Final Technical Report – Section I

Project Title: EGR Control for Emission Reduction Using Fast Response Sensors - Phase 1A

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3. Executive Summary

The overall objective of this project was to develop exhaust gas recirculation (EGR) control strategies using fast-response Particulate Matter (PM) sensors and NOx sensors to improve the quality of particulate and gaseous emissions from diesel engines. This project initially comprised three phases:

- Phase IA - sensor requirements to meet PM sensor specifications, NOx sensor assessment, and initial model development for EGR control;
- Phase IB - continue development on PM and NOx sensors, integrate the sensor signals into the control simulations, and finalize model development for control strategies; and
- Phase II - validation testing of the control strategies.

Only Phase 1A was funded by DOE and executed by Honeywell.

The major objectives of Phase 1A of the project included:

- Sensor validation and operation of fast-response PM and NOx sensors,
- Control system modeling of low-pressure EGR controls, development of control strategies, and initial evaluation of these models and strategies for EGR control in diesel engines,
- Sensor testing to understand applicability of fast-response PM sensors in determining loading rates of the particle trap,
- Model validation and sensor testing under steady-state and transient operational conditions of actual engines.

In particular, specific objectives included demonstration of:

- A PM sensor response time constant ($T_{10} - T_{90}$) of better than 100 milliseconds (msec)
- The ability to detect PM at concentrations from 0.2 to 2 Bosch smoke number (BSN) or equivalent
- PM sensor accuracy to within 20% BSN over the entire range of operation
- PM sensor repeatability to within 10% over the PM entire sensor range equivalent to a BSN of 0.2 to 2

Multiple key accomplishments were realized by Honeywell during this program. They include:

- Demonstration of PM sensor response time capability ($T_{10} - T_{90}$) of 10 msec to 30 msec
- Demonstration of PM sensor ability to measure signals to 0.005 g/hg-hr and 0.2 filter smoke number (FSN)
- Development of a lump-sum model that incorporate PM sensor and NOx measurements into EGR control system
- Extensive testing of PM sensor operation on-engine in both particulate filter loading and particulate filter failure monitoring configurations in conjunction with the University of Minnesota and tested in direct exhaust stream downstream of the engine at both the University of Minnesota and Oak Ridge National Lab
- Accomplished the first extensive charge concentration and distribution measurements in diesel exhaust upstream and downstream of a failed particulate filter, furthering understanding of particle transport methods in the engine exhaust system

In addition, this program enabled further development through Honeywell cost share funding and additional Honeywell internal funding:

- Fabricated and tested signal conditioning electronics and signal processing algorithms to amplify and process the PM sensor signal output for multiple emissions control applications including particulate filter loading and on-board diagnostics for particulate filter failure monitoring as specified in upcoming EPA regulations
- Identified materials and developed a mass-producible ceramic coating technology in order to fabricate a robust PM sensor capable of meeting electrical isolation requirements and robustness against thermal expansion for on-engine environments
- Tested PM sensor operation on-engine at an independent engine test facility to confirm market readiness for particulate filter loading applications
- Tested with governmental regulatory compliance agencies for direct exhaust and particulate filter failure monitoring application readiness
- Developed transfer function models that relate sensor output to mass concentration
- Developed finite element models of thermal distributions with the sensor
- Conducted and passed multiple environmental robustness tests including drop testing, salt testing, acid testing, and vibration testing
- Engaged Honeywell's Transportation Systems strategic business group to design and fabricate multiple probe housings and probe configurations. (Honeywell's Transportation Systems SBG comprises multiple automotive brands, including Autolite®, who provided the basis for the PM sensor package.)
- Engaged Honeywell's Specialty Materials strategic business group to investigate and understand strengths and limitations of oxide based probe coatings for electrical isolation
- Market shown to be ready for particulate filter loading and failure monitoring applications based on the OEM voice of customer analysis conducted by Honeywell business groups

Honeywell's ability to engage cross-function teams from multiple Honeywell business groups with expertise in sensors, automotive components, and specialty materials enabled a unique opportunity to develop and eventually commercialize PM sensor technology.

The program's goal was to look at both PM and NO_x sensing to control the EGR. The objectives of meeting accuracy to within 20% BSN over full range and 10% repeatability over a 0.2 to 2 BSN range were not explicitly met for the PM sensor. However, 25% accuracy was demonstrated and repeatability to within 25% was also demonstrated for the PM sensor. The time response of the commercial NGK NO_x sensor was found to be inadequate. Therefore, this sensor integration effort was not continued.

Honeywell continues to invest in PM sensor development with the expectation of product delivery for particulate filter failure monitoring applications commensurate with upcoming EPA regulations.

A summary of the outcome of this research at a high level of understanding of the associated problem area and a brief summary of the associated evaluation criteria are provided below:

1) How does the research add to the public understanding of the area being investigated?

Research conducted during this program provided the basis for understanding accuracy and response time capabilities and robustness of sensors that can be used in on-engine environments to measure particulate matter levels. Characterization of the charge distributions upstream and downstream of a failed particulate filter additionally enables the opportunity for development of new sensor technologies capable of monitoring particulate filter loading and failures. This research also supports understanding of new means to integrate PM sensors with NOx sensors in order to improve emissions controls.

2) What is the technical effectiveness and economic feasibility of the methods or techniques investigated

The PM sensor evaluated through this program appears to be economically feasible for mainstream adoption. Manufacturing and installation of the sensor is straightforward and the operating techniques (including the electronics and signal processing) are fairly modest. Some sensor characteristics (vibration response and other volume manufacturability issues) need additional development before the sensor can be mounted for on-road tests.

3) How is the project of benefit to public

PM sensors developed under this program have the potential to be used in multiple applications, including particulate filter loading, particulate filter failure monitoring, and emissions control for diesel engines for on- and off-road applications. Application in particulate filter loading may result in reduced cost of ownership for the diesel engine customer. Application of this technology in particulate filter failure situations provides a direct measurement technique to ensure EPA regulatory compliance. The application of this technology in emissions control facilitates improved engine operation and emissions reduction. Additionally, this technology could enable potential fuel savings in diesel engines by efficient control of the EGR loop.

4. Comparison of Actual Accomplishments to Goals and Objectives

The PM sensor is relatively easy to install, has no complex connection to the exhaust system, and has electronics that may easily be adapted to the engine environment. Figure 1 shows the final version of a PM sensor prototype that was developed under this program.

Figure 1. PM sensor prototype shielded to maximize SNR. This sensor was tested on-engine at multiple test sites

Testing the PM sensor against gravimetric standards (equivalent to mass concentration) shows good correlation between the two. Results are given in Figures 2 and 3. These figures illustrate the relative comparison of two different PM sensors located at different locations downstream of a diesel particulate filter (DPF). The results shown in Figure 2 are from a sensor that employs electronics having a signal amplifier with reduced noise and improved signal processing. Consequent improvement in the sensor correlation with the gravimetric measurements is readily seen.

The DPF was progressively failed in a controlled manner by incorporating holes drilled lengthwise through DPF to study the sensor response. Increasing the number of holes increases the leakage of particulates through the DPF, simulating a failure due to a lengthwise crack. Note that both Figures 2 and 3, and Figure 2 in particular, show that the PM sensor responds at particulate matter levels well below the EPA regulatory threshold (0.01 gm/hp-hr) starting year 2010 for on-board diagnostics of DPF failure.

Figure 2. Correlation of PM sensor using enhanced amplifier and gravimetric readings. Correlation shows ability of PM sensor to detect below OBD level

Figure 3. Comparison of PM sensor response and gravimetric measurement against failing a DPF – post-ORNL engine

Other measurements, as shown below in Figure 4, demonstrate that the sensor can provide a response within roughly 25% that of the Engine Exhaust Particle Sizer (EEPS) spectrometer

instrumentation. This information provided one basis, in conjunction with aethalometer and Scanning Mobility Particle Sizer (SMPS) measurements, for development of the transfer function that relates PM sensor signal output to mass concentration. Transfer function development is still on-going under Honeywell funding.

Figure 4. PM sensor response versus mass concentration. Indicates that sensor can detect minimal mass

In addition to the potential of correlating to the particle mass concentration in the exhaust stream, the sensor has a fairly rapid response time. Measurements have shown a response in the 10 msec to 30 msec range. There is a trade-off however, between response time and signal-to-noise ratio (SNR) (cf. Figure 18), which prompted development of improved signal conditioning electronics and signal processing algorithms. Additional test results, for example the results of the charge distribution studies downstream of a failed DPF, are given in Section 5 below.

Key demonstrations that were made under this program for the PM sensor technology are,

- A PM sensor response time constant ($T_{10} - T_{90}$) of better than 100 milliseconds (msec),
- The ability to detect PM at concentrations from 0.2 to 2 Bosch smoke number (BSN) or equivalent,
- PM sensor accuracy to within 20% BSN over the entire range of operation,
- PM sensor repeatability to within 10% over the entire PM sensor range equivalent to a BSN of 0.2 to 2.

Table 1 outlines the final PM sensor specifications achieved against the initial goals of the project. Response time and concentration level objectives were met. Accuracy and repeatability criteria, though close, were not met due to the variability of the test engine smoke numbers and manufacturability variations of the PM sensor.

Table 1. Comparison of PM sensor achievements against deliverables

Plan	Accomplishment	Comments
Response time T(10-90) better than 100 milliseconds	Response time of electronics and sensor is 30Hz or 33 msec	<ul style="list-style-type: none">• Testing at multiple sites confirmed response time. Testing at Oak Ridge National Lab (ORNL), however, did not, agree with the other response times most likely because probe operation negatively affected by probe orientation with respect to the exhaust flow
Detect PM at concentrations from 0.2 to 2 Bosch smoke number (BSN) or equivalent	Initial testing has shown detection down to 0.3 – 0.5 FSN; additional testing has shown detection down to 0.1 – 0.2 FSN after signal processing.	<ul style="list-style-type: none">• ORNL testing indicated detection down to 0.2 FSN• FSN values seen to vary quite a bit during data taking on other engines.• Testing outside ORNL has shown responses down to 0.005 g/hp-hr as tested under EPA conditions.• (FSN measures smoke by pulling exhaust to a filter, similar to BSN. FSN numbers are similar to BSN numbers.)
Accuracy to within 20% BSN over the entire range of operation	Demonstrated accuracy was below 25%.	<ul style="list-style-type: none">• Engine out conditions show accuracy up to 25%.• Post-diesel oxidation catalyst (DOC) location exhibits much less variance in signal, but with overall accuracies above 20%.
Repeatable to within 10% entire sensor range equivalent to a BSN of 0.2 to 2	Have not achieved 10% repeatability. Repeatability was approximately 25%	<ul style="list-style-type: none">• Repeatability in sensors was shown to be above the 10% goal. Attempts were made to address this large variance in the repeatability, but were unsuccessful.

5. Summarized Project Activities

a. Original Goals, Hypothesis

This project originally included three phases with the final goal of developing an EGR control system using fast-response PM and NO_x sensors. This control would use an optimized signature from the sensors to determine operation of the EGR system. The original project goal was to provide sensor validation and operation of fast-response PM and NO_x sensors, model the control strategies of low-pressure EGR controls, and use these strategies for initial evaluations of the EGR system for diesel engines. In addition to being used in developing these control strategies, the fast-response PM sensor was to be used for on-board diagnostics of the loading of the particle trap. The final goal was the development and testing of these control strategies under steady-state conditions as well as transient/operational conditions.

The original project was broken down into **three** phases:

- PHASE IA - sensor requirements to meet PM sensor specifications, NO_x sensor assessment, and initial model development for EGR control;
- PHASE IB - continue development on PM and NO_x sensors, integrate the sensor signals into the control simulations, and finalize model development for control strategies; and
- PHASE II - validation testing of the control strategies.

It should be noted that, at the time of the initial award of this cooperative agreement, only Phase IA of the effort was funded as detailed below. Phase IB and Phase II were not funded by DOE, nor worked on by Honeywell. A decision point was incorporated into the completion of Phase IA at which time the readiness of the sensor to be used for EGR control would be determined.

b. Approaches Used

- Design – Designing the sensor for optimized performance and be robust against vibration, thermal and electrical noise.
- Packaging – Matching the thermal expansion between the electrode and the electrical isolator by use of novel ceramic deposition techniques.
- Materials – Novel ceramic base coat material deposition and selection of such materials.
- Testing of sensor on-engine and correlation with particle measurements made by laboratory instrumentation.
- Measurement of the charge on the emission particles in order to try and correlate this charge to the PM sensor signal. This was deemed a very important parameter since the particle sensor is based on an induced charge mechanism.
- Measurement of the particle sensor response both upstream and downstream of the particle filter to assess the sensor's capability to operate in either of these locations.

- Modeling – Thermal, vibrational, and electrostatic modeling to optimize the sensor performance.

c. Problems Encountered and Departure From Planned Methodology

1. Problems with the development of a PM sensor that would meet the SNR and response time goals of the project.
2. Problems with initial sensor failure during installation in the diesel exhaust upstream of DPF. There were materials issues enabling adaptation of the electrical isolation layer on the sensor to survive harsh thermal environment both upstream and downstream of DPF
3. Testing and PM sensor modifications required more time than originally planned for Phase 1A.
4. Program was stopped in mid-2006 because of withholding of funds from DOE and did not re-start until late 2007.

d. Assessment of the Impact of Problems on Project Results

1. The issues (such as materials and noise) with the sensor took more time than anticipated. This led to reduction in effort for the modeling and NOx testing tasks. Materials and electromagnetic noise were resolved by redesigning sensor electrode, electronic amplifiers, and signal processing.
2. PM sensor issues were eventually resolved for the locations downstream of either a diesel oxidation catalyst (DOC) or DPF, however, there are still issues with the sensor for a location upstream of the trap system.
3. Testing and PM sensor modifications required more time that originally planned, even for Phase 1A. This caused subsequent tasks for PM sensor to be minimized.
4. Interruption of the funding had a schedule and resource impact. Additional time and labor were required to restart the program with the consequence of fewer tasks being able to be addressed.

Results from each of the programs tasks during Phase IA of the project are summarized below:

5.1 Test Protocol of PM Sensors and Diesel Engine Configuration

A test plan was developed which included the sensor tests, engine properties to be used in both modeling and testing of the sensors, and how steady-state and transient loads were to be generated during the test. Initial tests were steady-state at selected engine conditions (load, speed) while measuring the engine parameters, particle size distributions, particle mass concentration, and sensor output. These initial tests were conducted to improve the response of the PM sensor, evaluate the material and insulation properties at the high temperatures in the exhaust stream, and make a primary assessment of the signal/noise of the sensor. Later tests were conducted to determine the response time of the sensor, how well the sensor output correlated with smoke and gravimetric measurements, and correlation with engine parameters (temperature, pressure, and exhaust flow).

A diesel test engine was configured at the University of Minnesota to include engine hardware, standard engine monitoring systems (temperature, pressure, etc.), a low pressure EGR system, and diesel particulate filter (DPF). Figures 5, 6, and 7 show the engine and provide an indication of the sensor location and mounting, and how the DPF is mounted on the engine.

Figure 5. PM sensor mountings and locations downstream of the turbocharger (University of Minnesota)

Figure 6. Picture of Deere engine showing PM sensor test locations (University of Minnesota)

Figure 7. DPF mounted on Deere engine showing sensor location

The majority of the steady-state tests were conducted on a Deere engine at the University of Minnesota. Additional engine testing was conducted on a Cummins engine, a Mercedes engine, and a Volvo engine. Testing focused on evaluating the PM sensor signal-to-noise level and time response. Results of these tests were utilized to construct improved amplifier electronics. Test engine parameters are shown in Table 2.

Table2. Parameters of test engines used during this project

Engine Type	Volvo	Mercedes	Cummins
Num Cylinders	6	4	6
HP	465	105	275
Cert. Year	2003	2005	2007
Displacement	12.1L	1.7L	6.7L
EGR	Yes	Yes	Yes

5.2 PM Sensor Tests and Operational Optimization

This task was to establish the optimized PM sensor configuration (electrode geometry and location) as well as the testing of the design for the PM sensor to achieve the project goals. Testing was conducted to optimize signal strength, electrode configuration, as well as charge and size distribution of the exhaust particles at the sensor location. Most of the testing was done under steady-state conditions (AVL.8 test protocol and load acceptance modes along with different acceleration/deceleration modes). Measurements of additional engine parameters such as exhaust flow rate, pressure, and temperature were also taken. Sensor characterization was also conducted upstream and downstream of the particle trap to determine the use of the PM sensor for loading of the trap or to determine breakthrough from a faulty trap.

There have been continuing improvements in both the electrode configuration and electrical isolation in order to address various failure mechanisms of the electrodes. Figure 8 illustrates the sensor design evolution throughout the course of the program.

Figure 8. Time-line of PM sensor design evolution: electrical isolation, electrode geometry, and electrode packaging enhancements

To improve the SNR for the PM sensor, an electronics package was developed to do both the signal amplification as well as to process the signal electronically. Figure 9a and 9b show the integrated electronics package and the internal view of the signal processing board. This amplifier was designed to be used with two PM sensors. An FFT based algorithm is used to process 4800 bits of data in approximately one second. A different version of the amplifier allows resolution of a shorter signal response, but does not contain any signal processing, thereby requiring post processing of the signal on a computer system. Design choices may be made to optimize for either on-board signal processing or speed of signal response, pending application needs.

Figure 9. Integrated electronics for PM sensor: a) dual sensor package, b) internal view of signal processing board

Gravimetric measurements were made in conjunction with PM sensor and smoke number measurements in order to understand the applicability of the PM sensor to on-board diagnostics for DPF failure monitoring. As shown by Figure 10 the testing at the University of Minnesota indicated good correlation between the sensor and gm/hp-hr during tests at different loads and in a steady-state mode of operation. *This result, in conjunction with that shown in Figure 2, demonstrates that the Honeywell PM sensor is capable of responding with the same resolution as a laboratory standard to PM levels below the upcoming EPA mandated threshold for year 2010 and beyond.*

Figure 10. Comparison of PM sensor response and gravimetric response on Deere engine showing tight measurement correlation

Once these initial comparisons had been made, additional testing was done on a 2007 certified heavy-duty vehicle (HDV) engine. These tests offer a different comparison between gravimetric readings and the PM sensor output as shown in Figure 2 (and reproduced below in Figure11 for convenience). Here the dispersion between the PM sensor reading and the gravimetric measurement is large only in the area of a large opening in the DPF. This, in fact, is not an actual variance, but may be caused by the change in the exhaust flow characteristics incurred when a large number (> 1250) holes are drilled into the DPF, essentially opening up about one-half of the DPF area.

Figure 11. Comparison of PM Sensor output and gravimetric measurements for failing DPF on post-ORNL engine, indicating ability to measure below EPA threshold limits

To understand the operation of the PM sensor, a determination of the charge distribution in the exhaust stream is important. This implies that the charge on the particles is also known. To obtain this information, tandem DMA measurements were made at the University of Minnesota. These measurements provided data required to determine the fraction of charged particles as a function of particle diameter. This information was then used to determine how the PM sensor will respond for a certain load, as shown in Figure 12, where the load during the measurements was 450 Nm. Using this information, the charge flux past the PM sensor can be determined and thus the induced current in the probe.

Figure 12. Measured charged distribution upstream and downstream of a failed DPF with a Deere engine

5.3 Results of ORNL and Post-ORNL Testing – Flow Orientation Dependence

Per requirements of the program, testing of the PM sensor was conducted at ORNL in order to verify the correlation of the PM sensor output with smoke number and gravimetric measurements. Positions both upstream and downstream of the DPF were tested. Two primary issues arose during this test: failure of the amplifiers and improper sensor orientation resulting in reduced signal response. In addition, the engine used for testing at ORNL was characteristically much different than other engines tested elsewhere in terms of size, displacement, and power, which in-turn may have exacerbated some of the issues.

On account of the small exhaust pipe diameter relative to the probe length, the sensor was installed at an angle to the flow direction. Measured output of the sensor was extremely slow with minimal change in output signal as a function of exhaust particle charge levels. This effect was likely caused by the sensor effectively integrating the exhaust stream charge. In subsequent testing at the University of Minnesota, this effect was verified. These observations elucidated the fact that the PM sensor has to be mounted normal to the flow direction in order to provide a maximum signal.

Figure 13 shows the lack of PM sensor response. As a result of the issues encountered, the 10 msec to 30 msec response time measured elsewhere was not confirmed at ORNL. Nevertheless, testing at ORNL did result in a valid correlation of PM sensor with smoke number measurements for both amplifier configurations. This correlation is given in Figure 14. Subsequent measurements taken at another test facility confirm the correlation, as shown in Figure 15.

Figure 13. ORNL transient PM sensor test results showing lack of sensor response

Figure 14. ORNL PM Sensor measurement correlation with smoke number showing performance enhancement with improved amplifier design

Figure 15. PM sensor voltage compared to smoke number showing correlation and amplifier impact from testing subsequent to ORNL testing

Figures 16 and 17 show transient response characteristics of the PM sensor measured using supplementary engine testing (SET) test sequences. These measurements were taken prior to ORNL testing on a Ford engine. Figure 16 shows the behavior over a 20 minute test time, and Figure 17 shows details over a one minute test time.

Figure 16. Pre-ORNL test results demonstrating transient response of PM sensors for SET tests

Figure 17. Pre-ORNL SET results at one second time response

Additional transient testing was performed on-engine by conducting a Federal Test Procedure (FTP) test. FTP tests simulate the operation of a vehicle under “standard” city driving, including frequent stopping and starting. Test results, shown in Figure 18, demonstrate 50 msec response of the PM sensor.

Figure 18. Post-ORNL transient FTP testing showing 50 msec PM sensor time response

5.4 Summary of NO_x Sensor Tests

One of the program objectives included identifying, acquiring, and evaluating one or more NO_x sensors that may be used as closed loop elements in engine and EGR control. These sensors were to have been selected from known market products such as commercially available NGK sensors, Horiba’s zirconia-based devices, or other readily available prototype NO_x sensors that meet the response conditions for the control strategies.

Both the NGK NO_x sensor and a Honeywell prototype sensor were evaluated for response time and sensitivity in Honeywell laboratories and on-engine at an external test site. Additional parameters being examined: the minimum required speed of response and sensitivity in the exhaust and how well the existing devices met these needs. The Honeywell NO_x prototype sensor was found to be responsive to both NO₂ and NO. However, the sensor exhibited temperature control and packaging issues. Figure 19 shows response time characteristics of the Honeywell prototype sensor as packaged in a manifold.

Figure 19. NOx measurements showing Honeywell prototype sensor time-response packaged in a manifold

The NGK NOx sensor was also tested upstream of the DPF simultaneously with PM sensors located both upstream and downstream of a failing DPF. NOx sensor response measured during these tests indicated that there was little change in the NOx level as a function of DPF failure level. Figure 20 provides the measured NOx response versus DPF failure level.

Figure 20. NOx measurements during failing of DPF showing uniformity of NOx sensor response upstream of the DPF

There was a decrease in NOx level during initial DPF failure, e.g. at 10 and 60 holes, but this was due to failures with the oil system and turbine coolant. The response to the different operating modes of the engine did indicate different NOx levels were produced for different modes of operation. The modes tested are shown Figure 21.

Figure 21. Mode plot for post-ORNL engine testing showing different engine modes used to measure NOx sensor and PM sensor response

The correlation between the NOx sensor and the PM sensor measurements is shown in Figure 22. A rough inverse variation between the NOx sensor and the PM sensor was observed, as was expected.

Figure 22. Comparison of PM sensor response with NOx measurements showing inverse correlation

5.6 Model-Based Control

The program evaluated the use of Honeywell's existing lumped parameter model of engine performance and how it might be validated on the University of Minnesota's engine system consisting of a Deere engine with a turbocharger, a diesel particulate filter (DPF), and EGR. The model was initially configured for a different engine platform with a non-standard variable geometry turbocharger (VGT). Lumped parameter models of the fast-response sensors had been incorporated into the control model. It was also considered to use the PM sensor as a trigger for on-board diagnostics for DPF failure and perhaps to quantify the integrated loading of the DPF. The final model was to be comprised of models of the engine (with a turbocharger), a diesel particulate filter (DPF), and an EGR. Initial modeling was done in MATLAB[®]/Simulink but was also adapted to interact with different software platforms. The correlation of the PM and NOx sensors to the EGR response was evaluated.

A set of baseline engine performance parameters were developed and used for PM and NOx emissions under standard operating conditions. Initial testing did confirm the inverse correlation one would expect between NOx and particulate matter measurements, but not all of the parameters were configurable on the engine. Coarse correlation between the PM sensor and the EGR response was shown. However, since the results of the tests indicated that the response time, combined with sensor accuracy, of both sensors may not be adequate to meet the goals of EGR control, an improved model was not pursued.

5.7 Conclusions

Based on the work performed in the project and the results reported in this section, the following conclusions were reached:

- Demonstrated PM sensor response time capability ($T_{10} - T_{90}$) of 10 msec to 30 msec
- Integrating the amplifiers and electronic signal processing box allowed significant automated data processing capabilities for rapid data acquisition and post processing
- Demonstrated PM sensor is able to measure signals to 0.005 g/hg-hr and 0.2 filter smoke number (FSN)
- EGR control system model developed was able to incorporate both PM sensor and NOx measurements
- Particulate filter loading and particulate filter failure monitoring configurations were proven by testing Honeywell PM sensors at the University of Minnesota, Oak Ridge National Lab, and other test facilities
- Significant understanding of particle transport methods in the engine exhaust system due to first extensive charge concentration and distribution measurements in diesel exhaust upstream and downstream of a failed particulate filter

In addition, this program enabled further development through Honeywell cost share funding and additional Honeywell internal funding that led to the following additional conclusions:

- Signal conditioning electronics and signal processing algorithms can significantly amplify and process the PM sensor signal output to make it useful for multiple emissions control applications
- New materials and mass-producible ceramic coating technologies were developed to demonstrate a robust PM sensor capable of meeting electrical isolation requirements and robustness against thermal expansion for on-engine environments

- Developed finite element models of thermal distributions in the sensor
- Challenges remain for PM sensor to meet accuracy to within 20% BSN over full range and 10% repeatability over a 0.2 to 2 BSN range - the program accomplished 25% accuracy and repeatability

6. Identify Products Developed Under the Project

- a. Publications – None
- b. Website - None
- c. Networks or Collaborations Fostered:
 - i. University of Minnesota
 - ii. Oak Ridge National Labs
 - iii. Cummins engine vendors
 - iv. Volvo engine vendors
 - v. John Deere engine vendors
 - vi. Mercedes engine vendors
 - vii. Volkswagen engine vendors
 - viii. Aethalometer particulate tester vendor
 - ix. AVL particulate analyzer vendor
 - x. EEPS particulate analyzer by TSI
 - xi. Multiple Honeywell business groups
- d. Technologies/Techniques:
 - i. Signal conditioning electronics
 - ii. Signal processing algorithms
 - iii. EPA regulations specific to particulate matter and diesel emissions
 - iv. Ceramic coating techniques for reliable sensors
 - v. High temperature materials and pastes for the sensor coating, specifically oxide coatings.
 - vi. Noise minimization wiring and circuitry
 - vii. Diesel soot parameter characterization using various analytical instrumentation
 - viii. Diesel engine operating modes leading to soot generation and soot minimization
 - ix. Biofuel testing capabilities
 - x. Particulate filters and filter loading applications
 - xi. Charge distribution models and exhaust analysis
 - xii. Particle distribution models and exhaust analysis
 - xiii. EGR systems characterization and design approaches
 - xiv. NOx sensor applications in EGR
 - xv. Transfer function models
 - xvi. Finite element models
 - xvii. Drop testing, salt testing, vibration testing and acid testing
 - xviii. Transportation group's expertise in probe housing and probe configuration manufacturing.
 - xix. Diesel engine test facilities and instrumentation set up
 - xx. Packaging
 - xxi. Housing design and fabrication

- e. Invention/Patent Applications – None. Significant know-how has been developed to aid in future technology and product development.
- f. Other Products – None. Currently no PM sensor products have been developed under this project. However, there is still a strong interest within the business units at Honeywell to pursue these sensors for not only EGR control, but also for the detection of potential failures of a DPF unit.

In addition, this program enabled further development through Honeywell cost share funding and additional Honeywell internal funding:

- Fabricated and tested signal conditioning electronics and signal processing algorithms to amplify and process the PM sensor signal output for multiple emissions control applications including particulate filter loading and on-board diagnostics for particulate filter failure monitoring as specified in upcoming EPA regulations
- Identified materials and developed a mass-producible ceramic coating technology in order to fabricate a robust PM sensor capable of meeting electrical isolation requirements and robustness against thermal expansion for on-engine environments
- Tested PM sensor operation on-engine at an independent engine test facility to confirm market readiness for particulate filter loading applications
- Tested with governmental regulatory compliance agencies for direct exhaust and particulate filter failure monitoring application readiness
- Developed transfer function models that relate sensor output to mass concentration
- Developed finite element models of thermal distributions with the sensor
- Conducted and passed multiple environmental robustness tests including drop testing, salt testing, acid testing, and vibration testing
- Engaged Honeywell's Transportation Systems strategic business group to design and fabricate multiple probe housings and probe configurations. (Honeywell's Transportation Systems SBG comprises multiple automotive brands, including Autolite®, which provided the basis for the PM sensor package.)
- Engaged Honeywell's Specialty Materials strategic business group to investigate and understand strengths and limitations of oxide based probe coatings for electrical isolation
- Market shown to be ready for particulate filter loading and failure monitoring applications based on the OEM voice of customer analysis conducted by Honeywell business groups

Honeywell's ability to engage cross-function teams from multiple Honeywell business groups with expertise in sensors, automotive components, and specialty materials enabled a unique opportunity to develop and eventually commercialize PM sensor technology.

7. Computer Models

The computer modeling part of this project was to evaluate and use Honeywell's existing lumped parameter model of engine and variable geometry turbocharger (VGT) performance on the University of Minnesota's engine system consisting of a Deere engine with a turbocharger, a diesel particulate filter (DPF), and low pressure EGR. The longer-range goal was to calibrate and validate the model and its components for the Deere engine and evaluate the phase lags/shifts in the exhaust system. Effects on the EGR system were to be evaluated. The fast-response sensors were to have been incorporated into the control model along with

on-board diagnostics for trap failure and integrated loading of a particle trap using the PM sensor. The following is a summary for the modeling results:

a. Model description, key assumptions, version, source and intended use

The model is a lumped parameter model which inputs NO_x and PM sensor criteria as a set of non-linear functions. The model has been developed in MATLAB[®] and was originally intended for use in the control of VGT.

b. Performance criteria for the model related to the intended use

For the use of the model on the selected engines for this program, the performance criteria would have to be obtained from engine platform operation. This has not been fully completed in this first phase of the program.

c. Test results to demonstrate performance criteria met, validation

The initial model has been compared to experimental data taken on other engine platforms and has been validated for these engine platforms. This model has not been validated, however, on the Deere engine system at the University of Minnesota or adapted for low-pressure EGR control. Validation on the Deere system will require further modification of the model's parameters.

d. Theory behind model, expressed in non-mathematical terms

From the engine inputs (speed, torque, fuel usage, air flow, EGR rate, and combustion temperature) the NO_x concentration in the exhaust can be modeled. The model uses fuel, gas, engine, combustion models, and first order rate equations for NO_x to determine sensor response and NO_x production within the engine. The model for the PM sensor was empirically derived based on the measured particle generation during the combustion process (function of load, rpm, and cylinder parameters).

e. Were theory and algorithms peer reviewed?

The initial model and equations were validated under another program. Model was reviewed by Garrett, independent consultants, and a diesel engine manufacturer.

f. Hardware requirements

The model can be run on any Windows XP[®], UNIX, or any system that is capable of operating the MATLAB[®] software and has enough memory to accommodate calculating the matrices and other model calculations.

g. Documentation

Documentation has been prepared for the model to describe usage and parameter limits. The documentation was developed by Honeywell funding prior to initiation of this program and is Honeywell Confidential. Consequently, the documentation has not been included in this report.

Appendix I

This is protected data according to the DOE cooperative agreement.

Appendix III

This is protected data according to the DOE cooperative agreement.

Appendix II

Summary of ORNL Testing

Summary: Results of Testing Honeywell PM sensors (SN K07, K10, 407, 409, 410). PM testing was conducted under various engine load and speed conditions. Smoke number was monitored and gravimetric samples were taken.

Summary of ORNL test results:

- Testing of PM sensor was done on a smaller Mercedes engine. Sensors used for study were sized for 3-4 inch diameter pipe, and the exhaust pipe for the Mercedes engine was 2 inches. To ensure that the sensor electrode was not touching the exhaust pipe wall, the mounting was done at an angle of about 40 degrees (see Figure 1)
- Mounting of PM at an angle may have had an integrating effect of sensor response. This meant a limited response time.
- When sensor output was evaluated and there was no response when a high FSN pulse was generated (see Figure 3). Since there were issues with the electronics that occurred during the test as well as some probe resistance issues, we were not able to understand the cause behind the lack of signal.
- Two PM sensors were tested, each with a different amplifier. V07 is a voltage amplifier, and CA08 is a charge amplifier. There are different particulate mass flow conditions for these two tests. For these tests, the sensor output voltage is very low (on the order of 50 mVolts). This is much smaller than the voltage normally produced on other engine test systems
- Measurements that show good correlation of PM sensor output with filter smoke number were obtained

Although sensor response time of 10 msec to 30 msec could not be confirmed at ORNL, this response time was previously and subsequently measured at multiple other sites

Fig. 1: Schematic showing the sensor mounting in the exhaust system at ORNL test facility. Due to small diameter exhausts pipe, the sensor was mounted at an angle of about 45 degrees to prevent electrode from touching internal wall of exhaust pipe.

Figure 2: PM sensor output with two amplifiers tested, V07 and CA08, in steady state conditions. There are different particulate mass flow conditions for these two tests. The amplifiers are also not the same type. Notice how low the sensor output voltage is (on the order of 50 mV). This is much smaller than the voltage normally produced on other engine test systems.

Figure 3: PM response to sudden increase in smoke concentration in the exhaust. A large change was expected for the PM sensor response, based on previous testing and the FSN level of the response. This was not seen during the ORNL tests.

Nomenclature

AVL - AVL Emission Test Systems, GmbH
BSN – Bosch smoke number
DMA – differential mobility analyzer
DOC – diesel oxidation catalyst
DPF – diesel particle filter
EEPS – engine exhaust particle sizer
EGR – exhaust gas recirculation
EPA – Environmental Protection Agency
FFT – Fast Fourier Transform
FSN – filter smoke number
FTP – federal test procedure
HDV – heavy duty vehicle
NGK – NGK sparkplug
NO₂ – nitrogen dioxide
NO_x – oxides of nitrogen
OBD – onboard diagnostics
ORNL – Oak Ridge National Labs
PM – particle mass
SET – supplemental emissions test
SMPS – scanning mobility particle sizer
SNR – signal-to-noise ratio
TSI – Thermal Systems, Inc.
VGT – variable geometry turbochargers
ZrO₂ – zirconium dioxide