Experimental Studies for DPF and SCR Model, Control System, and OBD Development for Engines Using Diesel and Biodiesel Fuels

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Overview

Timeline

- Start: Oct 2009
- Finish: Sep 2012
- Status: 15% Complete

Partners

- Project Lead
  - Michigan Technological Univ.
- Industry
  - Cummins (Engine OEM)
  - John Deere (Engine OEM)
  - Johnson-Matthey (Catalysts)
  - Navistar (Engine OEM)
  - Watlow (Sensors)
- DOE Labs
  - Oak Ridge National Lab
  - Pacific Northwest National Lab

Barriers

- Understanding biodiesel and aging effects on NOx and PM aftertreatment component performance
- Meeting emission and OBD requirements with minimal fuel/energy penalty for:
  - engines using diesel or biodiesel fuels
  - high efficiency engines

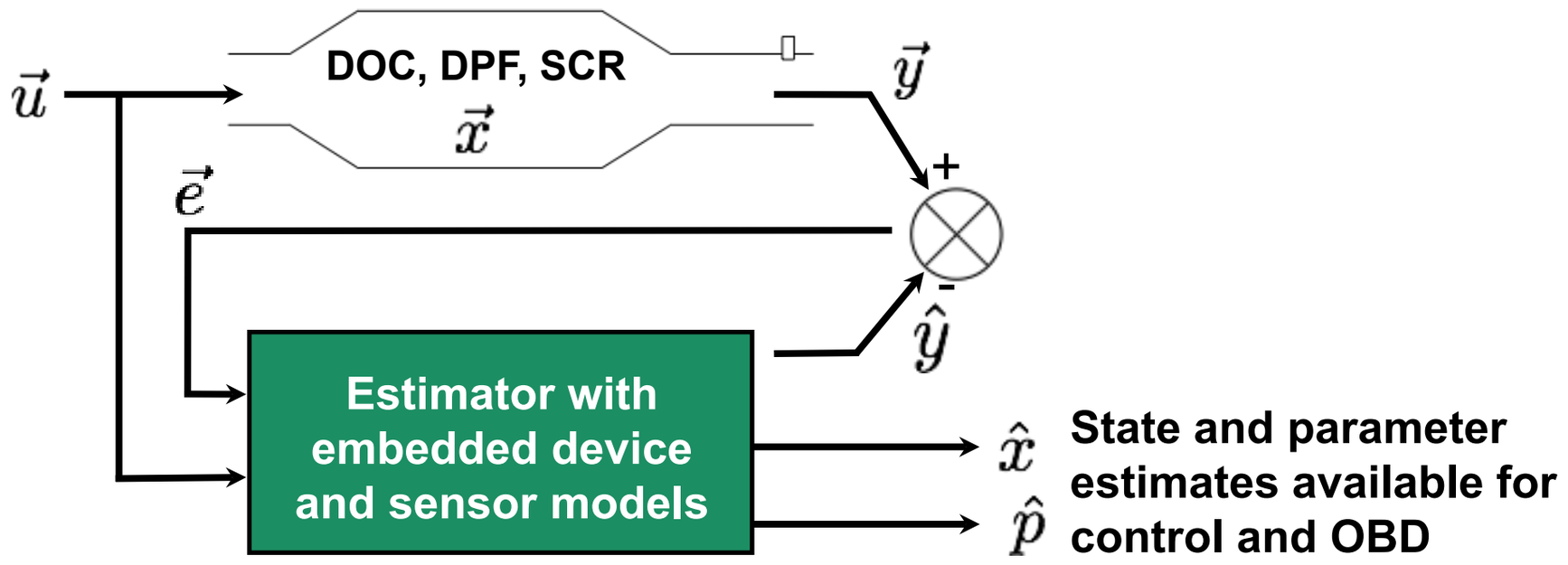
Budget

• Funding	Total	FY10
- DOE:	$1.8M	$583k
- Industry:	$0.7M	$235k
- University:	$0.3M	$105k
• Allocation		
- Mich Tech:	$2.3M	$768k
- DOE Labs:	$0.5M	$155k

Introduction

<u>Assertion</u>: Being able to compute aftertreatment system internal states will facilitate new control strategies that satisfy emission regulations with minimal fuel penalty and facilitate improved OBD algorithm development.

State Variables *- a set of time-dependent variables whose knowledge, along with knowledge of the system's inputs, allows one to completely compute the behavior of the system for all time.*



For a DOC, SCR or DPF **state variables include**: spatial variation of gas species, stored species, PM wall mass, PM cake mass, temperature, pressure, etc.

Objectives

Three-Year Objectives:

- Experimentally validated reduced order models and state estimation algorithms
- Increased knowledge of PM maldistribution, loading and NO_2/PM ratio effects on passive regeneration, and aging for DPFs
- Increased knowledge of NH_3 radial storage behavior, optimal NH_3 loading, HC poisoning, and aging for SCRs
- Understand effect of sensor type / configuration on estate estimation quality
- Optimal reductant strategies for SCR operation and DPF regeneration

This Year's Objectives:

- Install two engine /aftertreatment / instrumentation systems for project studies
- Launch a project-wide, web-based data repository system
- Complete a sensitivity analysis of passive oxidation rates to loading and oxidation conditions
- Start reduced order DOC, DPF, and SCR model form study
- Start engine tests to quantify/model DPF passive oxidation as a function of NO_2/PM ratio and fuel type

VT Program Relevance

- The VT program challenges include meeting NOx and PM emission standards with minimal fuel penalty for:
  - High efficiency engines
  - Engines running diesel or biodiesel fuels.

- DPF regeneration causes a **direct fuel penalty through injection** and an **indirect fuel penalty through decreased engine efficiency** due to back pressure. SCR ammonia injection causes an **indirect energy penalty due to urea usage**. Closed loop control is required for both actions, but could likely be improved if internal states are used in control strategies in lieu of direct, sensor output feedback.

- **The state estimation strategies developed in this project are directly relevant to and will impact the VT program since they will:**
  - **Increase fuel efficiency through reductant-efficient injection strategy development**
  - **Permit implementation of emission control strategies on high efficiency engine's operating on diesel or biodiesel fuel**
  - **Enhance life-time aftertreatment operation through intelligent OBD strategy development**

Milestones

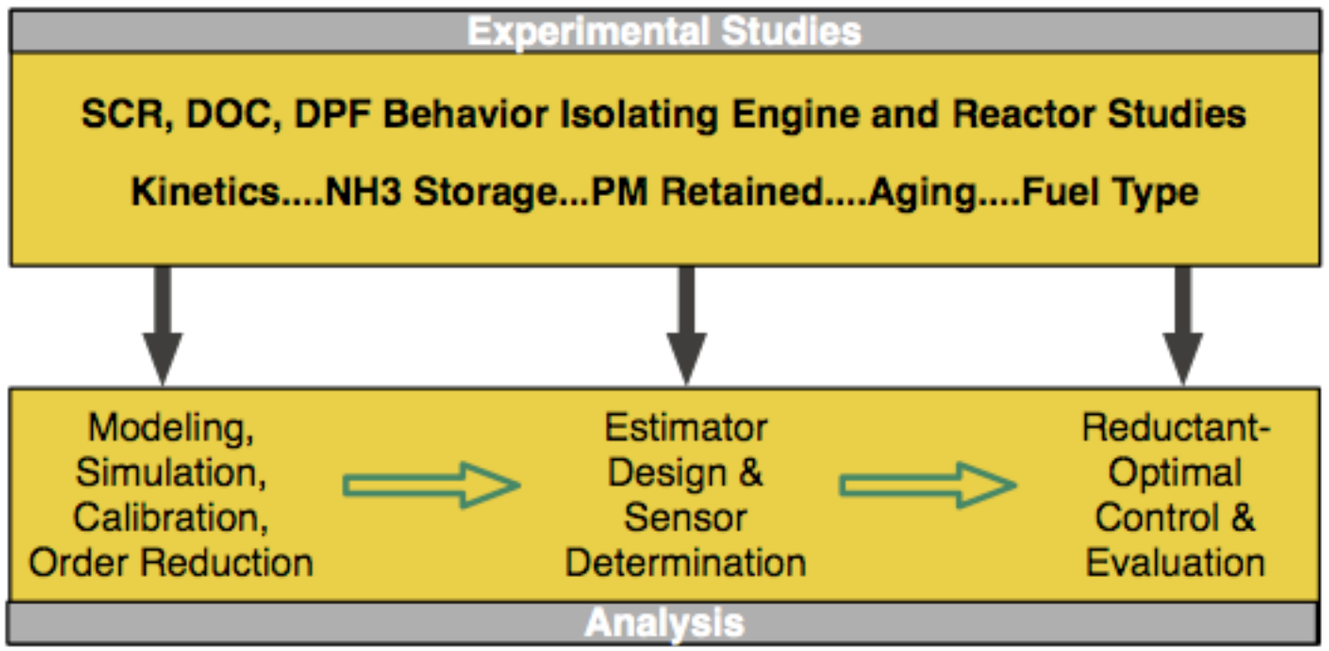
Month/ Year	FY10 Milestones	Status
Mar 2010	Data Inventory System Report	100%
Apr 2010	Engine / Aftertreatment Test Cell	100%
Jun 2010	PM Loading Simulation Study Report	50%

Month/Year	FY11 Milestones	Status
Dec 2010	SCR, DPF Sensor Estimator Model Form Report	Started
Dec 2010	DPF & SCR Estimator Strategy Report	Not Started
Mar 2011	SCR Spatial Ammonia Storage Study Report	Not Started
Jun 2011	DPF Loading & Passive Oxidation Test Report	Started
Jun 2011	DPF Active Regeneration Report	Not Started
Sep 2011	DPF Loading Maldistribution Test Plan	Not Started

Overall Project Approach

1. Develop fundamental understanding in several areas key to developing the reduced order models necessary for control-relevant, internal state estimation strategies
2. Combine engine test cell, novel instrumentation, and reactor studies to validate models, verify estimator designs, and demonstrate reductant-efficient control using both diesel and biodiesel fuels
3. Leverage team member (university, industry, national labs) expertise to match objective tasks
4. Connect state estimation results to VT programs in optimal catalyst design (UHouston) and nanomaterial applications for lean burn NOx reduction (UConn).

The combination of unique instrumentation and both conventional and new analysis methods will uncover behaviors not previously seen and relevant to state estimation



Objective-Specific Approaches

- **Data Inventory System:** Use a database-driven, web content management system for archiving and serving data to project participants
- **Test Cell Preparation:** Identify, develop and install engine / aftertreatment systems and new instrumentation and techniques to enhance the quality of project studies
- **DPF PM Loading and Passive Oxidation Kinetics Sensitivity Study:** Develop and test a new method for quantifying passive oxidation as a function of NO_2/PM ratio, temperature, and exhaust flow rate.
  - Use existing, calibrated simulation tools to determine passive oxidation rate sensitivity to NO_2/PM ratio, temperature, and exhaust flow rate
- **SCR Spatial Storage:** Use reactor studies with an in-situ, spatial gas concentration measurement technique (SpaciMS) to infer axial and radial storage inside SCR samples under relevant gas concentration conditions
- **Model Form Study:** Use existing DOC, DPF, and SCR models to create reduced order models suitable for real-time, internal state estimation strategy development. Leverage partner testing to aid sensor model development

Technical Accomplishments - FY10

- **Task 1** - Installed two new engine / aftertreatment / instrumentation systems in the project-dedicated test cell
- **Task 1** - Developed a novel exhaust heating system for expanding test condition range
- **Task 2** - Developed and deployed a data inventory system
- **Task 2** - Investigated temperature sensing accuracy downstream of a catalyst during HC injection events to support sensor model development
- **Task 5** - Developed a new passive oxidation test protocol

3-Year Project Technical Tasks

1. Test Cell Preparation
2. Baseline Estimator Model Development
3. DPF and SCR State Estimation
4. DPF and SCR Model Adaptation
5. DPF Loading and Passive Oxidation
6. DPF Active Regeneration
7. DPF PM Loading Maldistribution
8. DPF Fuel Optimal Regeneration
9. SCR Spatial Ammonia Storage
10. SCR Fuel-Dependent HC Masking
11. SCR Optimal Ammonia Storage

Technical Accomplishments - Task 1
Test Cell Preparation

Developed experimental capabilities to support model reduction, state estimation strategy development and reductant-optimal control studies.

Based on model development and estimation study data requirements, identified, acquired, and installed Cummins engines / aftertreatment / instrumentation systems:

-2002 ISM for DPF studies....2007 ISL for DPF studies....2010 ISB for SCR studies

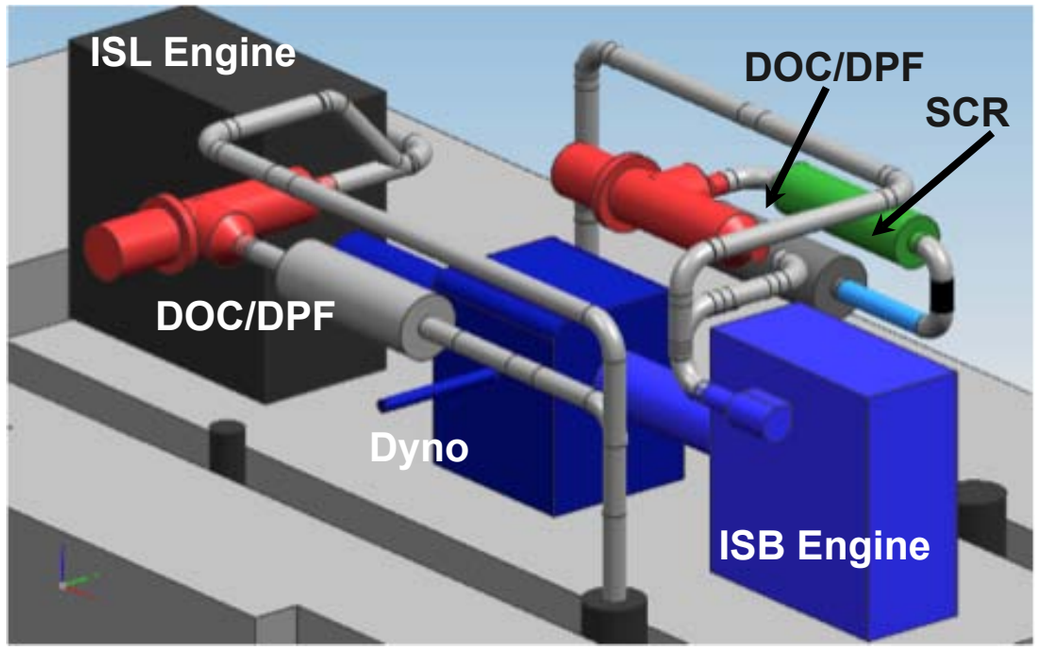
-**Instrumentation** - integrated data acquisition across multiple instruments, 5-gas analyzer, FTIR, scanning mobility particle sizer, high-resolution scale, PM hot sampler, fuel/air metering.

This preparation has reduced the risk of maintenance-related shutdowns and increased data quality achieved through instrumentation integration and single-bus data acquisition.

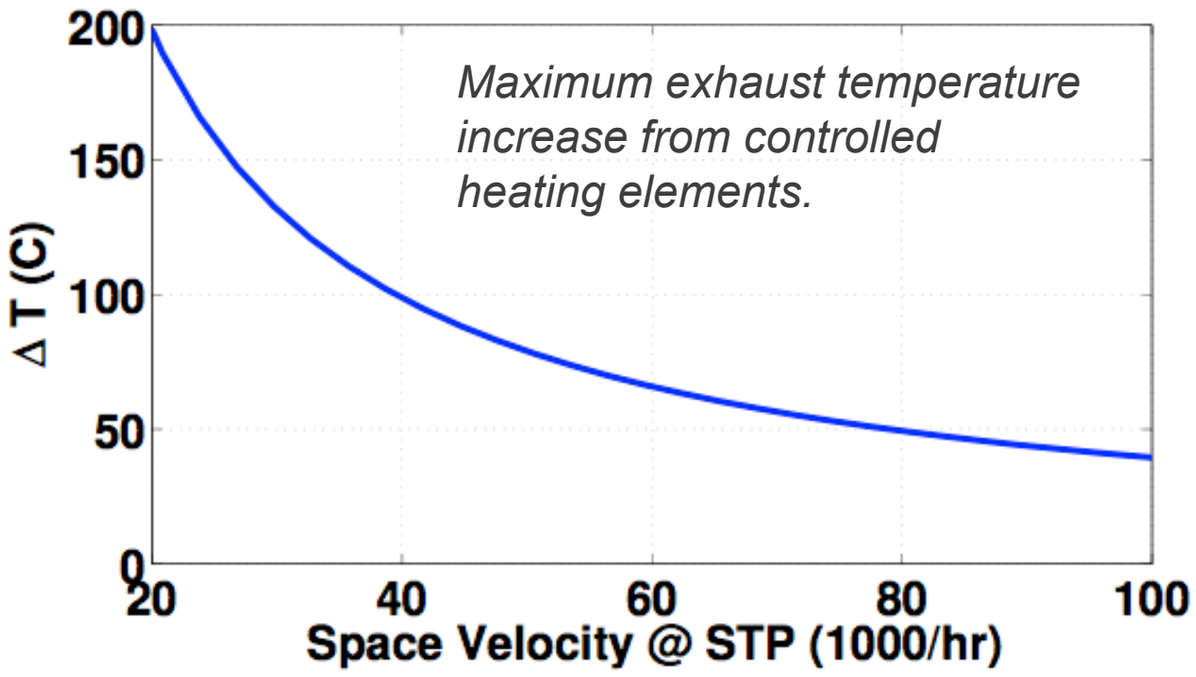
Technical Accomplishments - Task 1 Temperature Controlled Exhaust Heating

Designed an exhaust heating system to expand the space of temperature / exhaust gas species points attainable by an engine test cell.

Identifying temperature sensitive, reduced order model kinetic parameters is an important aspect of the project. In typical test cell studies the range of temperature / exhaust species concentration points is limited by an engine's characteristics.



Continuously controllable, 25kW heaters (red) placed at two locations in the ISL/ISB test cell.



The heating system allows decoupling of temperature from exhaust concentration. This feature will be leveraged across many of the studies, including the PM loading and oxidation tests currently being conducted.

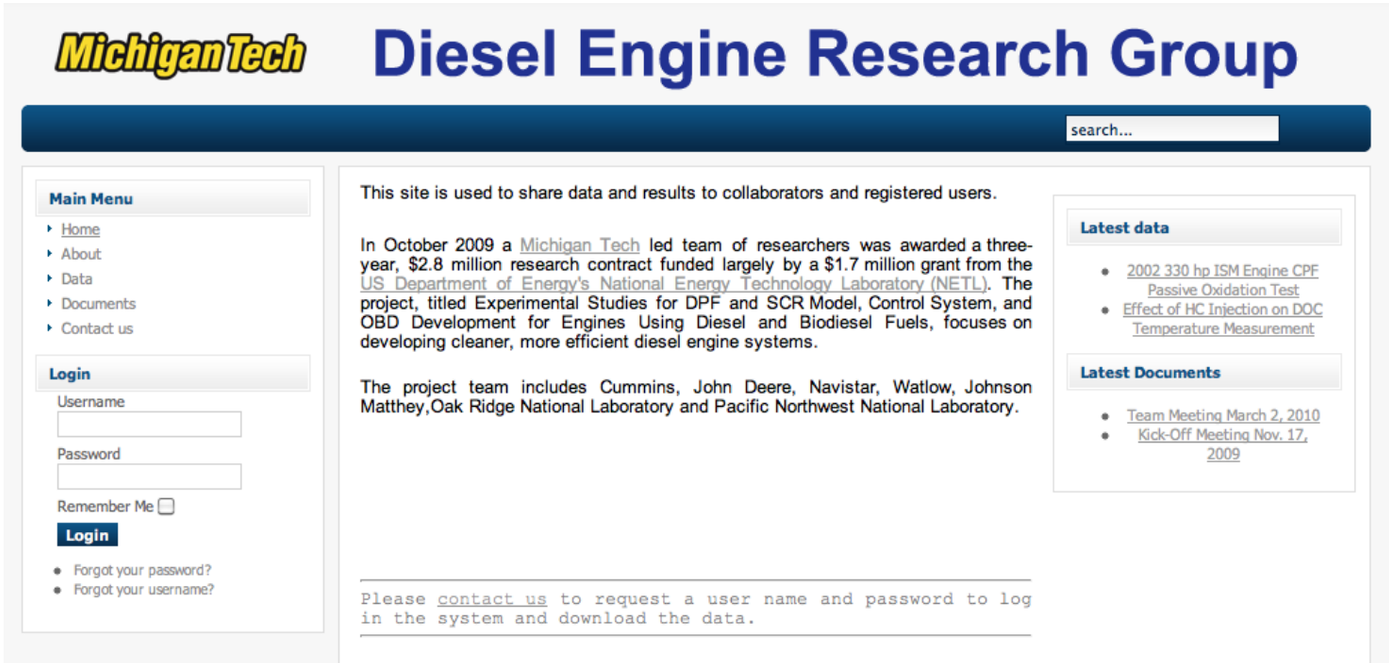
Technical Accomplishments - Task 2
Data Repository System

A secure, web-based data repository and server system was created and deployed.

- Data is loosely defined as any combination of raw data, supporting analysis documents, and test notes
- Data is tagged with multiple attributes (source, test purpose, instrumentation, date, etc.)
- The entire site is searchable through all tags yielding “spotlight” browse results to quickly locate data
- The application was expanded to also house project-related reports, presentations meeting minutes, etc.

http://diesel.mtu.edu

The repository expands communication amongst project participants, improves longevity of project results, and is designed to be expandable to future project-related collaboration.



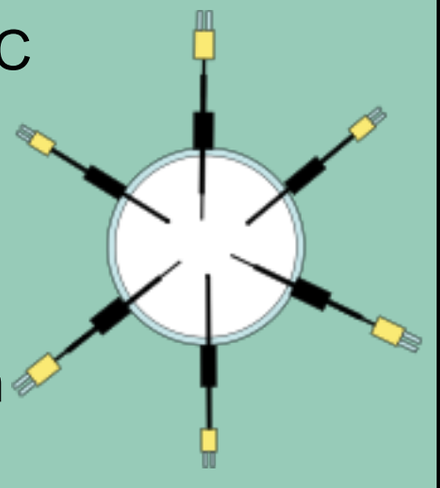
Technical Accomplishments - Task 2
Temperature Probe HC Effects Study

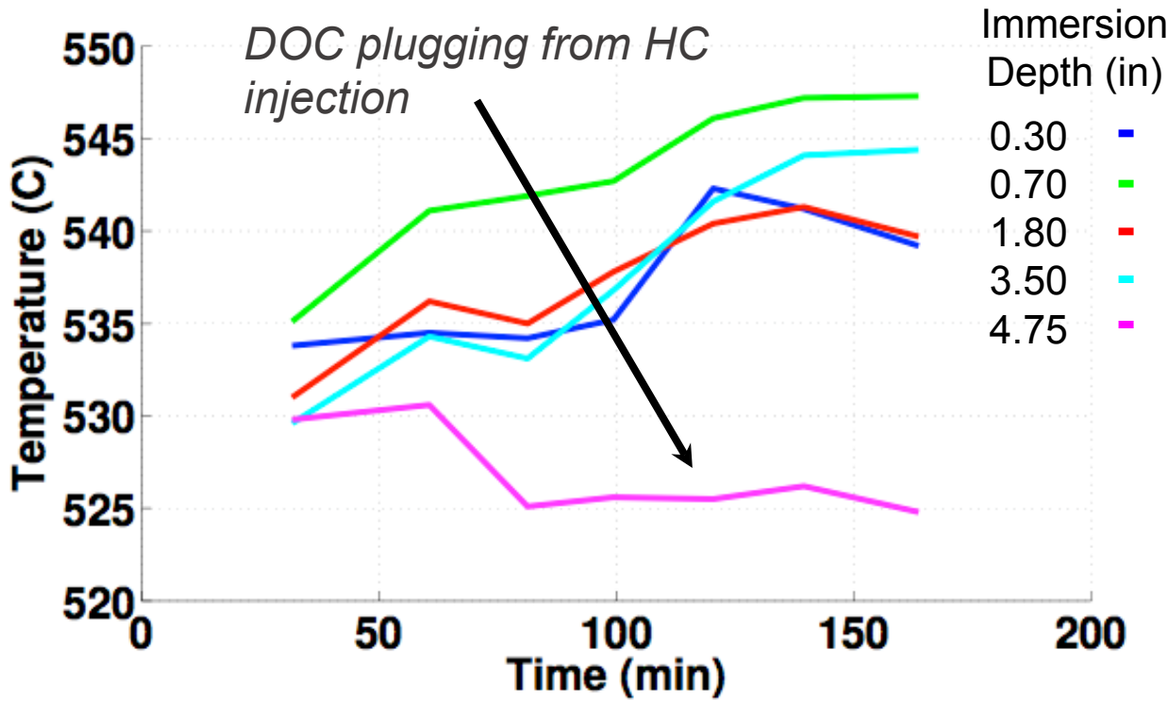
Designed a test method for quantifying temperature sensor sensitivity to HC injection and probe size.

Past experiments have indicated that probe geometry differences can lead to measurement errors of >10C downstream of a catalyst during HC injection events. Quantifying this relationship is important for state estimation sensor models.

Tests were conducted using 0.020” and 0.125” type K thermocouples placed at several immersion depths inside and downstream of a DOC. Step injections of HC upstream of the DOC were performed.

The test was inconclusive due to DOC partial plugging. An opposing thermocouple arrangement has been designed and will be used in future tests with lower HC levels.



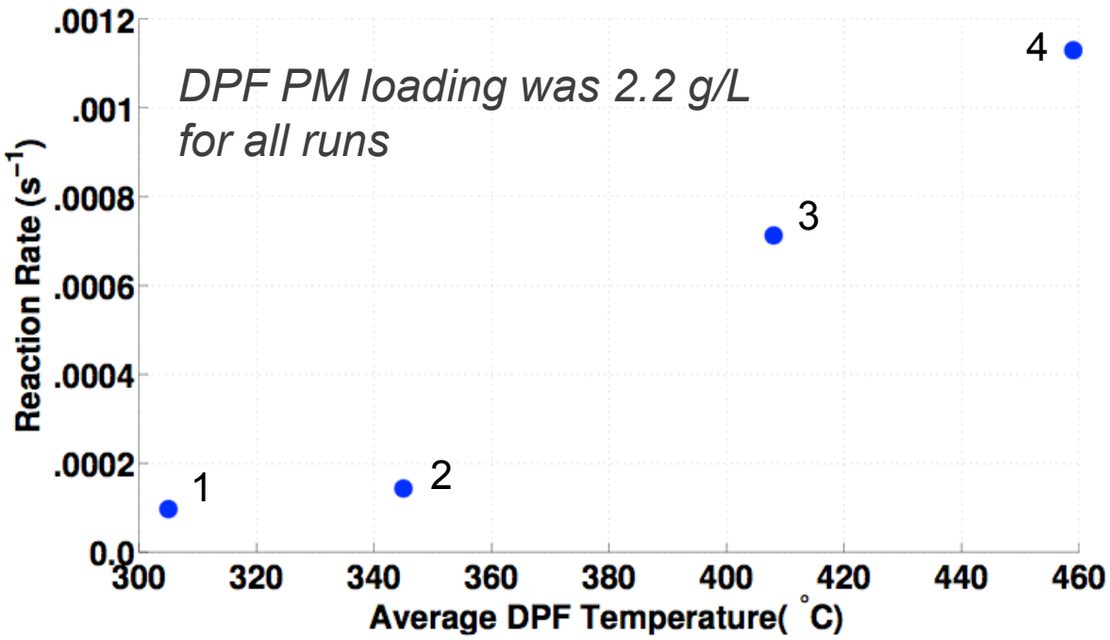


Technical Accomplishments - Task 5
DPF Passive Oxidation Protocol

Developed and validated a test procedure to measure a DPF's passive oxidation rate as a function of NO_2 concentration, temperature and PM filter loading, NO_2/PM ratio and exhaust flow rate.

The oxidation rate measurement technique was validated against rates found in the literature. It is an attractive alternative to the balance point approach since it captures sensitivity to the rate to multiple parameters in one test. In addition to exhaust gas and particle size distribution measurements, the procedure requires hot PM sampling and a high precision DPF weighing procedure.

Understanding and correctly modeling PM loading effects on passive oxidation is key to developing reduced order models for state estimation.



Passive Oxidation Test Conditions

Test #	NO2 Conc. Into DPF (ppm)	NO2/PM Ratio (n.d.)	Exhaust Mass Flow Rate (kg/min)
1	146	8.6	6.8
2	120	7.4	6.8
3	180	62.7	14.4
4	93	24.6	16.9

Collaborations

Team Collaborations:

- **Michigan Tech** : Modeling, analysis, and engine test execution on nearly all tasks.
- **ORNL** : Reactor studies for SCR spatial NH3 storage behavior (using SpaciMS for internal catalyst gas measurement), HC masking, and optimal NH3 storage.
- **PNNL** : DPF loading, passive oxidation, and active regeneration using SPLAT II in Michigan Tech test cell for PM morphology
- **Cummins** : Engine/aftertreatment system support for DOC, DPF, and SCR studies.
- **Navistar** : Engine and sensor testing for DOC and DPF studies.
- **John Deere** : Sensor model study support and DOC, DPF, and SCR model evaluation and aged component source.
- **Watlow** : Instrumentation design & installation, DPF thermal model support, and NOx and temperature sensor modeling studies
- **Johnson-Matthey** : Aftertreatment component model support and aged component support.

External Collaborations

- **Filter Sensor Technologies** : Developing a plan to incorporate a new soot sensor design into the Michigan Tech project test cell for state estimation strategy development studies.

Future Work

Remainder of FY10

- Complete model form study (currently 50% complete), including incorporation of NOx, and PM sensors into simulation tools
- Start ORNL SCR spatial ammonia storage study using reactor tests and SpaciMS
- Deploy PNNL's SPLAT II in Michigan Tech test cell for soot morphology study
- Complete DPF passive oxidation sensitivity study and continue experimental validation

Goals for FY11

- Complete estimator design study using reduced order models and conduct simulation evaluation
- Complete fuel-dependent SCR HC masking study at ORNL
- Complete DPF maldistribution study in conjunction with PNNL using Michigan Tech test cell

Project Technical Tasks

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Summary

Communication and collaboration between stake-holders - universities, national labs, engine OEMs, sensor suppliers, and catalyst suppliers - is a core aspect of this project. It is expected to facilitate achievement of emission regulations with minimal fuel penalty for a wide range of engines including those operating on diesel or biodiesel fuel.

Temperature controlled exhaust heating extends the range of engine test cell capability for understanding aftertreatment system behavior. The benefits of this new system will be quantified and used on nearly all phases of this project. It will help us create models with a wide range of applicability using a cost-effective test schedule.

Understanding passive oxidation rate sensitivity to PM loading is important for accurate reduced order models for state estimation. A new measurement technique has been developed as an alternative to using balance point data. It captures DPF oxidation rate dependence on temperature, NO_2 concentration, exhaust gas flow rate, and NO_2/PM ratio in one test.

This project started November 1, 2009 with a kick-off meeting held November 17, 2009 with all partners participating. Subsequent team meetings have been held to foster productive collaboration.