DETROIT DIESEL CORPORATION

Heavy-Duty Engine Technology for High Thermal Efficiency at EPA 2010 Emissions Regulations

Craig Savonen, Guangsheng Zhu, Houshun Zhang, Sandeep Singh, Rakesh Aneja
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Presentation Outline

- Technical Status Towards Project Objectives
- Technology Development Methodology
- Technology Building Blocks – Example Case Studies
  - ✓ Combustion
  - ✓ Fuel Injection System
  - ✓ Air and EGR System
  - ✓ Controls
  - ✓ System Integration
- Conclusions

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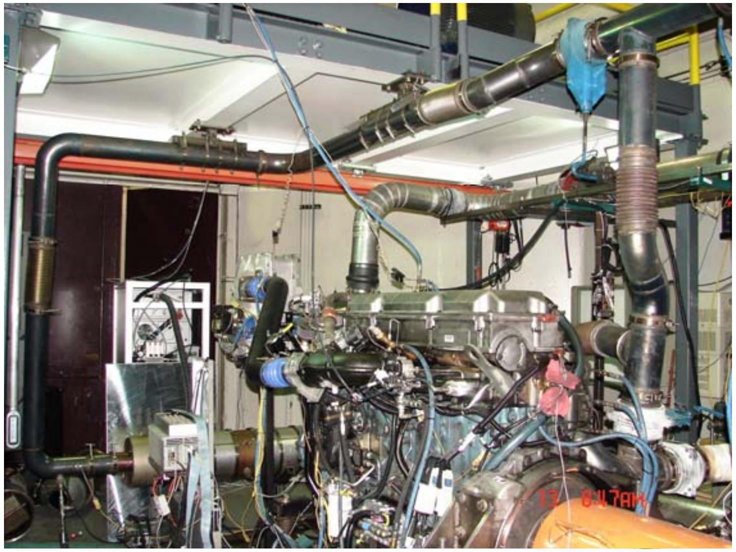
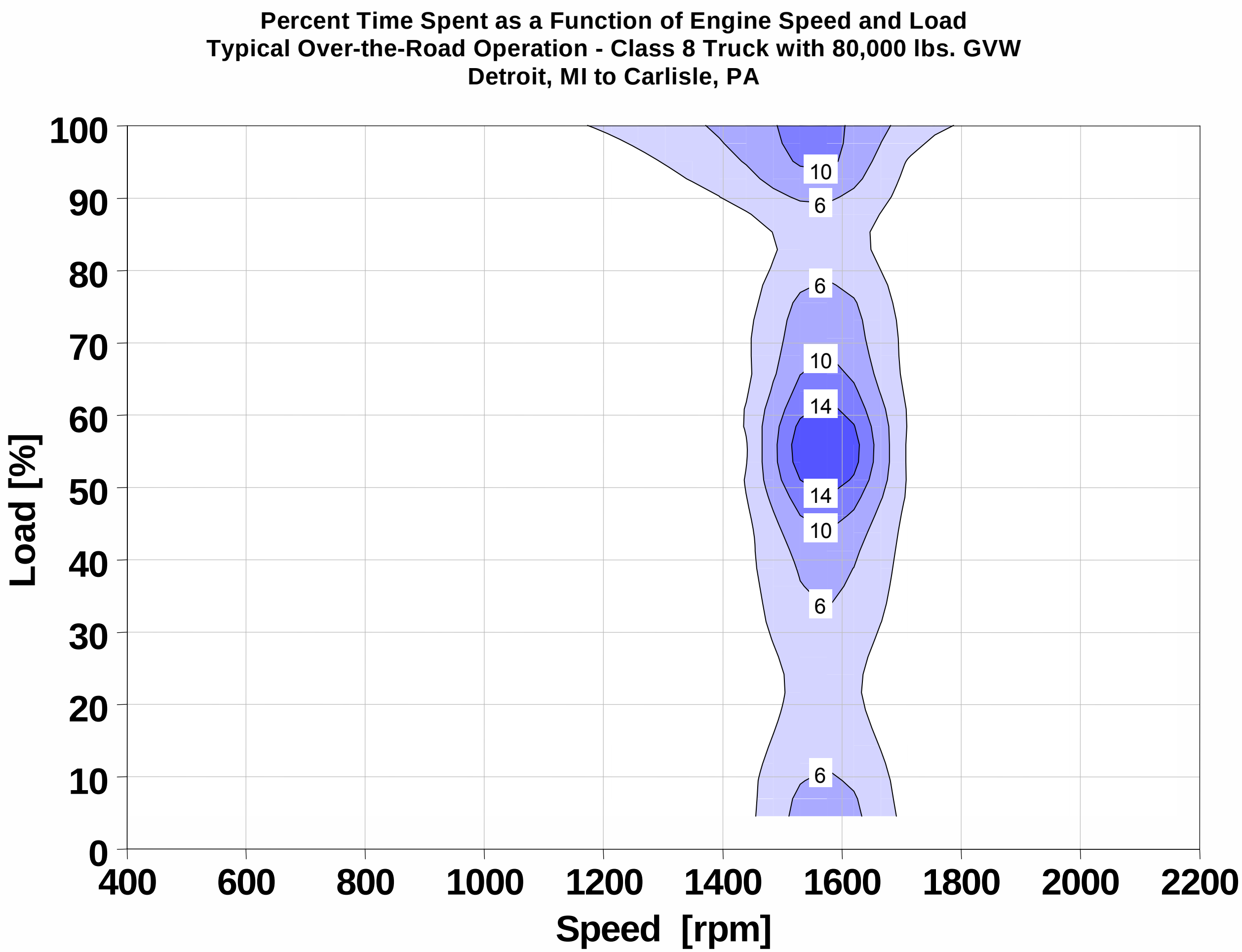
Project Objectives

- Develop and validate on-highway truck engine technologies for 50% thermal efficiency and near-zero emissions (NZ-50) that are viable for subsequent product development and eventual commercialization
- Project Duration CY2000-CY2006
- Project Sponsorship U.S. DOE, Office of Vehicle Technologies
- Emphasis on Enabling Sub-system Technologies
  - ✓ Low Emissions Combustion Processes
  - ✓ Fuel Injection Events
    - Flexible, Precise, Repeatable, Distributed, Modulated Pressure / Rate-shape
  - ✓ Engine Charge
    - Efficient Charging and EGR Cooling; Efficient, Variable Breathing
  - ✓ Controls and Automated Calibration Techniques
    - Model-based, Adaptive, Closed-Loop
  - ✓ Basic Aftertreatment and System Integration
    - Vehicle Boundary Conditions

NZ-50 Multi-cylinder Test-bed



Representative Over-the-Road Truck Route

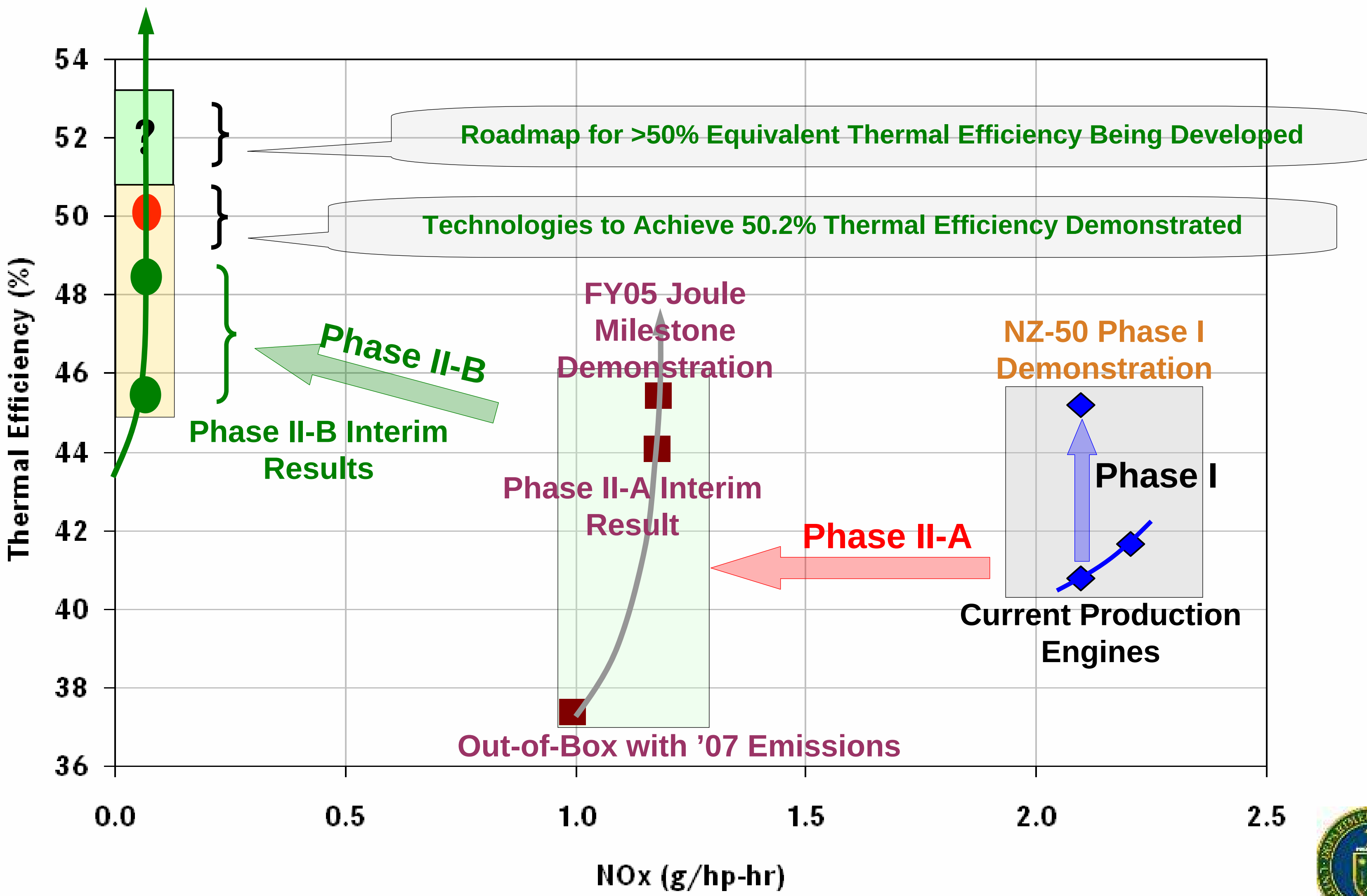


In addition to the project objective of peak thermal efficiency at a single operating condition, emphasis placed on fuel economy (equivalent thermal efficiency) during over-the-road representative cycles

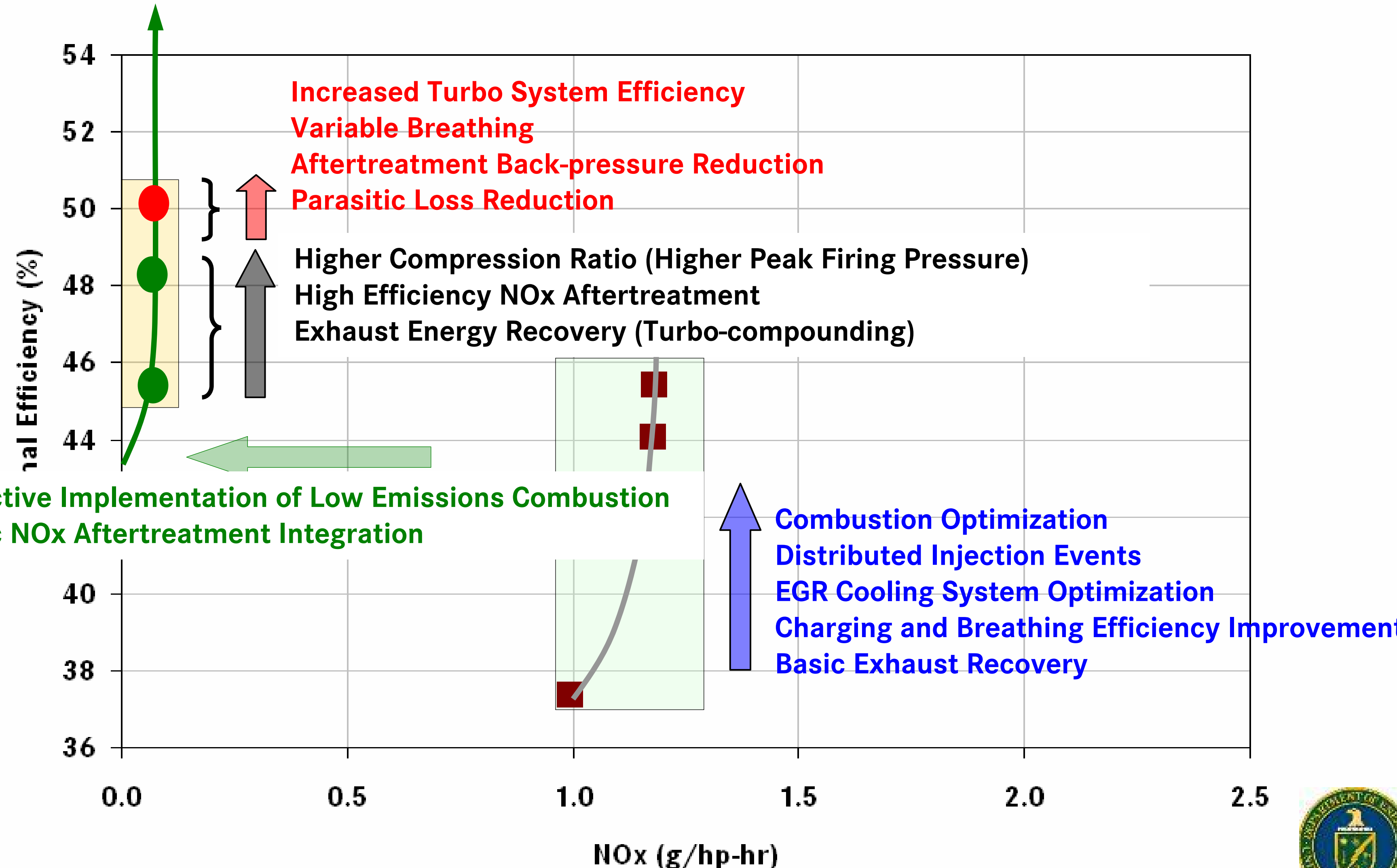
Thermal Efficiency Status

Integrated Experimental and Analytical Results

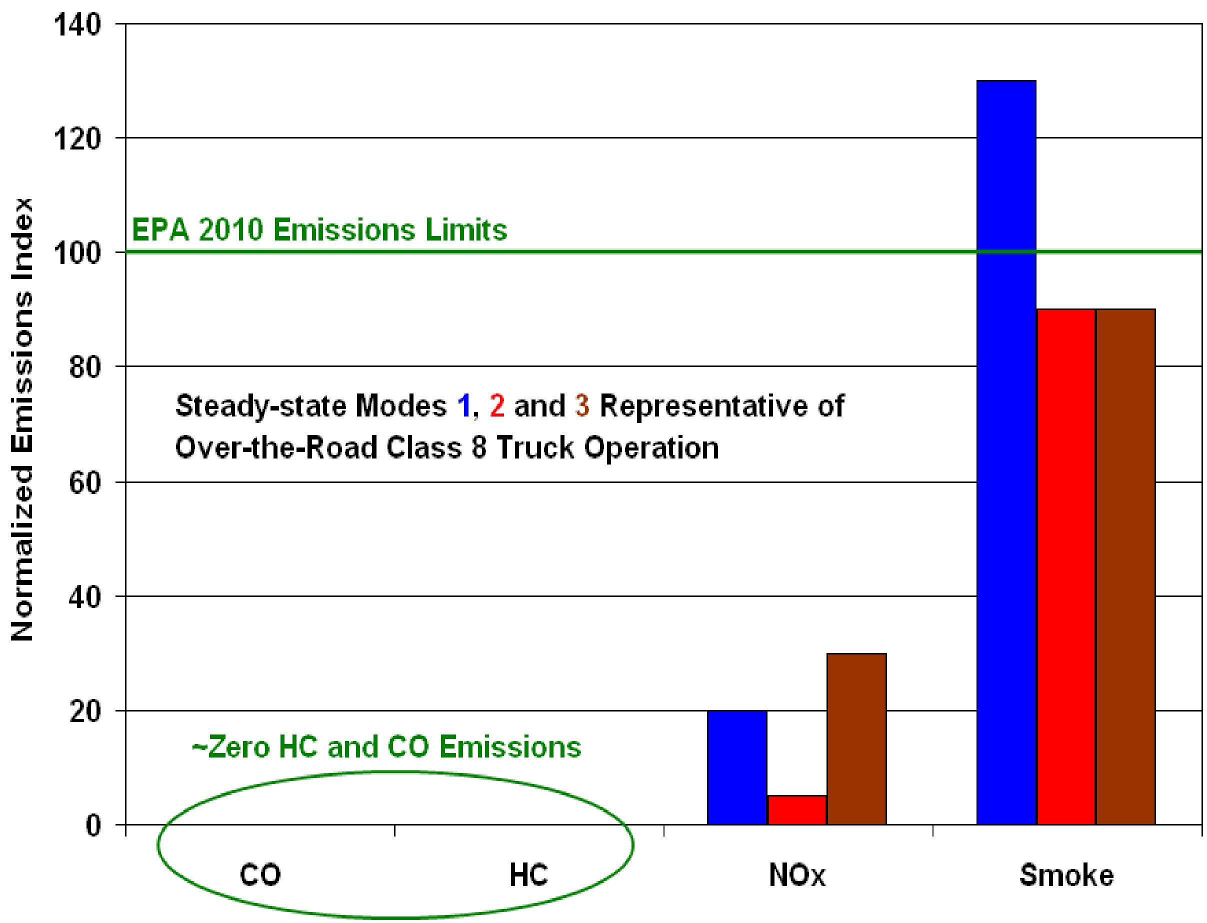
Peak Thermal Efficiency at a Single Operating Condition



Thermal Efficiency Roadmap - Key Building Blocks
Peak Thermal Efficiency at a Single Operating Condition

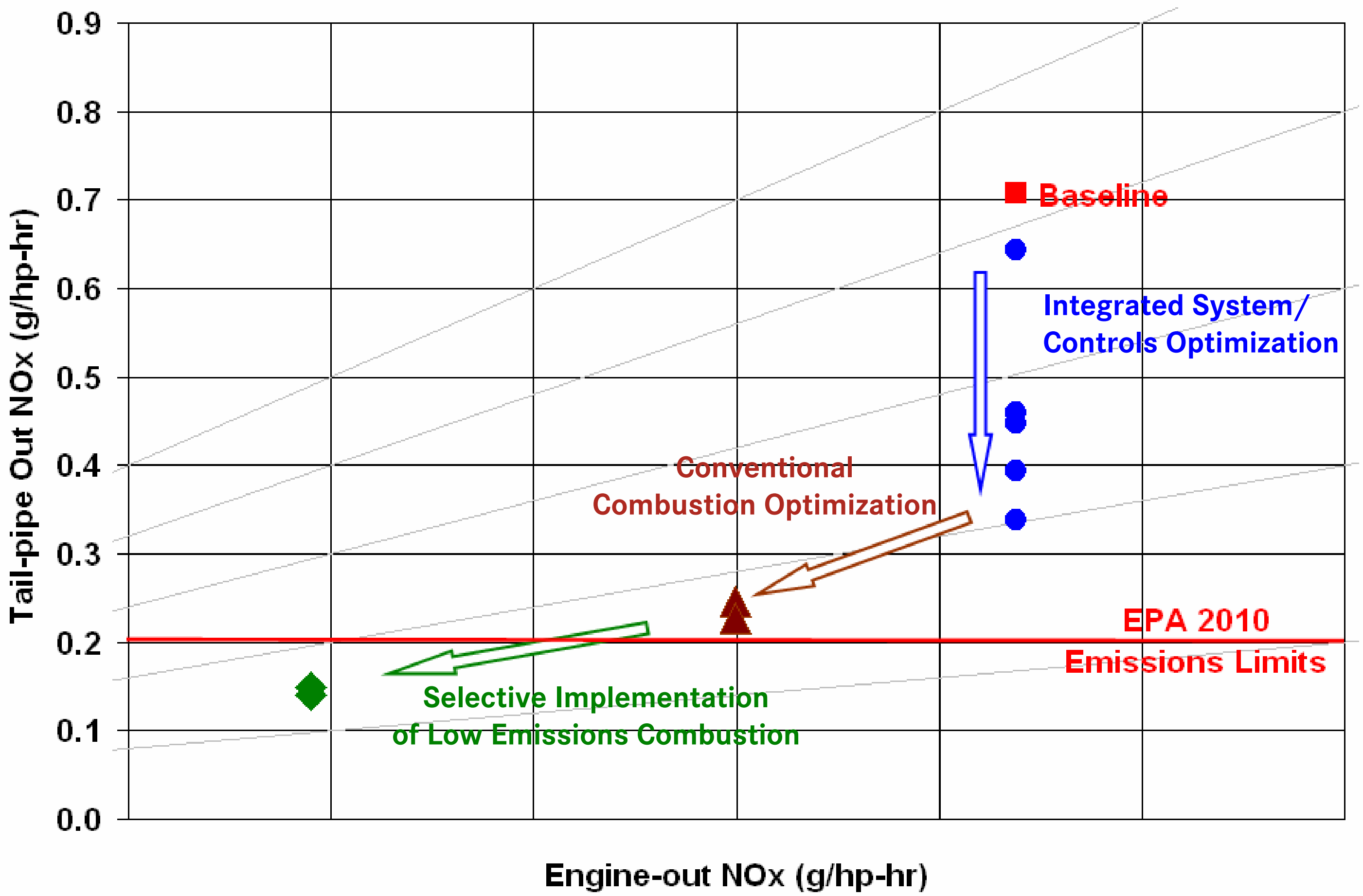


Progress Towards Near-zero Emissions
Experimental Multi-Cylinder Engine Results



System-out Emissions Demonstrated to be Below 2010 Emissions Levels over Representative Over-the-road Conditions

Progress Towards Near-zero Emissions
Experimental Multi-Cylinder Engine Results



EPA 2010 System-out Emissions Levels Demonstrated over Transient FTP

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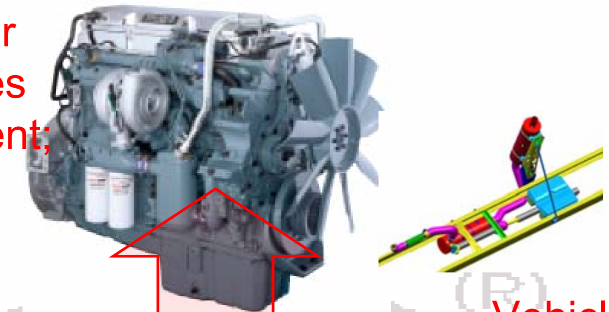
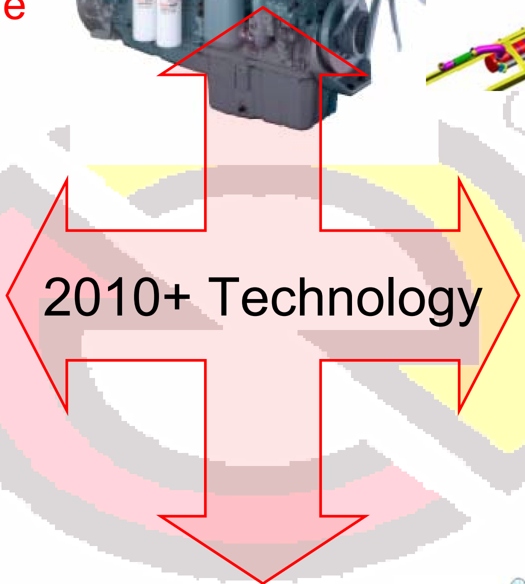
DDC's Integrated System Development Approach

Transient Multi-cylinder Development – Validates Steady-state Development; "Simulates" Vehicle

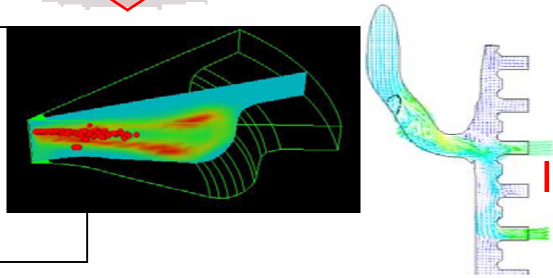




2010+ Technology

Vehicle Development – Validates Transient Development; Identifies Baseline for Next-generation

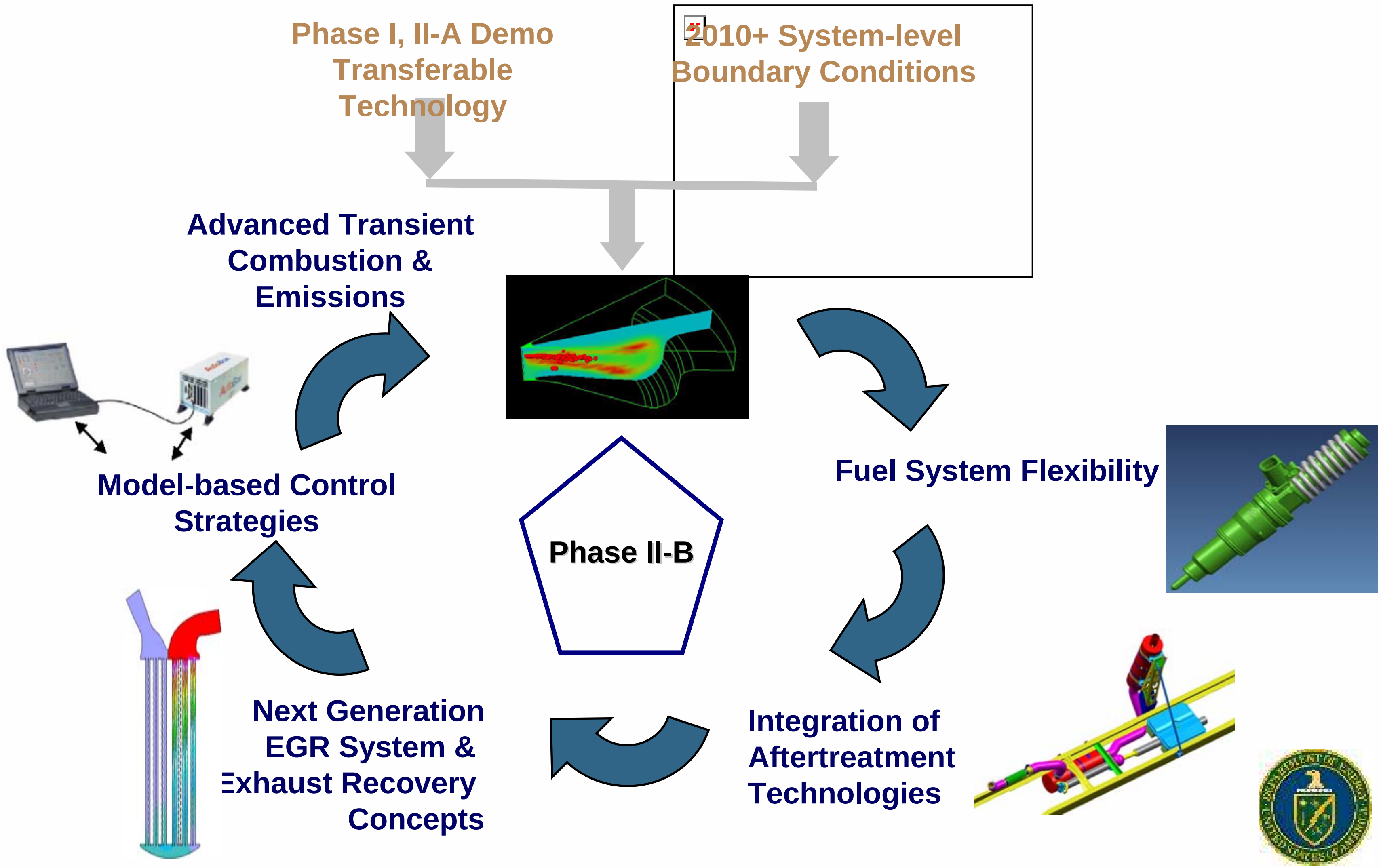
Steady-state Multi-cylinder Development – Validates Analysis; "Simulates" Transient



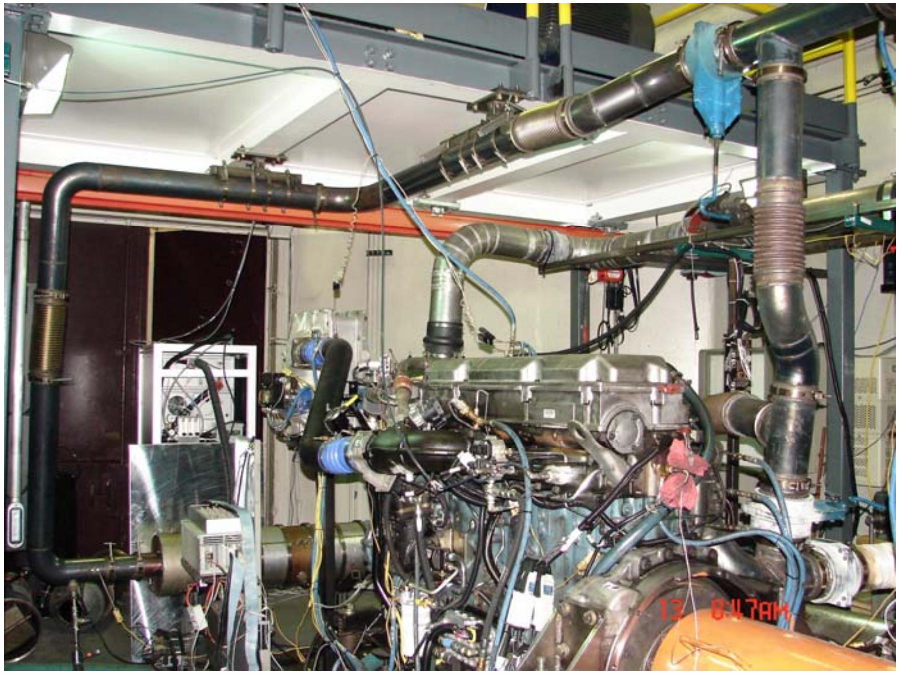
Conceptual Targets Identified via Analysis

NZ-50 Phase II-B Technology Integration

Builds on Phase I, Phase II-A



NZ-50 Phase II Multi-cylinder Test-beds



- NZ-50 Phase II Test-beds based on Multi-cylinder Series 60-2007 (shown above) and Prototype Heavy-duty Engine
  - Prototype Heavy-duty Engine Test-bed Equipped with Exhaust Energy Recovery Hardware and Increased Peak Firing Pressure Capability
  - Test-beds Equipped with Multiple-leg Exhaust System with Bypass to Provide Flexibility for Testing Engine-out and Tailpipe-out Configurations
  - Test-beds Equipped with Multiple Emissions Sampling Capability to Provide Spatial and Temporal Resolution of Exhaust Species for Low Emissions Combustion

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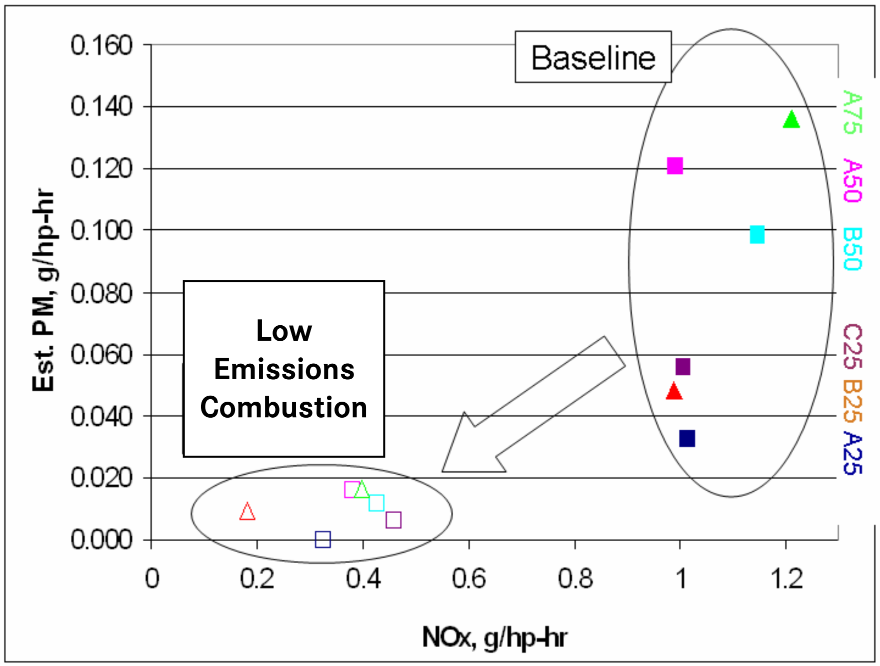
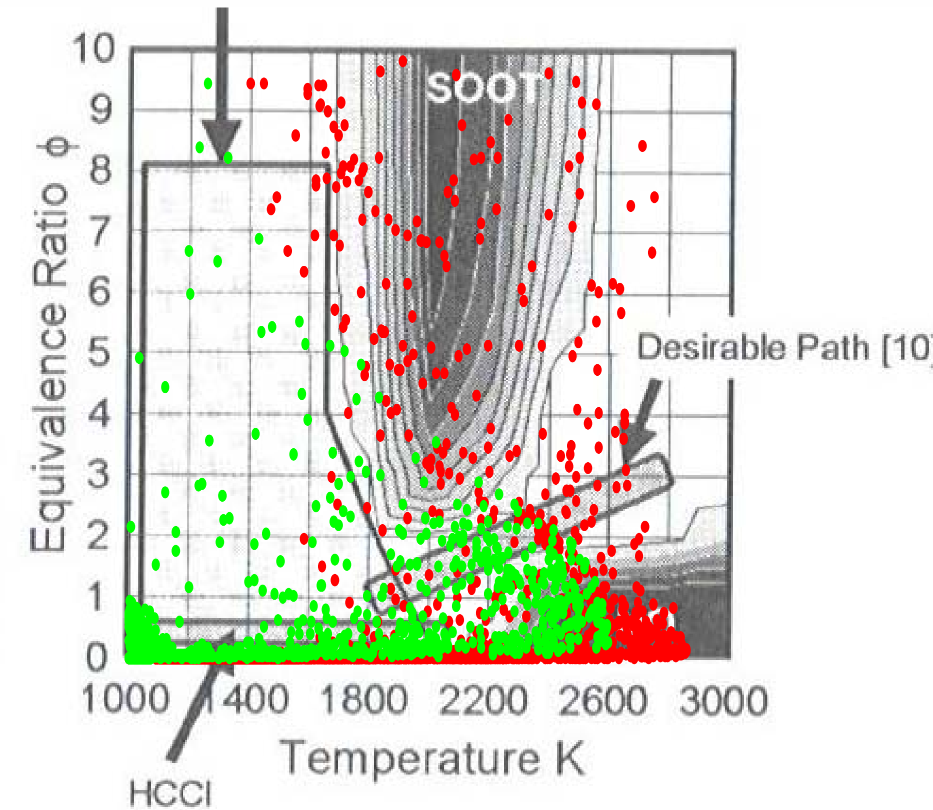
Low Emissions Combustion Development on NZ-50 Phase II-B Engine Demonstrated Up to 70% Load (~15bar BMEP)





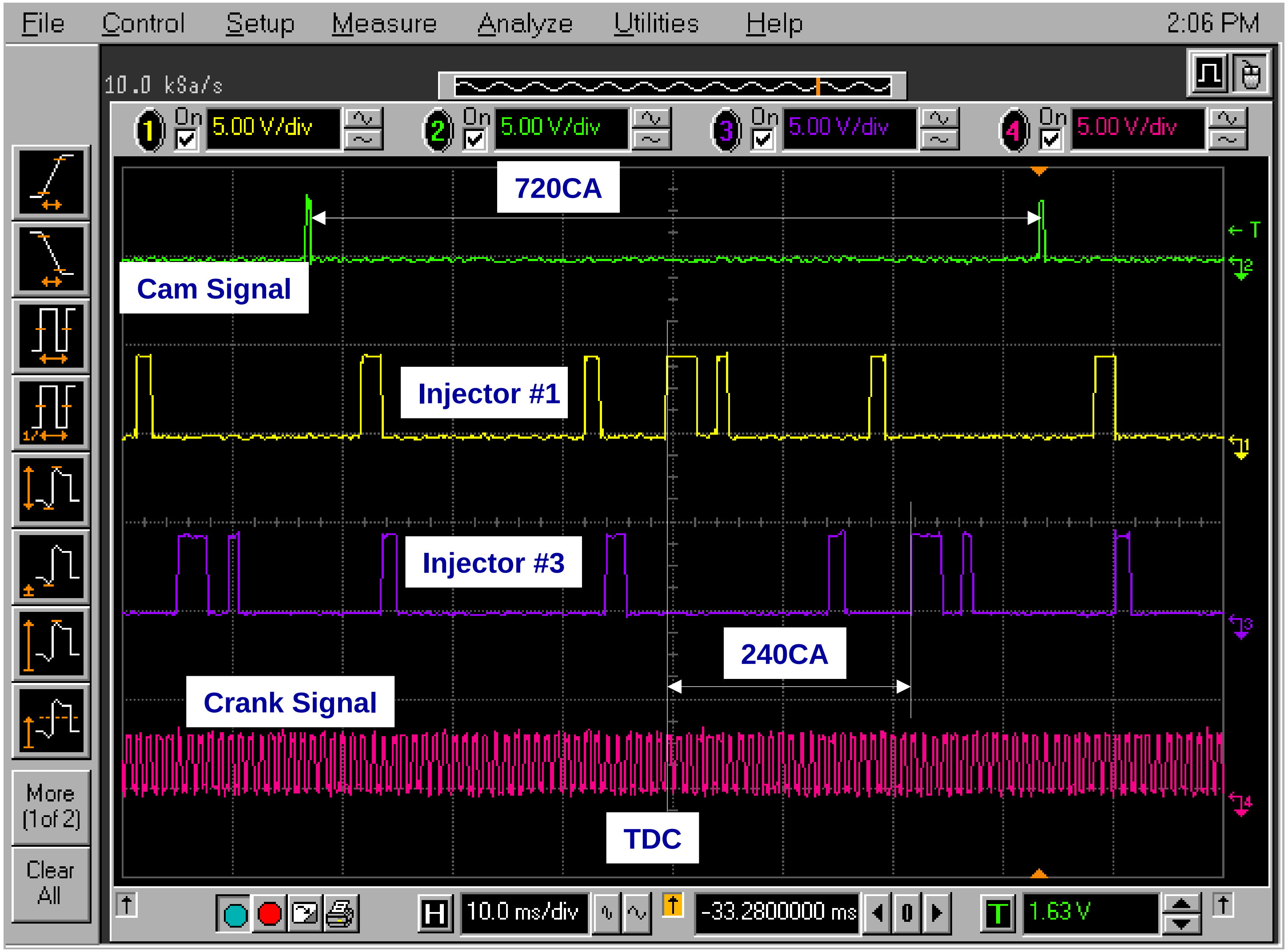
Technical Demonstration of EPA 2010 Emissions Engine-out

However, Technology not Viable for Commercialization in the Near-to-Mid Term due to Significant Thermal Efficiency Deterioration

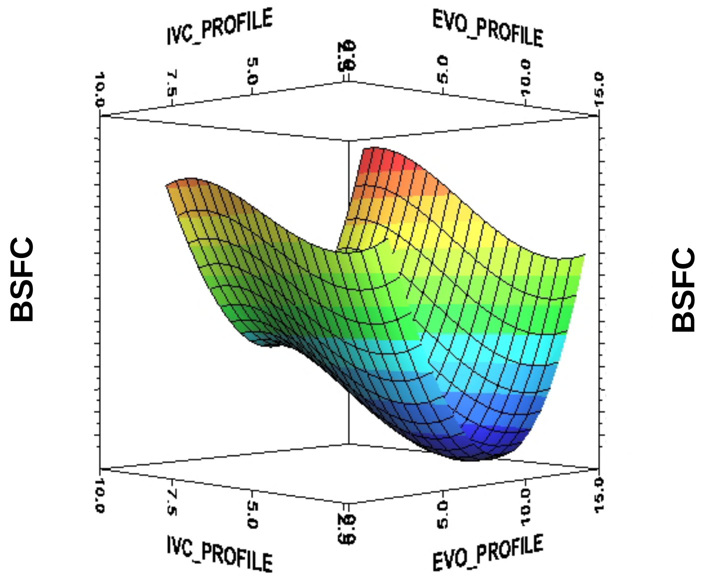
In-cylinder Spatial Distribution of Temperature and Equivalence Ratio for Traditional Diffusion Limited Combustion and Low Emissions Combustion

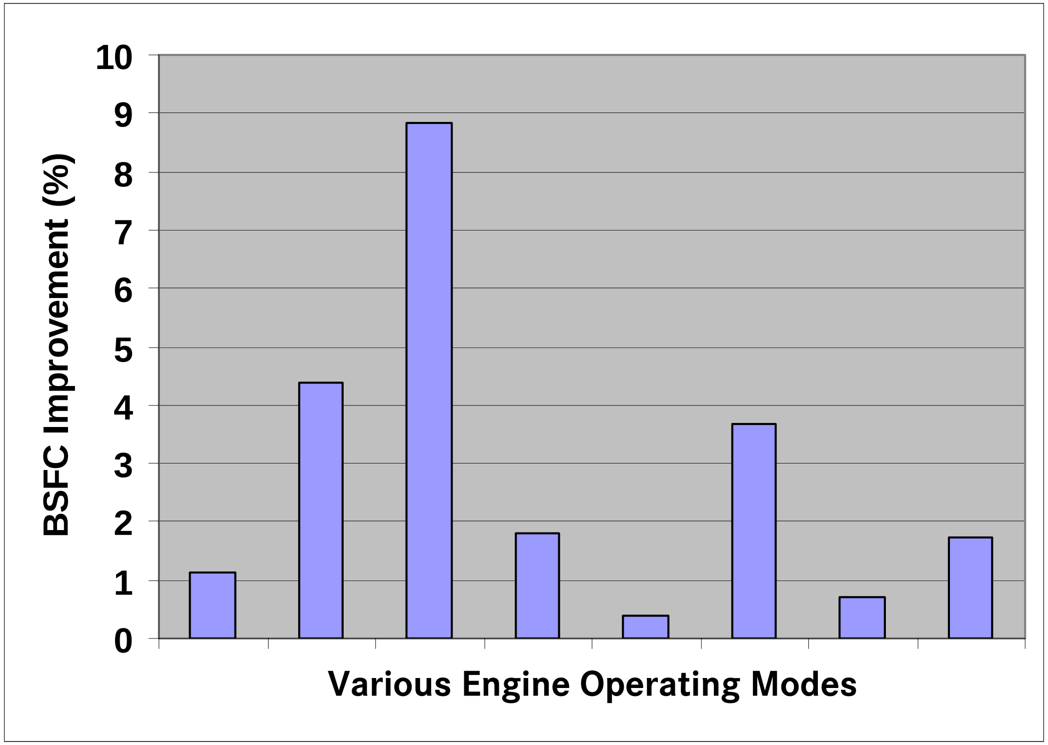
DOE-DDC Light Truck Program CY2002

- Simulated NZ-50 engine cam/crank timing configuration
- 5 injection events with –360 to 360 CA injection timing span
- There is overlapping of injection among six cylinders

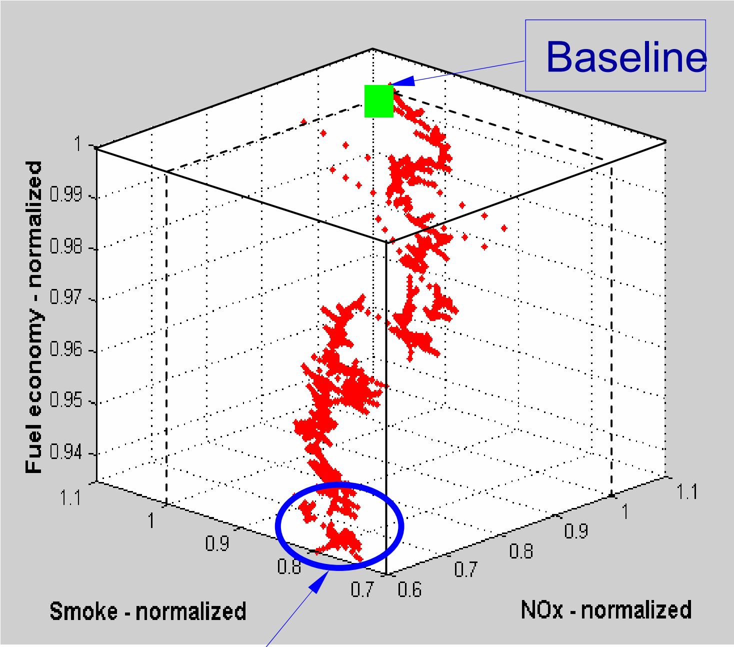


Example Air and EGR System Result
Variable Breathing Optimization of Exhaust Valve Event and Intake Valve Event Using Design of Experiments





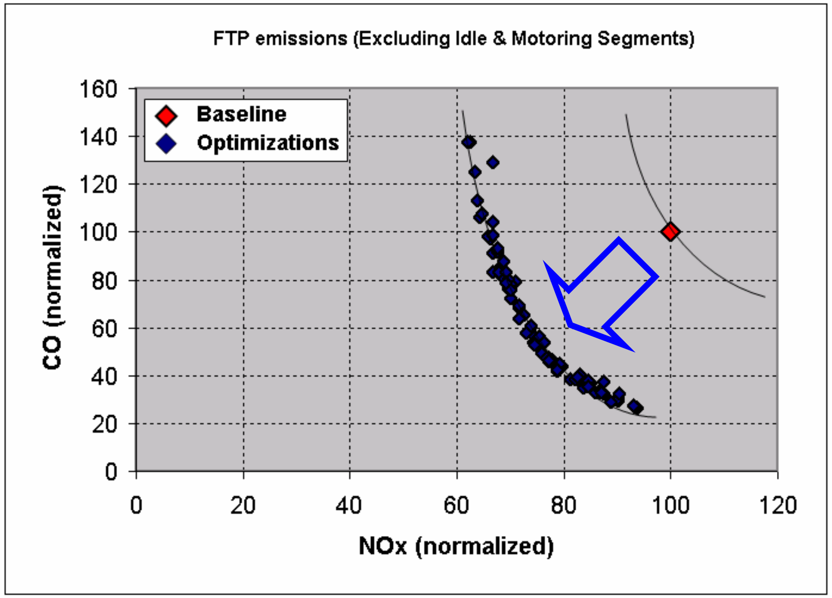
- Comprehensive Engine Cycle Simulation Model Developed and Calibrated
- Model Coupled with Design of Experiments and being Utilized to Analytically Optimize Engine Breathing Events to Reduce Pumping Losses, for Thermal Management and for In-cylinder Temperature Control for Low Emissions Combustion
- Initial Application of the Model over Steady-state Operating Conditions, Followed by Application over Transient Conditions

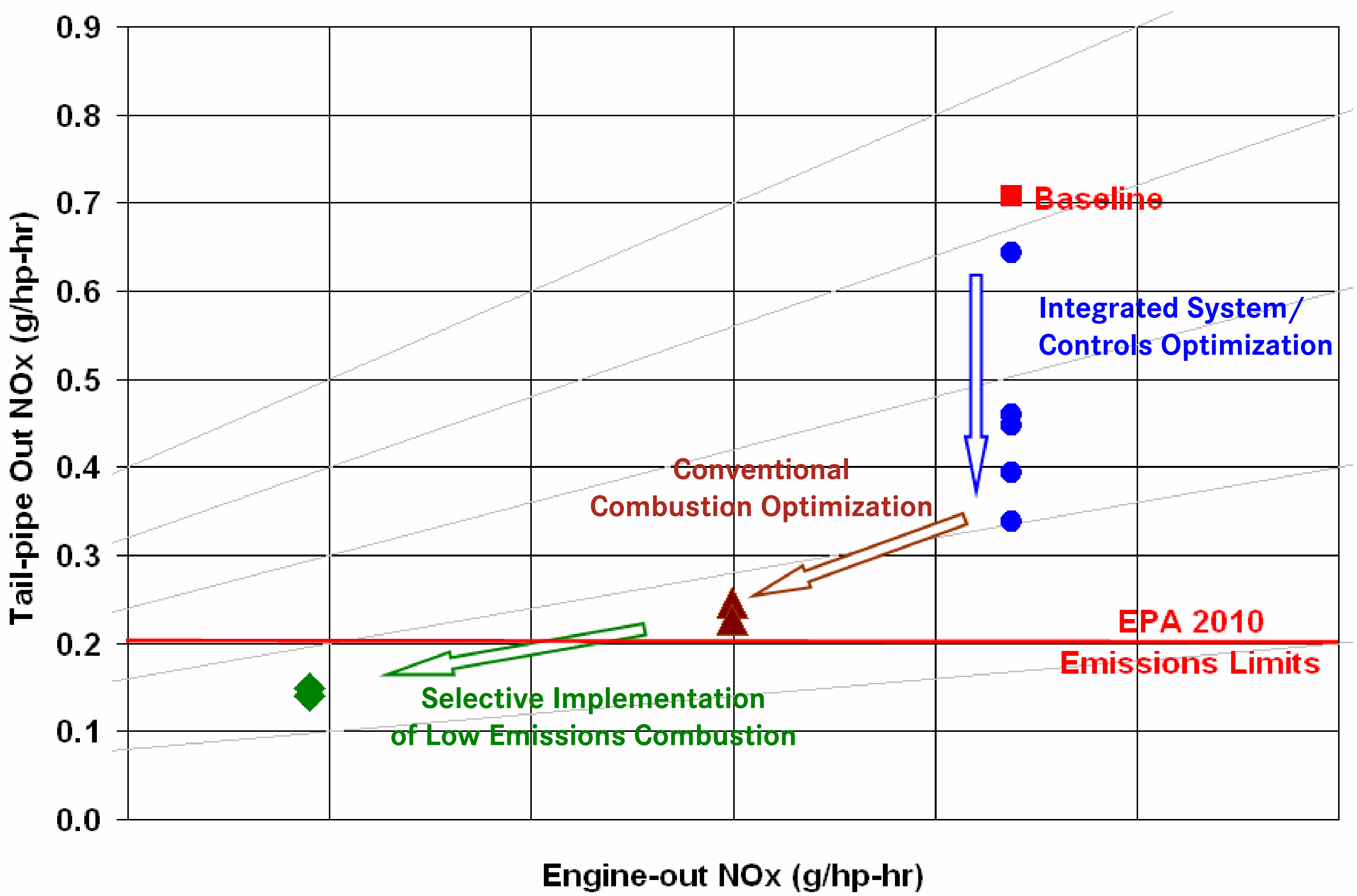


Optimized window showing improvement in NOx, Smoke and BSFC

Analytical example shown here demonstrates ~6% reduction in fuel consumption and over 20% reduction in NOx and smoke emissions

- Demonstrated improvement in FTP emissions (NOx, CO) and fuel economy
- Method emerging as a promising tool for calibrating and optimizing increasingly complex total system comprising engine, aftertreatment (NOx and PM) and vehicle systems
- The next step involves 2nd iteration of model generation and experimental validation over steady state and transient





EPA 2010 System-out Emissions Levels
Demonstrated over Transient FTP

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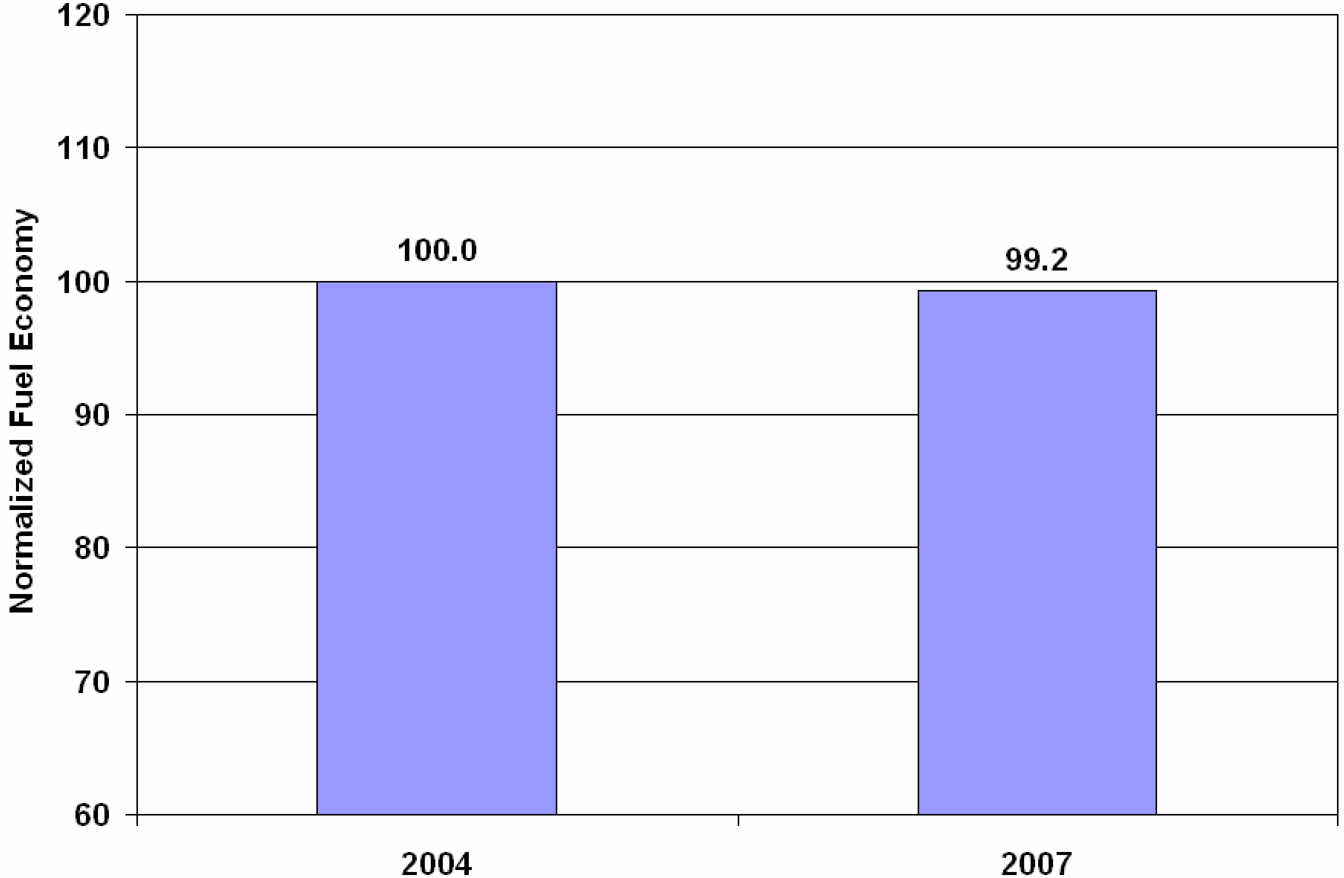
2004 vs. 2007 DDC Fuel Economy Comparison



Testing showed EPA07 engine to be within 1% of the EPA04 engine.
All runs were within 2% variance.
This test was a preliminary look at EPA07 vs. EPA04 Fuel Economy.

Conclusions

- Demonstrated Technologies, via Integrated Experiments and Analysis, to Achieve the Technical Objectives of the DOE-DDC Heavy Truck Project (NZ-50)
  - ✓ 50.2% Peak Thermal Efficiency at a Single operating Condition
  - ✓ EPA 2010 Emissions Regulations over Steady-state and Transient Operation
- Significant Risks and Challenges Remain for Application and Commercial Viability of Some of the Technology Enhancements
- However, Collaborative DOE-Industry Programs Lay a Strong Technology Foundation for Subsequent Industry-led Product Development to Address These Challenges
- Forward Engineering Methodologies Enabled by Analytical Tools were Beneficial to Develop and Validate the Technical Roadmap to Enhance Thermal Efficiency and Reduce Emissions

Acknowledgements

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  - ✓ Roland Gravel

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  - ✓ Jeffrey Kooser