High Efficiency Combustion and Controls

2010 Annual Merit Review
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Technology Programs and Analysis

This Presentation Does Not Contain Any Proprietary or Confidential Information

Agenda

DETROIT DIESEL

- Program Goals
- Combustion system
  - Approach, results
- Engine controls
  - Approach, results
- Turbocharger exhaust energy optimization
  - Approach, results
- Future work
- Collaborations/interactions

Program Objective

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- **Program Goal: Improve engine fuel efficiency by 10%, with significant focus being directed to combustion related topics.**
- **Building blocks:**
  - **Refinement of "conventional" combustion system with focus on calibration optimization, bowl shape modifications and real time in-cylinder combustion feedback control. Target = 4-6%.**
  - **Dual spray injection system for use with a PCCI combustion strategy. Target = 1-4%.**
  - **Real time, transient control optimization of calibration parameters (injection system and others) considering tradeoff of fuel economy vs engine emissions. Target = 3-4%.**
  - **Air system refinements were pursued as an area with improvement potential was encountered. Target = 1%.**

Combustion System Approach

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- DDC and ORNL have partnered to explore avenues for increasing heavy duty diesel engine efficiency through advanced combustion strategies
- A multi-pronged approach has been taken
  - Optimization of production hardware
  - Enabling advanced combustion through modern engine technology including real time combustion control
- By leveraging ORNL's strengths in advanced combustion and controls, DDC can more rapidly address pressing needs for meeting 2010 emissions regulations and potential CO_2 regulations

Engine Results: Combustion System

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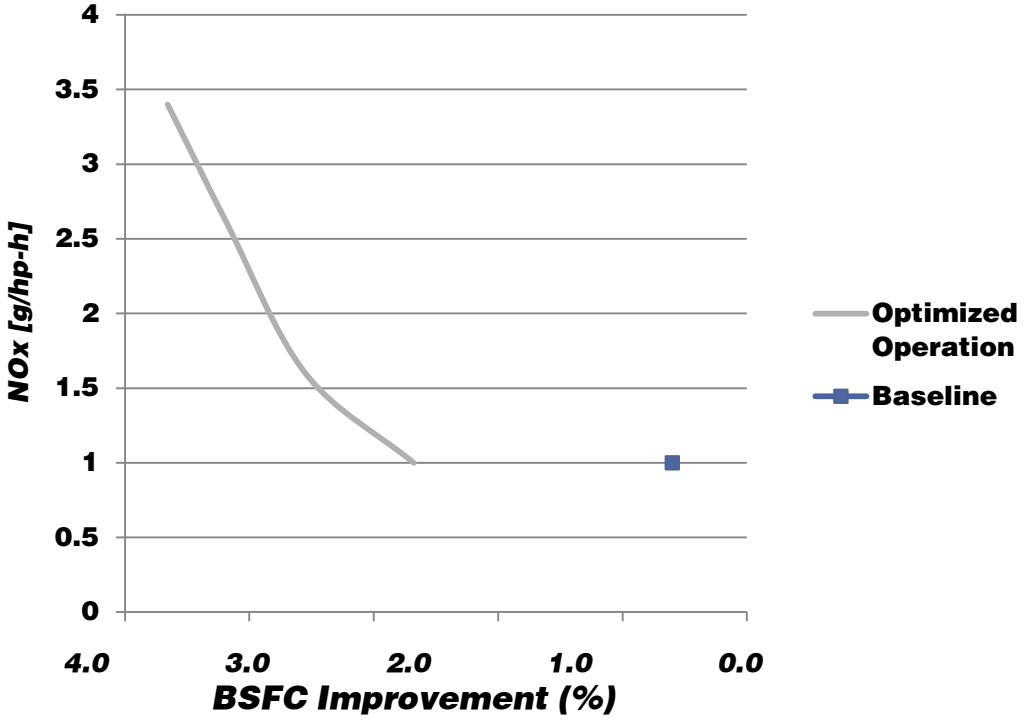
- **Goal: optimize BSFC at road load**
  - **Baseline engine fuel consumption improved by 2%**
  - **Hardware changes kept to a minimum with fuel consumption improvements largely via pushing calibration limits**
  - **Potential for nearly a 4% fuel consumption improvement if engine out NOx levels balanced against aftertreatment ability to maintain tailpipe emission compliance.**



OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Real Time Combustion Control - Motivation

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- Improve performance by minimizing variation in combustion system (cycle to cycle) to a tightly controlled window
- Negate fuel and ambient effects that could negatively impact engine performance
- Cylinder balancing – normal operation up to and including diagnostic benefits
- Could have significant benefit with a PCCI based combustion system
  - Combustion stability during PCCI
  - Transitioning between CI and PCCI modes
  - Cylinder balancing
- Production-feasible sensors are “available”, but not validated for heavy-duty applications
- Two sensor designs were selected for evaluation
  - Woodward and Continental
- Program attempting to address two issues: feasibility and benefit

Real Time Combustion Control Approach

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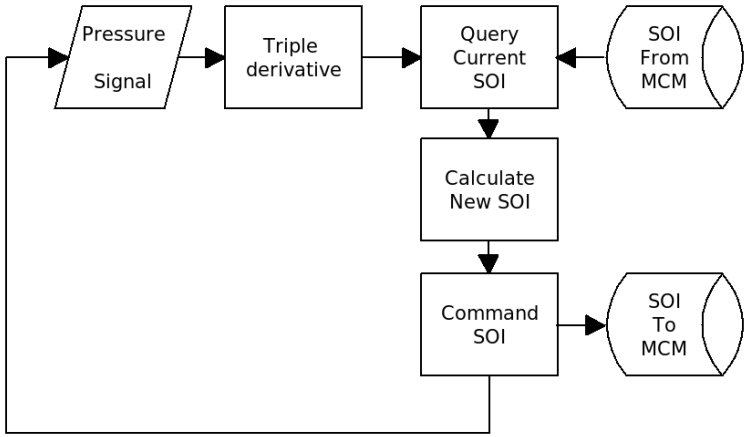
Measure
Incorporate Start-Of-Combustion sensors in individual cylinders and use this signal for closed-loop combustion control

Mode of operation
All times.

Potential
~ 1% - 4% fuel economy potential.

Status
Concept phase



Courtesy: Continental

Courtesy: Woodward

Engine Test Results

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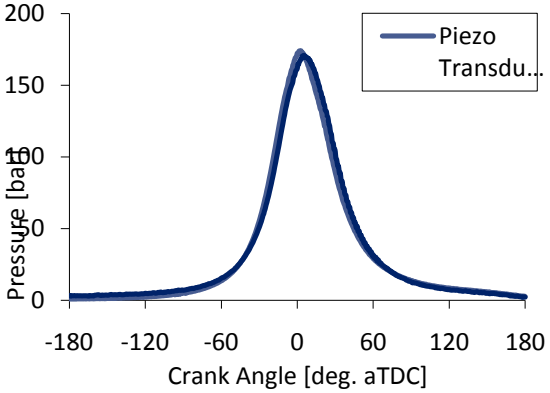
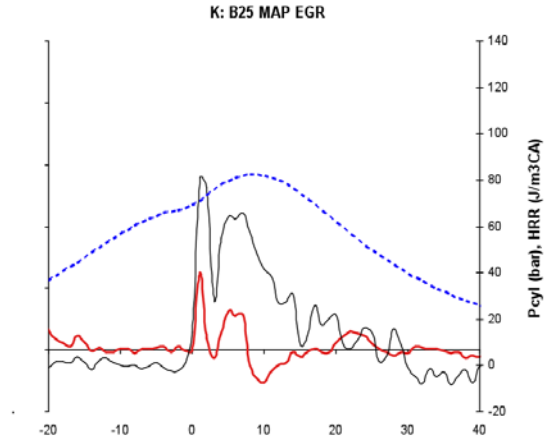
- **Both systems show favorable results under some operating conditions**
  - **Under certain operating conditions, systems have challenges requiring further development**
  - **Effort spent evaluating sensors and now progressing to focus on combustion control**





Dual Spray For PCCI Combustion

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Purpose

Low pressure hollow-cone spray early in cycle for partial pre-mixed component of PCCI, then high pressure multi-hole spray for balance of fuel injection, all in one injector body.

High level of mechanical complexity but potential of dual injection modes from one injector is very beneficial. The classic high risk, high reward.

Mechanical Evaluations

Injector testing on injector flow bench had some positive results showing injector to be functional, but there were mechanical issues causing significant concern about functionality/stability for running on an engine.

A second iteration injector design is required

Plan Moving Forward

Technical and programmatic issues have lead to reevaluation of risk-reward for this hardware configuration, and decision has been made to redirect program effort to areas with higher likelihood of allowing demonstration of fuel economy benefits within program timing.

Why Predictive Controls ?

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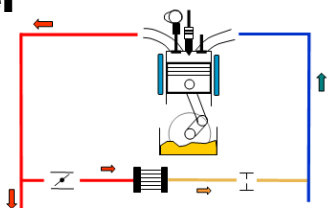
Individual Component Level



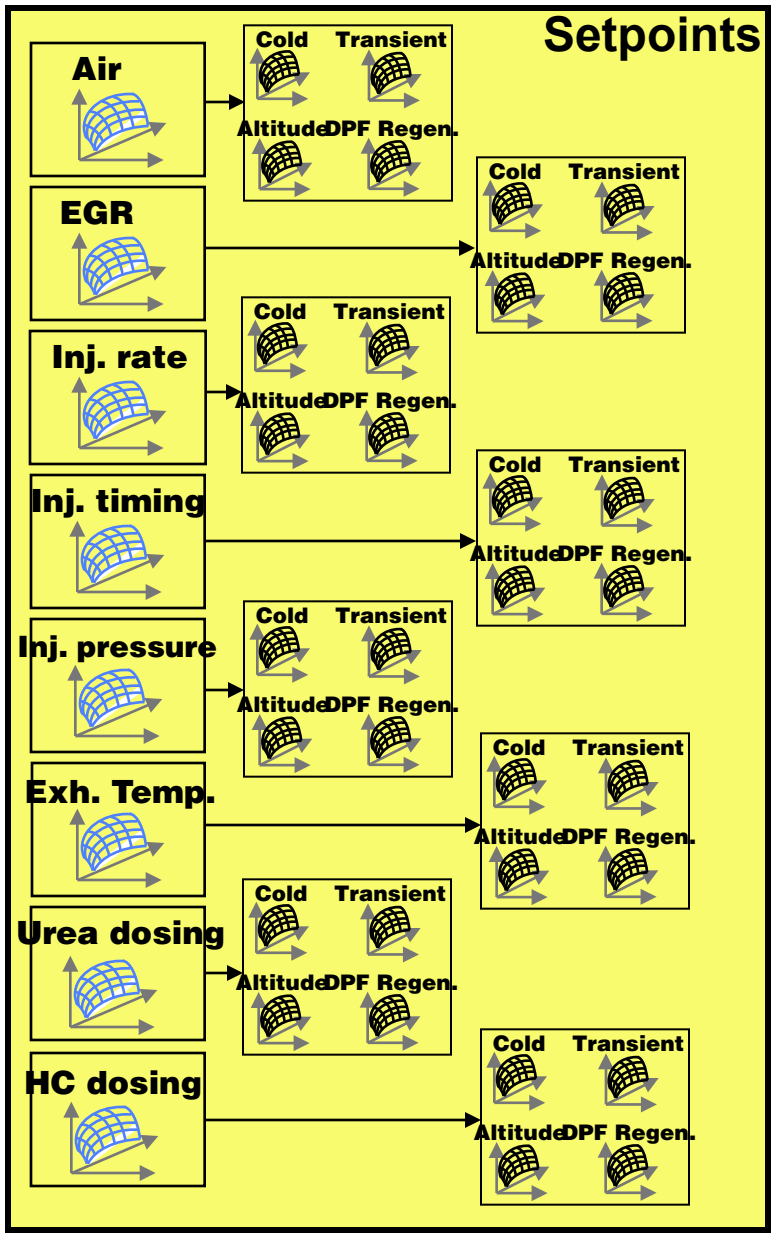
System Level

Engine Level

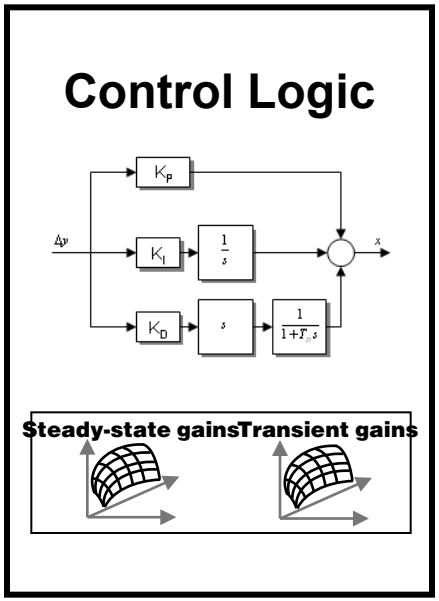
Truck Level

- Increasingly complex calibration
  - More degrees of freedom
  - Additional actuators
  - Hybridization
  - Thermal management
  - Heat rejection
  - Vehicle integration
- More stringent requirements
  - Control stability
  - Transient response
  - Fuel economy
  - Urea consumption
  - Emissions
  - Life-cycle cost
  - Durability
  - Diagnostics

Approach: Illustration of Engine Maps



- **Factorial increase in calibration space**
- **Multiple performance targets**



Performance targets

- Torque
- Drivability
- Durability
- Fuel economy
- NOx / PM / NMHC
- NO/NO_2 ratio
- NH_3 storage
- Urea consumption
- SCR efficiency

Collaboration: Atkinson LLC & FEV

1st Step Results: Performance Model Evaluation

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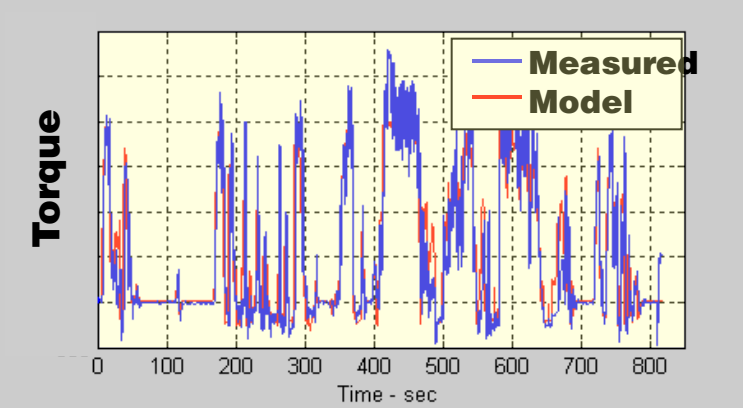
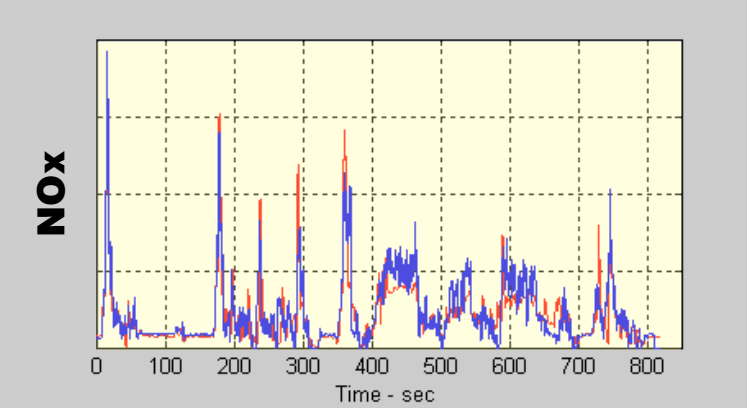
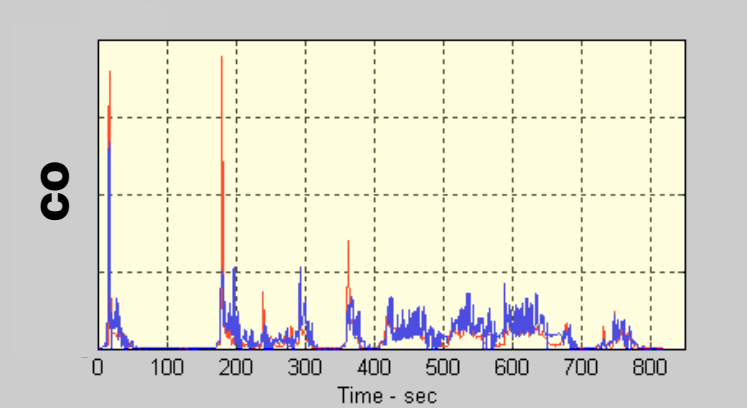
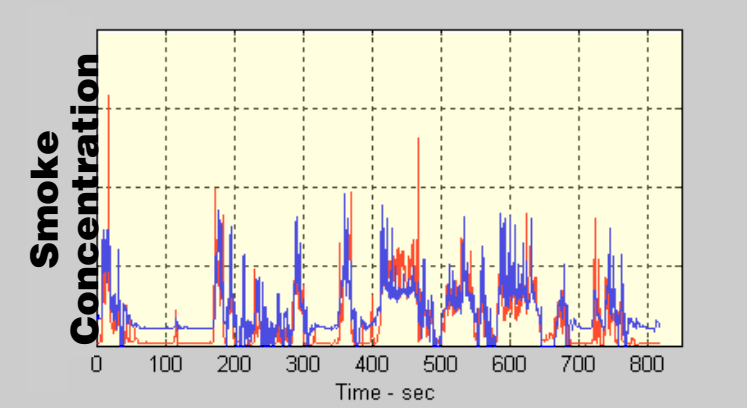
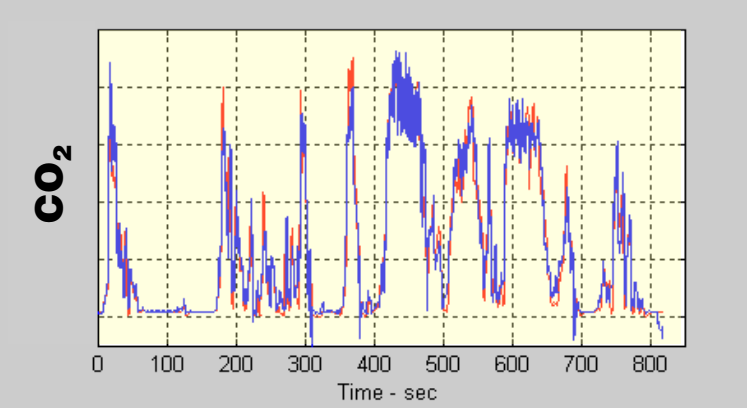


Performance model accuracy is satisfactory over a wide range of operating conditions









2nd Step Results: Optimized Set Point Evaluation

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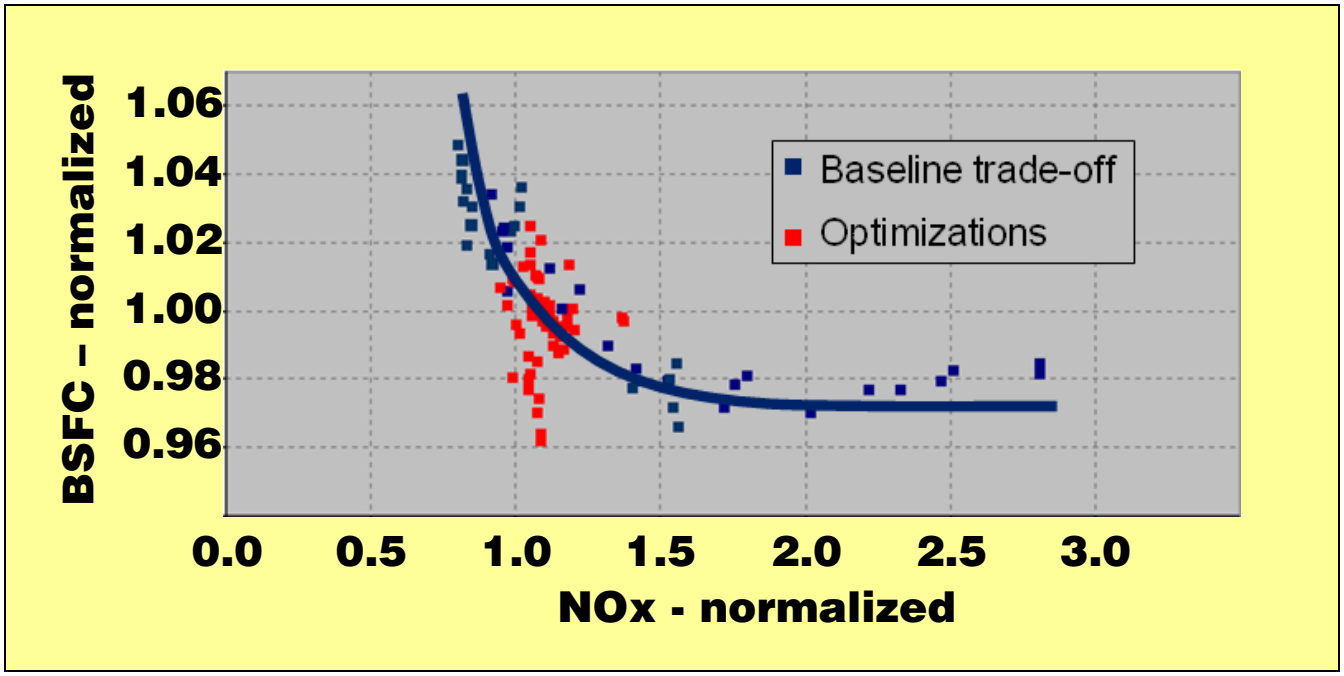
- Exercised the controller model offline
- Resulting engine set points were evaluated at the test cell
- Measurable gains in fuel economy



3rd Step Results: Experimental

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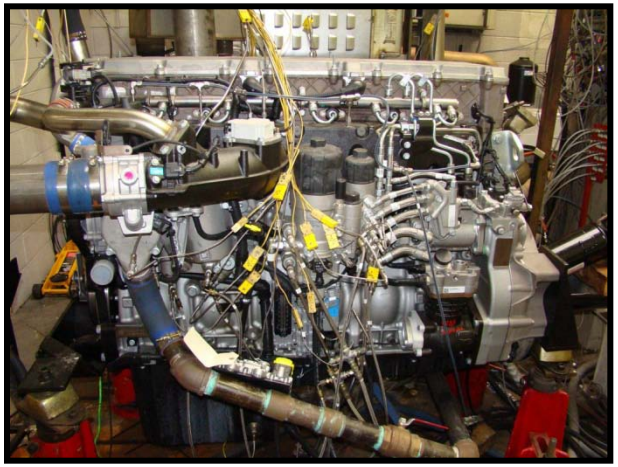

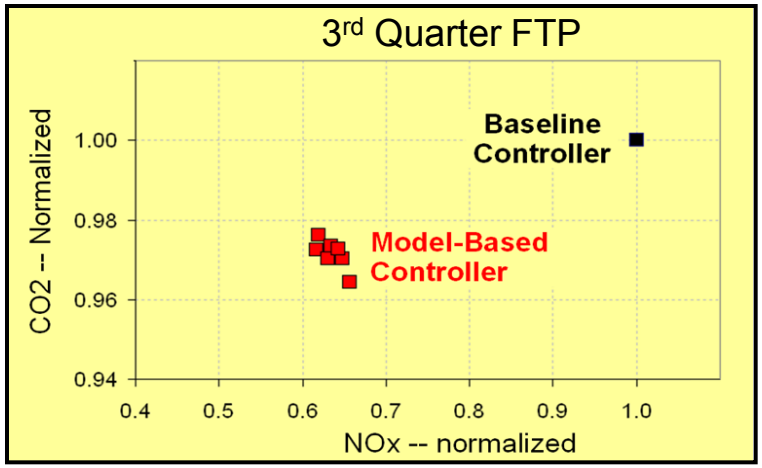

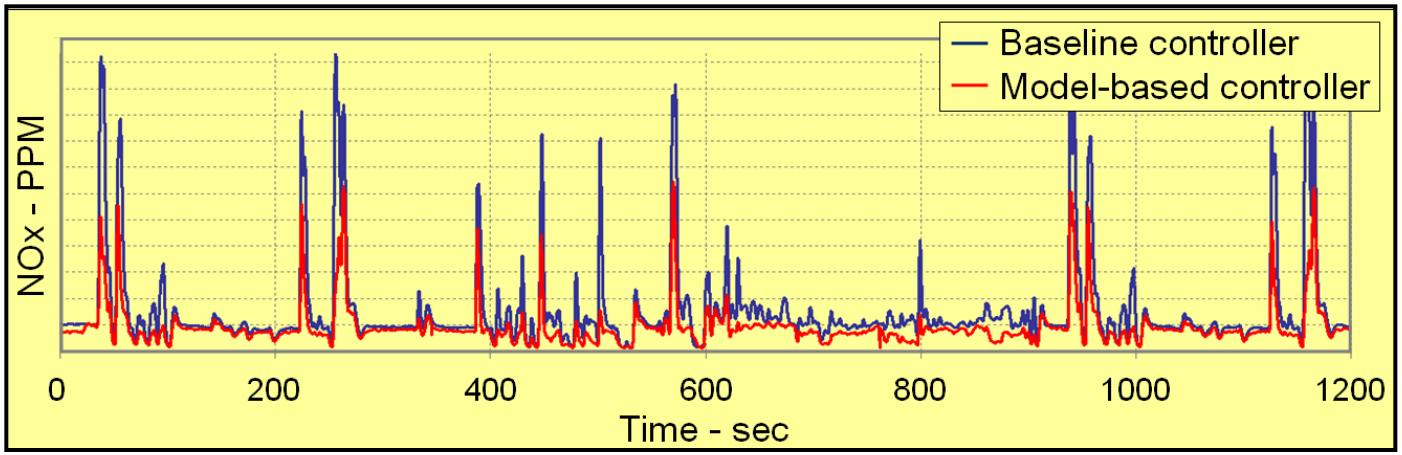

Test cell evaluation of predictive controller:

- **Successful real-time optimization**
- **Measurable CO2 reduction**

Turbocharger Approach

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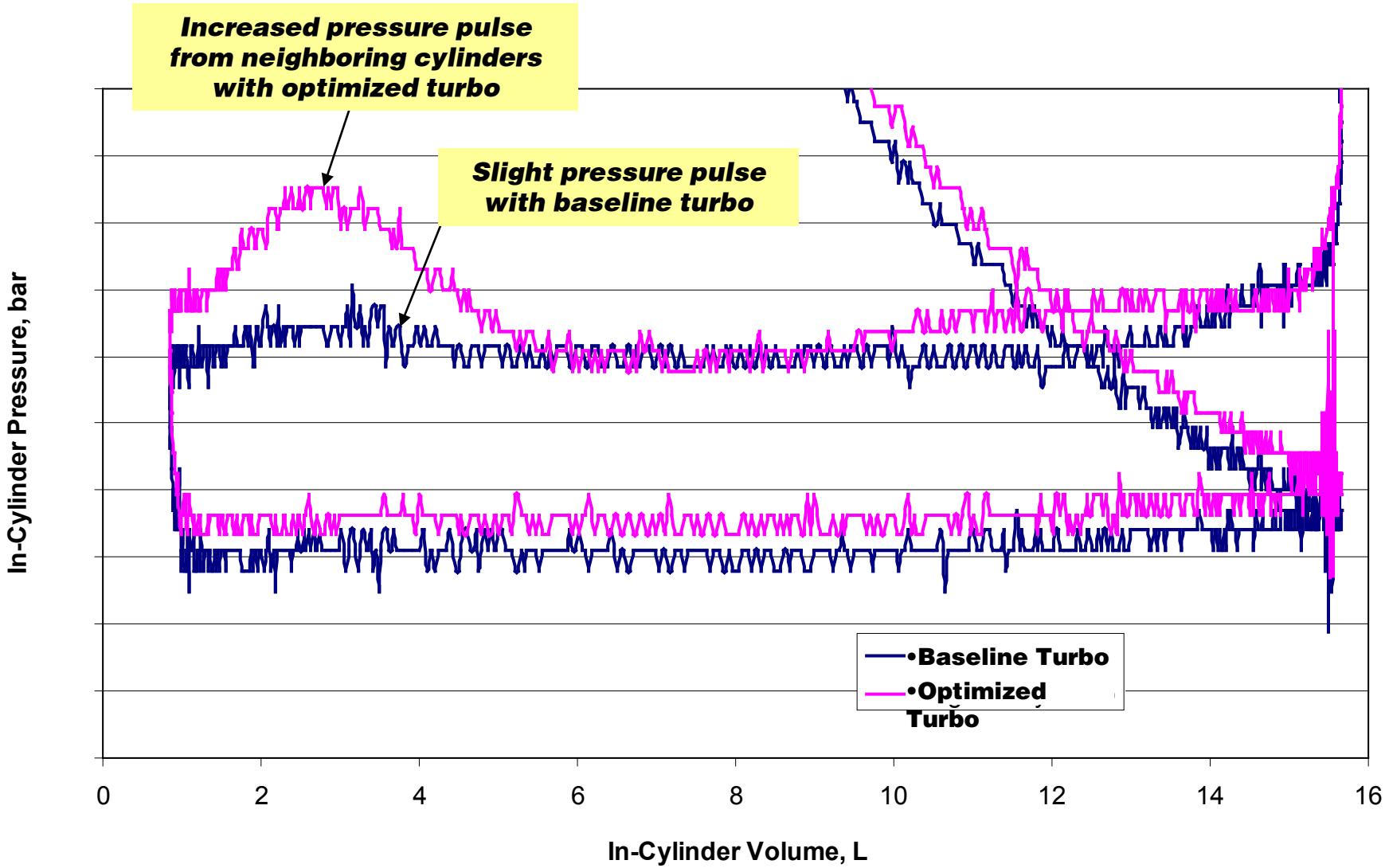
- Testing and simulations revealed potential to better match turbocharger with exhaust system
  - Objective: maximize exhaust pulse energy at turbine wheel to give higher instantaneous turbine wheel efficiency
  - Expectation was improved engine bsfc would result
- Test plan: evaluate on engine configured for 2010 emissions
  - Tested over complete fuel map plus FTP and ESC cycles

Experimental Results – Pulse Energy



Experimental Results – Fuel Economy

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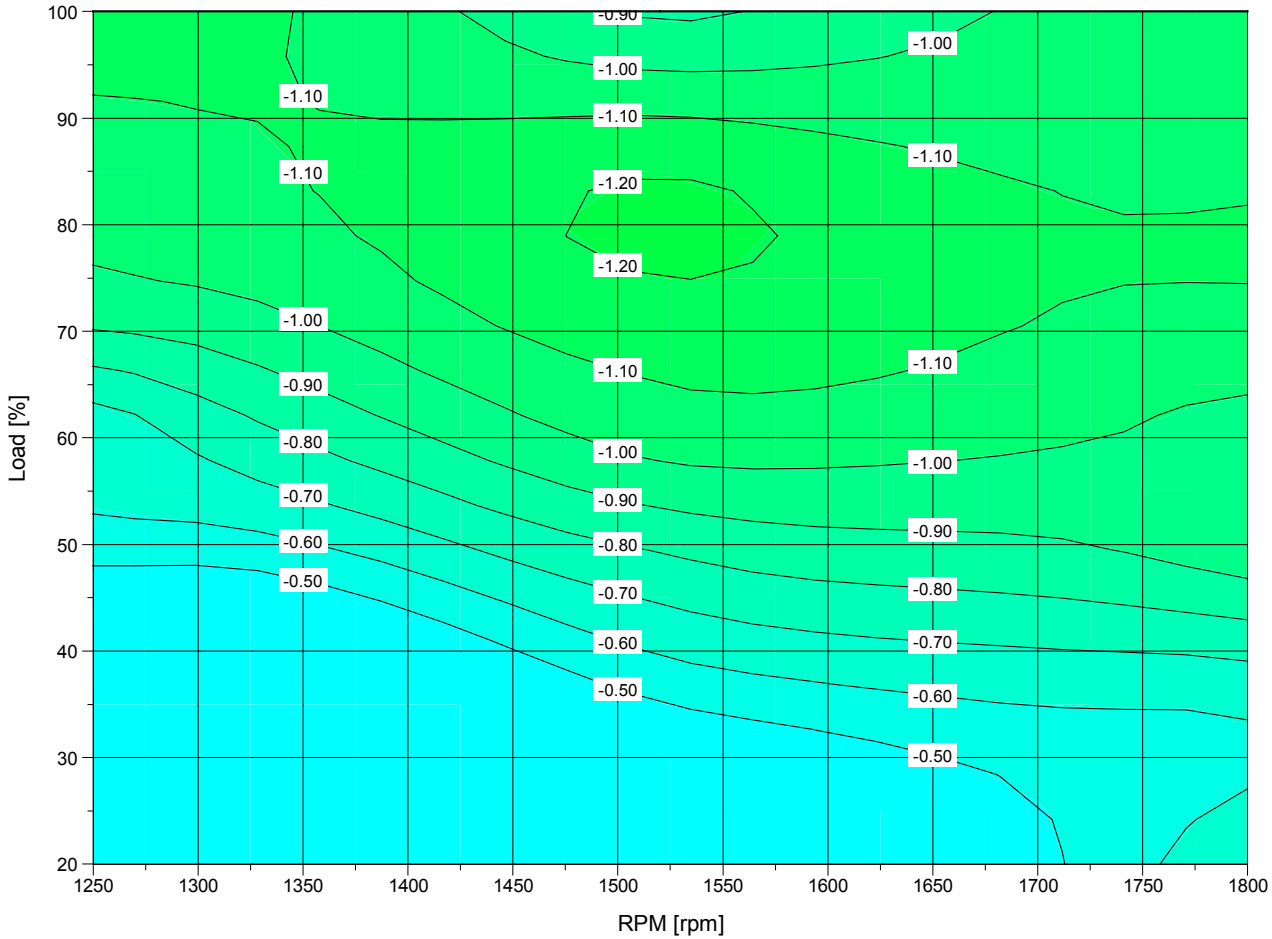
- **Higher pressure pulsations with optimized turbocharger results in improved BSFC compared to baseline turbocharger**
  - **Approximately 1.0% improvement seen over fuel map**



Summary and Future Research

DETROIT DIESEL

- **Combustion system; approx. 4% fuel efficiency improvement demonstrated + 2% expected prior to completion of program. Moving forward:**
  - **Refinement of bowl shape and fuel injection system matching to take advantage of previous years work plus in-cylinder real time combustion control**
  - **Real time in-cylinder combustion feedback continues**
  - **Engine testing initiated with high performance fuel system to study advanced combustion strategies including (i) multiple injections, (ii) modified injector & piston geometries, and (iii) interaction of combustion strategy with turbocompound recovery**
  - **Dual spray approach terminated**
- **Controls; approx. 3% fuel efficiency improvement demonstrated. Moving forward:**
  - **Expand the use of the control technique to include additional systems, e.g., in-cylinder combustion control and aftertreatment**
  - **Evaluate the controller over full transient cycles and over-the-road drive cycles in vehicle for back to back fuel economy comparisons**
- **Turbocharger developments .. approx. 1% fuel efficiency improvement demonstrated**
  - **Efforts completed for this program.**
- **Program will result in 10% fuel efficiency improvements having been identified and program will be completed in calendar year 2010.**

Collaboration and Support

DETROIT DIESEL

- ***Oak Ridge National Laboratory***
  - **Combustion system development**
  - **Real time combustion control**
- ***Continental***
  - **Supply and support unique in-cylinder pressure measurement device**
- ***Woodward***
  - **Supply and support of ion based in-cylinder pressure measurement devices**
- ***Atkinson LLC***
  - **Advanced engine controls**
- ***FEV Inc.***
  - **Advanced engine controls**
- ***Department of Energy Head Quarters***
  - **Gurpreet Singh**
  - **Roland Gravel**
- ***National Energy Technology Laboratory***
  - **Carl Maronde**
  - **Jeffrey Kooser**