature-corrected EmiSense PMTrac sensors calibration with gravimetric during SS testing

Figure 13 shows a more detailed view of the section of exhaust pipe containing 12 each PMTrac sensors. This testing was quite successful. Some of the results are summarized in Figure 14 which shows the EmiSense PMTrac sensor correlation against gravimetric measurements and several other PM measurement standards. The PMTrac correlation coefficient had an R^2 of 0.93, as shown in the Figure.

Much of the effort in September 2010 was devoted to writing a technical paper for the Society of Automotive Engineers' 2011 World Congress. This paper presented the results of sensor testing at UT and at UC-Riverside. A view of the new generation sensor is given in Figure 15. This sensor includes a new outer shroud designed to provide a reproducible quasi-axial flow through the housing to minimize effects of sensor orientation in the flow. In August 2010 wind-tunnel testing of this new sensor design was initiated at UT. Hot-wire anemometry is being performed to validate an EmiSense CFD model of flow through the sensor. Figure 16 shows flow patterns in and around the sensor when inserted in an engine exhaust pipe as calculated by the CFD model.

The hot-wire was placed at the tip of the sensor to measure the exit flow rate as a function of the free-stream velocity for a flow perpendicular to the sensor axis. Preliminary results show a linear relationship between free-stream velocity and the flow rate through the sensor.

Figure 15 - EmiSense electronic soot sensor with improved housing for reproducible hydrodynamics and minimal orientation effect.

Figure 16 – CFD results for a) improved and b) baseline PMTrac sensor housings

Efforts toward commercialization of the sensor continued during this period. EmiSense established a business relationship with Watlow, Inc. In this arrangement Watlow was to concentrate on developing the heavy-duty market for the sensor while EmiSense pursued the light-duty market. The sensor was evaluated by a major U.S. OEM in June 2010 and by at least two European companies.

The first quarter of 2011 was rather slow from the UT perspective. EmiSense

sold out of Series A PM sensor evaluation kits in December 2010 and there was a delay of about two months in getting sensor electrode ceramics from Coorstek to make more. They did finally receive the materials in late March 2011 and once again offered sensors and evaluation kits. In January 2011 a new 12 month cooperative development agreement was formalized between UT and EmiSense in which EmiSense provided funding for continued sensor development at UT. UT continued both engine testing of sensors in the exhaust of the Cummins engine and wind tunnel testing of new EmiSense sensor housings. This included a new shorter sensor designed for smaller diameter exhaust pipes.

Further development of the sensor continued at the University of California-Riverside, and at EmiSense's research and development facility in Salt Lake City, Utah. In addition, the research EmiSense sponsored at Southwest Research Institute in San Antonio was completed in March 2011. The SwRI work was an experimental study of sensor fundamentals. The goal was a better understanding of the fundamental mechanisms governing sensor operation. The results of those studies were not released to UT.

The second quarter of 2011 saw UT engaged in three testing roles for EmiSense. Firstly, we continued our wind tunnel testing of the EmiSense sensors which includes a version of the venturi-housing sensor having a shorter housing. These included spatially resolved pitot-tube measurements of the velocities in the sensor wake to determine the flow drag a sensor will cause when inserted in an exhaust pipe of a given diameter.

Secondly, we performed a small number of tests of a new sensor design in the Cummins engine exhaust. Early in the quarter EmiSense sent us two new sensors to examine and one set of sensor electronics.

The new sensor had a new electrode configuration consisting of the high voltage electrode on the sensor axis and used a baffle between the housing the electrode as the ground electrode. The electronics were reconfigured to sense the charge lost by the high voltage electrode rather than detecting the charge gained by the ground electrode. This configuration is illustrated in Figure 17

Figure 17. Most recent configuration of EmiSense sensor.

We investigated effects of EGR and sensor orientation on PM sensor sensitivity and time-response. The behavior the new-type sensor was quite different from that of previous design. The signal increased with increasing rates of EGR, opposite the trend of the previous design. Personnel from EmiSense visited UT in mid-August to perform further testing where results were compared against a TSI Dust-track. Unfortunately, the TSI Dust-track malfunctioned early in the testing, so comparison data were limited. We did, however, verify the response of the new sensors to operation with and without EGR and found the sensors did respond positively to the increases in PM concentration associated with increasing levels of EGR.

The third task was a project to visualize carbon dendrite surface growth on the sensor electrodes. This was in response to observations that the sensors' sensitivities change over the first few minutes to hours of operation and are therefore subject to a de-greening process. A two-electrode sensor without a housing was used for testing.

Figure 18 Image of the surfaces of the two electrodes of a PM sensor. The spacing between the two electrodes is about 2 mm.

Figure 19 Electrodes after approximately 50 minutes of engine operation.

Figures 18 and 19 present some preliminary data. Figure 18 shows an image of a cleaned set of electrodes prior to engine operation. Figure 19 shows the same electrodes after approximately 50 minutes of engine operation. Small whisker-like growths are clearly seen in the image of Figure 19.

The twin electrode sensor was tested for differences in sensitivity between a recently cleaned vs. a dirty sensor. The cleaned sensor was cleaned both by heating the bases of the electrodes with the built in heat to burn off carbon and also the electrodes were physically cleaned by wiping with solvents. The dirty electrode was cleaned only by

heating the base of the electrodes prior to testing. The rest of the electrodes were covered with varying amounts of carbon dendritic growth which was imaged to be about a few hundred microns high in maximum length. We found no statistically significant difference in the sensitivity of the clean vs. dirty electrodes. This was the status of the project at the formal end of the DOE sponsorship on September 30th, 2011.

The following peer reviewed papers were published during the DOE sponsored work:

Diller, T.T., Hall, M.J., and Matthew, R.D. "Further Development of an Electronic Particulate Matter Sensor and Its Application to Diesel Engine Transients," Society of Automotive Engineers Paper 2008-01-1065, 2008.

Hall, M.J., Diller, T.T., and Matthew, R.D. "Fast-response electronic particulate matter sensor for diesel engine control and DPF failure detection," 8th International Symposium on Combustion Diagnostics, ISBN 978-3-00-022057-9, Editor Peter Ziegler, AVL Europe, Baden-Baden, Germany, June 10-11, 2008.

Diller, T.T., Osara, J., Hall, M.J., and Matthew, R.D. "Electronic Particulate Matter Sensor – Mechanisms and Application in a Modern Light-Duty Diesel Vehicle," Society of Automotive Engineers Paper 2009-01-0647, 2009.

Osara, J.A., Diller, T.T., Hall, M.J., Matthews, R.D., and Heinrich, J. "Particulate Matter Emissions from a High-Emitting Diesel Vehicle Measured with an On-Board Electronic PM Sensor, American Society of Mechanical Engineers Paper ICEF2010-35055, 2010.

The following US patents were issued during the project:

Time-Resolved Exhaust Emissions Sensor, Matthew J. Hall, U.S. Patent # 7,650,780 B2, Date of Issue: Jan. 26, 2010.

Rigid Particulate Matter Sensor, Matthew J. Hall, U.S. Patent# 7,891,232 B2, Date of Issue: Feb. 22, 2011.

Particulate Matter Sensor with a Heater, Matthew J. Hall, U.S. Patent# 7,998,417, Date of Issue: Aug. 16, 2011.

Project status at the end of 2011

Development of the UT/EmiSense PM sensor was continuing. The new sensor embodiment showed good sensitivity to PM mass emissions with sensitivity to less than 1 mg/m³. EmiSense was successful in developing low cost electronics for the sensor which should aid commercialization. A focus at the end of the project was durability testing. The sensor durability was yet to be proven sufficient for widespread adoption for OBD compliance. UT and EmiSense were laying the groundwork for a revised royalty agreement. This was reflective of EmiSense' desire to simplify the existing agreement and broaden its licensed fields of use to encompass all areas of combustion emissions. Commercialization efforts were continuing, both by EmiSense and Watlow, and the sensors were being evaluated by OEM suppliers and vehicle and engine manufacturers in the US and Europe. The first target commercial application remained use as an OBD sensor for detecting diesel particulate filter failure with a target date of 2016 for adoption.

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