Integrated Engine and Aftertreatment Technology Roadmap for EPA 2010 Heavy-duty Emissions Regulations

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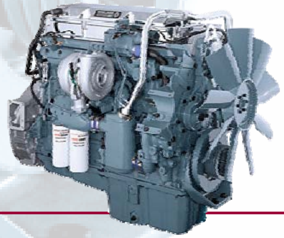


Series 60

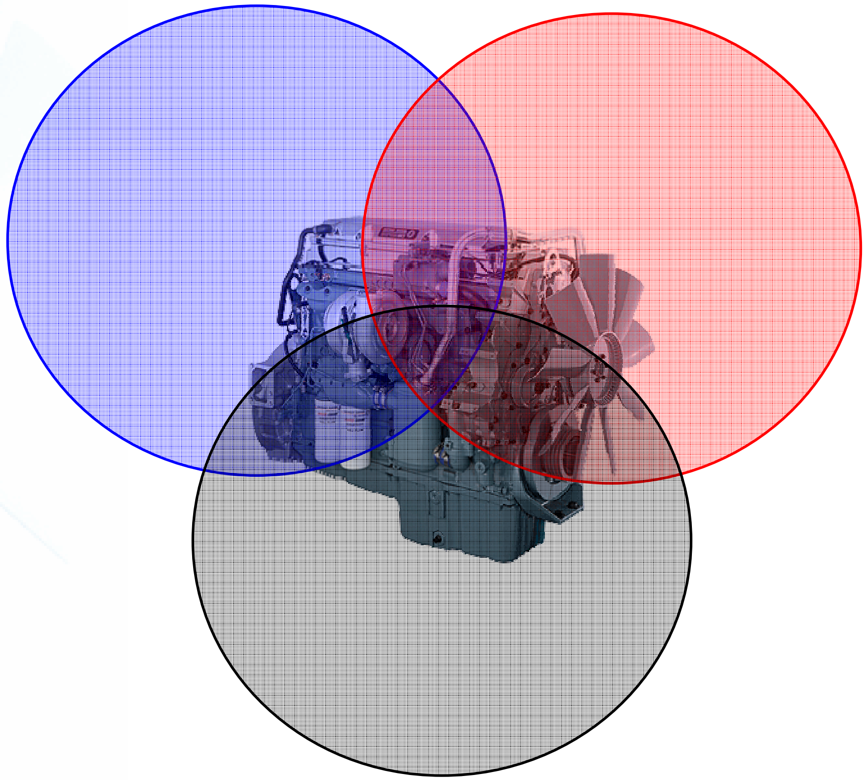
MBE 900

MBE 4000

Presentation Outline

- Typical considerations in engine development and design
- NOx reduction approaches for 2010
  - Advanced combustion
  - NOx aftertreatment
    - Urea-based SCR
- Urea infrastructure scenarios
- Technology development methodology

Typical Considerations in Engine Development and Design



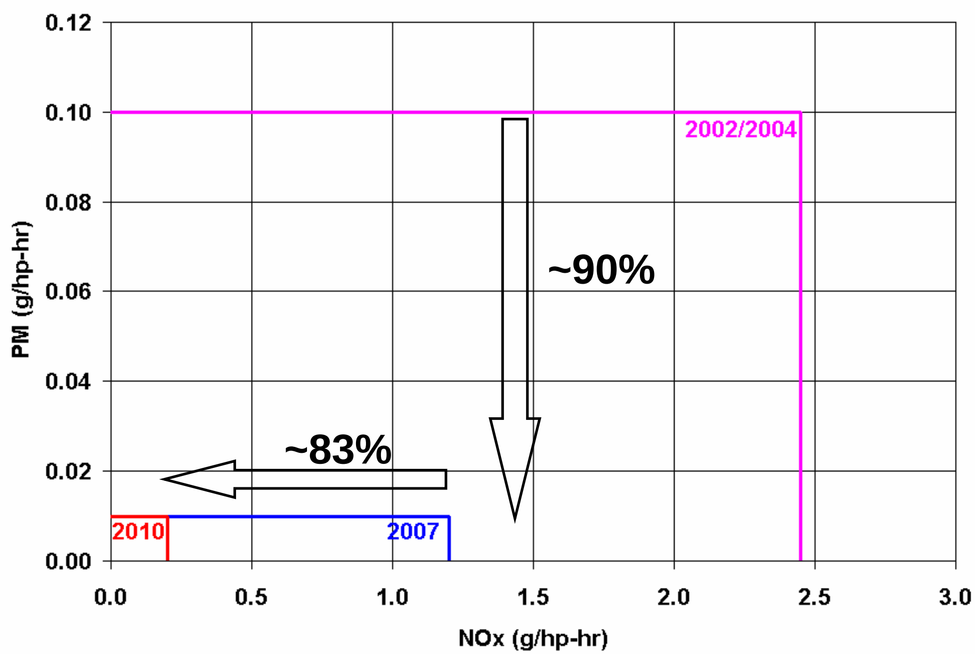
REGULATORY
- Emissions
- In-use Testing
- On-board Diagnostics
- Emissions Useful Life
- Safety
- Noise
- ….

CUSTOMER
- Lifecycle Costs
  - Initial Costs
  - Fuel Economy
  - Maintenance
- Performance
  - Torque, Power
  - Drivability
  - Gradeability
  - NVH
  - Heat Rejection
- Packaging
- Technology Complexity
- Durability, Reliability
- Serviceability
- …

ENVIRONMENTAL AND SOCIAL
- Fuel Economy
- Unregulated Emissions
- Safety
- ….

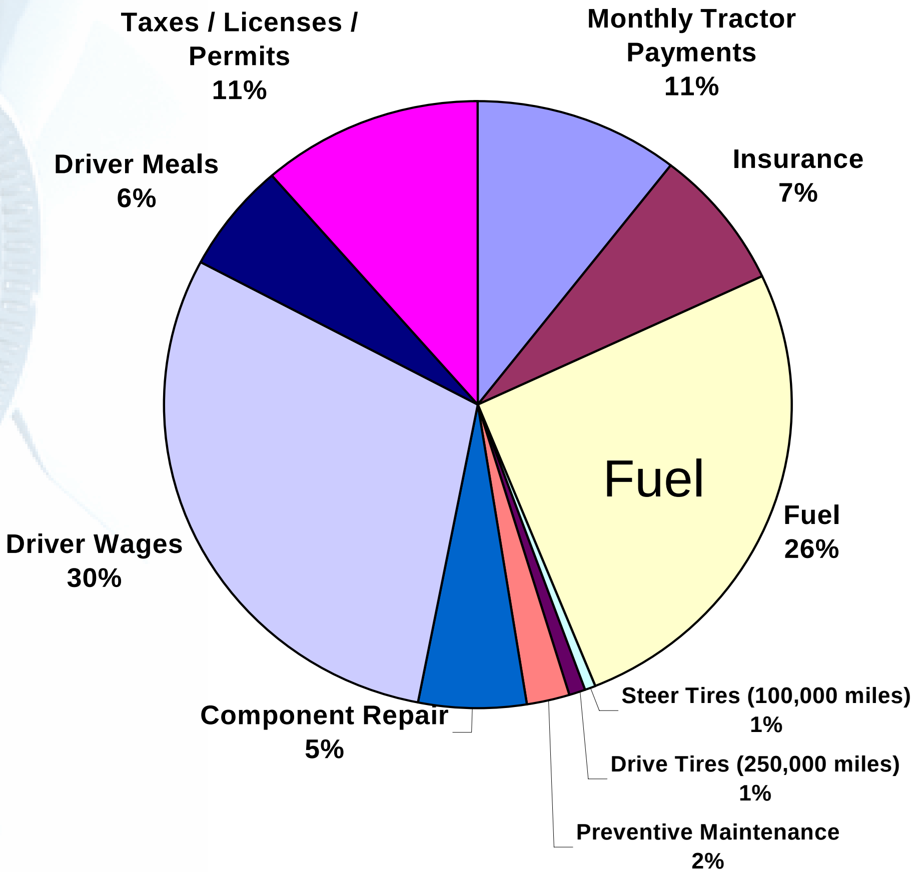
The 2010 Challenge

- ~83% reduction in NOx compared to EPA 2007
- Next-generation on-board diagnostics (OBD) requirements
- Adjustment factors for emissions during regeneration
- Not-to-exceed (NTE) enforced through in-use emissions test run by manufacturer
- 435,000 miles useful emissions life



Significant effort required to minimize increase in initial and lifecycle operating costs

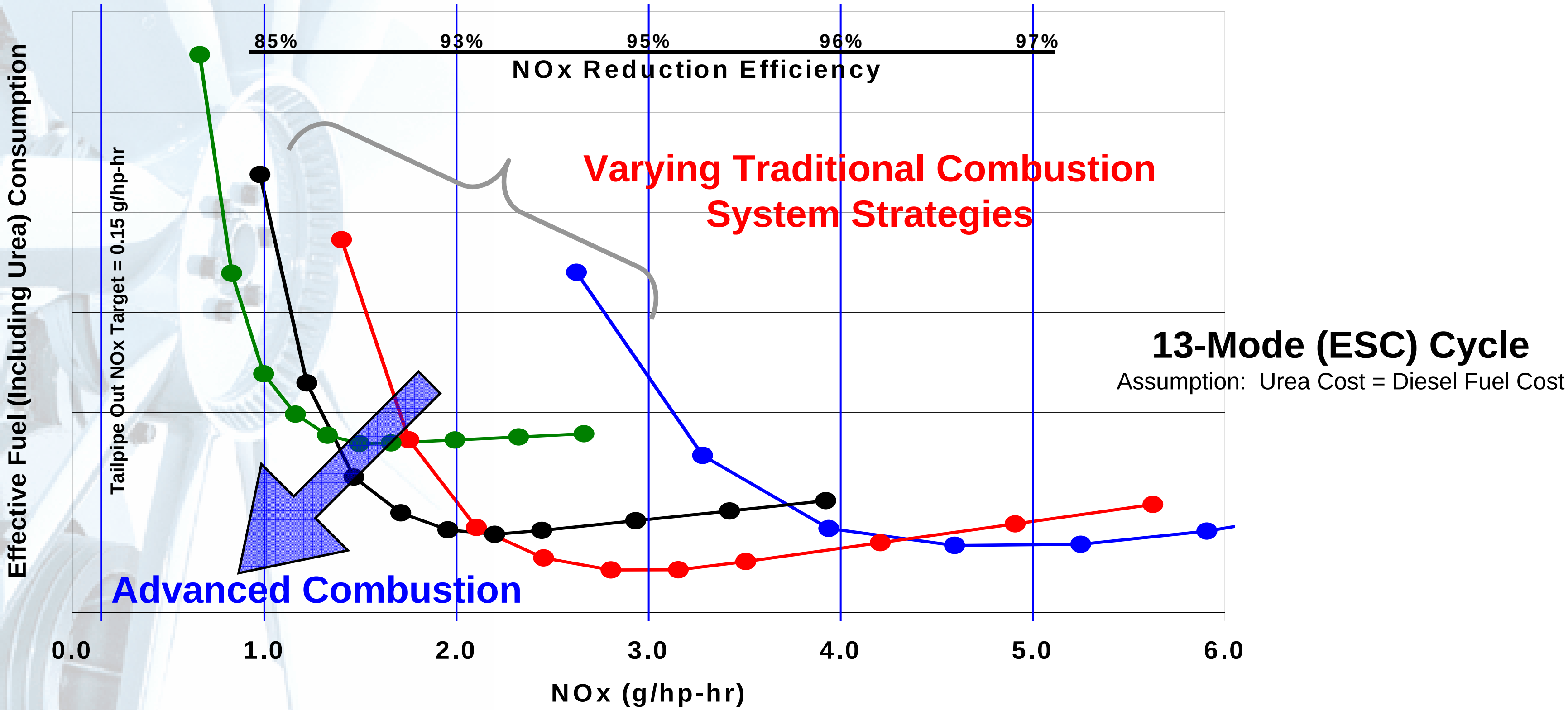
Typical Lifecycle Cost Distribution
U.S. Line Haul Trucks



Source:
White Paper on Life Cycle Cost
Kenworth Truck Company
www.kenworth.com

Fuel expense typically constitutes 25% - 30% of the lifecycle cost

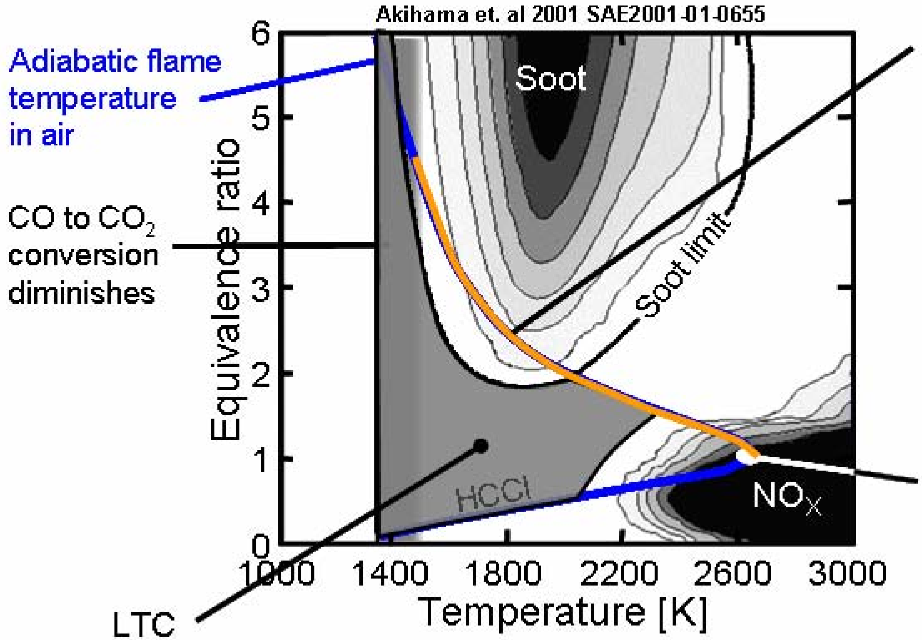
Combustion / Aftertreatment System Integration
Establishing An Optimum Combination for 2010 with respect to Fuel Consumption



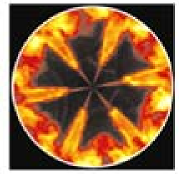
Proportion of NOx reduction targeted via in-cylinder combustion optimization versus that via aftertreatment devices depends on lifecycle cost and engineering margin considerations

Combustion Processes and Pollutant Formation

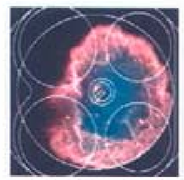
Source: Dr. Dennis Siebers, Sandia National Laboratory



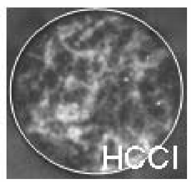
Diesel combustion
- controlled heat release (mixing)
- controlled combustion timing
- wide load range
- high efficiency (relative to SI)
- **NOx and PM emissions**



Spark ignition (SI) combustion
- controlled heat release (flame propagation)
- controlled combustion timing
- wide load range
- three-way catalyst
- **low efficiency** (relative to diesel)



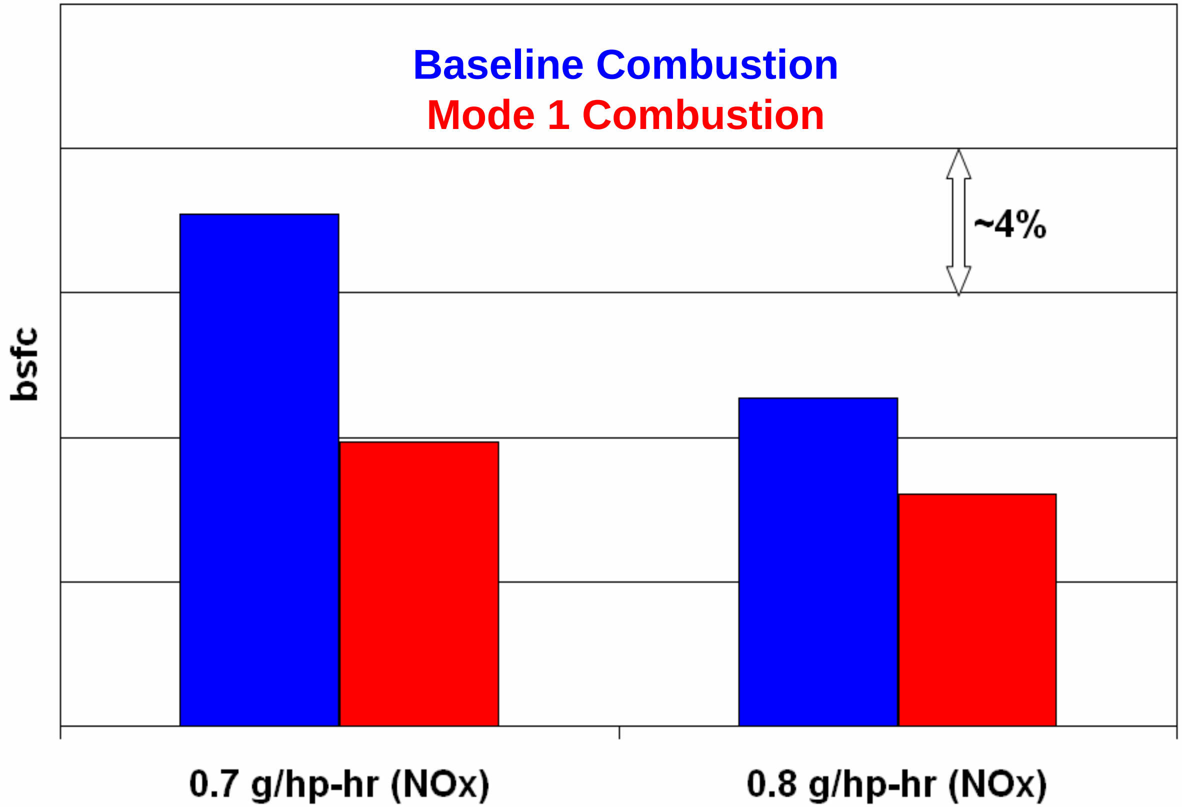
LTC
- offers diesel-like efficiency (high CR & no throttling)
- low NOx and particulate emissions
- **load range?**
- **combustion timing?**
- **heat release rate?**
- **transient control?**
- **fuel?**



Emissions Control via In-cylinder Combustion Optimization

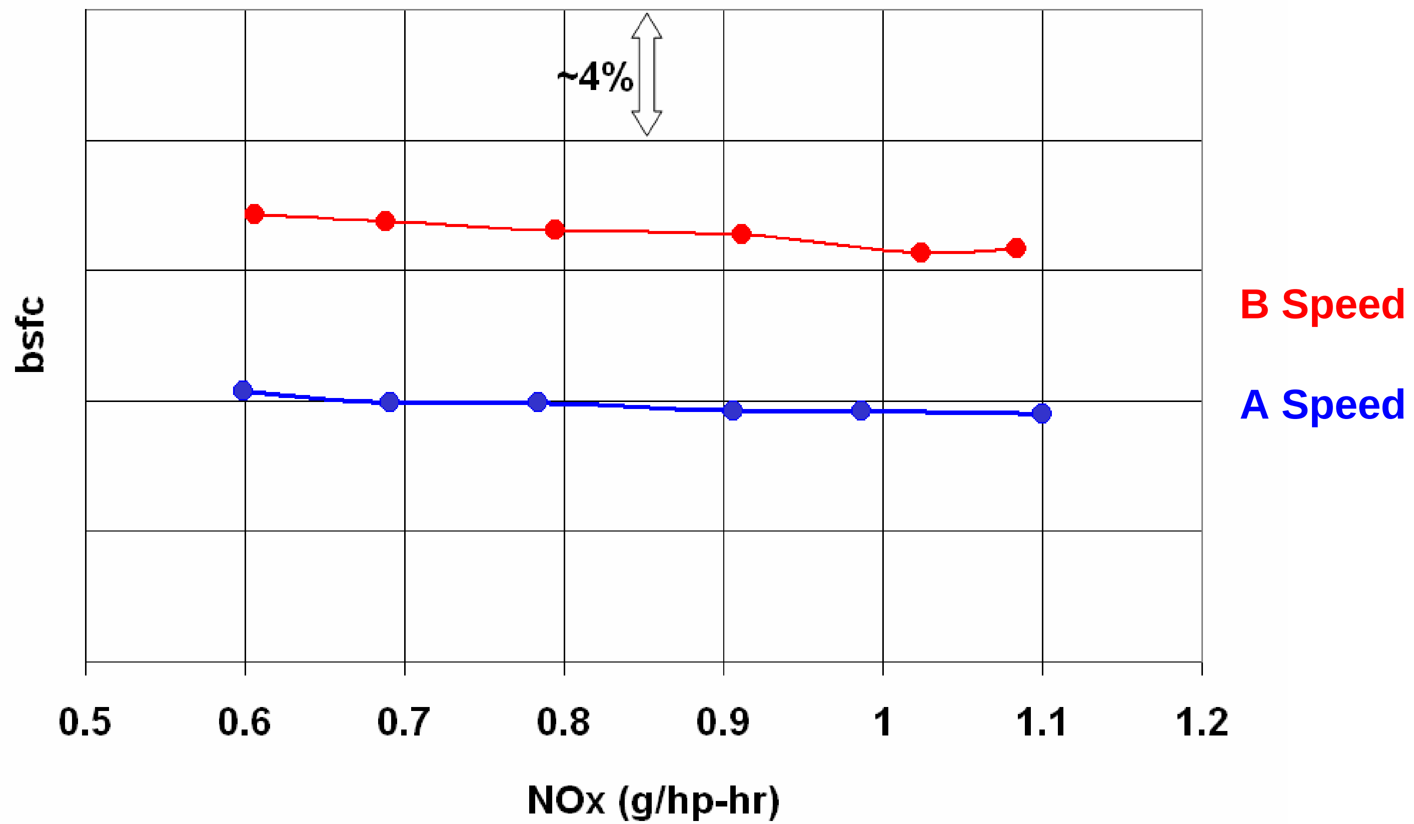
- Multiple-mode combustion concept is emerging that seeks to locally optimize the combustion event across the engine speed and load range
- Multiple-mode combustion concept targets favorable temporal and spatial distribution of in-cylinder equivalence ratio and temperature to reduce pollutant formation
- Preliminary, proof-of-concept results demonstrated on a multi-cylinder engine
  - Substantial effort still required before these concepts can evolve into viable commercialization strategies

Mode 1
~10 bar BMEP
Multi-cylinder 14.0 L Heavy-duty Test-bed Experimental Results – Engine Out



Baseline combustion adequate for ~1 g/hp-hr NOx levels but yields bsfc penalty at sub 1g/hp-hr NOx levels
Mode 1 combustion provides 3%-6% bsfc improvement over baseline combustion at ~0.7-0.8 g/hp-hr NOx

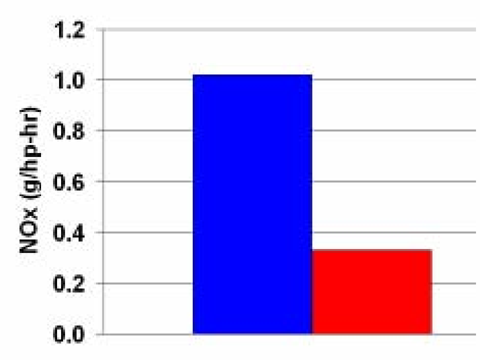
Mode 2
~5 bar BMEP
Multi-cylinder 14.0 L Heavy-duty Test-bed Experimental Results – Engine Out

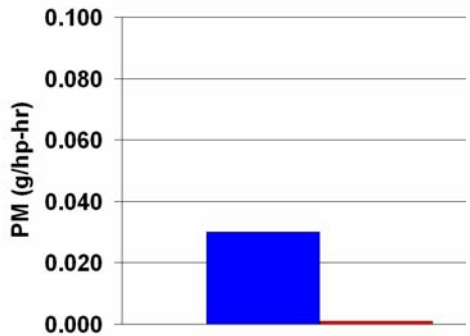


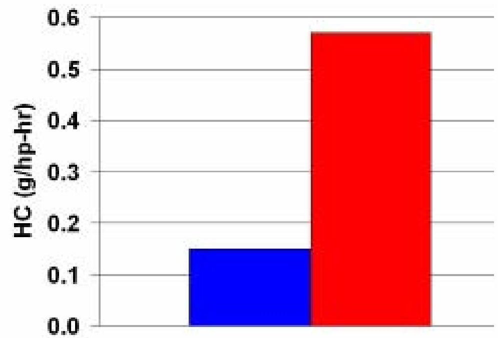
Mode 2 combustion flattens the NOx-bsfc trade-off and shows potential to reduce NOx by ~50% with a ~1% bsfc penalty

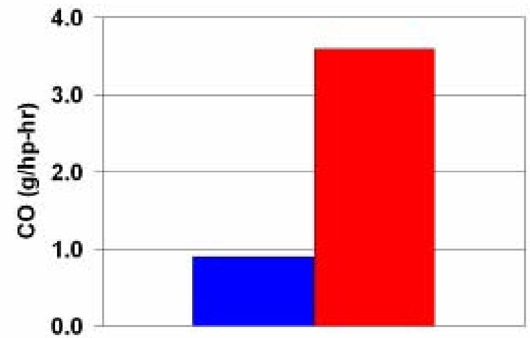
Mode 3
~5 bar BMEP

Multi-cylinder 14.0 L Heavy-duty Test-bed Experimental Results – Engine Out





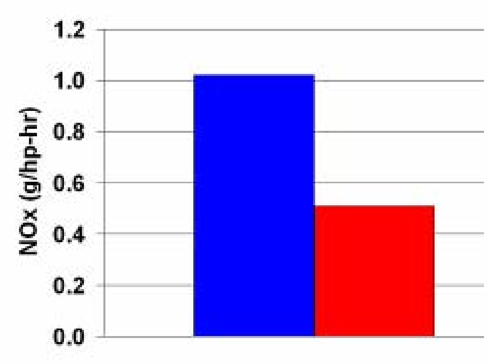


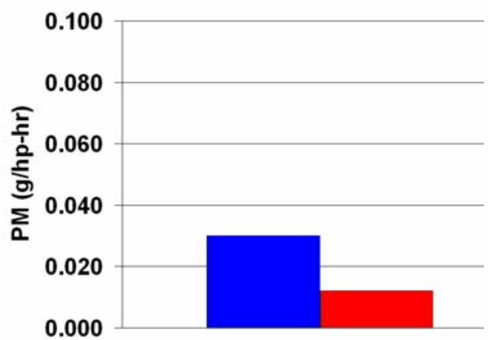


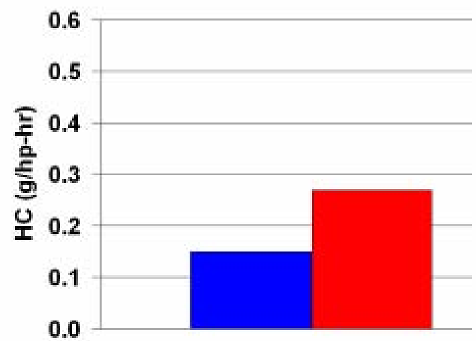
~65% reduction in NOx obtained with near-zero PM

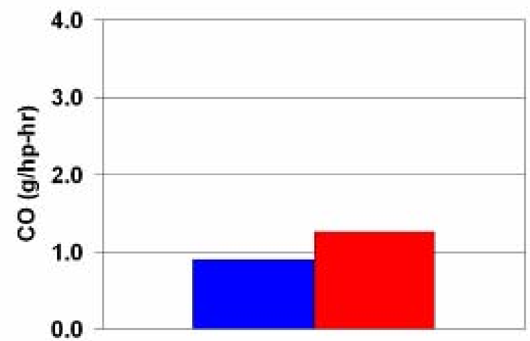
However, substantial increase in HC and CO typical of low temperature combustion observed

Potential strategy demonstrated to mitigate increase in HC and CO, although at the expense of magnitude of NOx and PM reduction

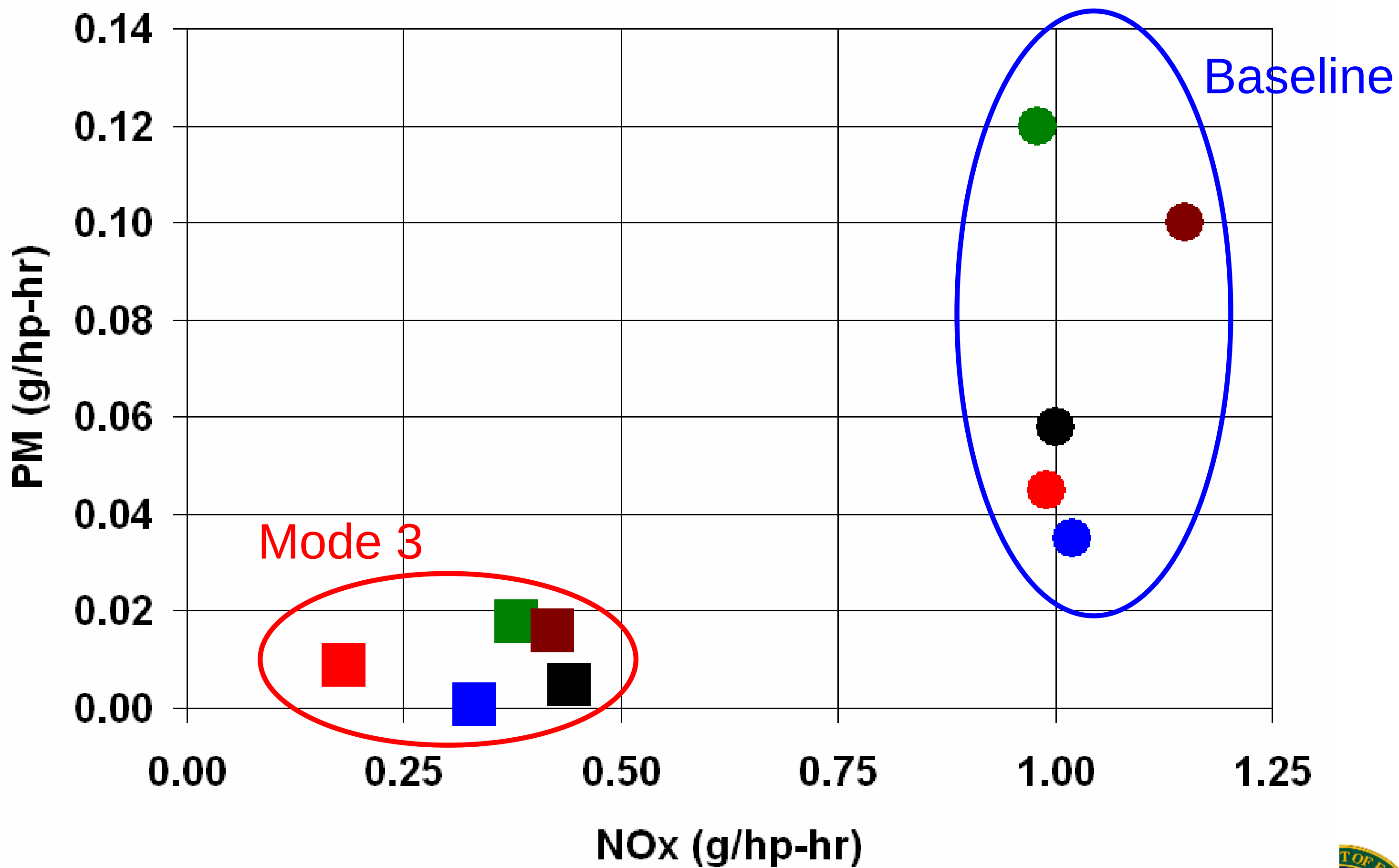




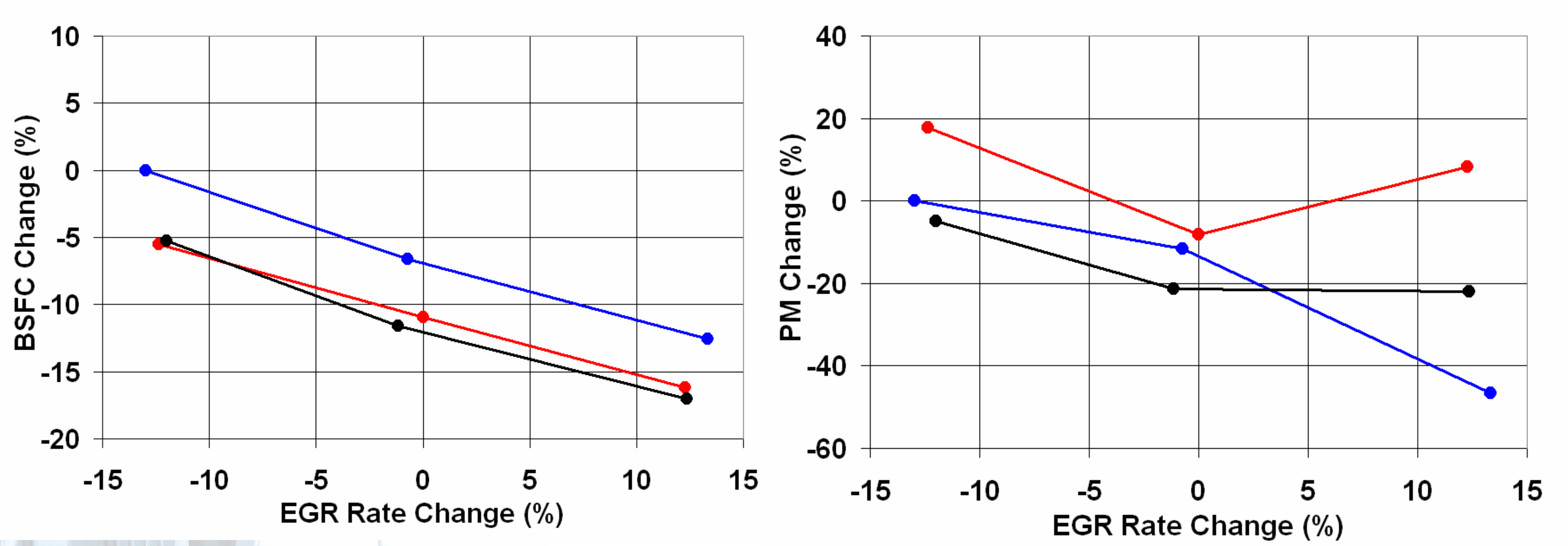




Mode 3
Range of Engine Speeds and Loads - Up to 10 bar BMEP
Multi-cylinder 14.0 L Heavy-duty Test-bed Experimental Results – Engine Out

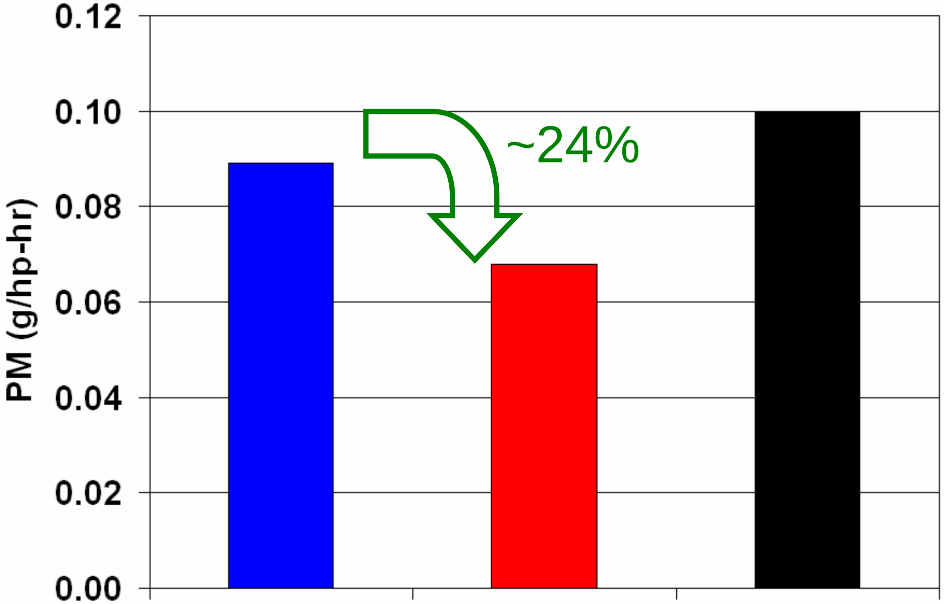


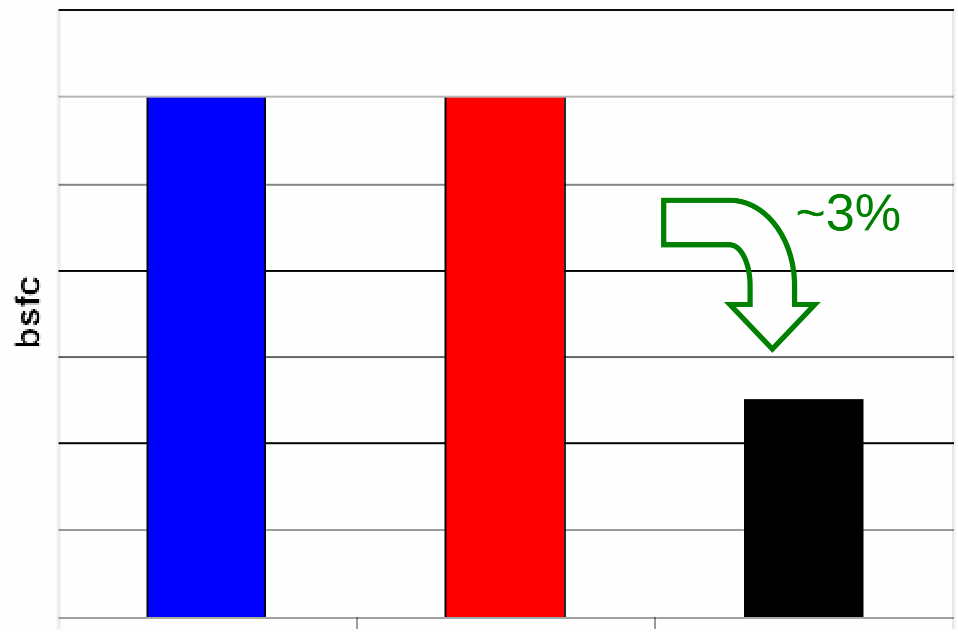
Mode 4
~20 bar BMEP
Multi-cylinder 14.0 L Heavy-duty Test-bed Experimental Results – Engine Out



Single Injection Event, Baseline Injection Pressure
Single Injection Event, Reduced Injection Pressure
Multiple Injection Event, Reduced Injection Pressure

Mode 4
Composite 13 Mode Test
Multi-cylinder 14.0 L Heavy-duty Test-bed Experimental Results – Engine Out





Baseline Configuration
PM Reduction Configuration
Fuel Economy Improvement Configuration

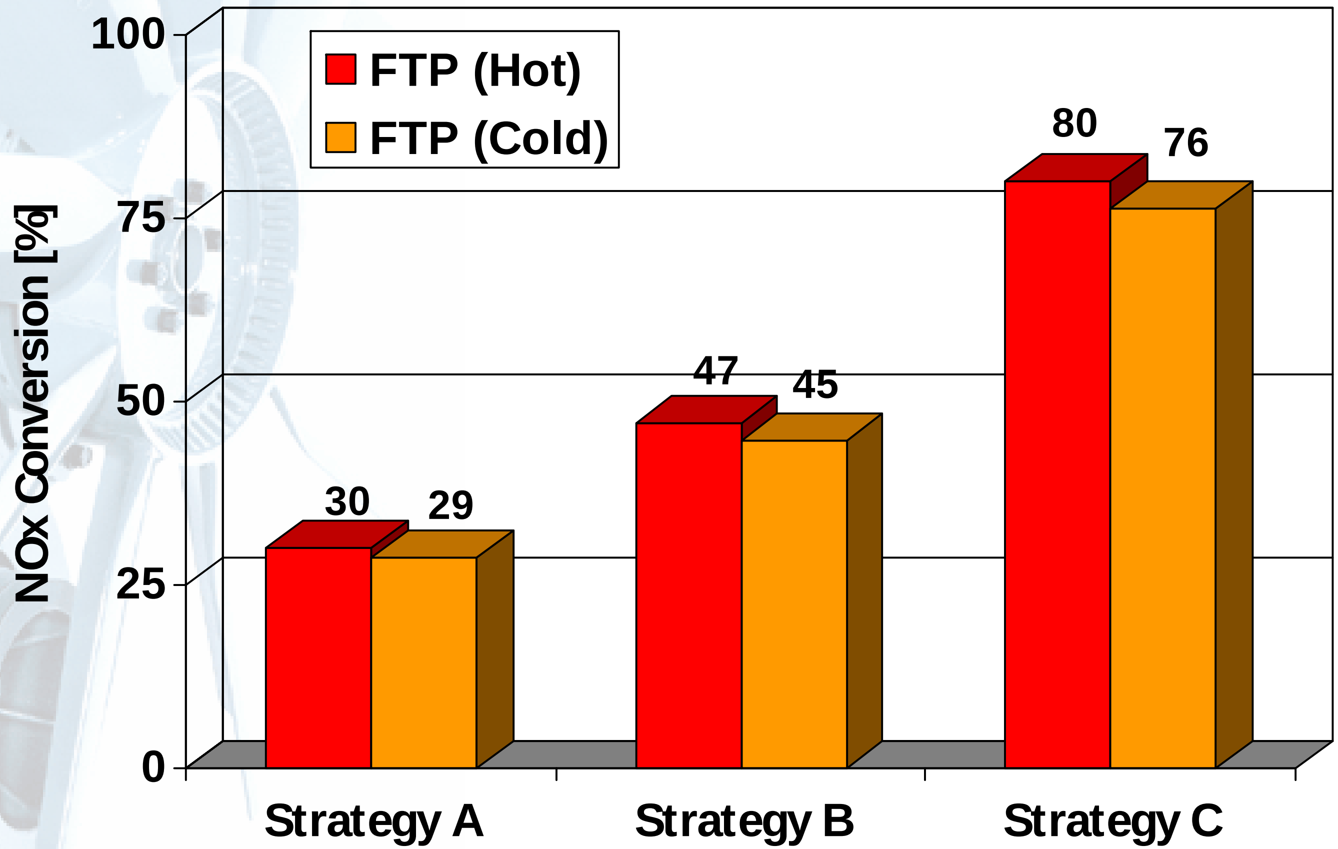
Challenges

- Enhancing thermal efficiency while simultaneously reducing emissions
- Seamless inter-mode transition in multiple-mode combustion concept
- Combustion phasing and control
- Rate of in-cylinder pressure rise
- NVH
- Oil dilution
- Treatment of HC, CO
- Increase in electronic control unit processing requirements
- Realizing stable, repeatable and controllable response of enabling technologies with increasing degrees of freedom
- Calibration of increasing degrees of freedom
- …

Substantial effort still required before these concepts can evolve into viable commercialization strategies

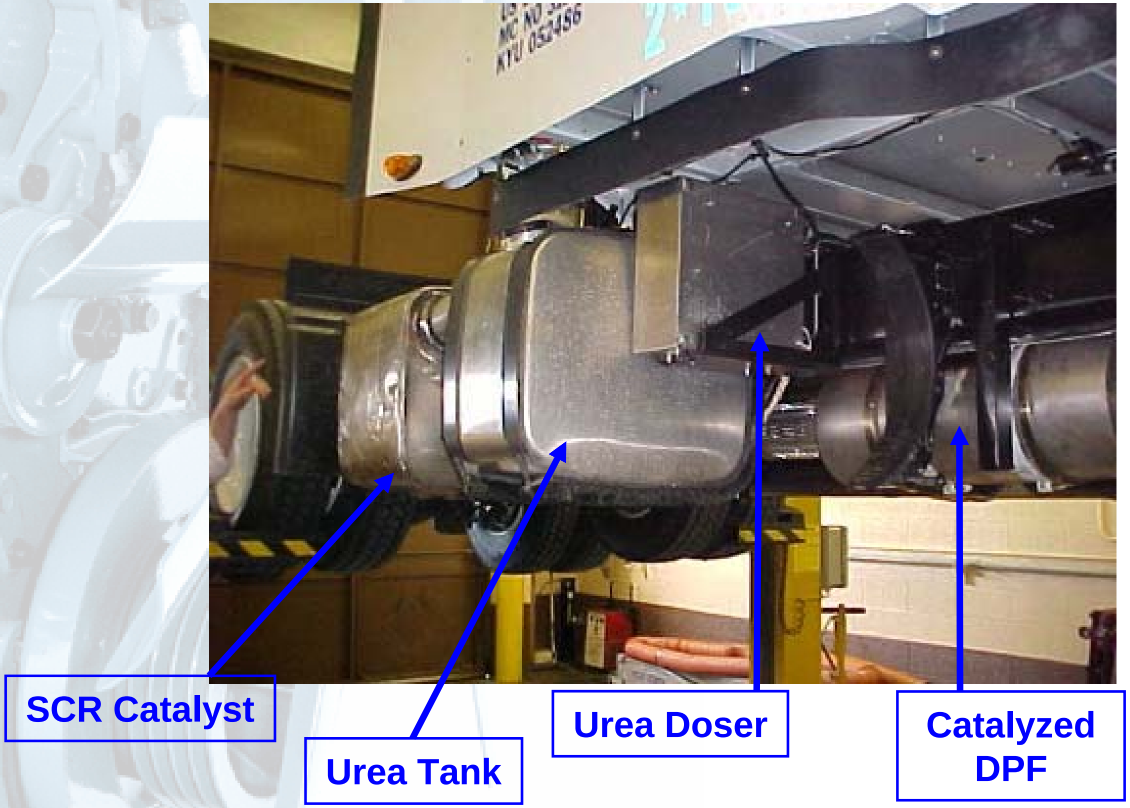
SCR NOx Reduction Potential

US Transient Test (FTP) Cycle



Additional NOx reduction possible via precise exhaust temperature management

Typical SCR Application in a U.S. Heavy-duty Truck



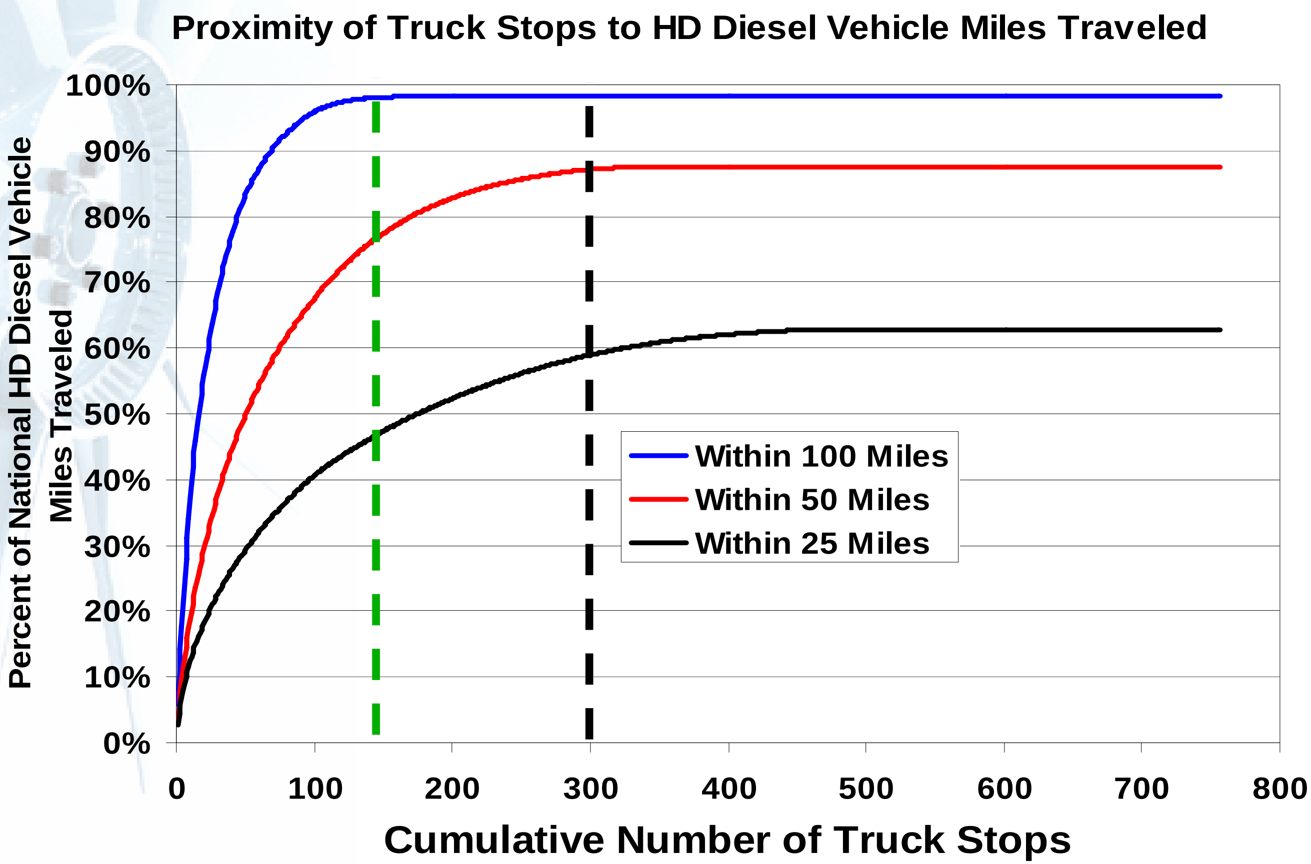
With the low engine-out NOx targeted for 2010, there is an opportunity to significantly extend vehicle driving range between urea refills

~25 k Miles with a 30 gallon tank (~1% urea to fuel consumption)

Opportunity to synchronize urea refill with vehicle maintenance intervals

Progressive Urea Infrastructure Implementation

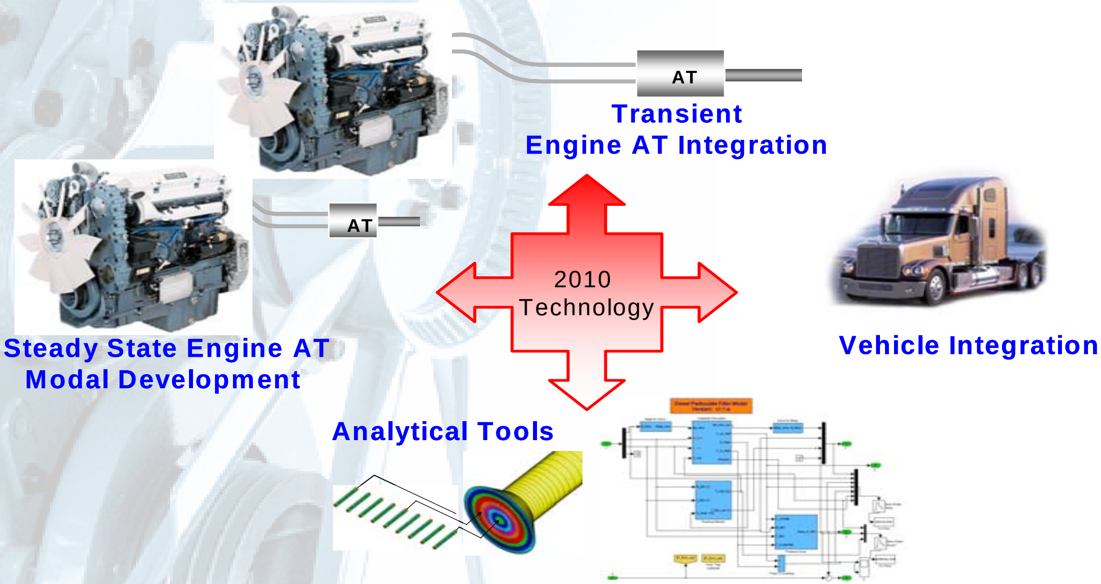
140 Truck Stop Locations (Less Than 3% of All Truck Stops) Can Ensure Urea Availability Within a 100 mile Radius for Greater Than 95% of the Heavy Duty Vehicle Miles Traveled



Technology Development Philosophy

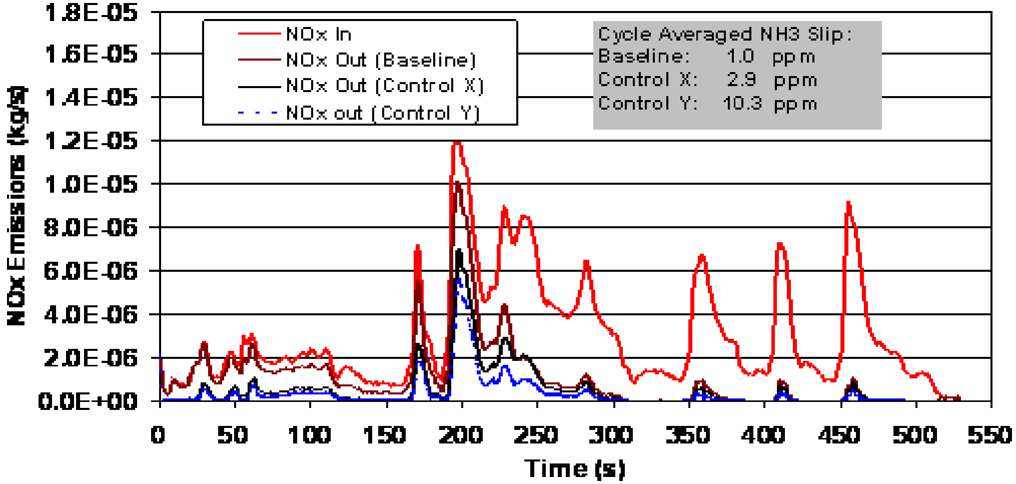
- Increasing technical complexity inherently requires a system (engine, aftertreatment, vehicle) approach to technology development
- System level technology development benefits substantially from integrated analytical and experimental development
- Require increased emphasis on advanced analytical tool development for advanced combustion regimes and aftertreatment
- Government / industry / academia collaborative partnerships accelerate the technology development process

Integrated System Development Approach



- Develop Conceptual Targets
- Simulation Screens Major Sub-systems Concepts
  - ✓ Combustion, Air, EGR, Fuel, Aftertreatment
  - ✓ Cooling, Thermo-mechanical
- Down-select and Procure Prototype Hardware
- Steady-state Test Cell
  - ✓ Validates Simulation Conceptual Design
  - ✓ Screens Options
  - ✓ Simulates Transient Performance
- Transient Test Cell
  - ✓ Validates Steady-state Test Cell “Simulation”
  - ✓ Screens Options
  - ✓ Simulates Vehicle Performance
- Vehicle Integration
  - ✓ Validates Transient Test Cell “Simulation”
  - ✓ Identifies Benchmark Results

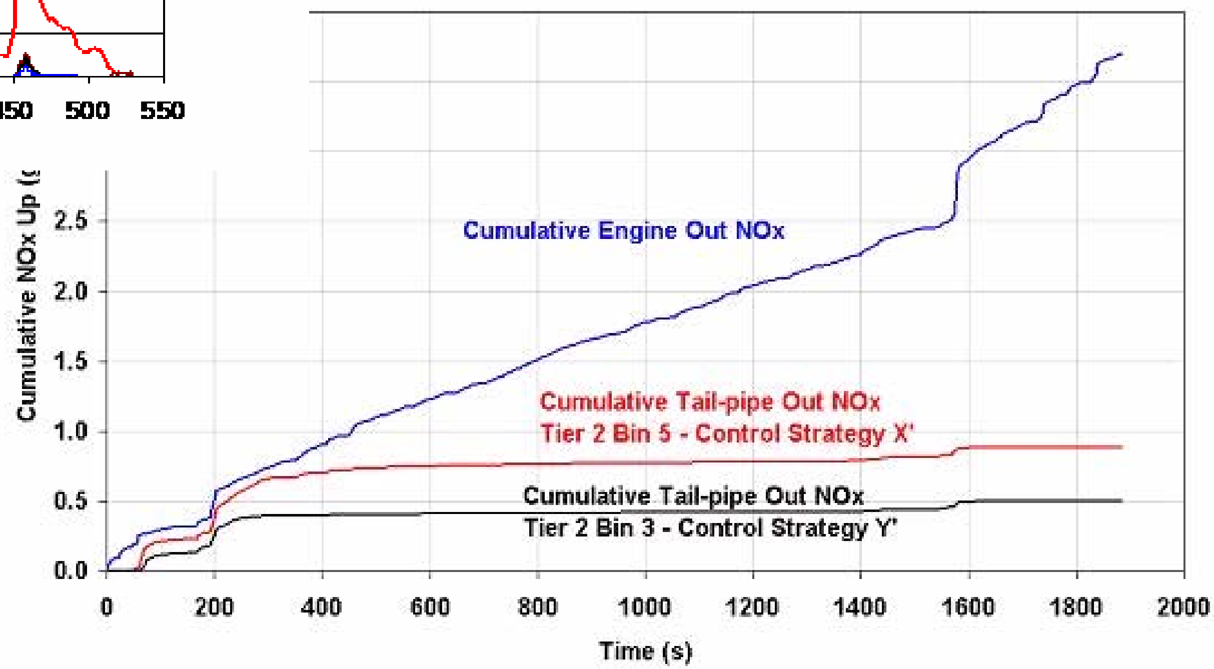
Integrated Analytical and Experimental Development Methodology Example - Urea Injection Control Strategy Development



Analytical tools applied to understand NOx reduction and NH3 Slip trade-offs resulting in a down-selection of urea injection control strategies

Down-selected strategies validated on chassis dynamometer test-bed

Collaborative DOE-DDC LEADER program



Summary

- Increasing Technical Complexity Inherently Demands a System (Engine, Aftertreatment, Vehicle) Approach to Technology Development
  - System Level Technology Development Benefits Substantially from Integrated Analytical and Experimental Development
- NOx Reduction Technologies for 2010 Likely Include a Combination of In-cylinder Combustion-based Approaches Integrated with NOx Aftertreatment
  - Proportion of NOx reduction targeted via in-cylinder combustion optimization versus that via aftertreatment devices depends on lifecycle cost and engineering margin considerations
  - Multiple-mode combustion concept is emerging that seeks to locally optimize the combustion event across the engine speed and load range
- Urea-based SCR Devices are a Viable NOx Aftertreatment Choice for Several Worldwide Applications Including US2010, Euro IV, Euro V and JP05
  - Model Based Control Systems with Feedback Sensors Will Enhance NOx Conversion Efficiencies, Determine Plausibility, and Help Detect NH3 Slip, Failure Modes, and Tampering

Acknowledgements

- Selective multiple-mode, advanced combustion results shown were first demonstrated as part of the DOE-DDC collaborative Heavy-Truck Project

- Department of Energy
  - Gurpreet Singh
  - Roland Gravel

- National Energy Technology Laboratory
  - Carl Maronde
  - Jeffrey Kooser

Technology & Products that Continue to Benefit the Environment

Fuel Economy

- Supplier of the most fuel efficient diesel engines for various applications within the United States for nearly 20 years.
- Engines that help our customers reduce diesel fuel consumption in America by 2.5 million gallons per day.

Emissions

- Detroit Diesel meets the highest clean air standards for today and is a leader in developing clean burning diesel engines for the future.
- 2007 Detroit Diesel engines will emit 70% less pollutants than they did in 1998 – helping to preserve the clean air that Americans breathe.

Hybrid Technologies

- Detroit Diesel and Freightliner are working together to develop diesel hybrid electric engines that will:
  - Improve fuel economy
  - Reduce emissions
- Development of hybrid technologies is gaining momentum and will lead to high quality jobs and industry growth.

Celebrating 20+ Years of DOE & DDC Collaboration