Thermal Efficiency Improvement While Meeting Emissions of 2007, 2010 and Beyond

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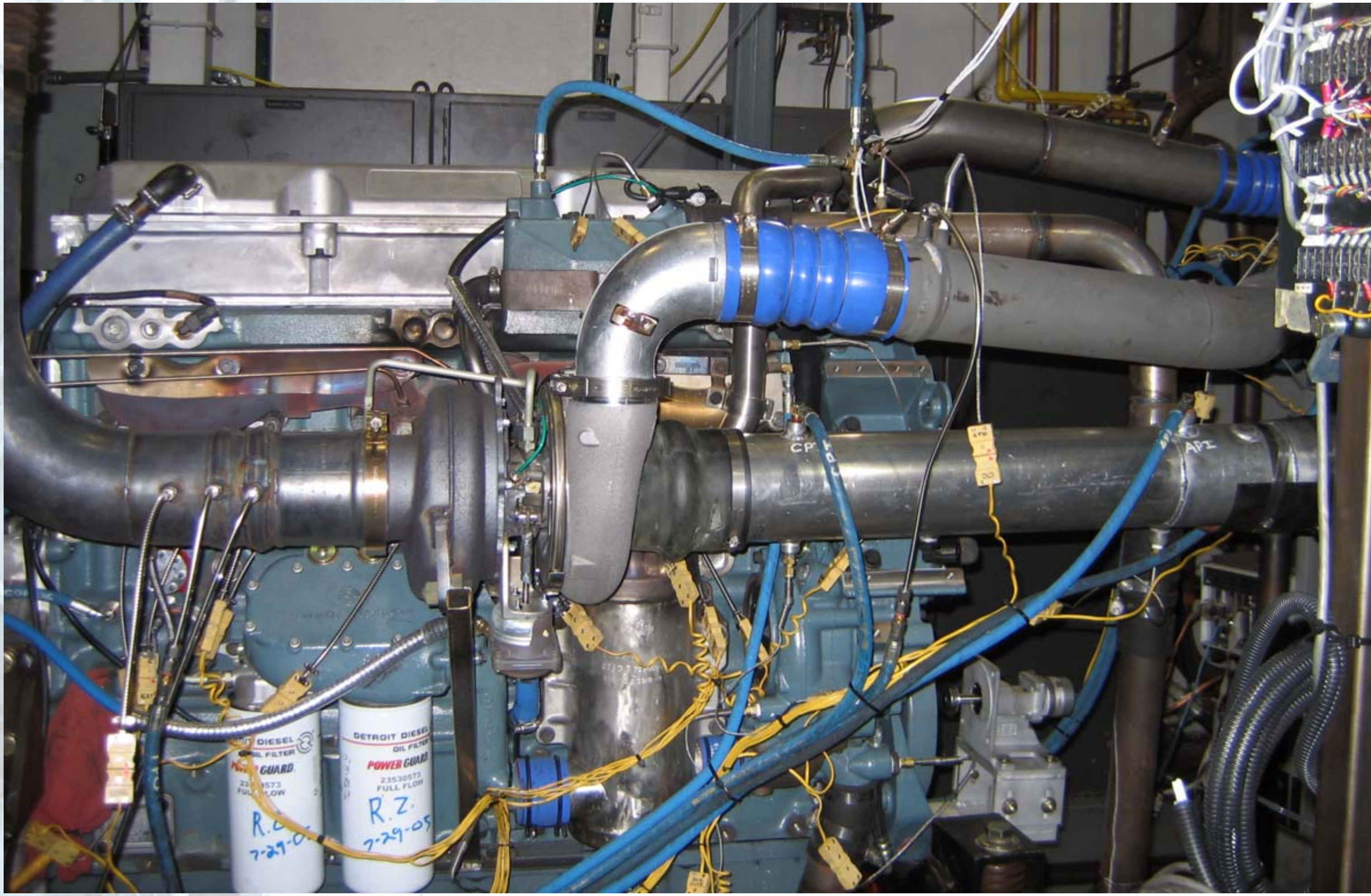
Overview

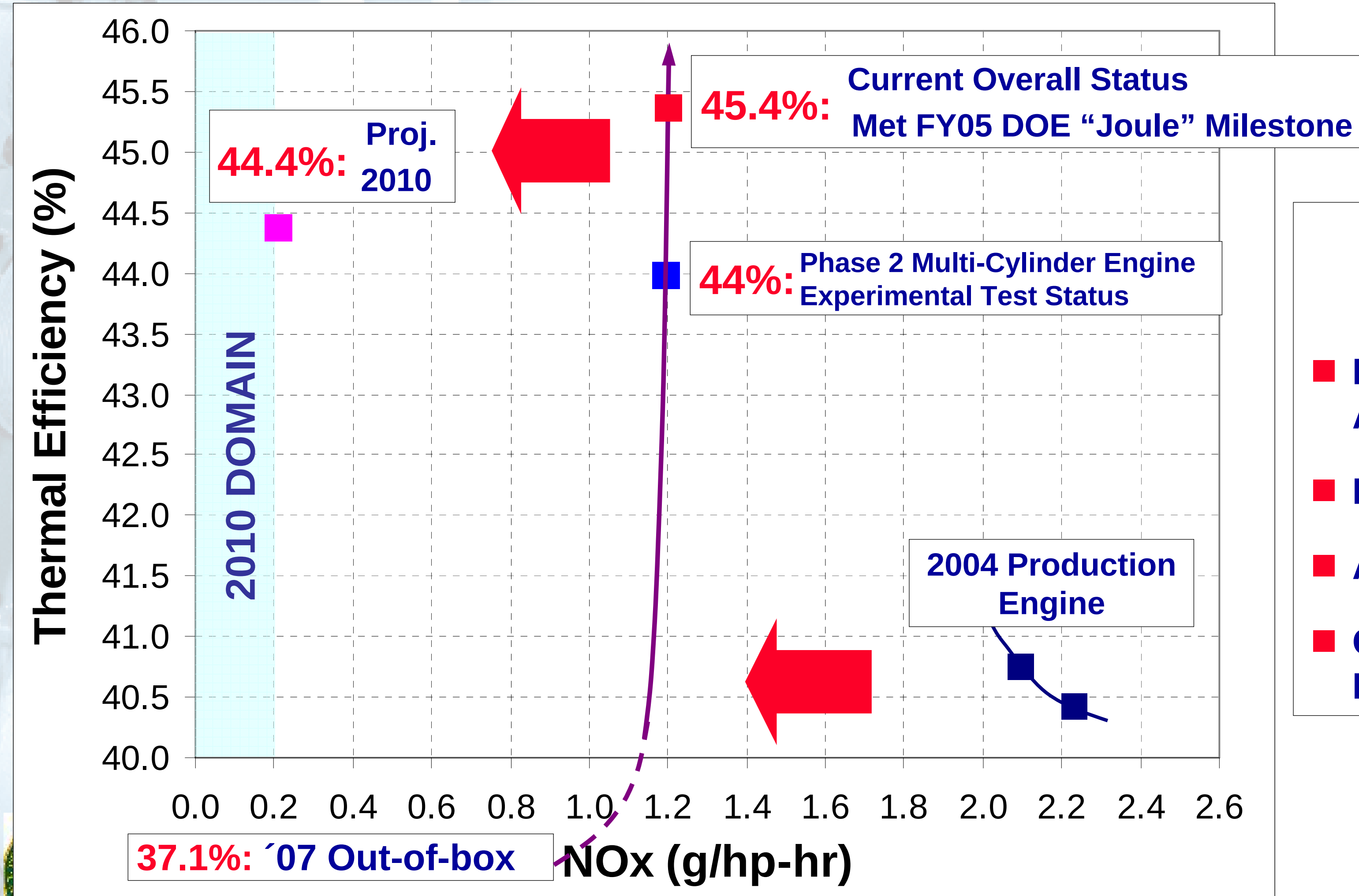
- Thermal Efficiency Achievement and Status
- Technical Roadmap to Success
- Forward Engineering Approach to Developing Needed Technologies
- Critical Subsystems Enhancement & Challenges for Thermal Efficiency Improvement at 2010 Emissions and Beyond

NZ50 Phase 2 Engine Testbed



- Series 60 Engine Platform Provides Excellent Foundation
- Advanced Fuel Injection System; Air/EGR Delivery System Enhancements; Combustion System Technology; Heat/Energy Exchange Improvement

Phase 2 Brake Thermal Efficiency and NOx Emissions Achievement

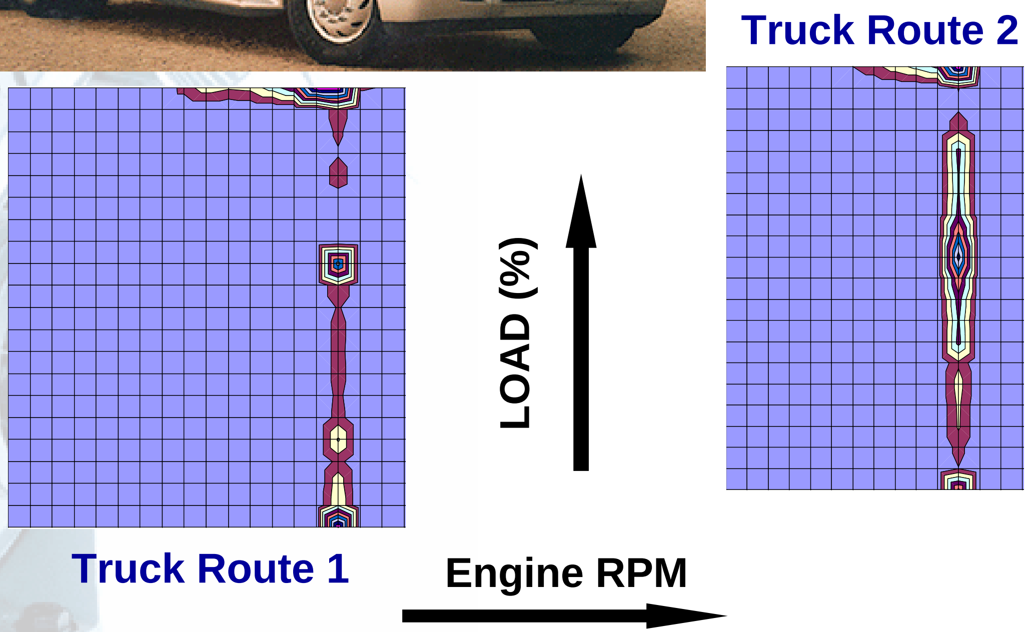


NZ-50 Sponsored Technologies

- Fuel Injection System Advancement
- Premium EGR Cooling
- Air System Enhancements
- Optimized Combustion Processes

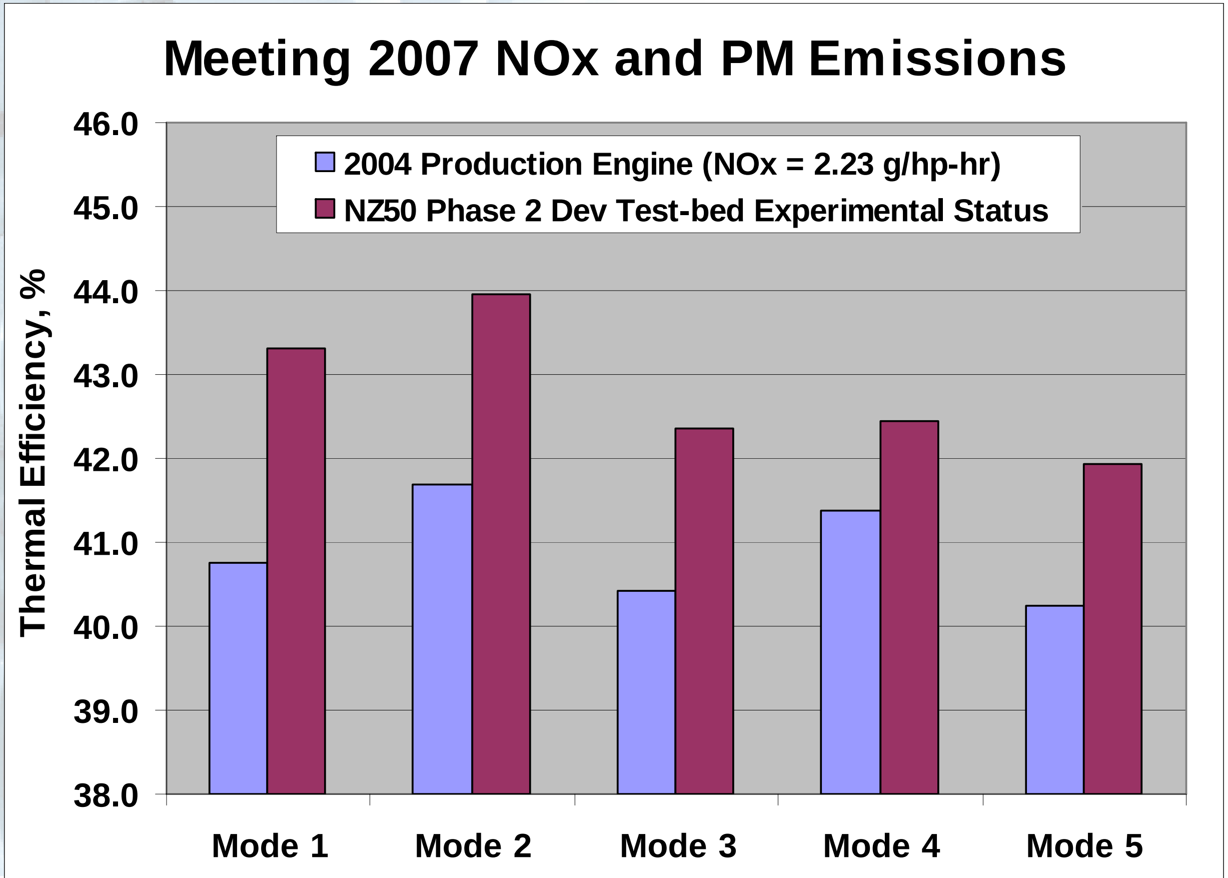
DDC

Example Series 60 Powered Heavy-Duty Truck Road-Load Engine Operating Characteristics



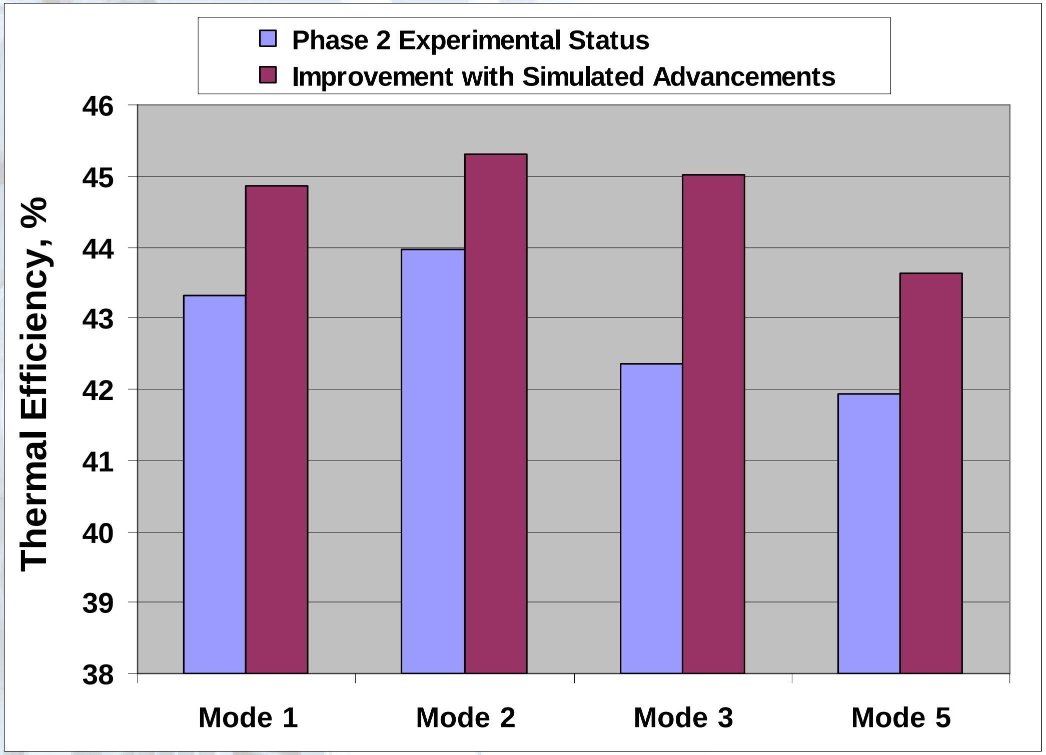
- Strongly depend on truck configuration
- Provide representative points for evaluating thermal efficiency gains
- Useful for quick assessment of potential impact on vehicle MPG
- Five modal points used for evaluating NZ50 Phase 2 achievement

Experimental Status of Thermal Efficiency Improvement At Truck Road-load Modal Points

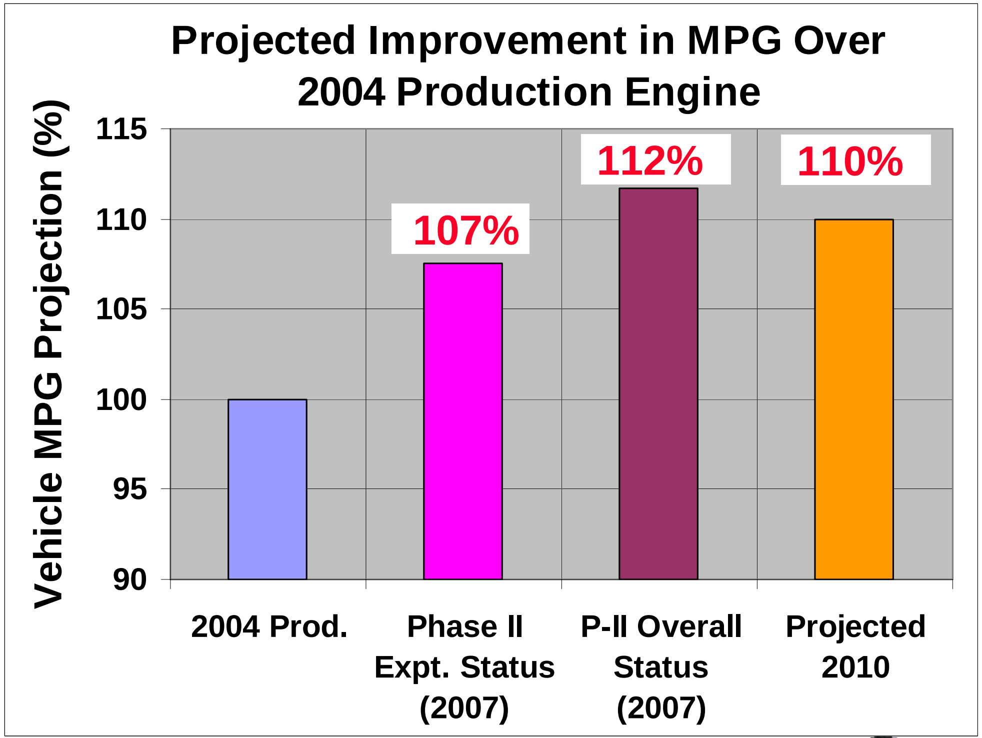


- Technology demonstration results showing potential for 2.5 to 6% thermal efficiency gains over 2004 production engine
- Meeting 2007 emissions constraints across operating speed and load

Projected Thermal Efficiency Improvement and Potential Impact on Vehicle Fuel Economy



- High thermal efficiency at most road-load points provides better promise to improve MPG
- Potential for up to 10% MPG improvement at 2010 emissions level

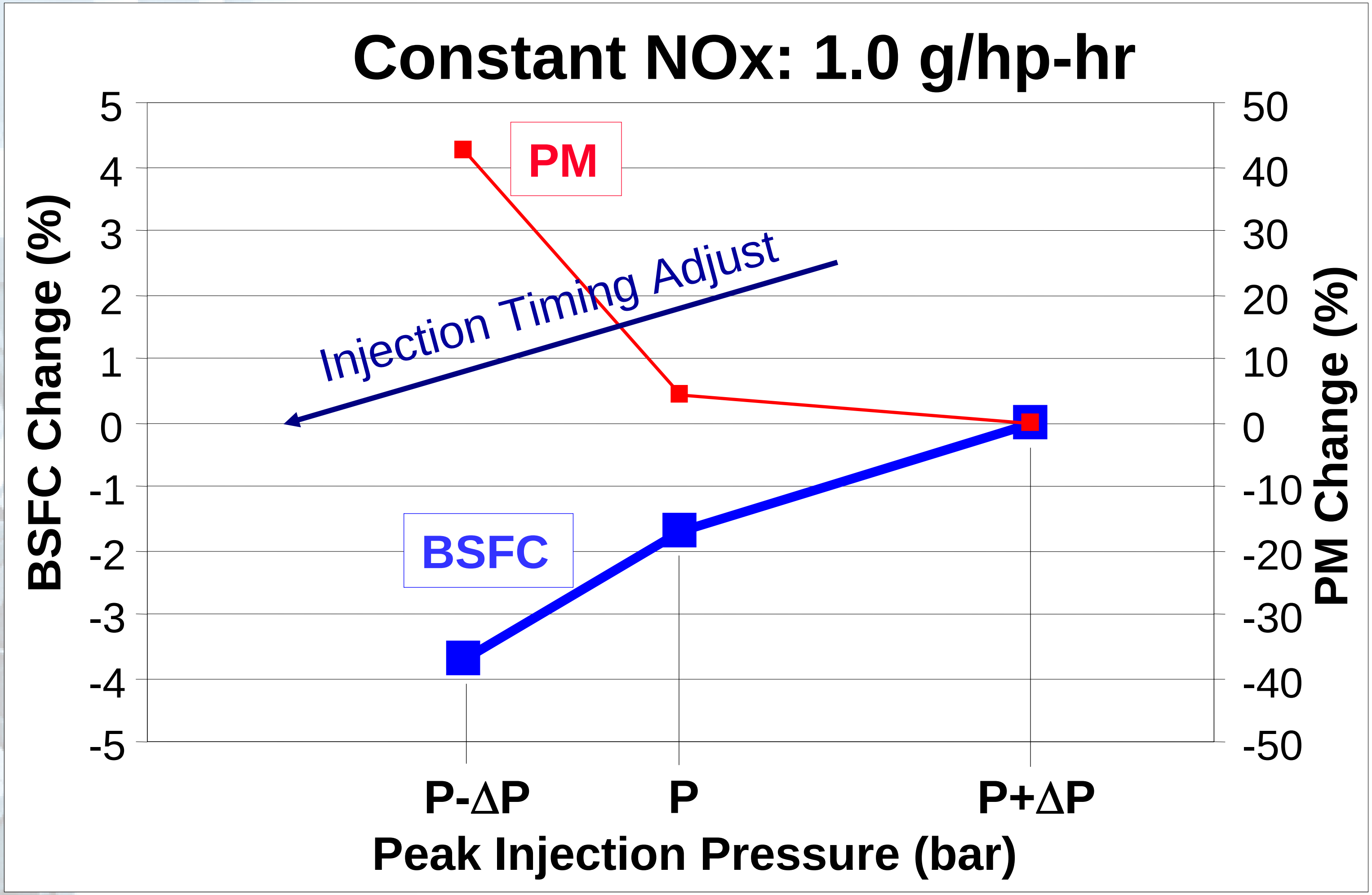


- Near 45% efficiency across road-load modal points
- Substantial improvement at least efficient points providing better optimized road-load efficiency

Technical Roadmap Enabling Achievement of Thermal Efficiency & Emissions Milestone

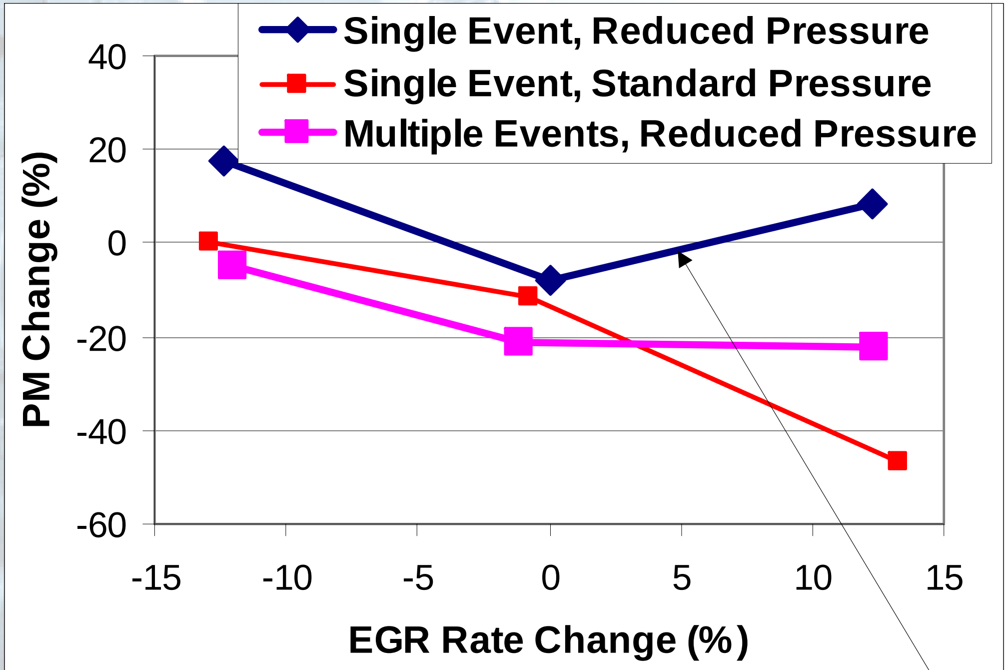
- **Phase 2 Multi-Cylinder Engine Testbed**
  - Advanced Fuel Injection System
  - Combustion System Optimization
  - Model-Base Controls Advancement
  - Efficient EGR Cooling
  - Expanded Engine Thermo-Mechanical Constraints
- **Advancements on Other Testbed & Advanced Simulation**
  - Reduced Pumping Loss and Optimized Valve Events
  - Improved Turbocharger Efficiency and Matching
  - Integration of Basic Exhaust Recovery Process

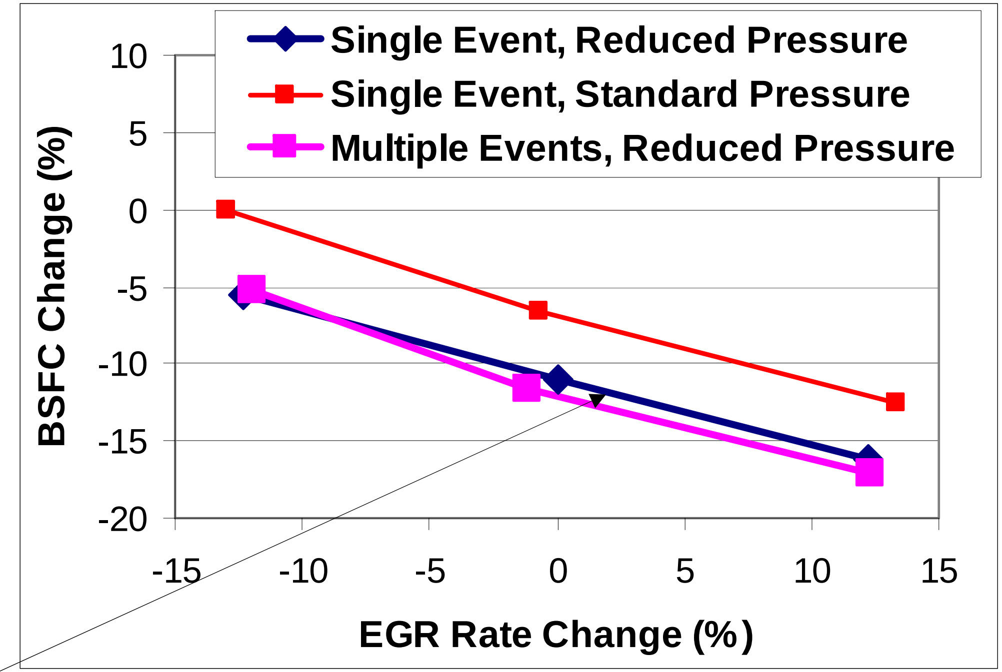
BSFC and PM Emissions Sensitivity to Injection Pressure and Timing



Simultaneous BSFC and PM Benefits with Multiple Injection Strategy at High Engine Operating BMEP

1 g/hp-hr NOx at 2007 Level PM

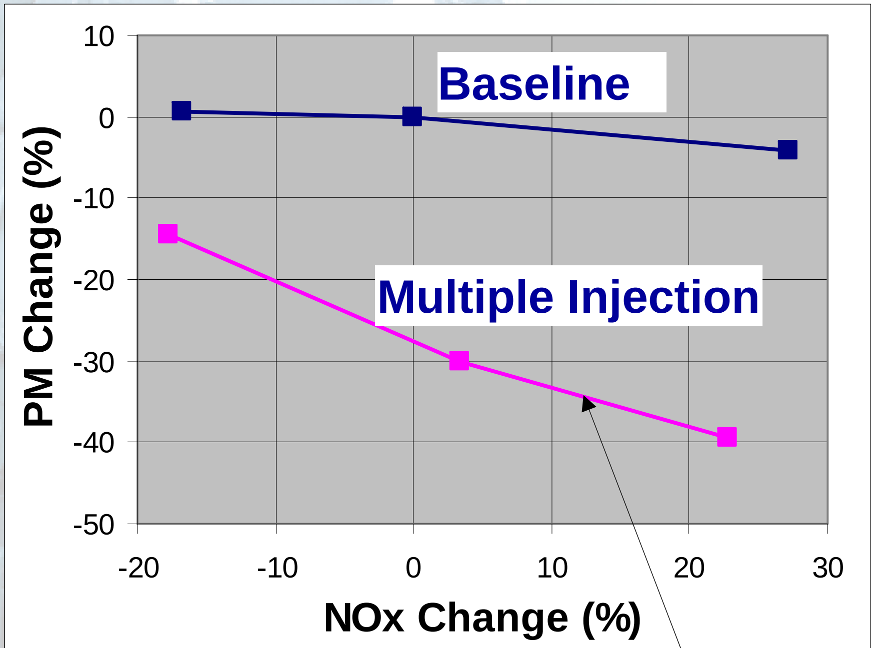


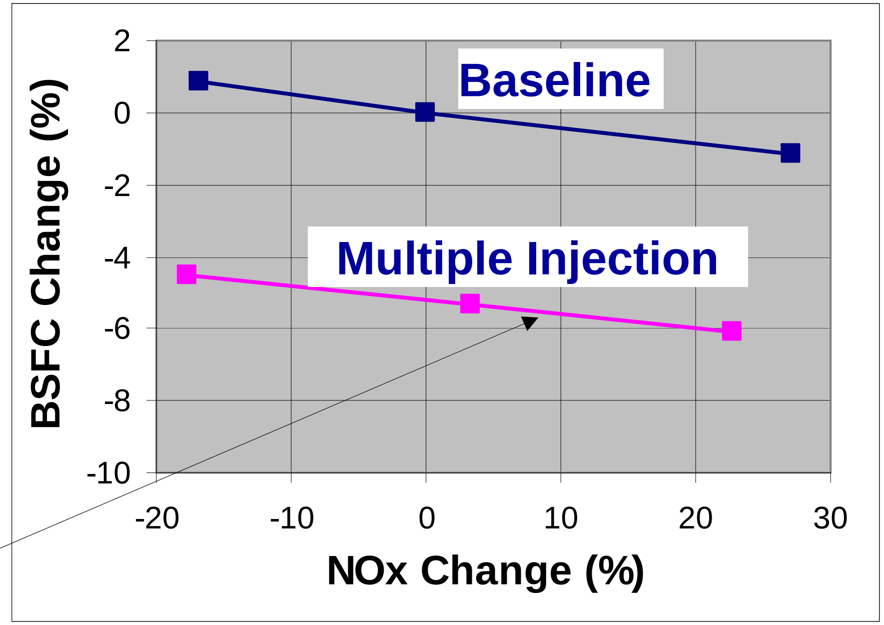


- Reducing injection pressure under high load conditions allows injection timing optimization to improve BSFC, but it also significantly raise the PM emissions
- Strategic application of multiple injection events minimizes the penalty in PM emissions while allowing the BSFC benefits to be achieved

Simultaneous BSFC and PM Benefits with Multiple Injection Strategy at Low Load

Reference NOx = 0.97 g/hp-hr

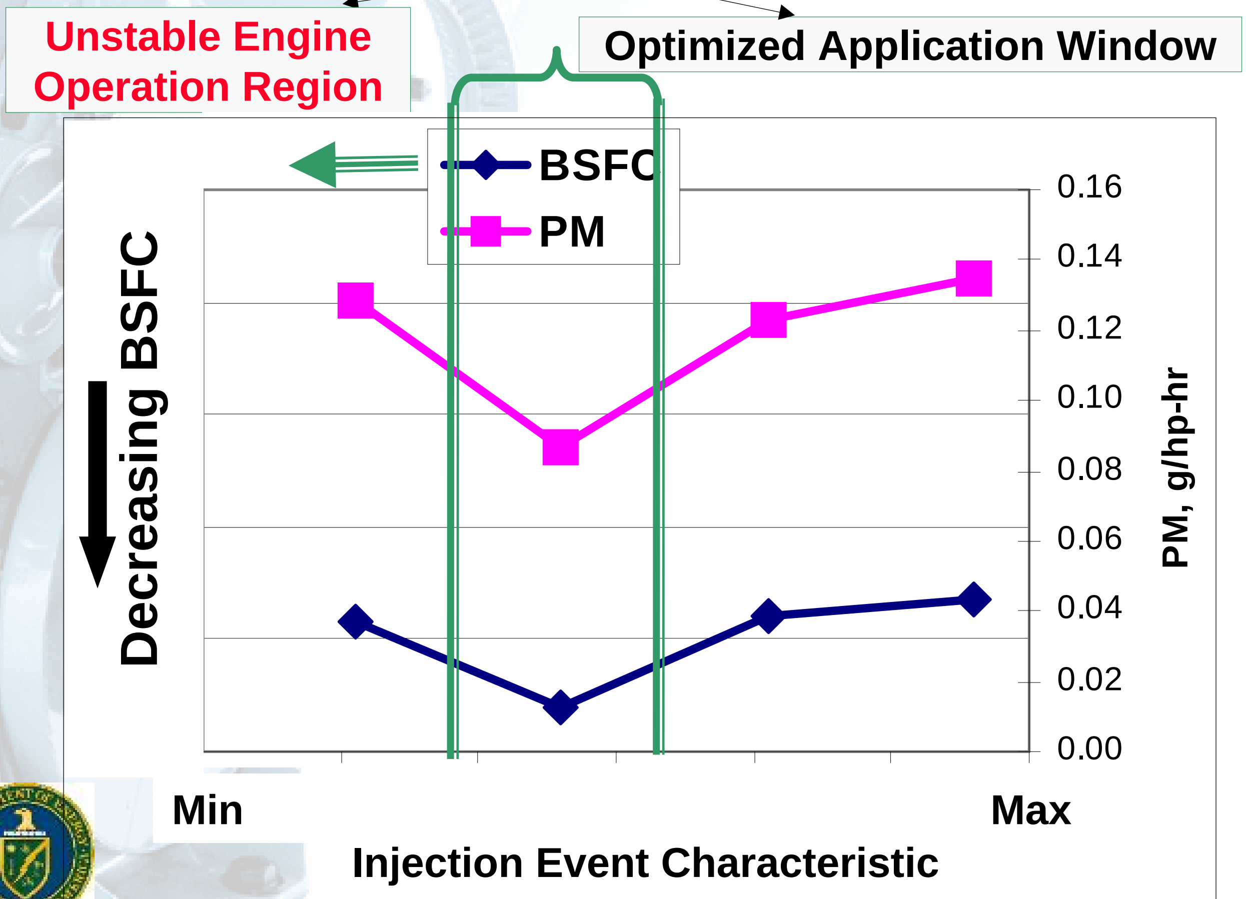




Under low-load operation, application of multiple injection events provides capability for low emissions with sustained BSFC

Risks and Challenges for Successful Application and Commercial Viability

Will change depending on engine load point, target emissions levels, atmospheric conditions, road terrain, fuel injection system hardware, etc

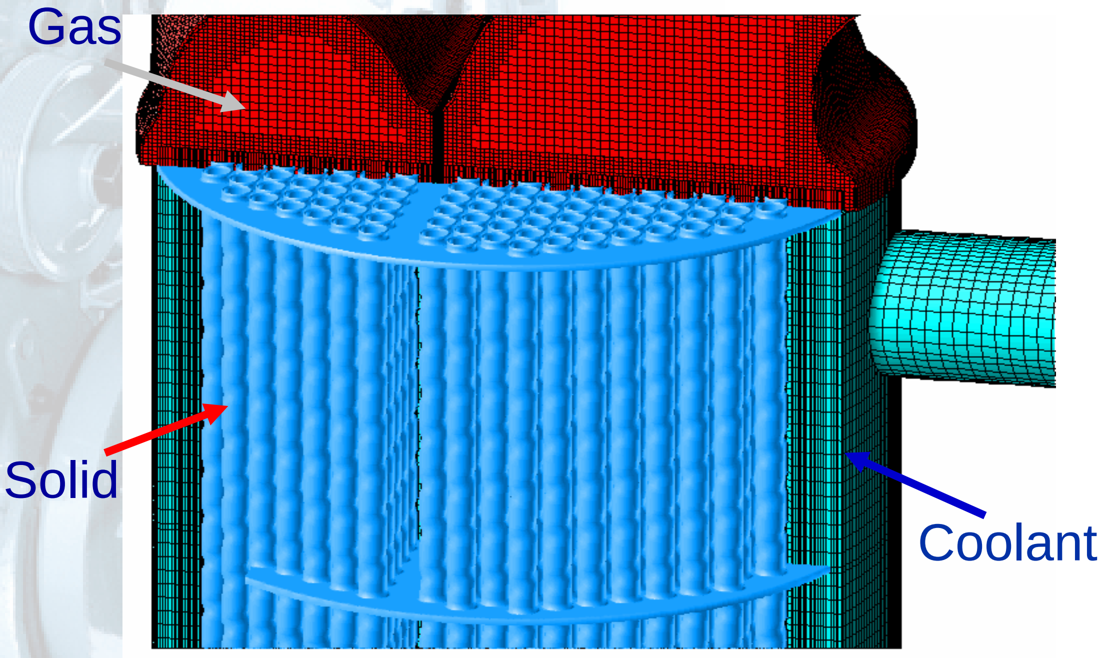


Potential Road-Blocks to Commercial Viability

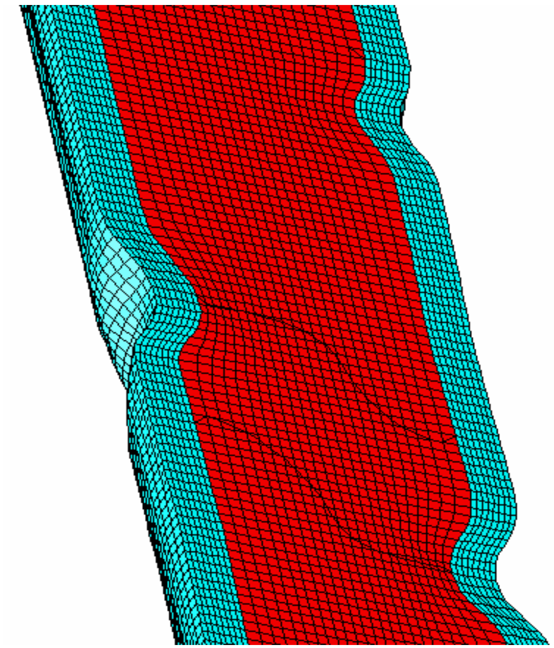
- Accurate control of the multiple events over FTP
- Stability of operation (both phasing and quantity)
- Durability of injection system hardware

Detailed Resolution of Intricate Flow and Heat Exchange Patterns to Optimize Performance and Reduce Impact of Fouling

- **High Resolution CFD Model of the Cooler**
  - **Coolant, gas (EGR) and solid sides of the cooler model simulated simultaneously**
  - **Approximately 10 million cells required**



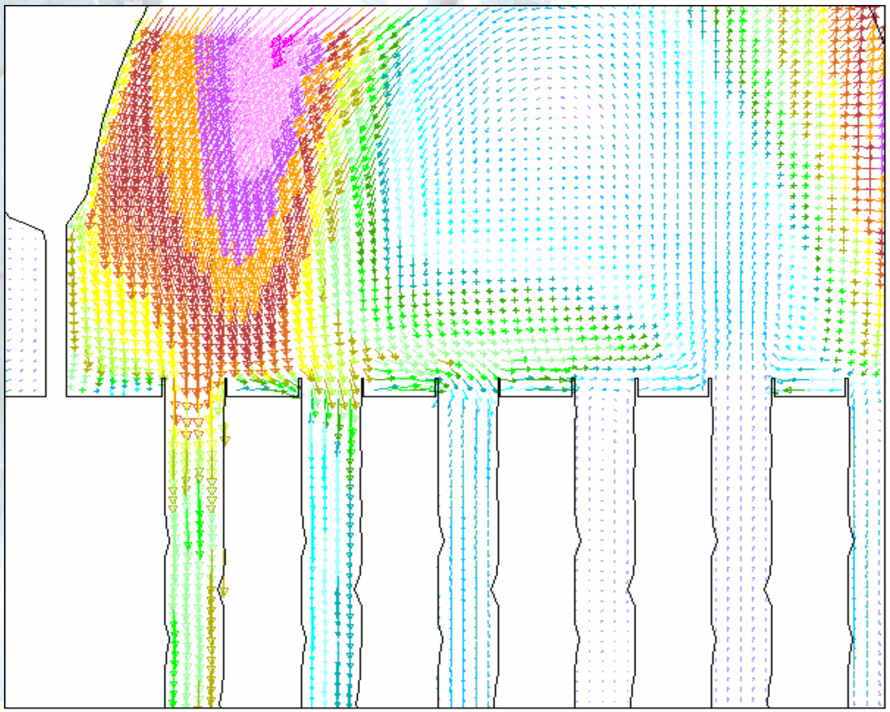
Despite size of model, small features of gas tubes not sufficiently resolved



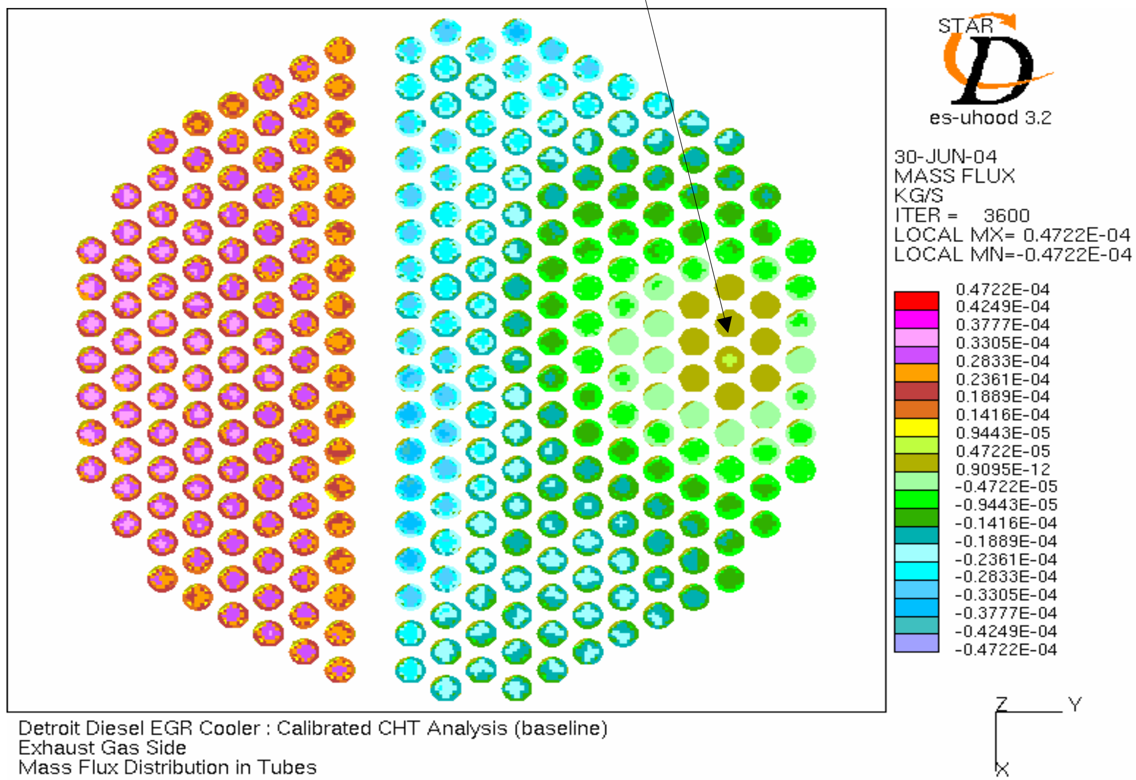
High resolution single gas tube model used to scale heat transfer coefficients for the full model to improve accuracy

Resolution of Detailed Local Characteristics Enabled Problems Areas to be Identified

Gas re-circulation on the inlet side of the header tank causes uneven gas mass flux distribution to the inlet tubes and reverse flow in ~10 tubes.



Detroit Diesel EGR Cooler : Calibrated CHT Analysis (baseline)
Exhaust Gas Side
Velocity Vectors (plot at centerline)



Detroit Diesel EGR Cooler : Calibrated CHT Analysis (baseline)
Exhaust Gas Side
Mass Flux Distribution in Tubes

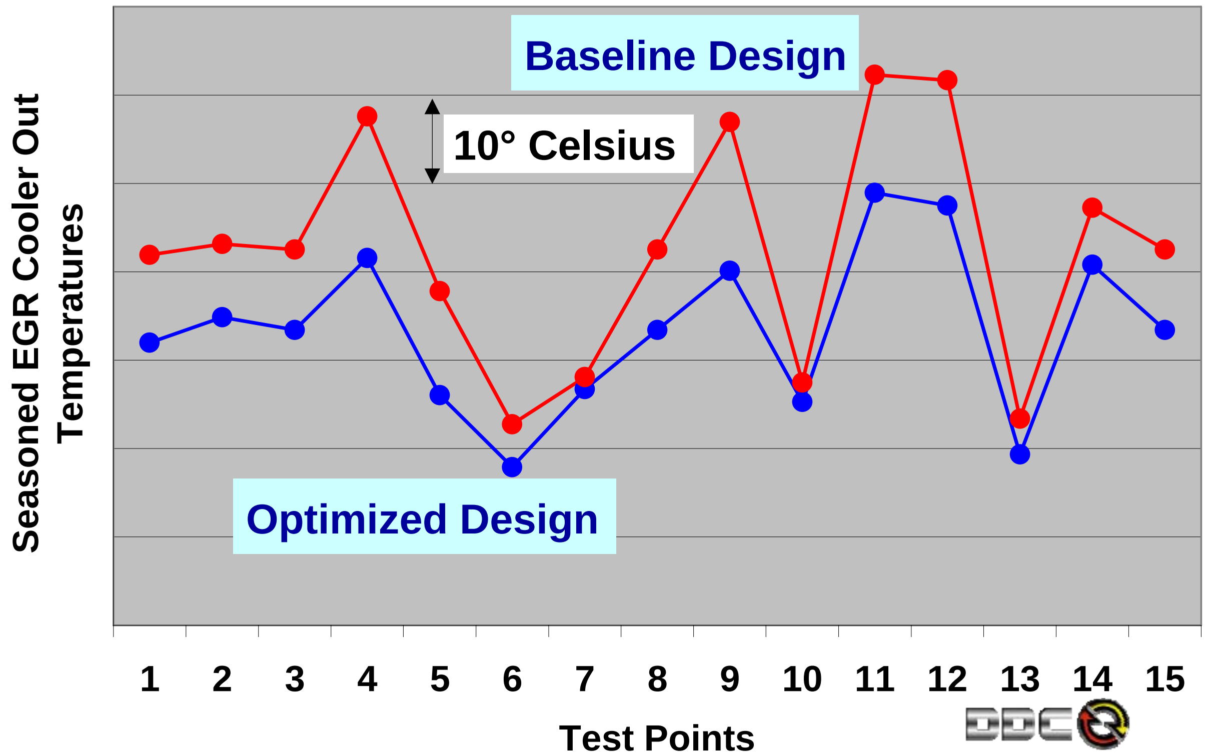
Forward Engineering of EGR Cooler Design Optimization and Its Verification

Optimized EGR Cooler Design

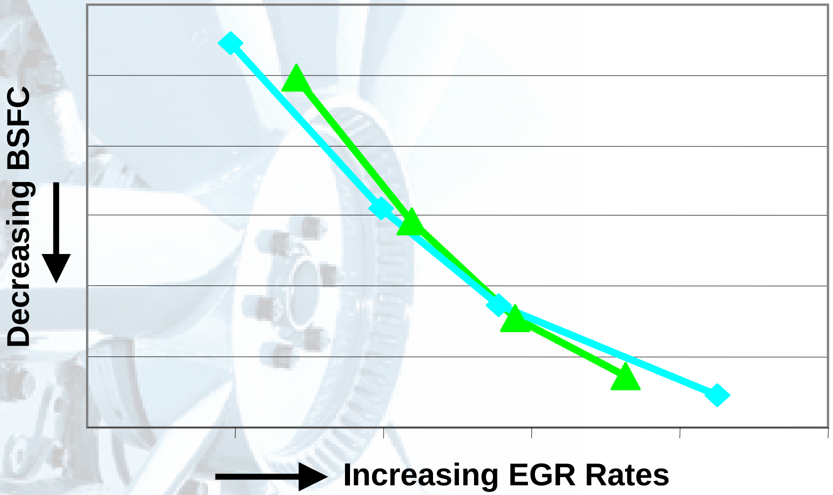
10 to 15 deg Celsius lower EGR Gas Temperature Out After 50 Hours

Key Desirables from EGR Cooler

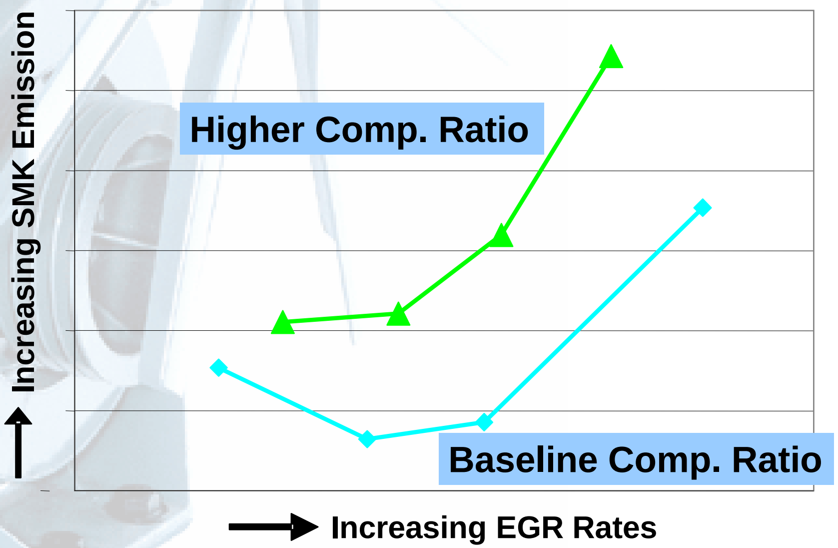
- **Efficient EGR Cooling:**
  - ➔ **(EGR Gas T_{IN} – EGR Gas T_{OUT})**
- **Minimized Fouling Effects**

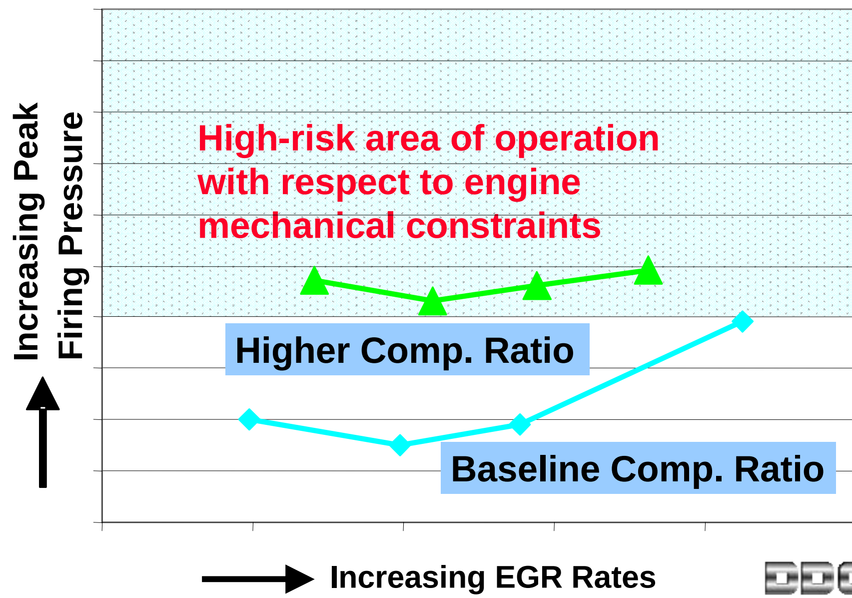


Expanding Boundaries of Engine Thermo-Mechanical Limits to Improve Thermal Efficiency

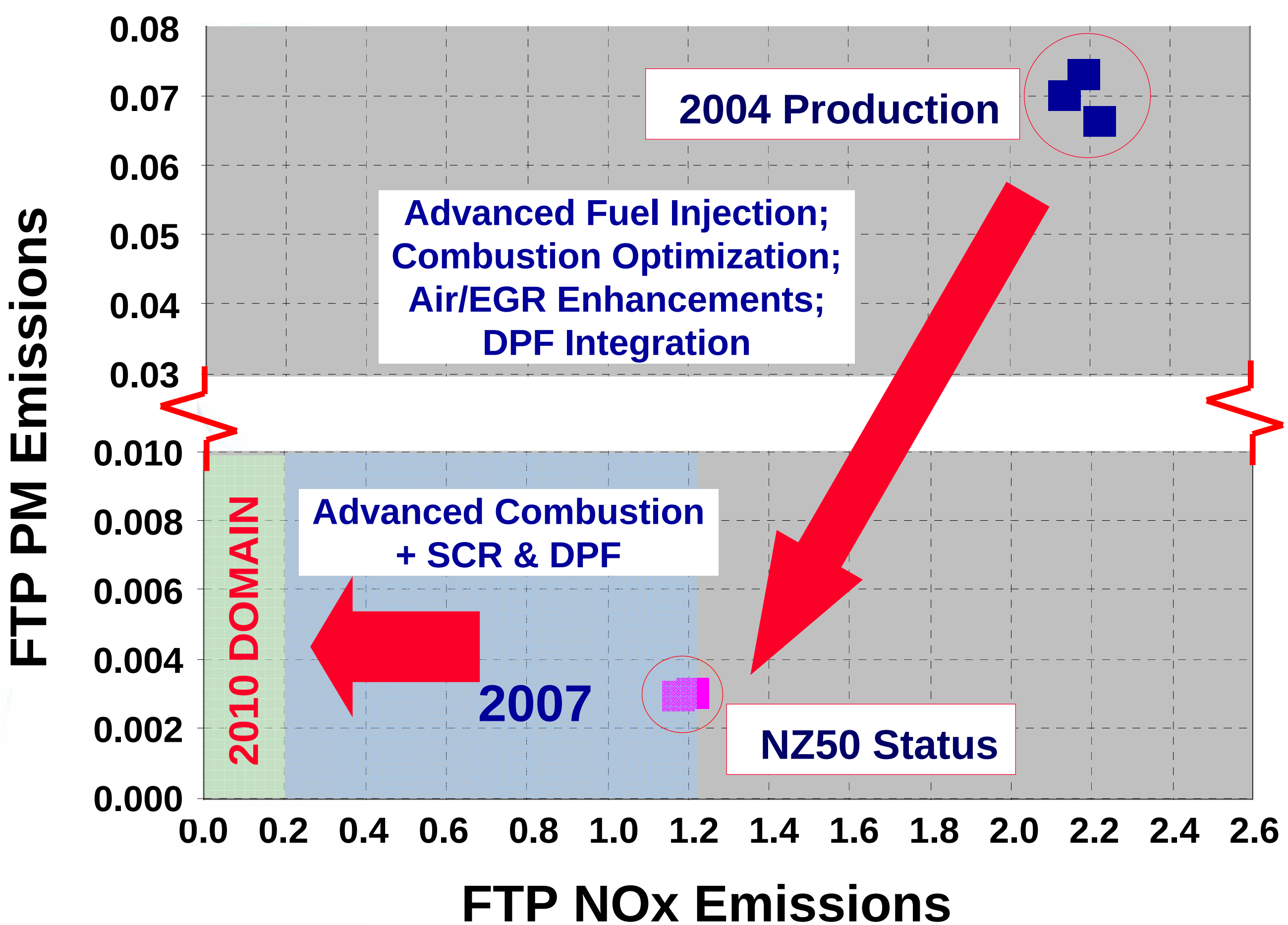


- Pushing engine thermo-mechanical boundaries to improve thermal efficiency
- More intelligent and versatile control schemes employed for complex control of subsystem operation and total engine system integration
- Effective transient emissions control capability allows higher compression ratio options to be employed



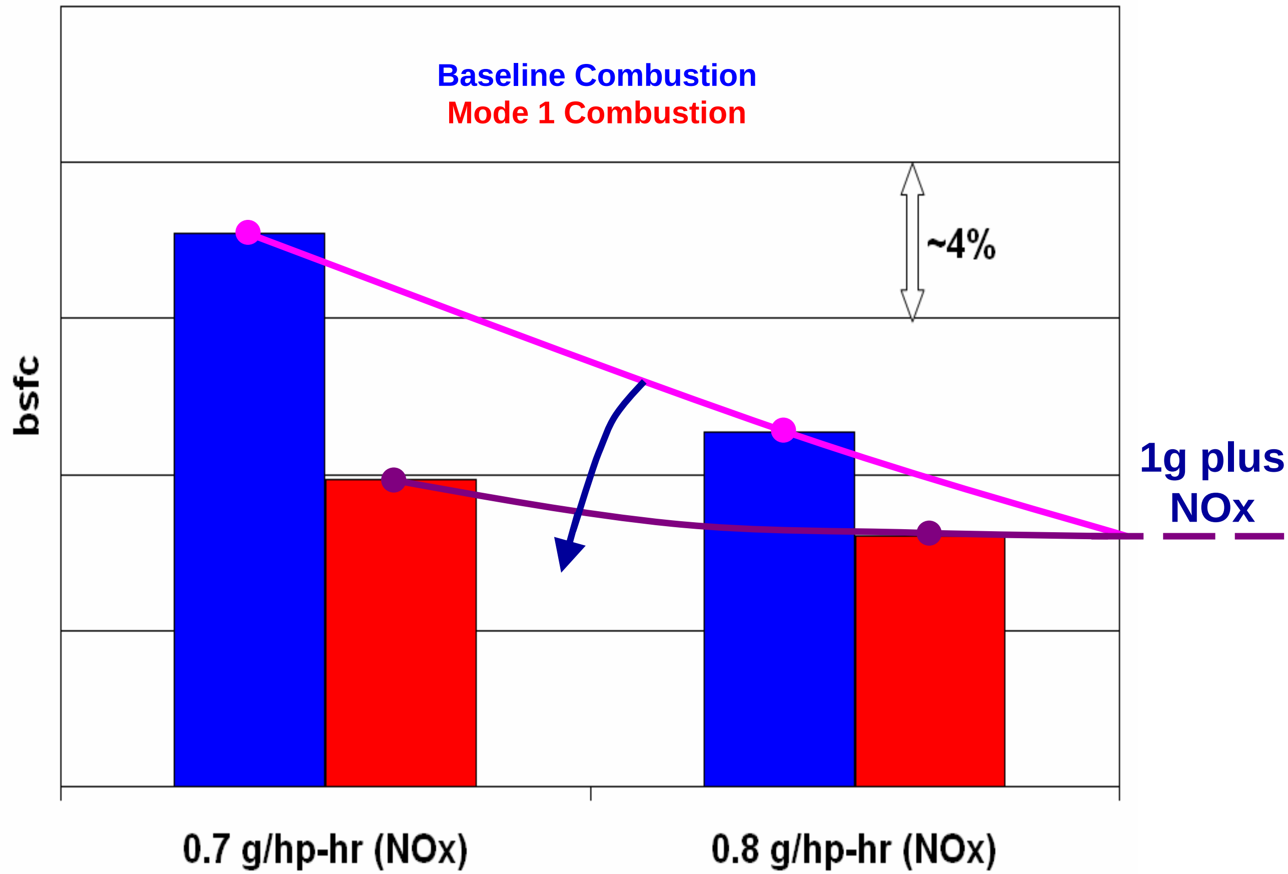


Development Path to Achieving Emissions Regulations

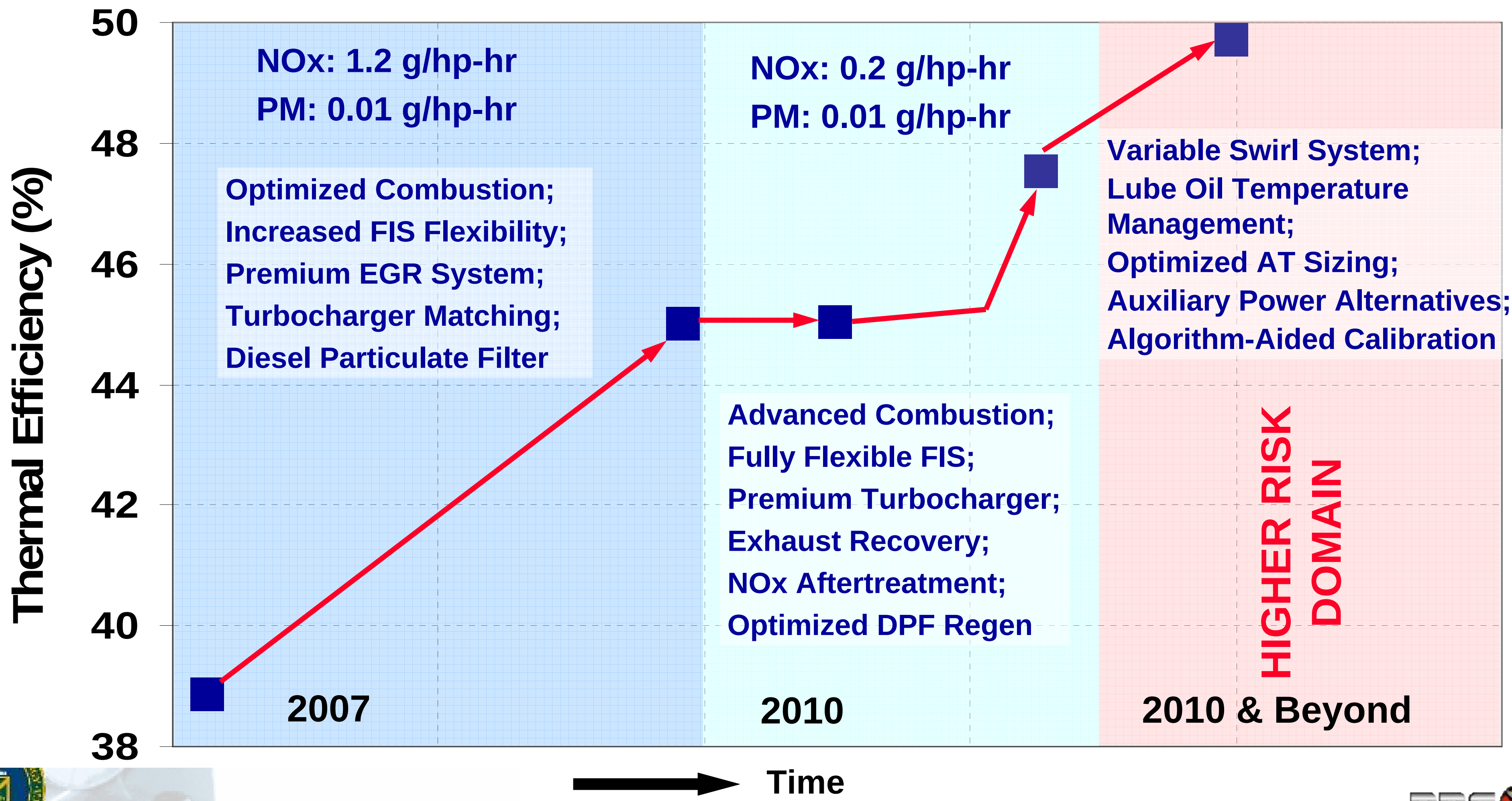


Improving Thermal Efficiency at 2010 Emissions Levels and Beyond

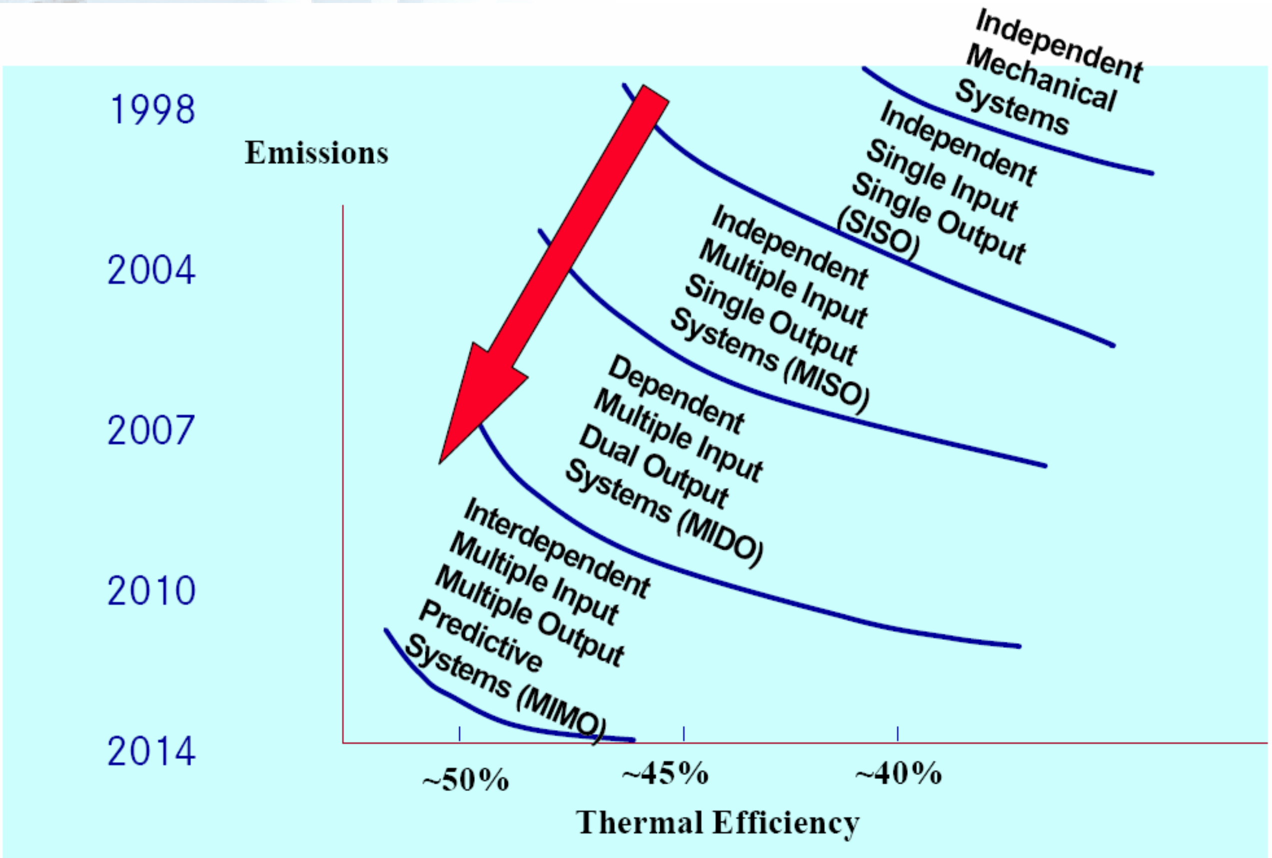
- Advanced Combustion
- Fuel Injection System
  - Higher Pressure
  - Increased Flexibility
- Higher Rates of Cooled EGR
- Total System Optimization (Engine + Aftertreatment)



Technology Roadmap and Milestones for Thermal Efficiency Reaching 50% at 2010 Emissions



Progressive Increase in Controls Sophistication to Meet Low Emissions and Thermal Efficiency Needs



Increasing controls sophistication to optimize total-system operation

Summary

- DOE FY05 Joule milestone met at 2007 emissions levels
- Developed technical roadmap towards achieving 2010 emissions while potentially improving thermal efficiency
- Significant risks and challenges exist for application and commercial viability of some of the technology enhancements
- Demonstrate the importance of forward engineering using analytical tools for the development and evaluation of the potential of thermal efficiency enhancing technologies

Acknowledgements

- 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