Enabling High Efficiency Clean Combustion

2009 Semi-Mega Merit Review

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Research & Technology

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Agenda

- Goals and Objectives
- Collaborations/Interactions
- Approach
- Accomplishments and Future Work
  - Heavy Duty 15L ISX Engine
  - Light Duty 6.7L ISB Engine
- Fuels Impact
- Summary

Statement of Project Objectives

1. Improve brake thermal efficiency by 10% while meeting US EPA 2010 emissions
   - Baseline is current production engine meeting 2007 US EPA emissions compliance
2. Design and develop enabling components and subsystems (air handling, fuel injection, base engine, controls, aftertreatment, etc.)
3. Specify fuel properties conducive to improvements in emissions and fuel efficiency
4. System integration for fuel economy optimization (engine and vehicle)

Project Layout

- Budget Period I – October 2005 thru September 2006
  - Applied Research & Exploratory Development
- Budget Period II – October 2006 – September 2007
  - Component Technology Exploration and Development
- Budget Period III – October 2007 – September 2009
  - Multi-Cylinder Engine System Integration
- Budget Period IV – October 2009 – September 2010
  - Engine and Vehicle Fuel Economy Optimization

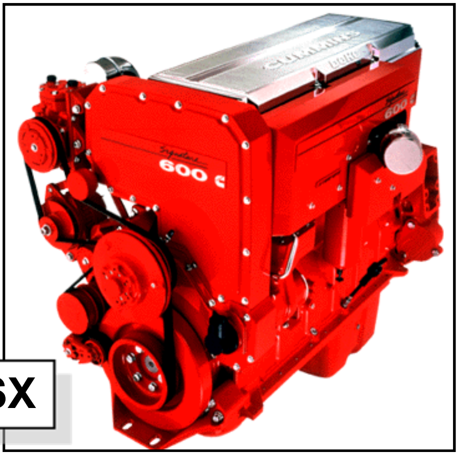
Funding
- FY2008: $3.2M DoE Funding and $3.2M Cummins Funding
- FY2009: $2.7M DoE Funding and $2.7M Cummins Funding

Collaborations/Interactions

- Oak Ridge National Laboratory
  - Fuels research
  - Engine performance analysis
- Purdue University
  - Engine testing with renewable fuels
  - Collaboration on fuel sensing technologies
  - VVA controls
- BP – Global fuels technology
  - Evaluation of future market fuels
  - Fuel supplier
  - Collaboration on the fuel properties conducive to HECC operation
- OEM Partners (Chrysler and Paccar Inc.)
  - Definition of vehicle and power-train requirements
  - Vehicle packaging and performance impact
  - Provide vehicle for demonstration

Engine Platforms

- Heavy duty diesel automotive market
  - Commercial use
  - Class 8 trucks

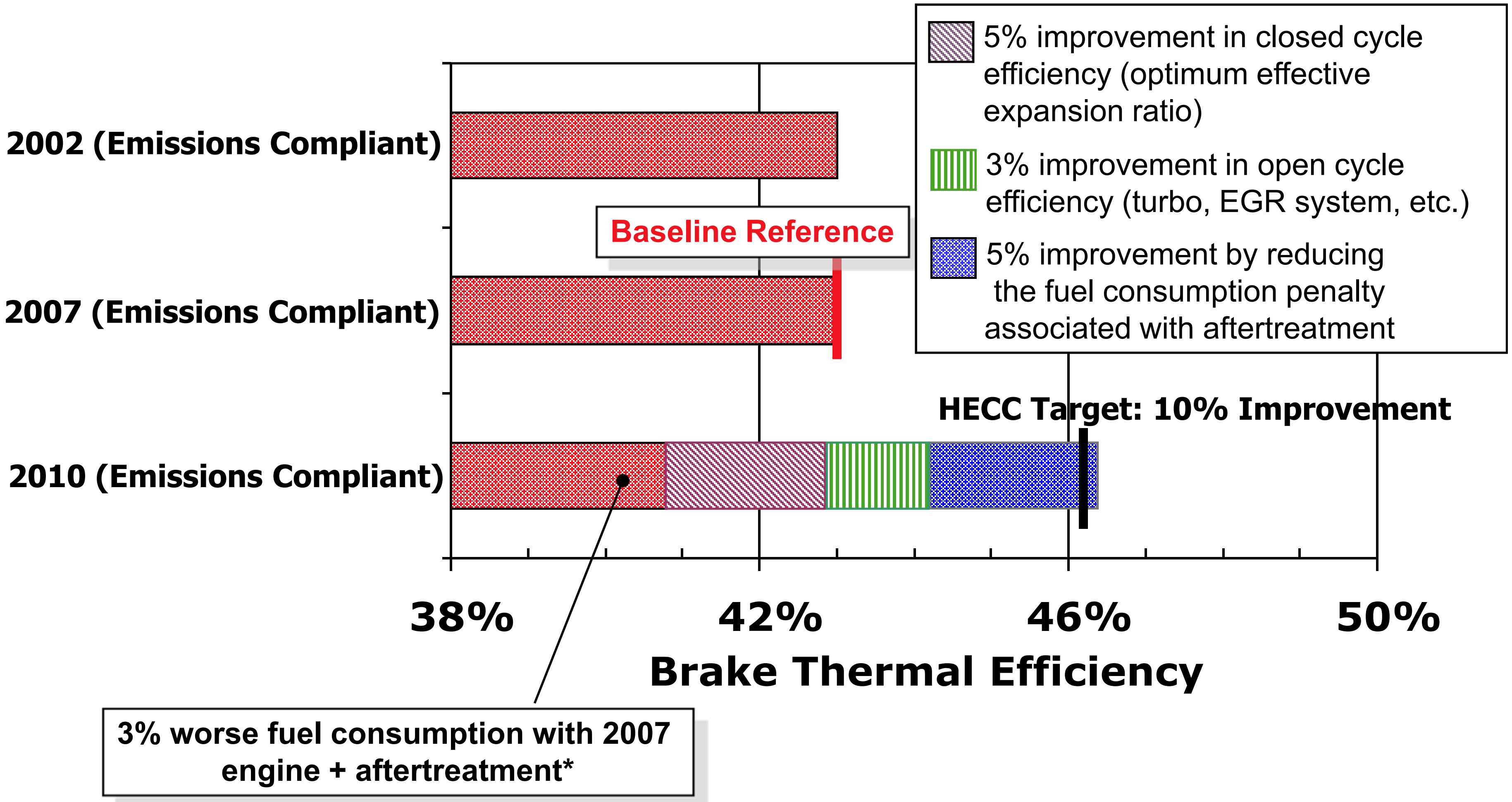


15L ISX

- Medium duty diesel automotive market
  - Commercial use
  - Personal use

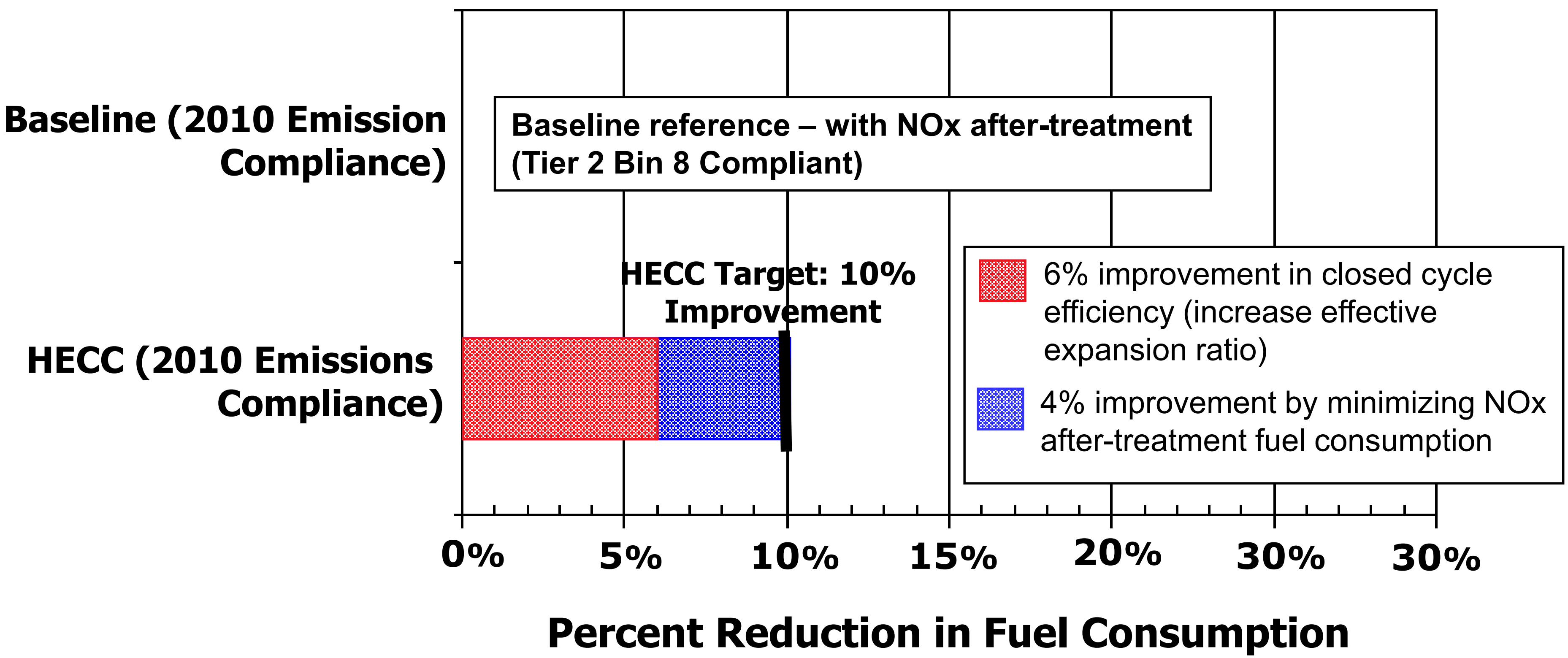
6.7L ISB

Path to Target
15L Heavy Duty Engine



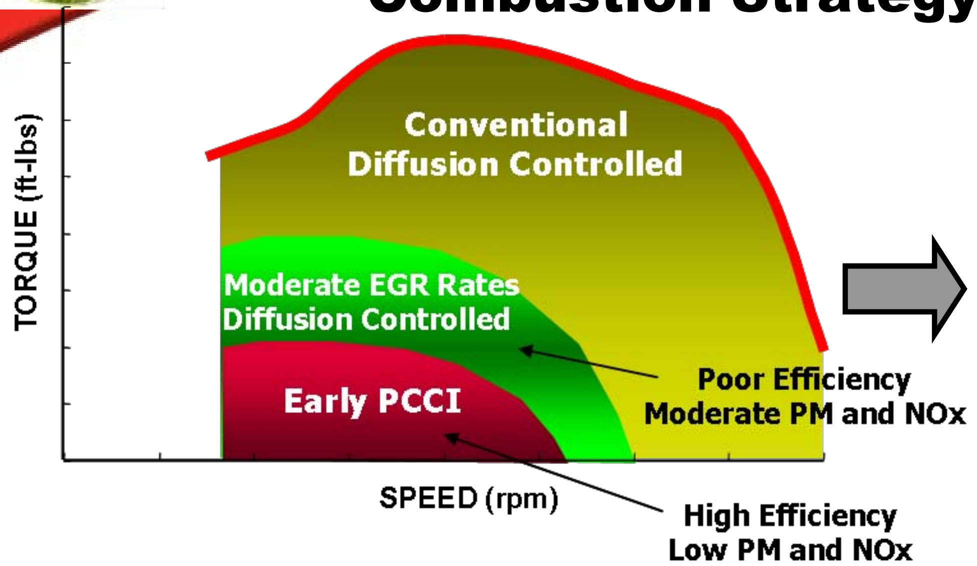
*Includes impact of thermal management of aftertreatment, fuel consumption for soot filter regeneration, and equivalent fuel consumption for NOx aftertreatment (e.g. SCR NOx aftertreatment)

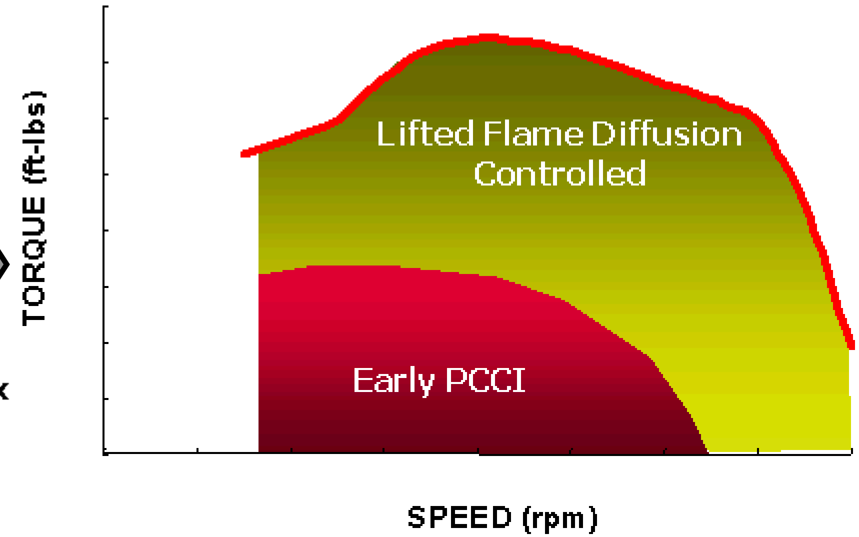
Path to Target
6.7L Light Duty Engine



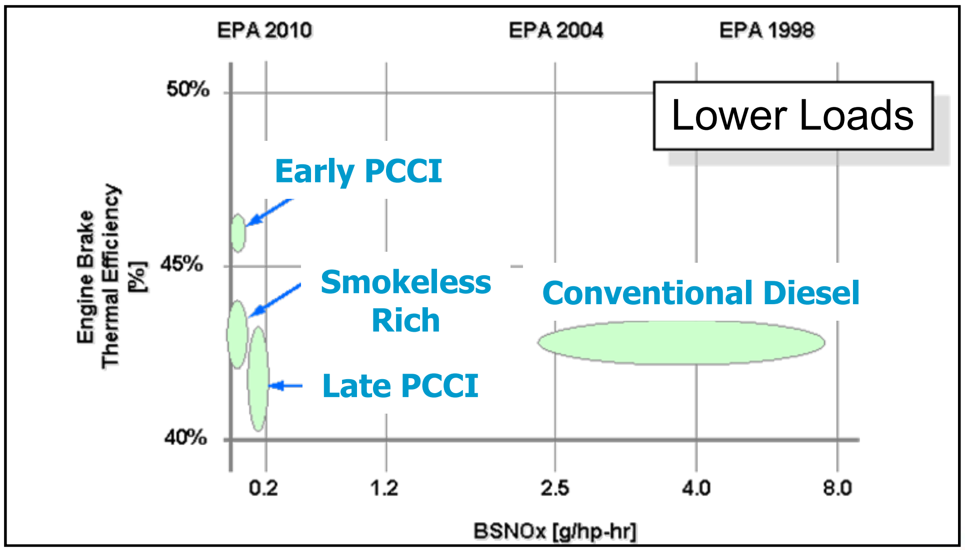
Technical Approach

Combustion Strategy for High Efficiency





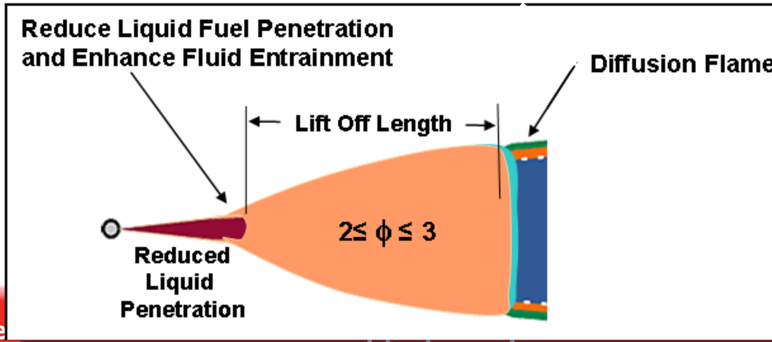
Low Temperature Combustion: Early PCCI



Lifted Flame Combustion Strategy

Higher Loads

- Enhanced mixing
- Higher EGR tolerance
- Improved NOx vs PM tradeoff
- Favorable combustion phasing for efficiency improvement



Approach

- Develop technology that provides engine efficiency improvements over a wide range of engine out NOx levels to support two types of engine architectures that meet US EPA 2010 emissions compliance
  - In-Cylinder NOx Control (no NOx aftertreatment)
  - Integrated SCR NOx Aftertreatment

- Same engine technology has been used to provide efficiency improvements for both in-cylinder NOx control and SCR NOx aftertreatment engine architectures

- Leveraging Cummins Component Business technologies for subsystem development
  - Examples: Fuel systems, turbomachinery, aftertreatment, electronics, combustion system, and base engine

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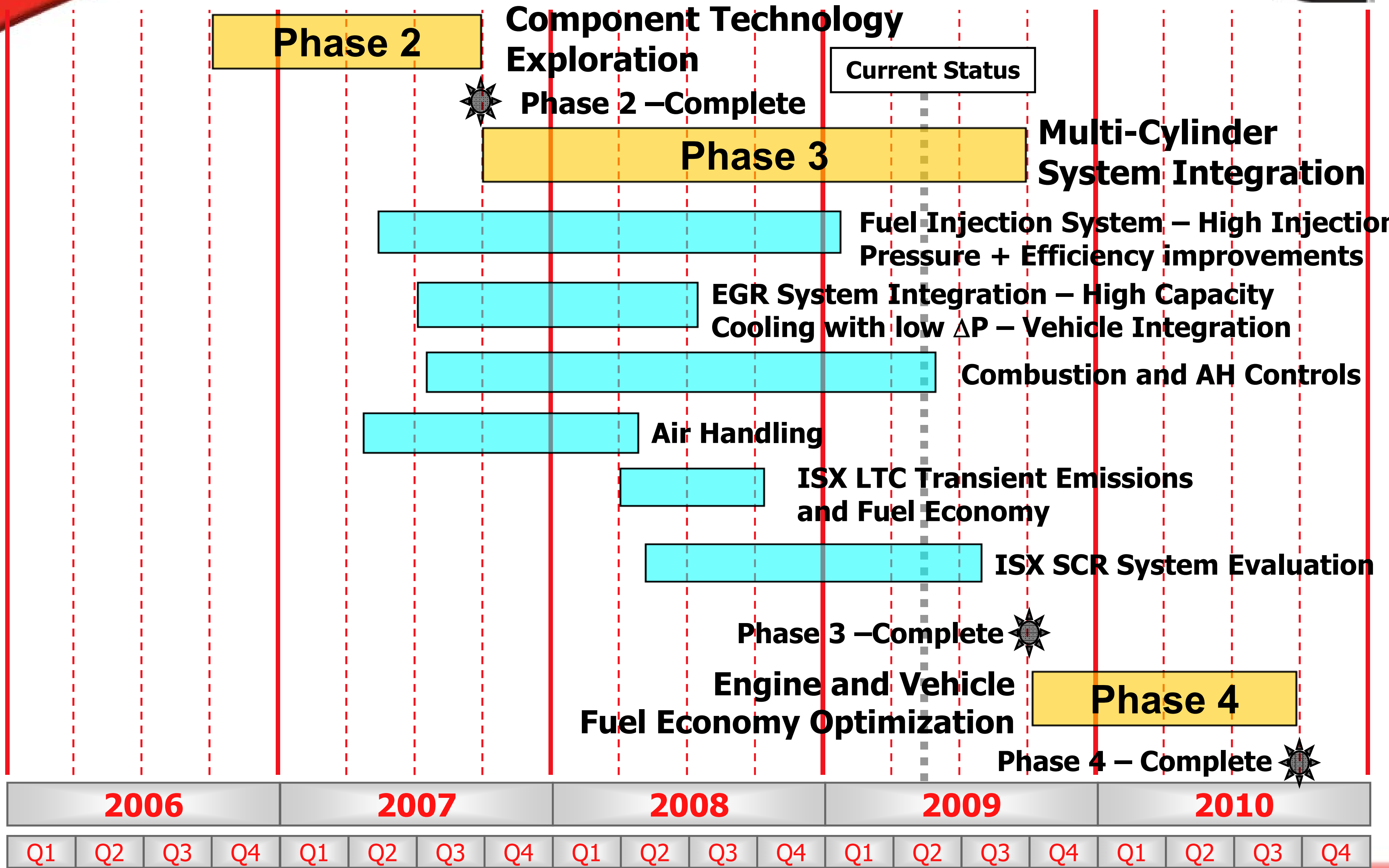
HECC Heavy Duty Program Schedule



ISX Technology Roadmap for Efficiency Improvement

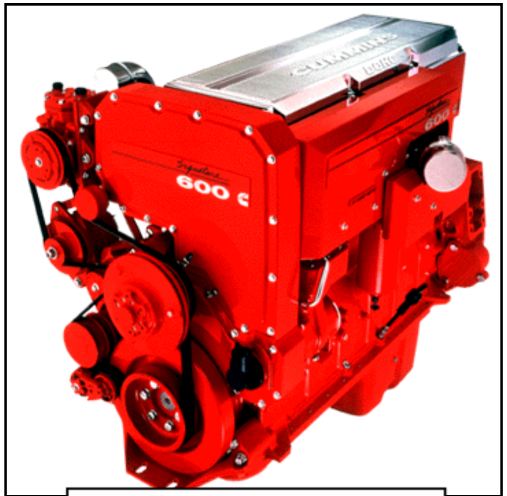
Black – Enabling Technology for Phase 2

Variable Valve Actuation

Fuel System
- -High Injection Pressure
- -Piston Bowl/Nozzle
- -Multiple injections

Advanced LTC
- -Enhanced PCCI
- - Mixed Mode Combustion

Variable Intake Swirl



Phase 2: 2007

Controls
- -Charge Air Manager
- -MAF
- -Closed Loop Combustion

EGR Loop
- - Lower Pressure Drop
- - Alternative Cooling

Electrically Driven Components

Turbo Technology

Aftertreatment

ISX Technology Roadmap for Efficiency Improvement

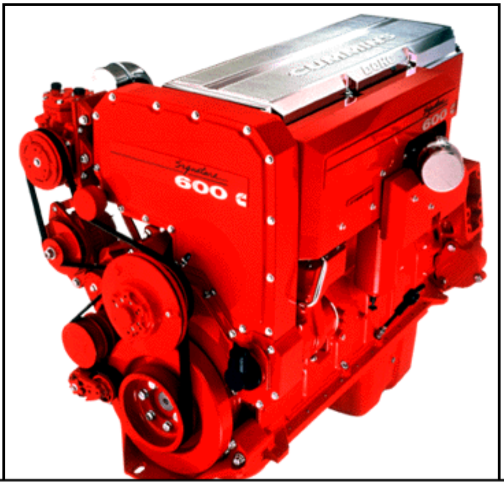
Black – Enabling Technology for Phase 3

Variable Valve Actuation

Fuel System
- High Injection Pressure
- Piston Bowl/Nozzle
- Multiple injections

Advanced LTC
- Enhanced PCCI
- Mixed Mode Combustion

Variable Intake Swirl



Phase 3: 2008 - 2009

Controls
- Charge Air Manager
- MAF
- Closed Loop Combustion

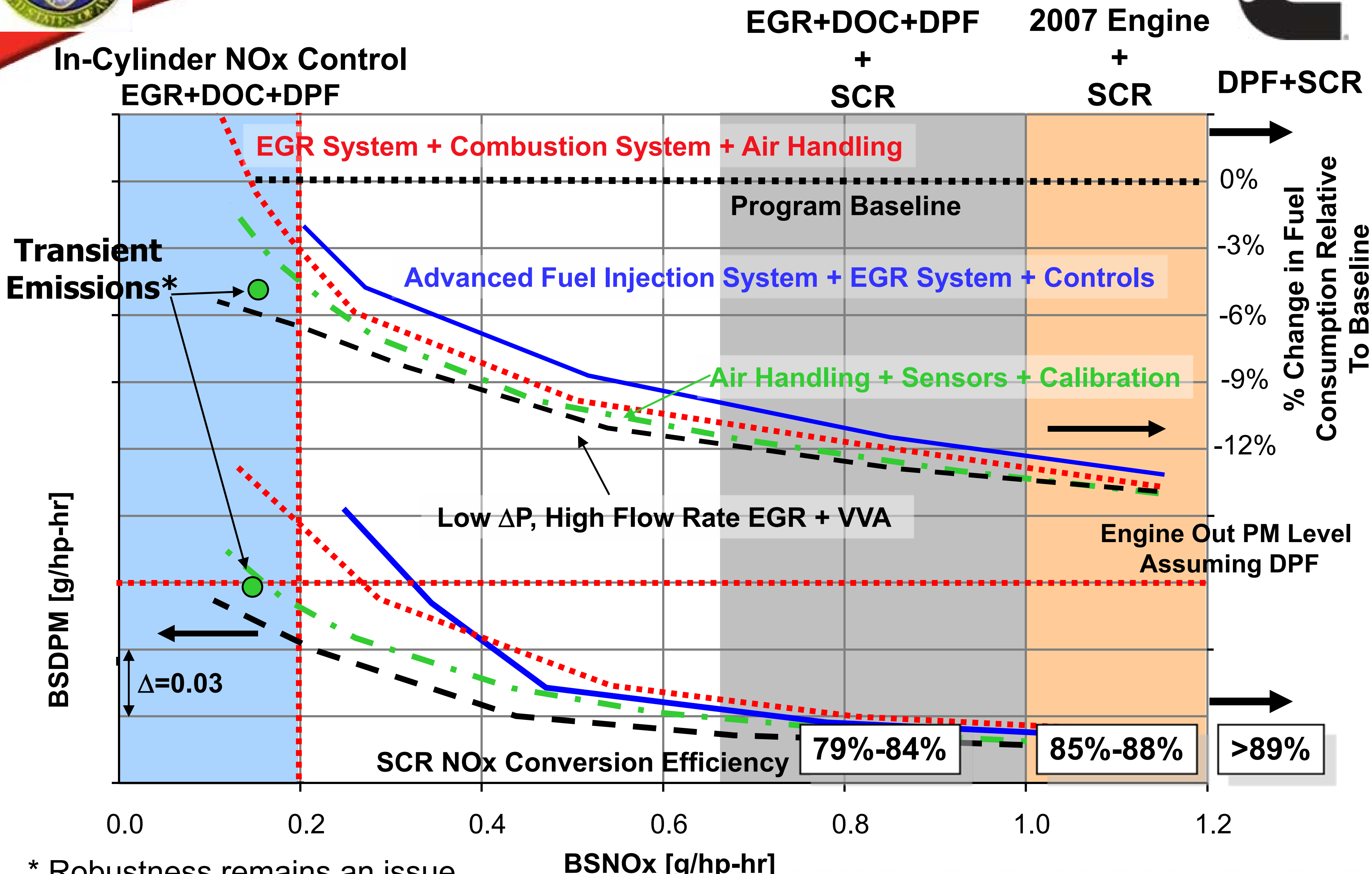
EGR Loop
- Lower Pressure Drop
- Alternative Cooling

Electrically Driven Components

Turbo Technology
- Electrically Assisted
- 2-Stage

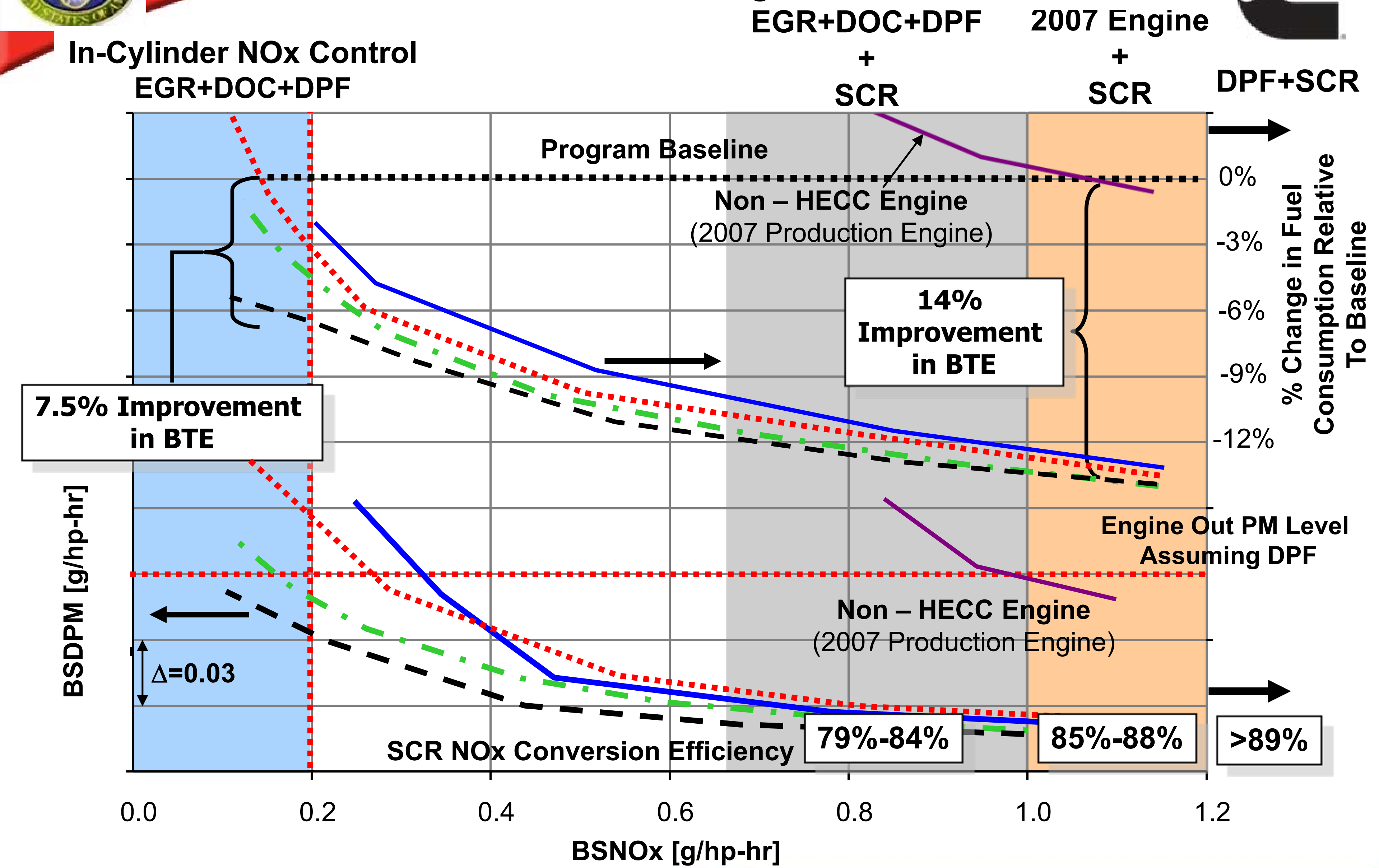
Aftertreatment
- DOC
- DPF
- SCR
- Sensors

Achieving a Wide Range of Engine Out NOx Capability



* Robustness remains an issue for In-Cylinder NOx Control

Fuel Consumption Comparison of the In-Cylinder vs SCR NOx Control Engine Architectures



Technical Barriers with Possible Solutions

<u>In-Cylinder NOx Control</u>

- Vehicle heat rejection
  - Low temperature radiator configuration (multiple options considered)
- Power density limitations
  - Increased vehicle heat rejection capability
  - Cylinder pressure capability
- Robustness
  - Reduce charge flow and fuel flow variation
    - Control algorithms
    - Sensor technology
    - EGR cylinder to cylinder distribution
- Transient response
  - 2-stage turbo
  - Electrically assisted boost
  - CAC bypass

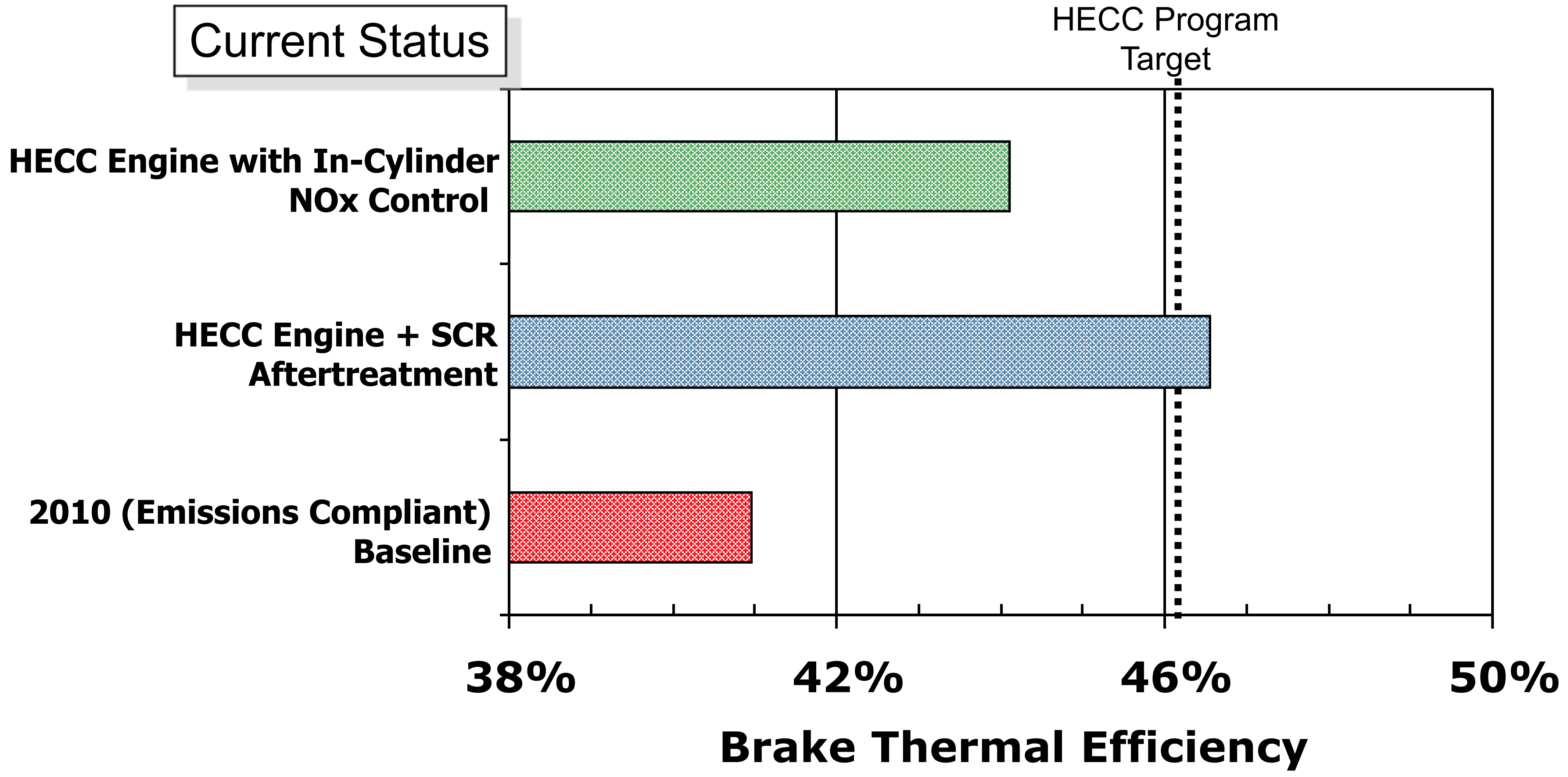
<u>High NOx Conversion Efficiency SCR</u>

- >95% conversion efficiency over relevant drive cycles
  - Conversion of urea to ammonia (eliminate urea derived deposits)
  - NOx selectivity of the ammonia slip catalyst
- System pressure drop
- Packaging
  - Unique arrangements defined
  - Reduce catalyst size via zone coating
  - New substrate material for smaller size
- Fuel efficient thermal management for transient emissions (FTP)
  - Turbomachinery
  - Injection strategy
  - EGR cooler by-pass
  - Compressor by-pass

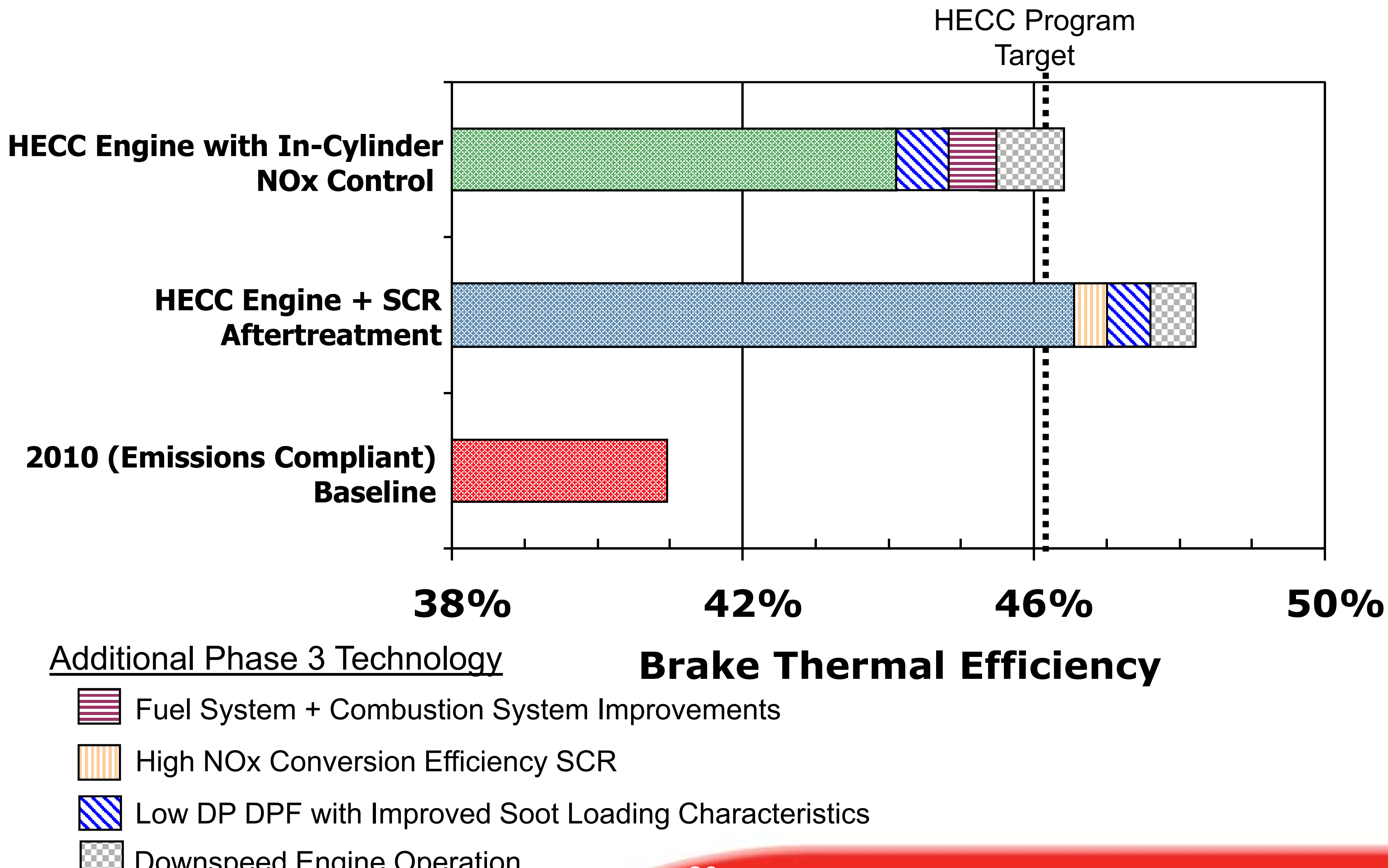
Summary of 2008 Accomplishments for Heavy Duty ISX 15L Engine Development

- All 2008 milestones have been met
- HECC engine technologies have been developed for a wide range of engine out NOx levels to support:
    - In-cylinder NOx control engine architecture
    - Integrated SCR aftertreatment architecture
- An in-cylinder NOx control engine architecture can meet US EPA 2010 emissions with a 7.5% improvement in engine efficiency
    - Identified additional technology integration opportunities to achieve the 10% program goal
- An integrated SCR aftertreatment architecture can meet US EPA 2010 emissions with a 14% improvement in engine efficiency which exceeds the program goal

Summary of Heavy Duty Efficiency Improvements and Future Potential Improvements



Summary of Heavy Duty Efficiency Improvements and Future Potential Improvements



Key Deliverables for FY 2009

Heavy Duty 15L ISX Engine

SCR Engine Architecture:

- HECC engine integration with a high NOx conversion efficiency SCR system (>95% conversion efficiency)
- Demonstrate engine efficiency improvement associated with next generation DPF
  - Low ΔP
  - Improved soot loading characteristics
- Controls development for engine + aftertreatment
  - 5 initiatives for engine efficiency improvements
- Transient emissions and fuel consumption demonstration of the Phase 3 aftertreatment system
- Engine downspeed assessment

In-Cylinder NOx Control: (PM Robustness Focused)

- VVA testing
- Combustion system development for lower PM emissions
- Fuel system improvements for multiple injection control
- Engine downspeed assessment

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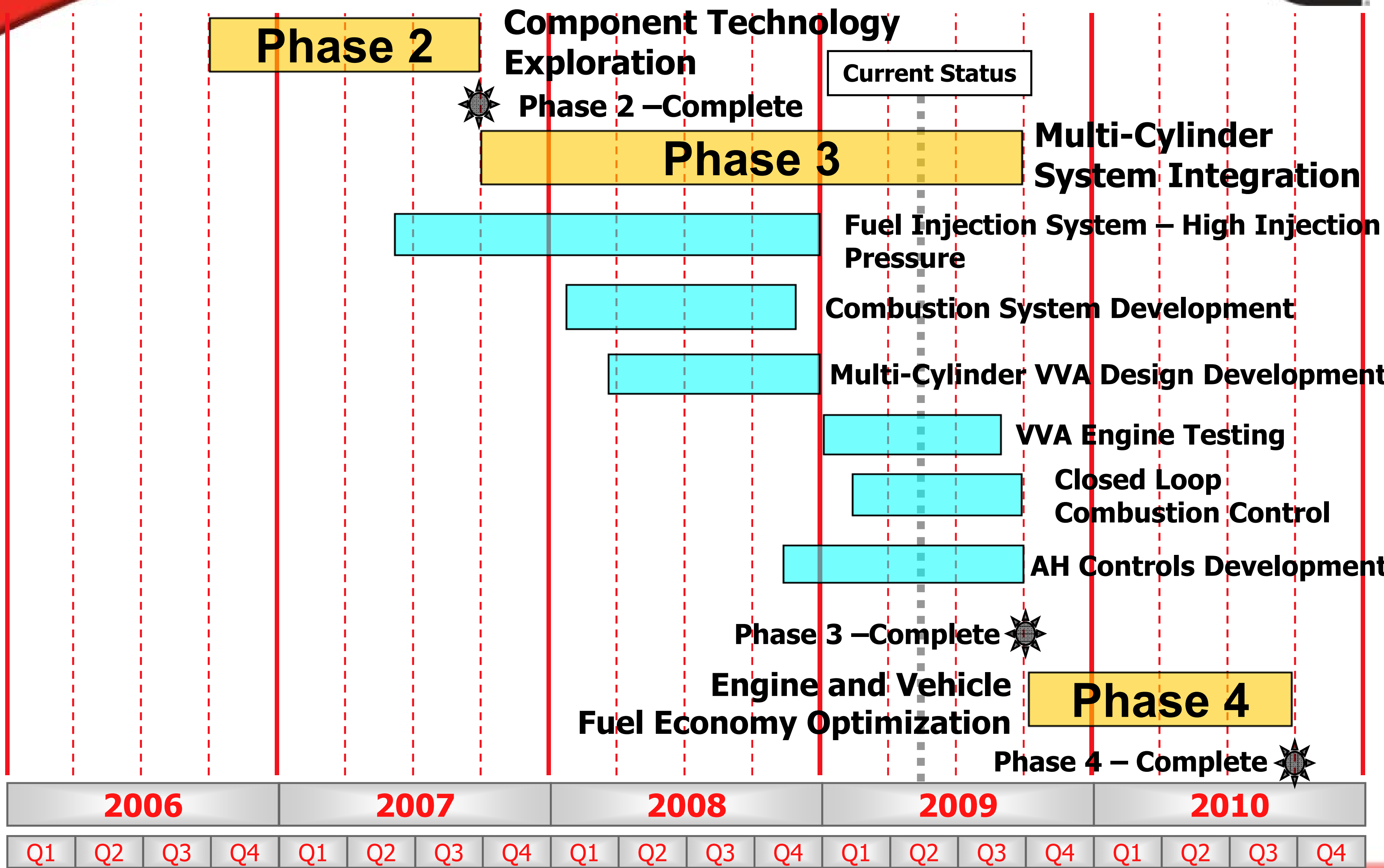
HECC Light Duty Program Schedule



ISB Technology Roadmap for Efficiency Improvement

Variable Valve Actuation

Fuel System
-Piston Bowl/Nozzle
-Multiple injections

Advanced LTC
-Enhanced PCCI
- Mixed Mode Combustion

Variable Intake Swirl

Phase 2

Controls

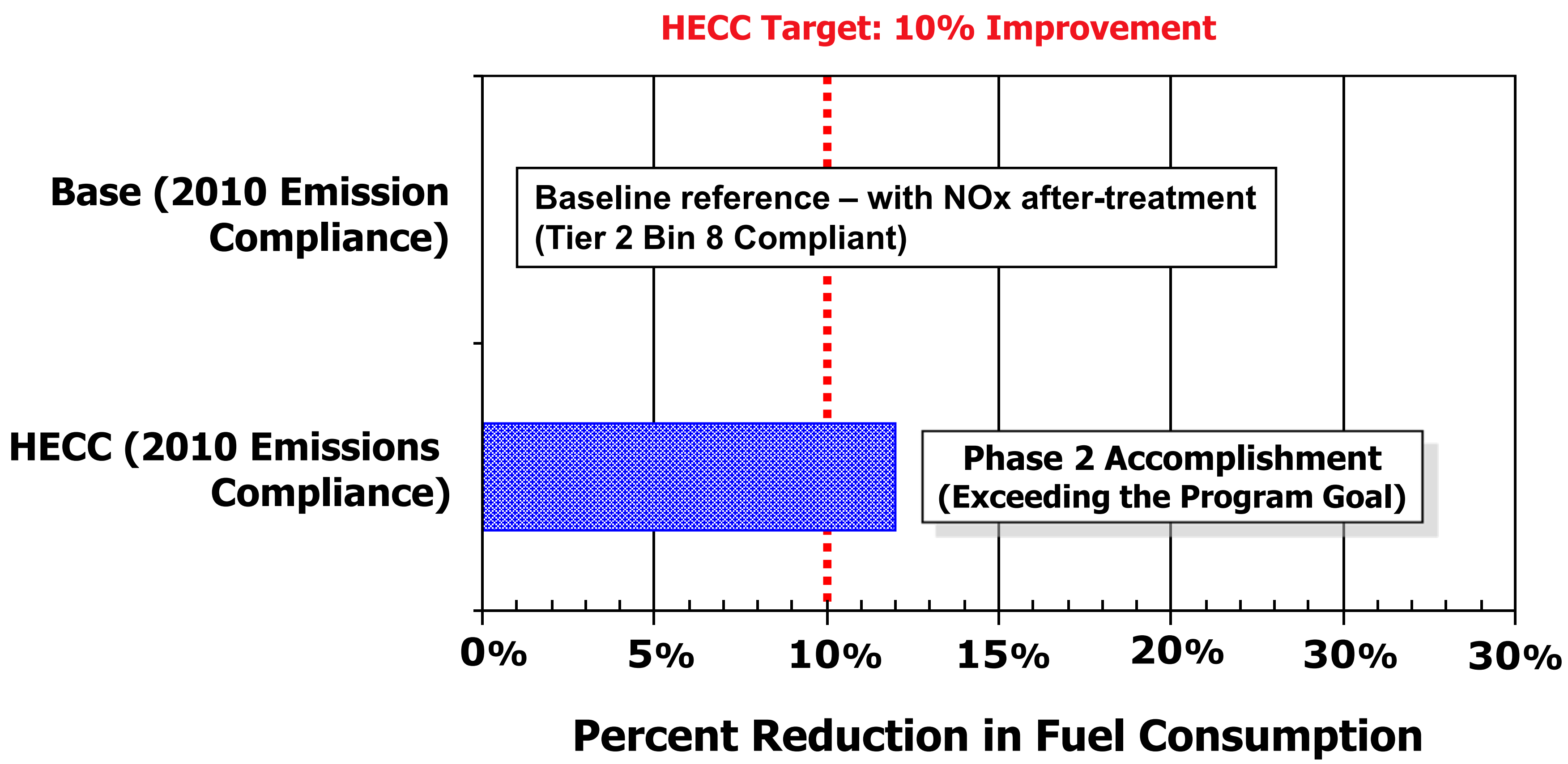
EGR Loop
- Lower Pressure Drop
- Alternative Cooling

Electrically Driven Components

Turbo Technology
-2 Stage

Aftertreatment
- HC and CO control

Status of Efficiency Improvement
6.7L Light Duty Engine



ISB Technology Roadmap for Efficiency Improvement

Variable Valve Actuation

Fuel System
-Piston Bowl/Nozzle
-Multiple injections
-High Injection Pressure*
-Precision Control

Advanced LTC
-Enhanced PCCI
- Mixed Mode Combustion

Variable Intake Swirl

Controls
-Closed Loop Combustion
-Charge Manager

Phase 3: 2008 - 2009

EGR Loop
- Lower Pressure Drop
- Alternative Cooling

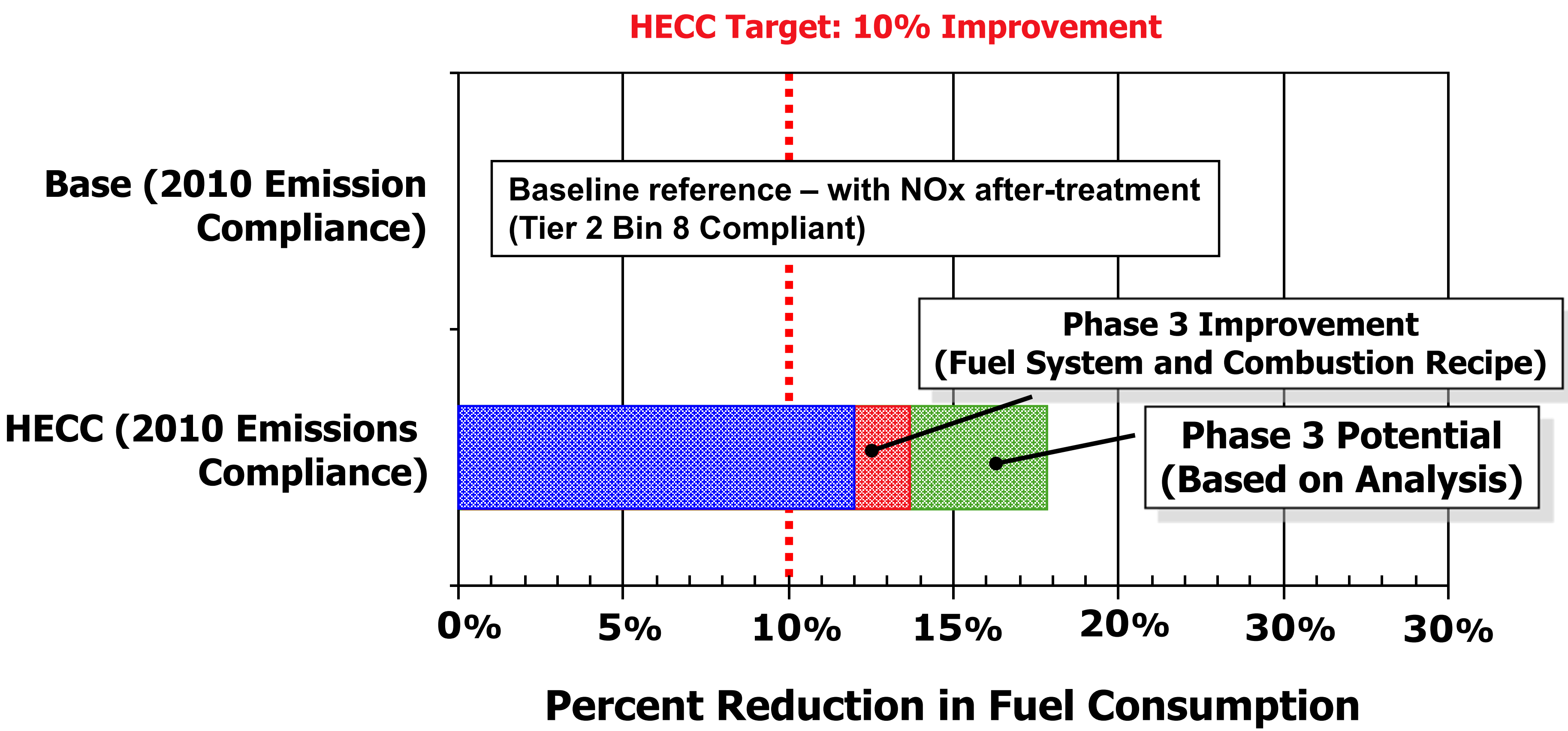
Electrically Driven Components

Turbo Technology
- 2 Stage

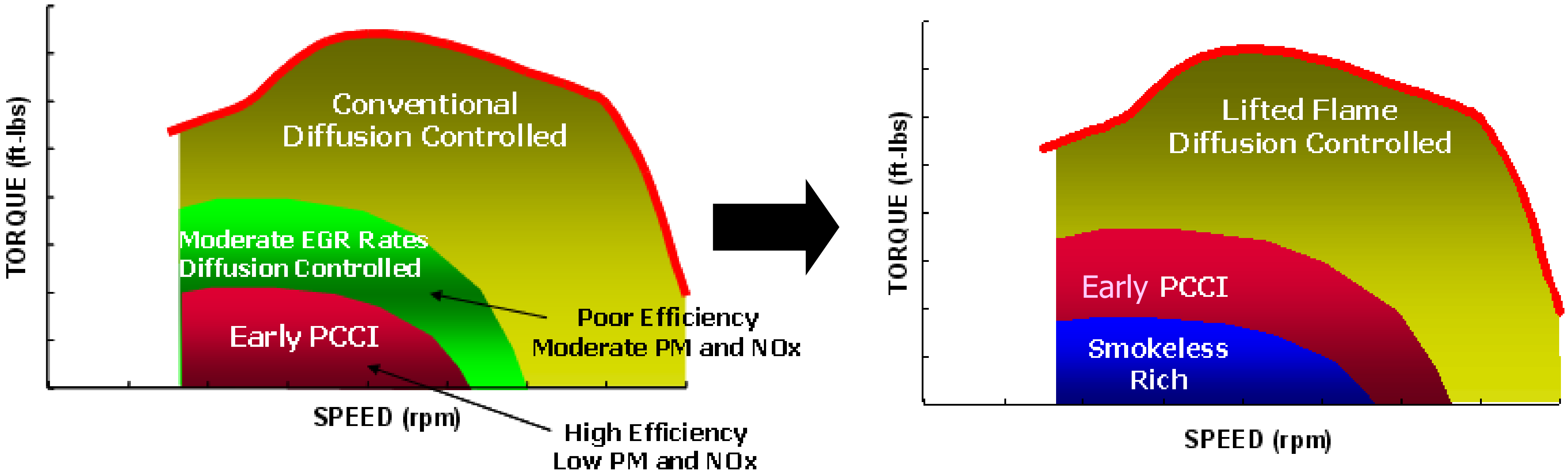
Aftertreatment
-HC and CO Control

* Used for power density improvements and US06 cycle emissions compliance associated with potential SFTP2 emissions regulation

Potential Phase 3 Efficiency Improvements
6.7L Light Duty Engine



Combustion Strategy for Additional ISB Fuel Economy Improvements



- Demonstrated robust smokeless rich combustion
- Extended the early PCCI mode of combustion with acceptable noise
- Additional work required for lifted flame combustion

Key Deliverables for FY 2009
Light Duty 6.7L Engine

- Closed loop combustion controls strategy

- Multi-cylinder VVA engine testing
  - Extending early PCCI combustion mode
  - Transient engine operation (combustion mode transition)
  - Aftertreatment thermal management

Fuels Related Work – 2008 Accomplishments

- Continued to develop fuel consumption and emissions models as a function of fuel properties for diesel and biodiesel fuel blends
  - Cummins – soy based biodiesel testing (diesel fuel study completed in 2007)
  - Purdue University – soy based biodiesel testing
  - ORNL – variety of diesel blends and biofuel feedstock
  - BP – fuel supplier and analysis support
- Models are being used to study the impact of fuel properties over a variety of drive cycles
  - Most engines operate in mix mode combustion
  - Impact of fuel properties varies depending on combustion mode
  - Drive cycle assessment best means to study the impact of fuel properties on efficiency
- Developing controls strategies to minimize fuel consumption penalty associated with biodiesel
  - Development of virtual fuel sensors is on-going
  - Real sensor evaluation for biofuels has been completed

Commercial Viability

- Leverage Cummins Component Business Unit
  - HECC program used to identify research areas
  - Establish investment strategy
  - Cummins can supply all key subsystem technologies
- Align HECC program with Cummins Engine Business product plan
  - Phase 2 impact on 2010 products
  - Phase 3 and 4 impact on beyond 2010 products
- Comprehensive Total Cost of Ownership (TCO) models used to evaluate commercial viability with collaboration with OEM partners
- Addressing On-Board Diagnostics (OBD) issues associated with HECC technology – only new and unique aspects

Conclusions

- Program is on path to meet objectives
  - All 2008 milestones met
  - All fuel economy targets have been met or exceeded with engine testing (vehicle based demonstration is part of Phase 4 work)
- Cummins component technologies needed to achieve full emissions compliance and fuel economy targets are being developed
- Additional fuel economy improvements expected during the Phase 4 Engine and Vehicle Optimization efforts.
- Robust PM emissions compliance for the heavy duty in-cylinder NOx control architecture remains a challenge for the heavy duty engine effort
  - Phase 3 work identified to improve robustness
- Commercial viability remains high as technology is transitioning to product development programs

