# Advanced Diesel Engine Technology Development for HECC

## (Program Close Out)

### 2009 Semi-Mega Merit Review

Innovation You Can Depend On.™


**Donald Stanton**

**Research & Technology**


**June 10, 2010**

Project ID: ace040

# Agenda

- Objectives
- Partnerships
- Approach
- Heavy Duty 15L Engine Application
  - Technology Selection
  - Fuel Efficiency Results
  - Technical Barriers
- Medium Duty 6.7L Personal Use Application
  - Technology Selection
  - Fuel Efficiency Results
- Fuels Collaboration
- Conclusions

# Statement of Project Objectives

1. Improve brake thermal efficiency by 10% while meeting US EPA 2010 emissions
   - Baseline is 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 that promote improvements in emissions and fuel efficiency
4. System integration for fuel economy optimization (engine and vehicle)

# Project Layout

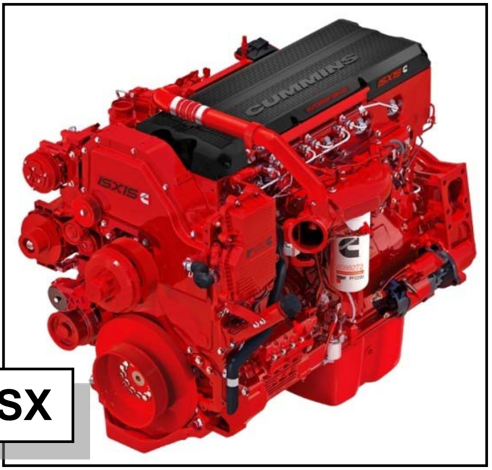
- Budget Period I – October 2005 thru September 2006
  - Applied Research & Exploratory Development
- Budget Period II – October 2006 – September 2007
  - Component Technology Exploration and Development
- Budget Period III – October 2007 – September 2009
  - Multi-Cylinder Engine System Integration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

# 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



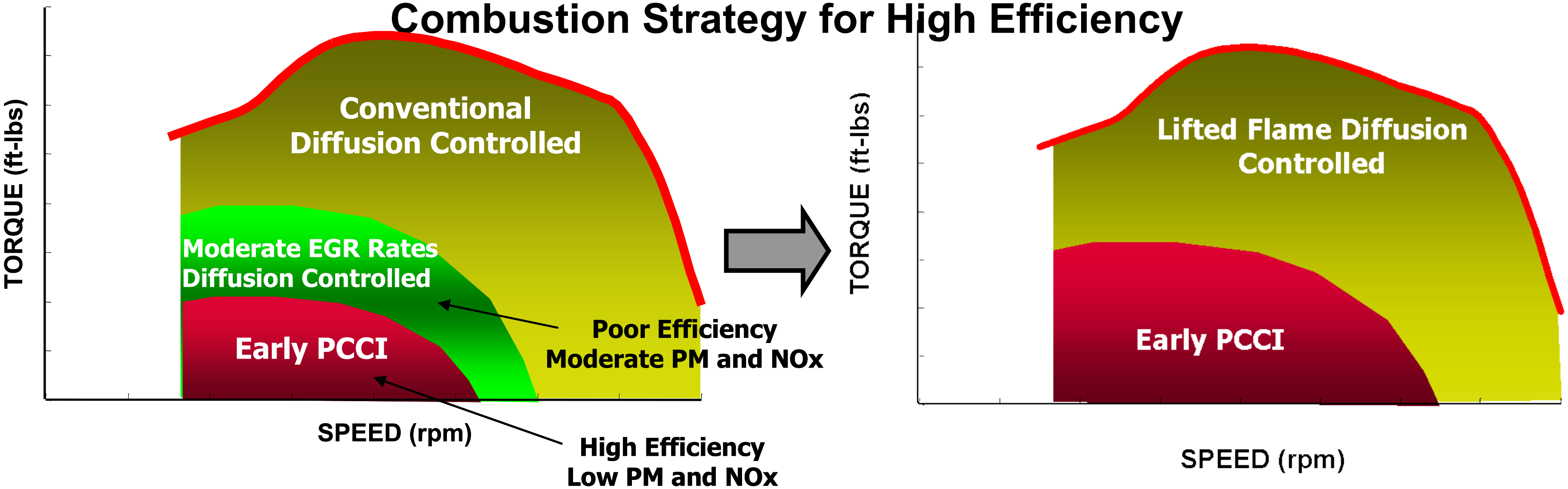

15L ISX

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

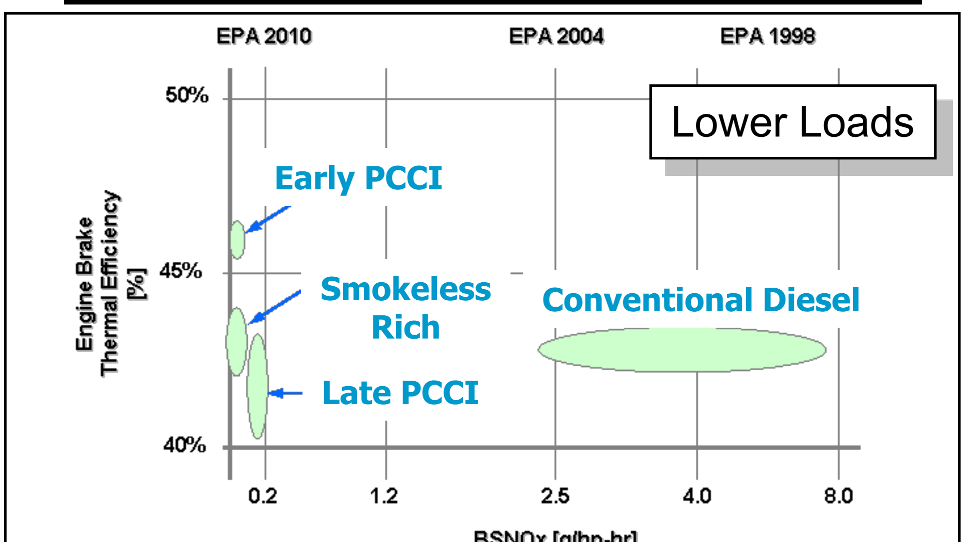
6.7L ISB

# Technical Approach

## Combustion Strategy for High Efficiency



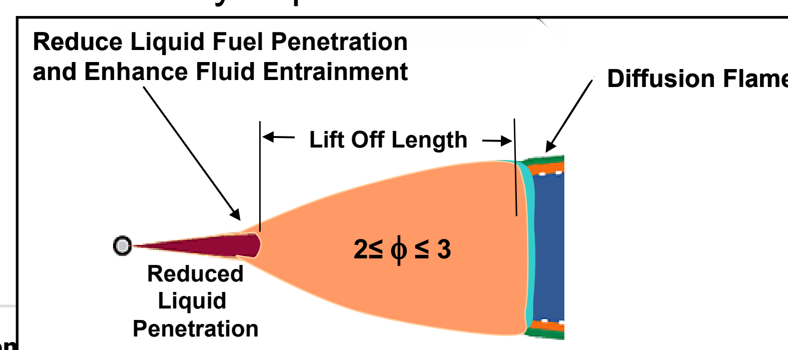

## Low Temperature Combustion: Early PCCI




## Lifted Flame Combustion Strategy

Higher Loads

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

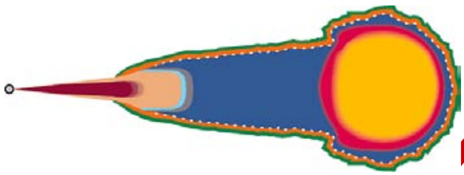


# Approach

- 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 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

# Integration of Cummins Component Technologies

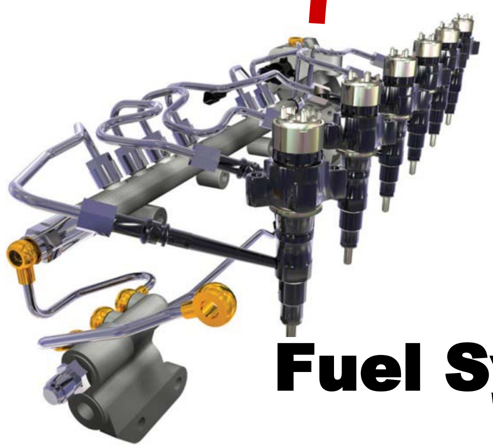
Air Handling & EGR



Combustion

Aftertreatment


Electronic Controls



Fuel Systems

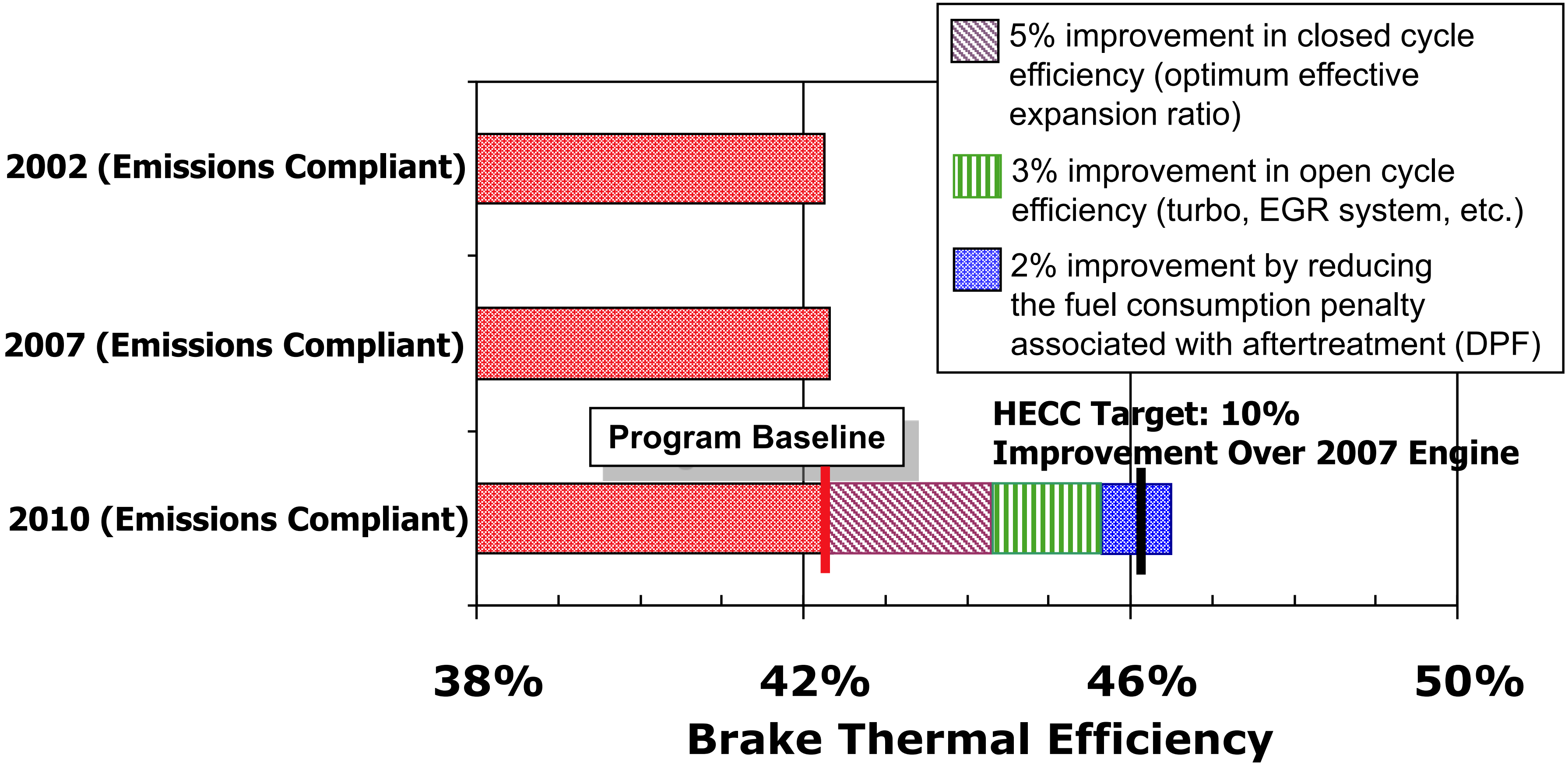
Innovation You Can Depend On

# Agenda

- Objectives
- Partnerships
- Approach
- **Heavy Duty 15L Engine Application**
  - Technology Selection
  - Fuel Efficiency Results
  - Technical Barriers
- Medium Duty 6.7L Personal Use Application
  - Technology Selection
  - Fuel Efficiency Results
- Fuels Collaboration
- Conclusions

# Path to Target

## 15L Heavy Duty Engine



# Criteria for Downselecting Technologies

- Emissions Certification Capability
- Meet Fuel Consumption Targets
- Supplier Readiness
- Intellectual Property Assessment
- Justified via Total Cost of Ownership
- Meet Remaining Product Profile Requirements

# Heavy Duty Engine System Technology Funnel
# In-Cylinder NOx Control

## Exploratory (Deselected)

**Combustion**
- Full Load HCCI
- Late PCCI Combustion

**Air Handling**
- Electrically Assisted

**Base Engine**
- Increased PCP
- Exhaust Port Liner

## HECC Technology

**Combustion**
- Full Load HCCI
- Early PCCI Combustion
- Late PCCI Combustion
- Lifted Flame Combustion
- Mixed Mode Combustion
- Increased CR Piston

**Air Handling**
- 2-Stage Turbo w/ Intercooler
- Electrically Assisted
- Efficient VGT
- Variable Valve Actuation

**Fuel System**
- HD XPI >2600 bar
- Reduced Parasitics

**Base Engine**
- Increased PCP
- Exhaust Port Liner
- Friction/ Parasitic Reductions

## Selected

**Combustion**
- Early PCCI Combustion
- Lifted Flame Combustion
- Mixed Mode Combustion
- Increased CR Piston

**Air Handling**
- 2-Stage Turbo w/intercooler
- Efficient VGT
- Variable Valve Actuation

**Fuel System**
- HD XPI >2600 bar
- Reduced Parasitics

**Base Engine**
- Friction Reduction – Piston, rings, Low viscosity oil, Plasma coated liner
- Parasitics – Intake port design, Variable flow lube pump

# Heavy Duty Engine System Technology Funnel
# In-Cylinder NOx Control

## Exploratory (Deselected)

**EGR System**
- 2-loop

**Controls/Sensors**
- Fuel Quality
- CLCC

## HECC Technology

**EGR System**
- Reduced ΔP
- High Capacity Cooling – LTR, 2-loop, Dual Coolers, etc.
- Mixer

**Controls/Sensors**
- MAF, PM, cylinder pressure, and fuel quality sensors
- Closed loop combustion control (CLCC)
- 2-stage turbo controller

**PM AT**
- Reduced DP DPF Substrate
- DPF Regen Control
- Reduce PGM DOC
- Thermal Management
- Insulation

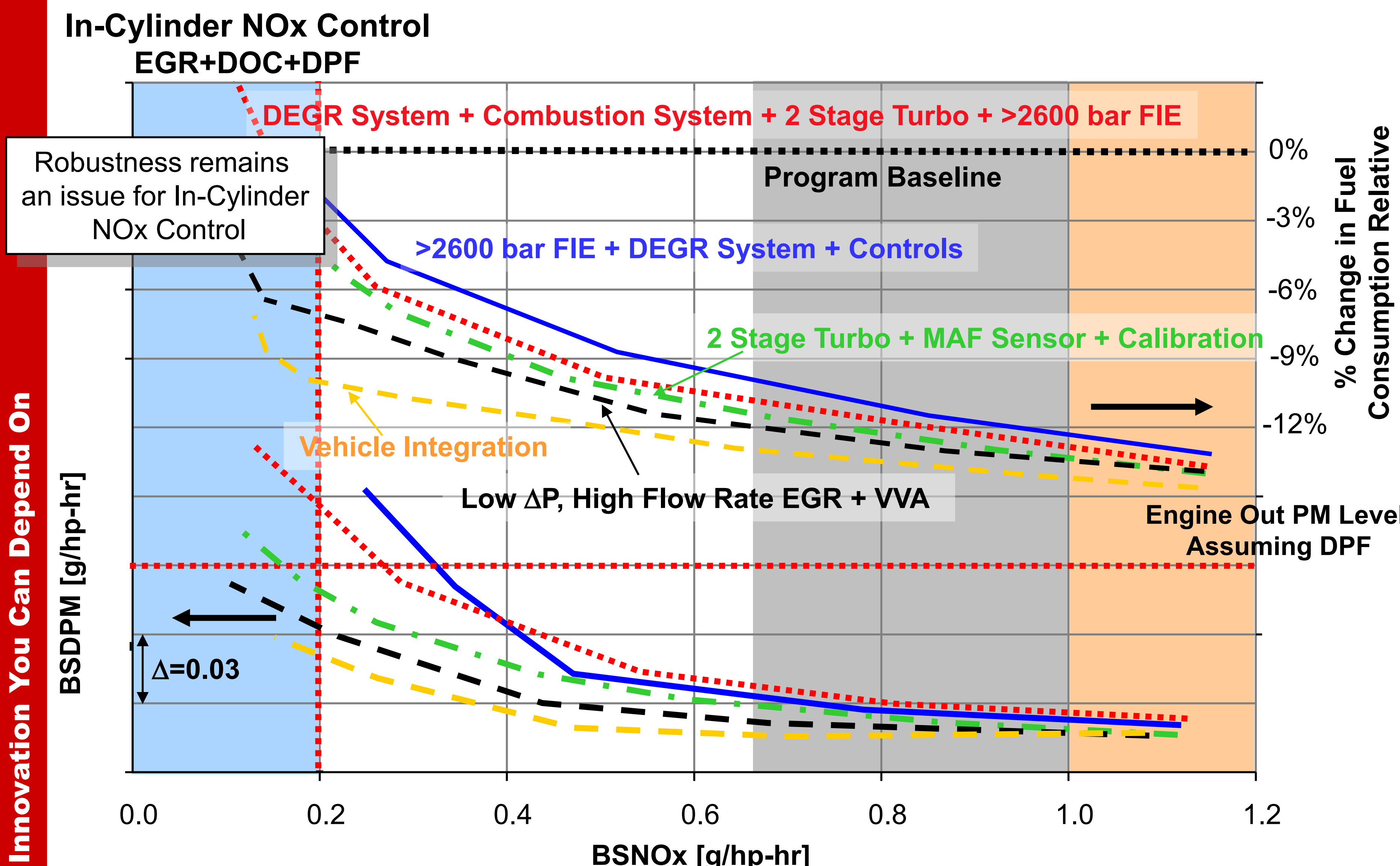
## Selected

**EGR System**
- Direct Air to EGR Cooler
- Dual Coolers
- Mixer

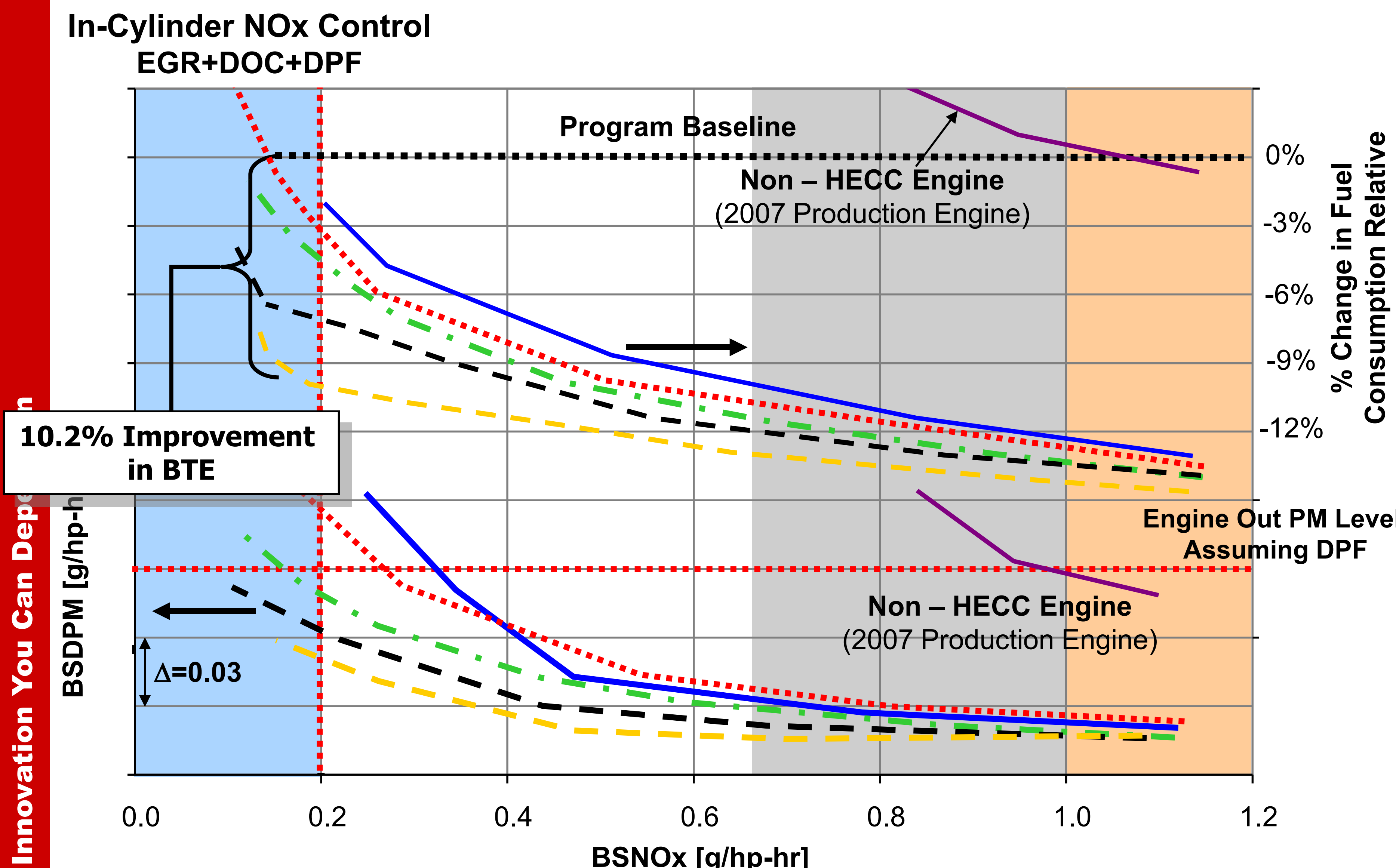
**Controls/Sensors**
- MAF and PM
- 2-stage turbo controller

**PM AT**
- Reduced DP DPF Substrate
- DPF Regen Control
- Reduce PGM DOC
- Thermal Management
- Insulation

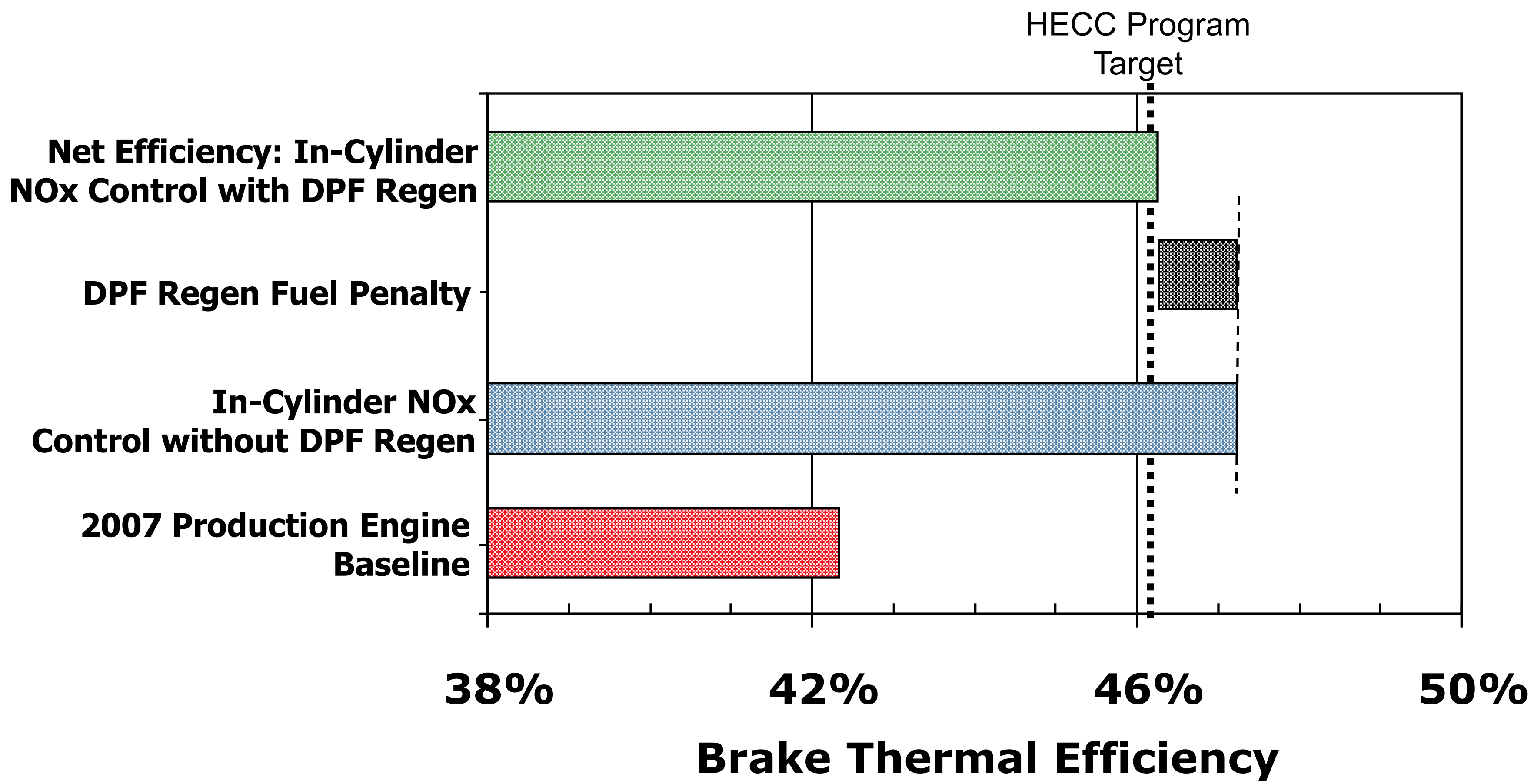
# Achieving In-Cylinder NOx Control with Improved Efficiency



# Achieving In-Cylinder NOx Control with Improved Efficiency

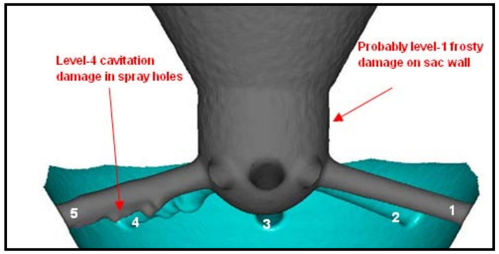


# Summary of Heavy Duty Efficiency Improvements for the In-Cylinder NOx Control Architecture



# Technical Barriers for In-Cylinder NOx Control Architecture

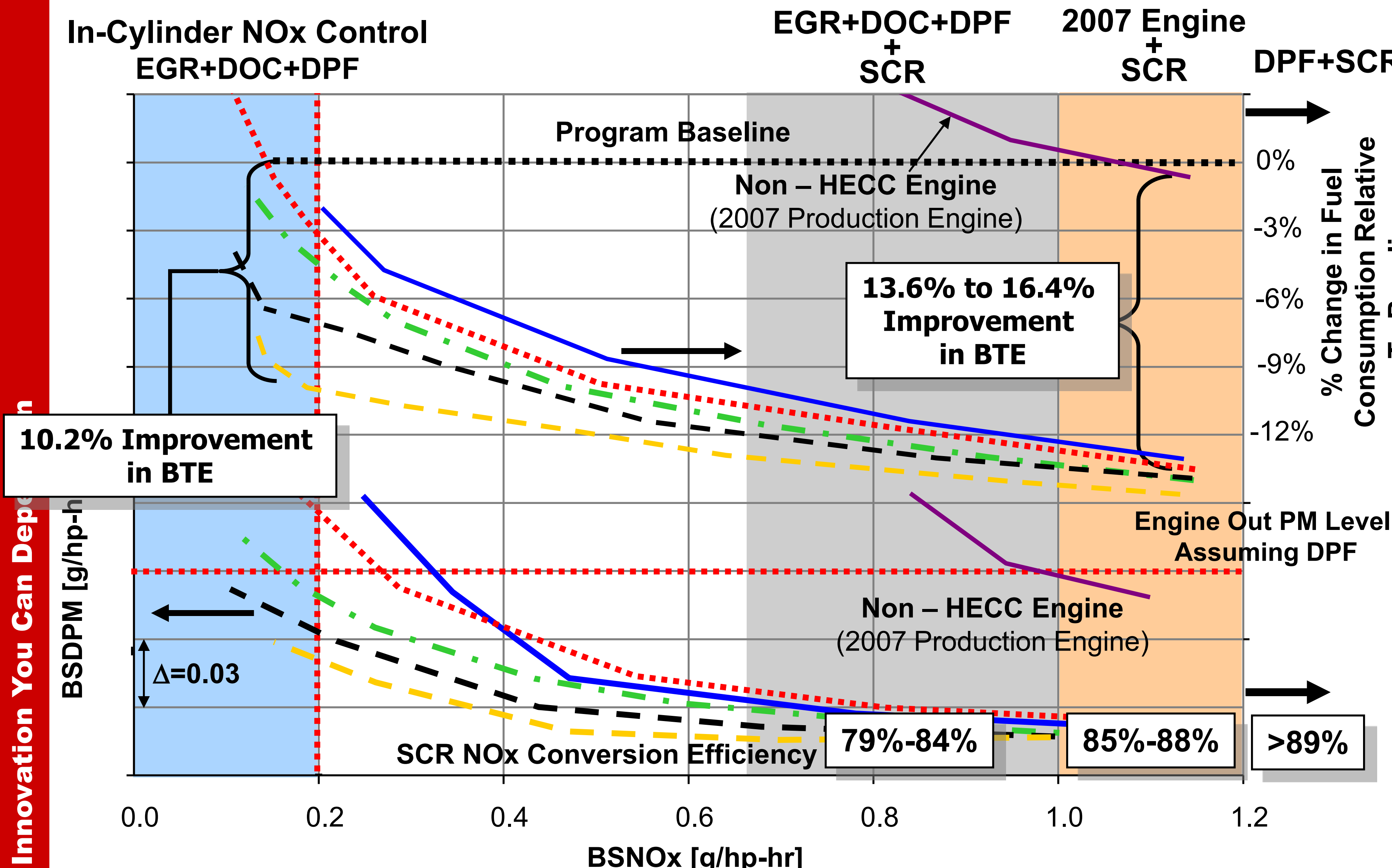
- Further development of key component technologies
  - Variable valve actuation (million mile durability)
  - High injection pressure (mitigate cavitation damage)
  - Engine cooling strategies (large amounts of water condensation)



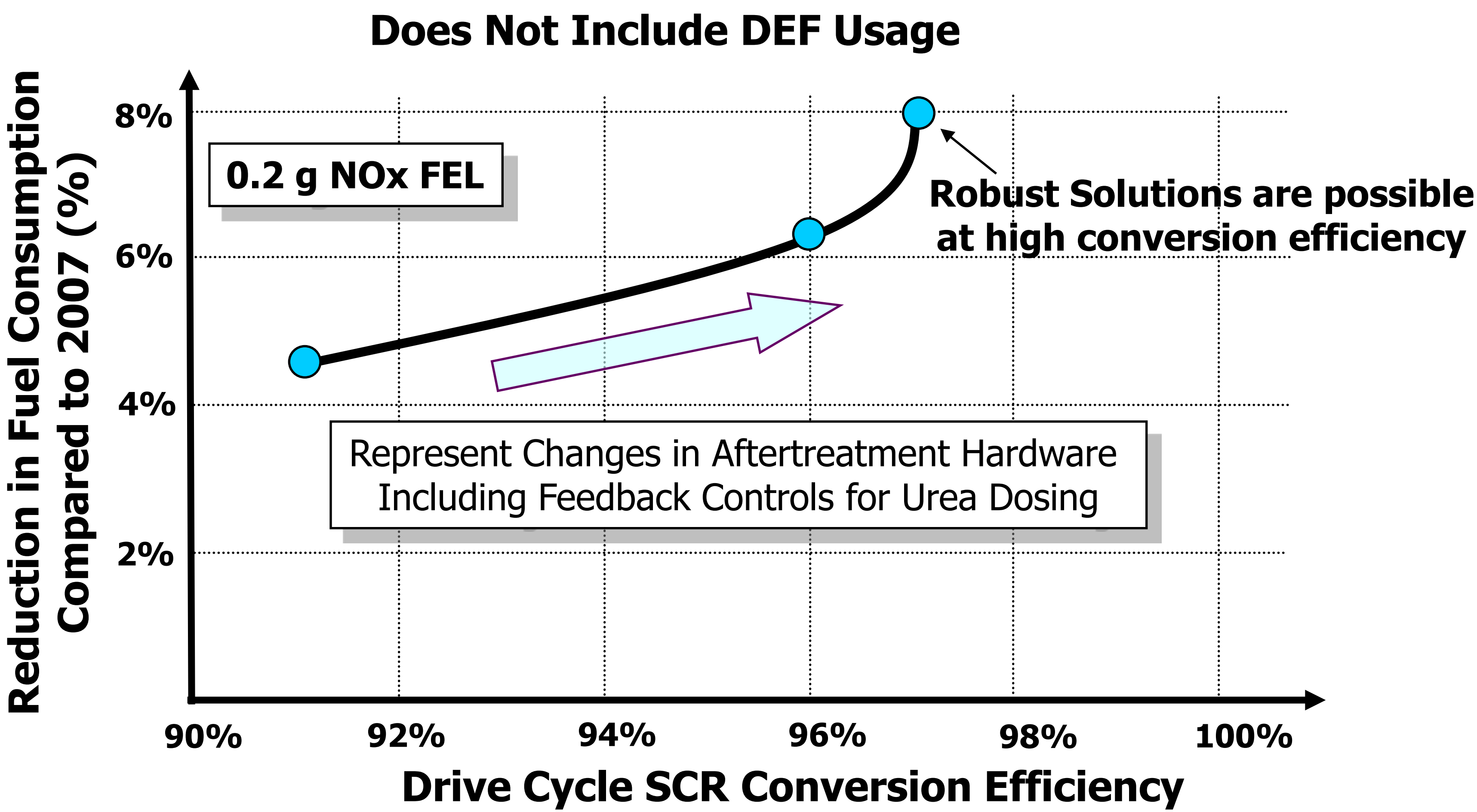

- Power density
  - In-cylinder NOx control limited to 550 HP
  - Current product highest rating 600 HP
  - Limitations: Vehicle Heat Rejection Capacity
- Fuel consumption robustness
  - Jeopardized by PM robustness
- Unknown transient response
  - Limited Phase 4 vehicle work
  - Concern is turbo lag with moving large amounts of EGR

Innovation You Can Depend On

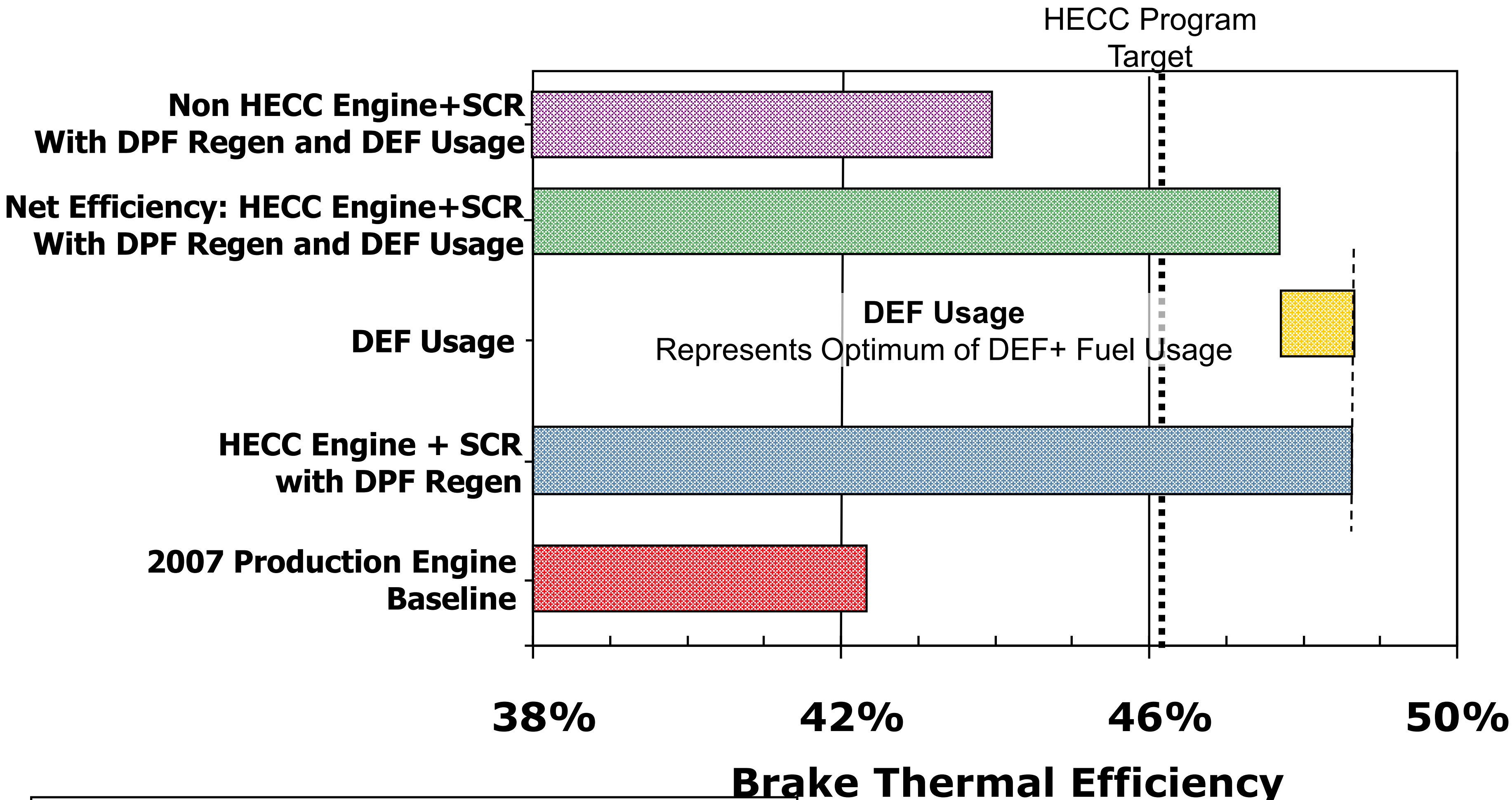
# Combining HECC Engine with Cummins High NOx Conversion Efficiency SCR



# Evolution of High Efficiency SCR



# Summary of Heavy Duty Efficiency Improvements for HECC Engine + High Efficiency SCR




**Engine Architecture:**
- No VVA
- 2600 bar Injection Pressure
- 2010 Vehicle + Engine Cooling Capability

# Technical Barriers for HECC Engine and High NOx Conversion Efficiency SCR

- Conversion of DEF to NH3 (eliminate DEF derived deposits)
  - Off-line decomposition
- Packaging
- Weight
  - Alternative sources for NH3
  - Reduce catalyst sizes
- Fuel efficiency thermal management

# Agenda

- Objectives
- Program Structure
- Partnerships
- Approach
- Heavy Duty 15L Engine Application
  - Technology Selection
  - Fuel Efficiency Results
  - Technical Barriers
  - Technology Implementation to Production
- **Medium Duty 6.7L Personal Use Application**
  - Technology Selection
  - Fuel Efficiency Results
- Impact of Fuels
- Conclusions

# 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**

6.7L ISB

**Controls**

**EGR Loop**
- Lower Pressure Drop
- Alternative Cooling

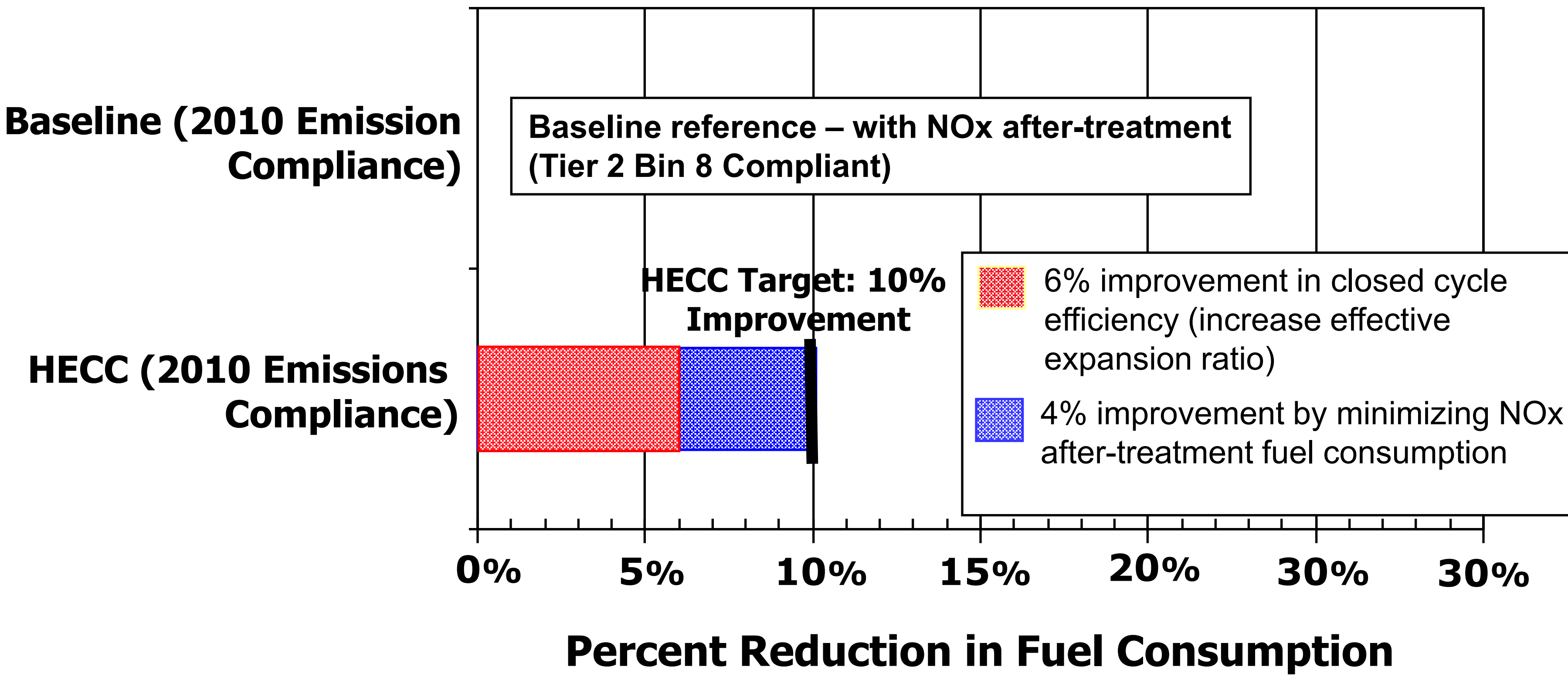
**Friction and Parasitics**

**Turbo Technology**
- 2 Stage

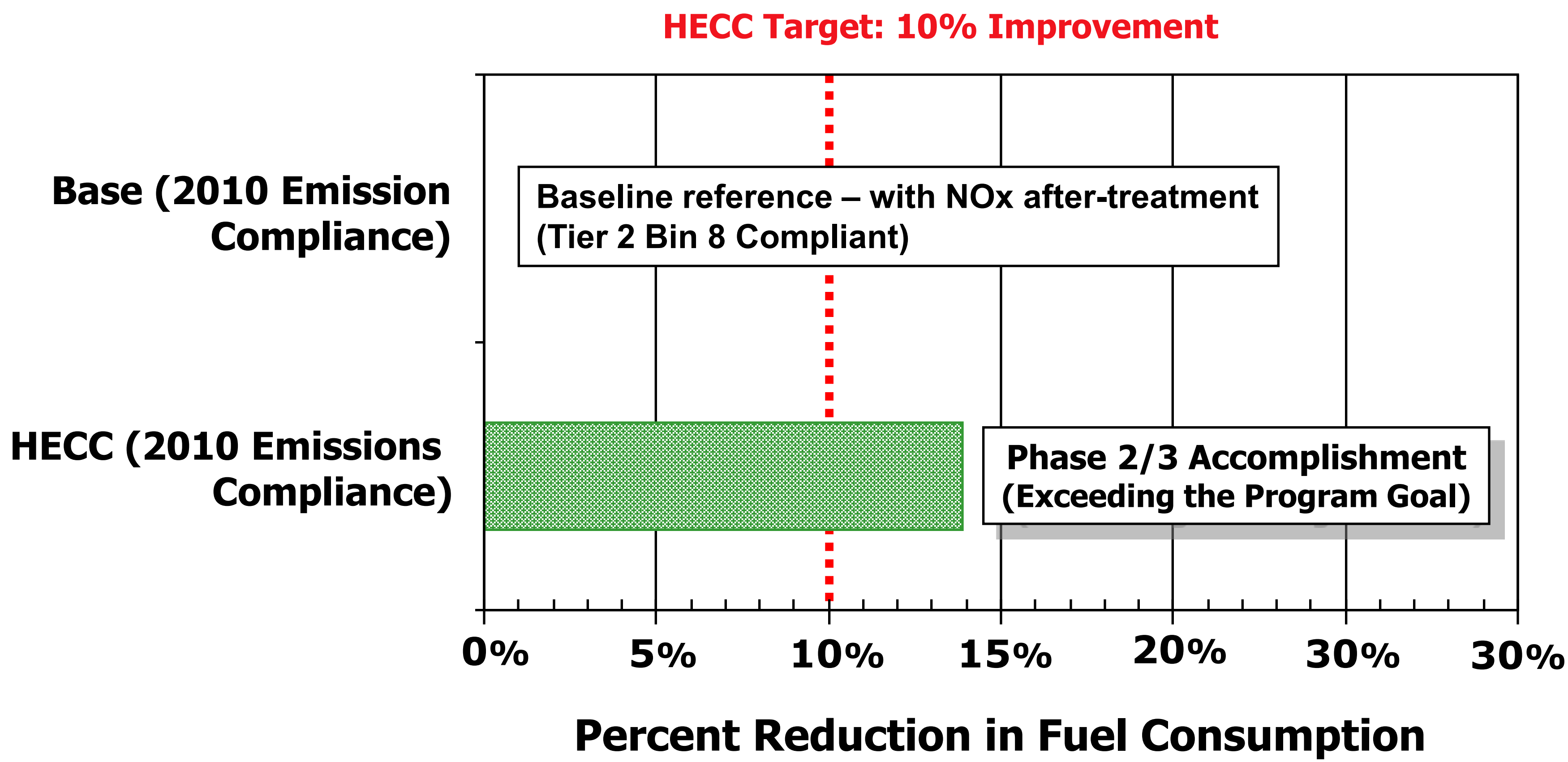
**Aftertreatment**
- DPF and DOC

# Path to Target

## 6.7L Light Duty Engine

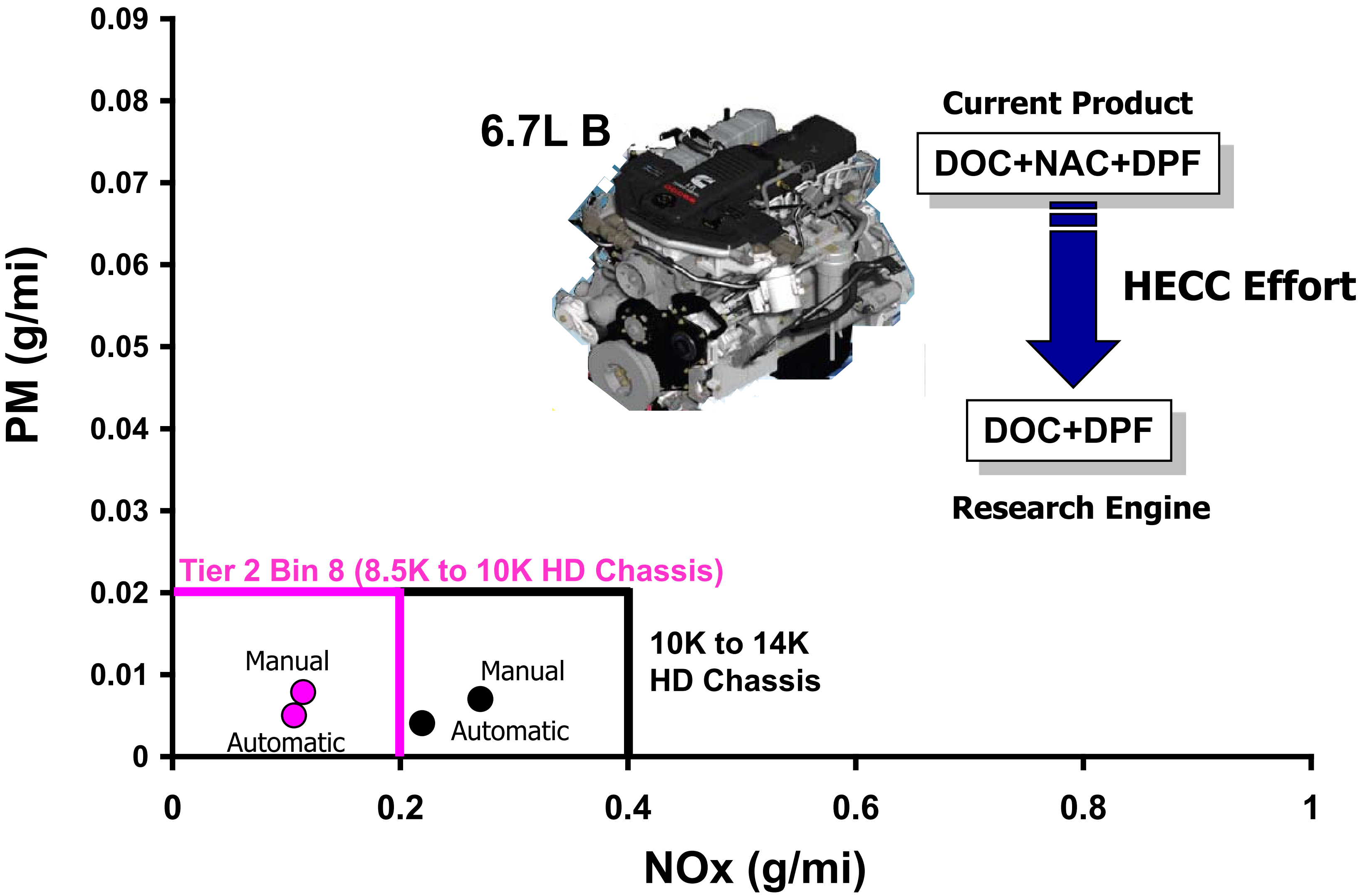


# Status of Efficiency Improvement
## 6.7L Light Duty Engine




Innovation You Can Depend On

# ISB Pickup Engine Architecture



# Agenda

- Objectives
- Program Structure
- Partnerships
- Approach
- Heavy Duty 15L Engine Application
  - Technology Selection
  - Fuel Efficiency Results
  - Technical Barriers
  - Technology Implementation to Production
- Medium Duty 6.7L Personal Use Application
  - Technology Selection
  - Fuel Efficiency Results
- **Fuels Collaboration**
- Conclusions

# Fuels Collaboration Key Questions

1. What fuel properties are conducive to promoting fuel efficiency and emissions improvements?

2. Are the HECC engine technologies compatible with biodiesel?

# Impact of Fuel Property Variation on Fuel Efficiency

- Completed the development of fuel consumption and emissions models as a function of engine calibration parameters and 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 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 process to study the impact of fuel properties on efficiency

- A fuel blend of diesel + gasoline is desirable for HECC engine technology
  - Cummins has submitted 3 invention disclosures related to the process used to determine optimal fuel properties
  - Cummins and BP have submitted 2 invention disclosures on specific fuel blends
  - 6 SAE papers and 4 journal articles have been published

# HECC Engine Efficiency with Biodiesel

- Drive cycle optimization with a variety of biodiesel blends has been completed
- Difficult to maintain fuel efficiency at desired emissions levels with biodiesel given the lower energy content of the biofuel
- Seeking cost effective ways to sense variation in biodiesel blends
  - Virtual and real sensor evaluation completed
  - Study includes variations in biofuel feedstock
  - If no sensing of biofuel takes place along with the associated change in engine control parameters, fuel efficiency will degrade by 1% to 6% for B20
  - Initial results show the ability to offset the NOx increase associated with the use of B20 while limiting the fuel consumption penalty to 0% to 3%
- Seeking cost effective ways to develop engine control strategies for variation in biodiesel blends
  - Can not develop unique engine calibrations for biodiesel blends
  - Significant progress demonstrated, but additional work required for production implementation (What is the business case?)

# 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
- 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

# Program Conclusions

- All objectives completed
  - Fuel efficiency targets have been met or exceeded with engine testing (15L and 6.7L engines)
  - Cummins has put forth commercially viable solutions
- Cummins component technologies are being developed
- Two heavy duty engine architectures to meet US EPA 2010 emissions and fuel consumption targets were developed
  - In-cylinder NOx control with a 10.2% improvement in fuel efficiency
  - SCR compatible with a 16.4% improvement in fuel efficiency
- Robust fuel consumption for the heavy duty in-cylinder NOx control architecture remains a challenge
- Tier 2 Bin 8 emissions levels have been achieved on the 6.7L ISB engine without NOx aftertreatment with approximately a 14% improvement in fuel efficiency
- All HECC technologies are B20 compatible

# Light Duty Efficient Clean Combustion

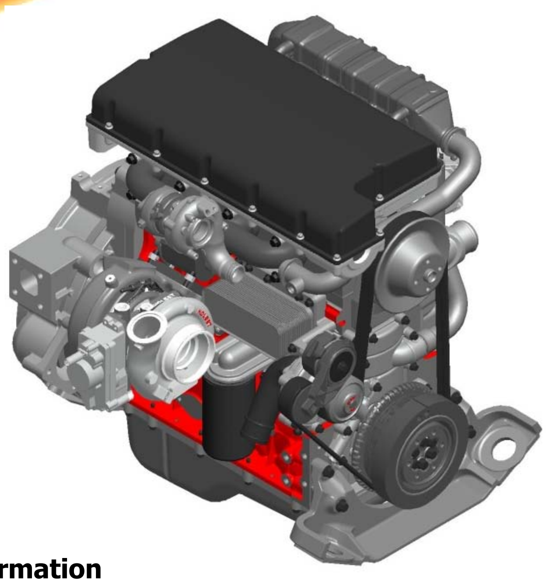
## 2009 Semi-Mega Merit Review

Innovation You Can Depend On.™


Donald Stanton

Research & Technology


June 10, 2010



# Agenda

- Objectives
- Approach
- Path to Target
- Schedule/Milestones
- Engine and Aftertreatment Architecture
- Fuel Economy Status
- High NOx Conversion Efficiency SCR
- Fuel Efficient Aftertreatment Thermal Management
- In-Cylinder NOx Control (No NOx Aftertreatment)
- Conclusions

# Statement of Project Objectives

## Goal

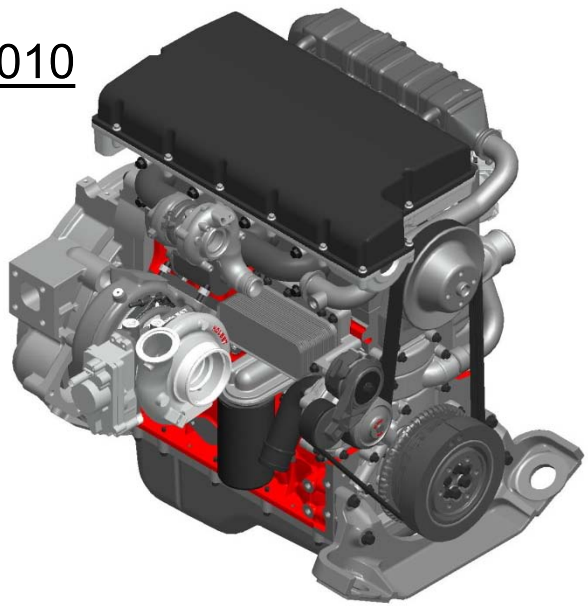
Improve the efficiency of diesel engines for light duty applications through technical advances in system optimization and critical subsystem component integration.

## Objectives

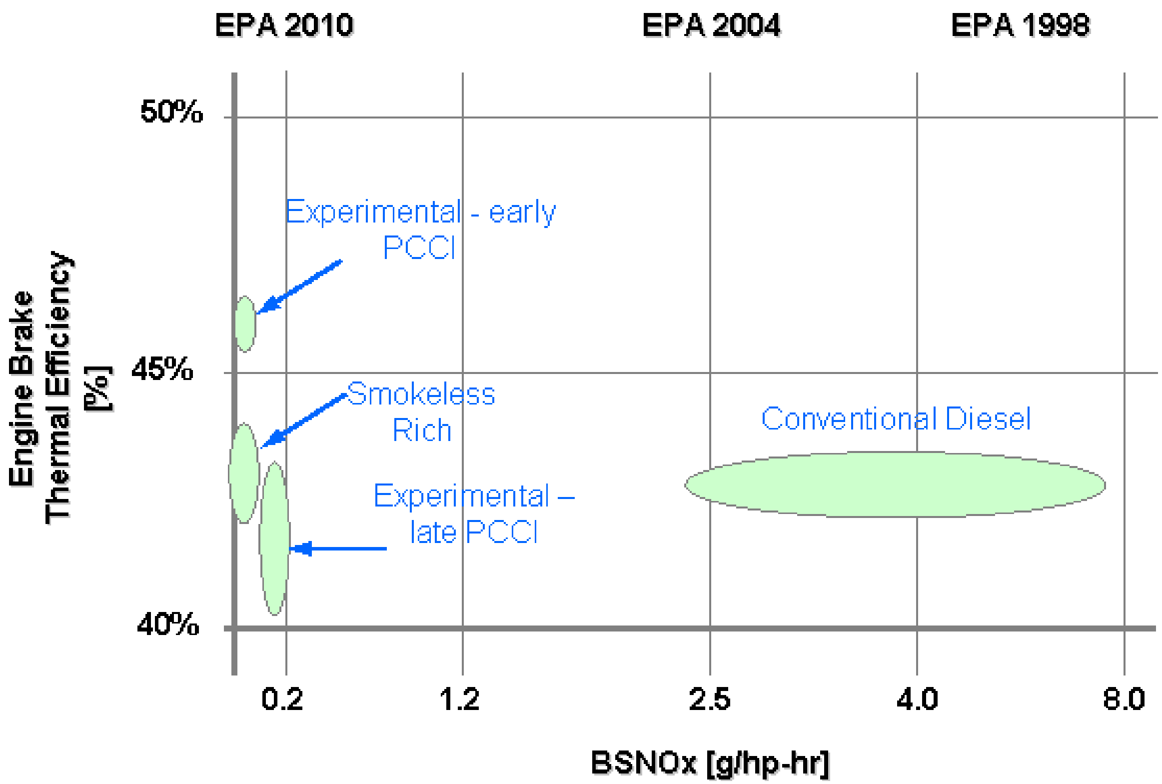
- Improve light duty vehicle (5000 lb test weight) **fuel efficiency** over the FTP city drive cycle by **10.5%** over today's state-of-the-art diesel engine.
- Develop & design an advanced combustion system that synergistically meets **Tier 2 Bin 5 NOx and PM emissions** standards while demonstrating the efficiency improvements.
- Maintain **power density** comparable to that of current conventional engines for the applicable vehicle class.
- Evaluate different fuel components and ensure combustion system compatibility with commercially available **biofuels**.

# Project Layout

- Budget Period I – October 2007 thru December 2008
  - Applied Research & Exploratory Development
  - $834K DoE Funding and $834K Cummins Funding
- Budget Period II – January 2009 – September 2009
  - Advanced Development
  - $735K DoE Funding and $735K Cummins Funding
- Budget Period III – October 2009 – November 2010
  - Engineering Development
  - $820K DoE and $820K Cummins

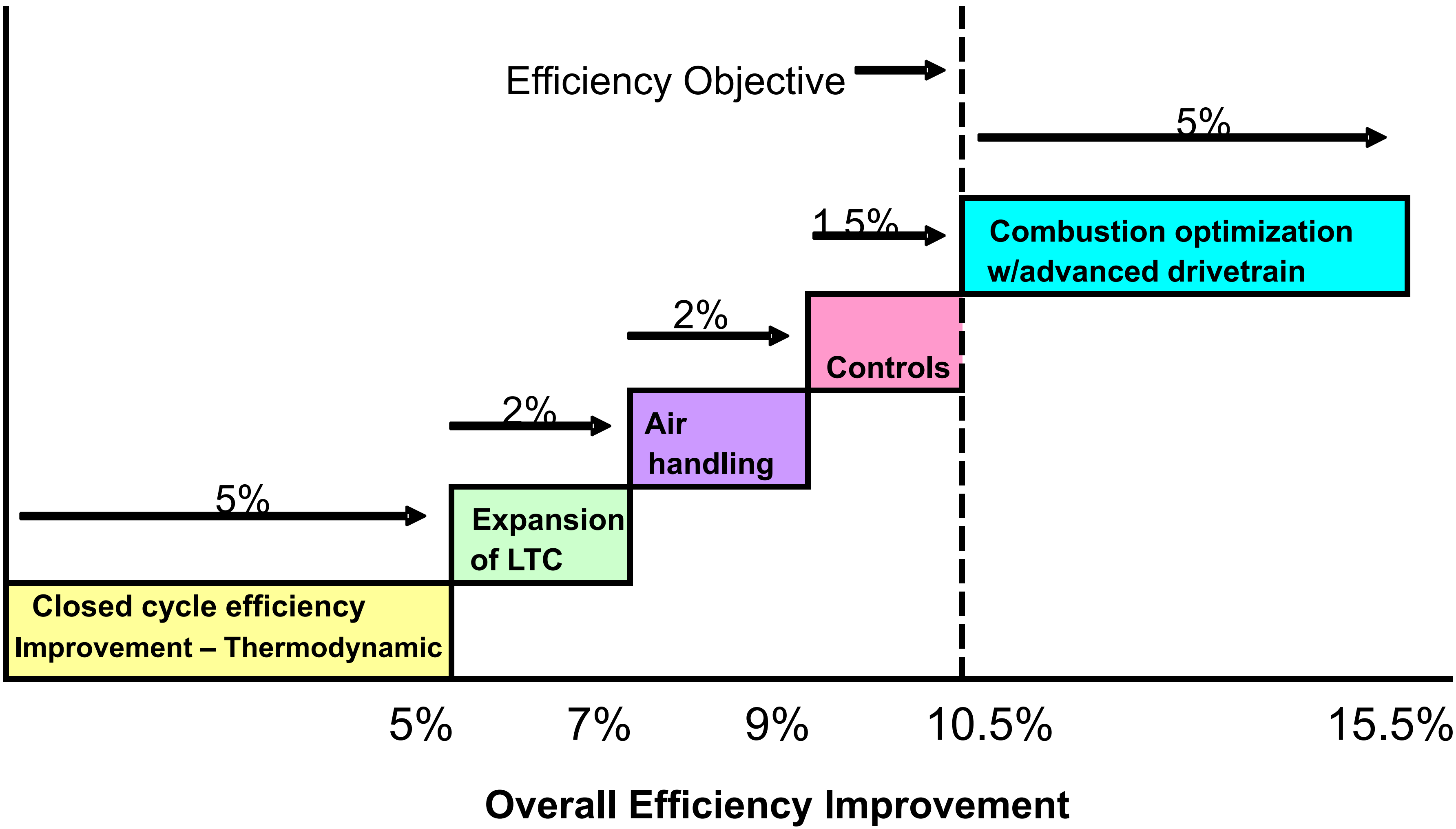


## Expand Low Temperature Combustion at Part Load




Early PCCI and Smokeless Rich Combustion provide for simultaneous reduction in NOx & PM while maintaining or improving fuel consumption

# Path to Fuel Efficiency Target

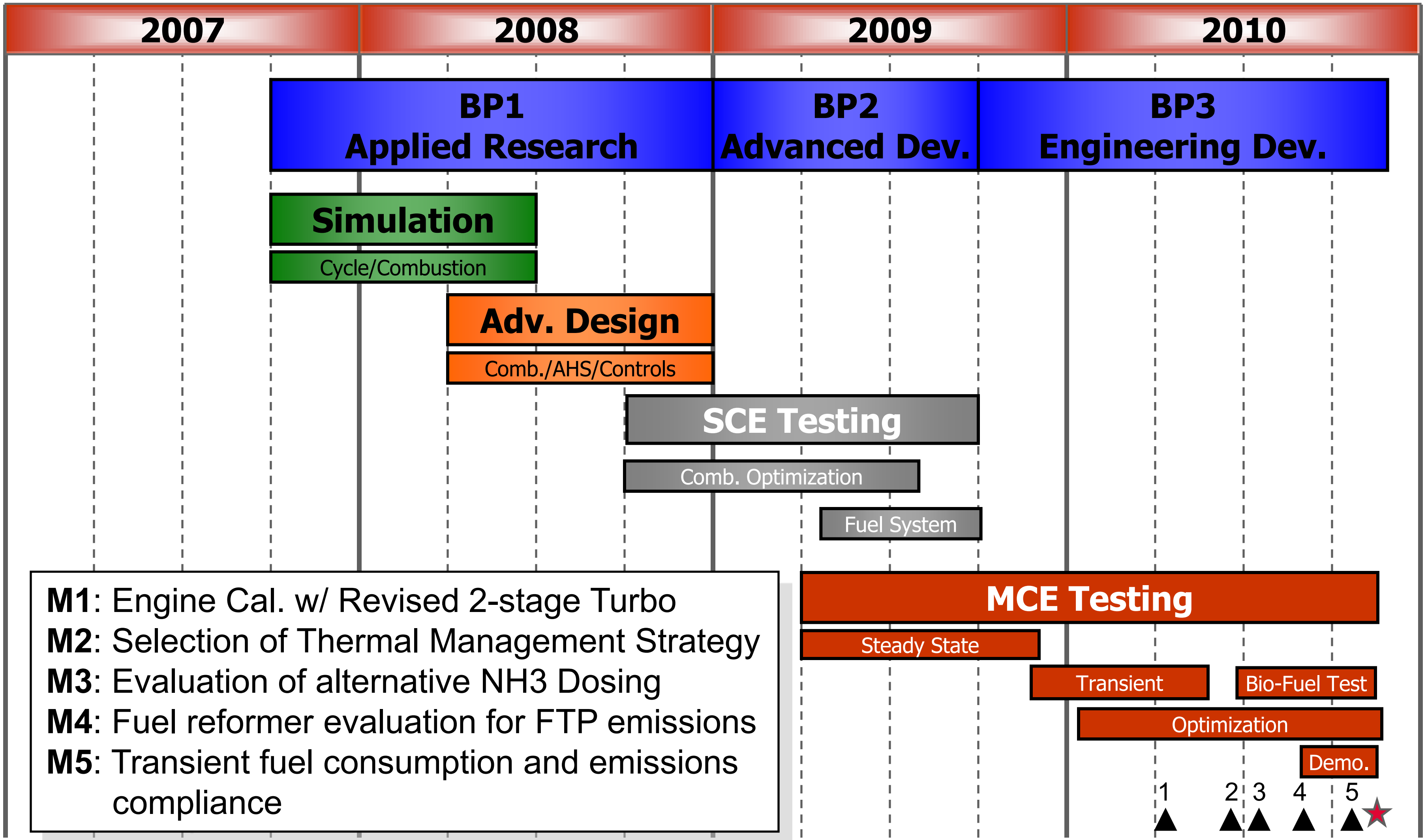


# Enabling Technologies

Four distinct areas of enabling technologies to drive fuel economy improvements

I. Fuel Injection Systems
II. Air Handling System
III. Controls and Sensing System
IV. Aftertreatment (DOC, SCR, and DPF)

# LDECC Master Schedule






BP3 Milestones

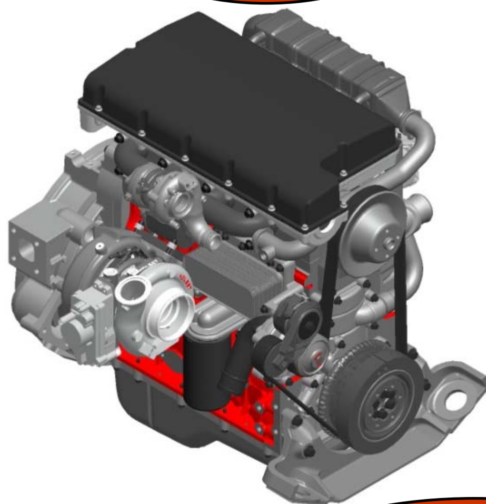
# Light Duty Technology Roadmap

**Fuel System**
- Precision Injection
-High Injection Pressure
-Piezo

**Variable Valve Actuation**

**Advanced Combustion**
-Enhanced Early PCCI
-Lifted Flame Combustion

**Variable Intake Swirl**



**Controls**
-Closed loop combustion
- Charge air manager

**Aftertreatment**
- Low Temperature SCR
- Low $\Delta P$
- Low Soot Loading
- Partial Filter
-Interstage AT

**EGR Loop**
- Lower Pressure Drop
-Alternative Cooling
-2-loop Cooling

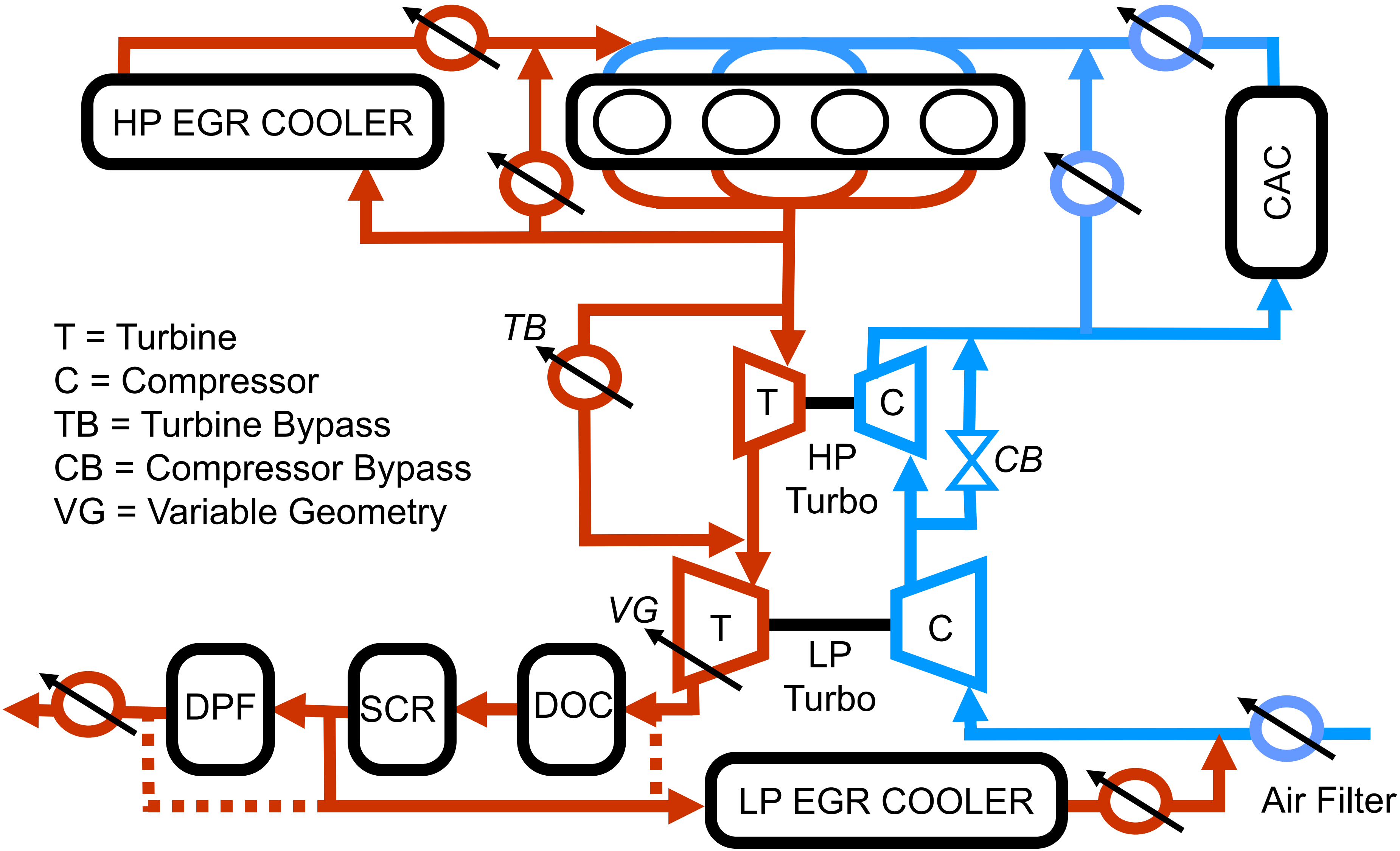
**Turbo**
-Two Stage
-HP Stage VGT

**Friction/Parasitics**
-Variable displacement pumps
-Piston
-Bearings
-Lube oil

# SCR Architecture

# High Pressure/Low Pressure EGR System – SCR NOx AT

**System is not commercially viable – high cost**




T = Turbine
C = Compressor
TB = Turbine Bypass
CB = Compressor Bypass
VG = Variable Geometry

# Light Duty Engine Architecture for BP3 Development

Fuel System

- 2200 bar injection pressure – Piezo System
- Up to 7 injection events
- New combustion system (piston bowl profile, nozzle, swirl)

Air Handling

- 2-stage, sequential turbo with option of a LP stage VGT
- ~~SOHC and DOHC VVA designs~~

EGR System

- Combined low pressure and high pressure system
- ~~EGR cooler bypass on the~~ high pressure loop

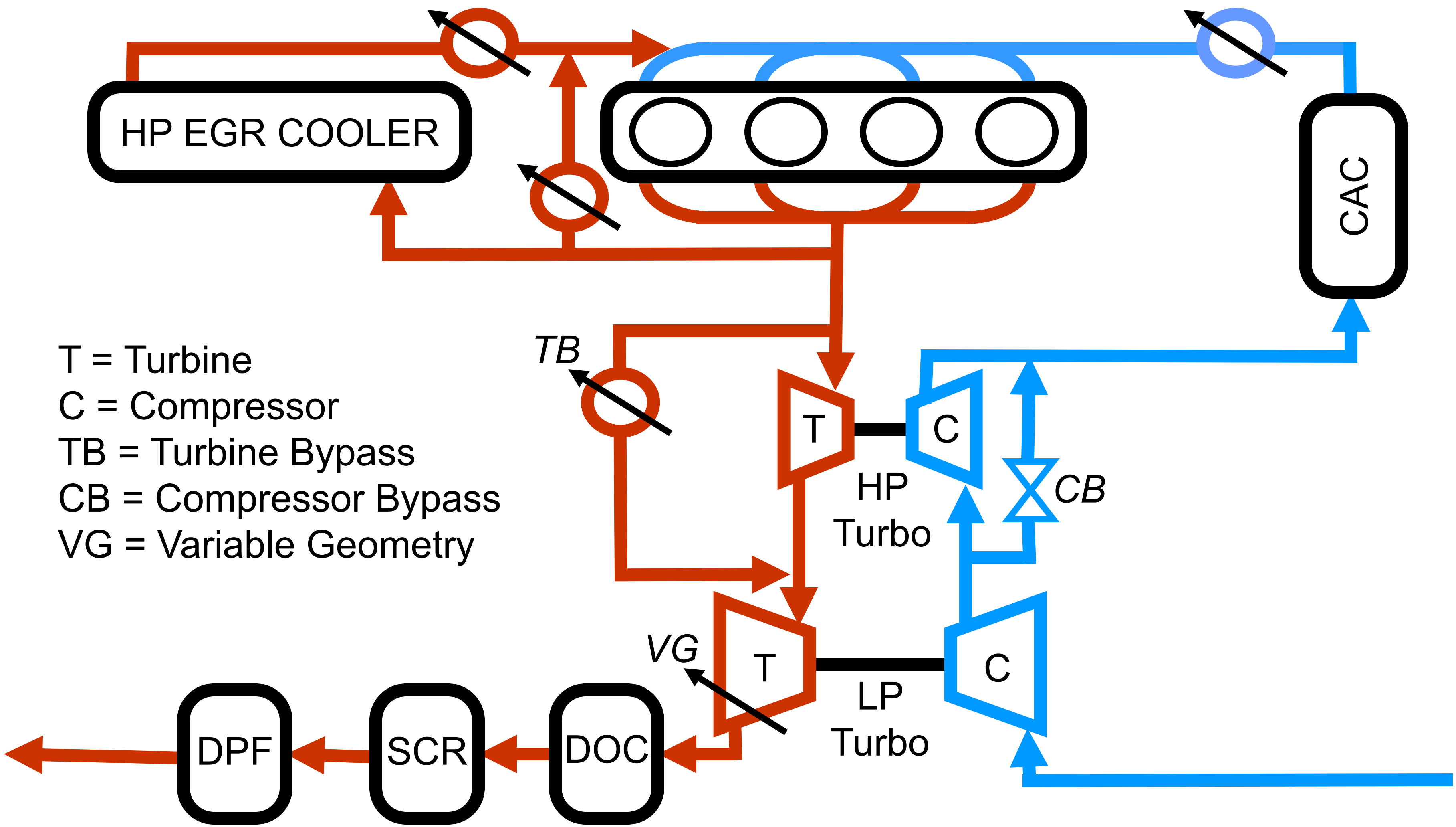
Aftertreatment

- DOC
- Low DP DPF substrate with improved soot loading characteristics
- Testing with and without SCR system

Sensors

- ~~Cylinder pressure for closed loop combustion control~~

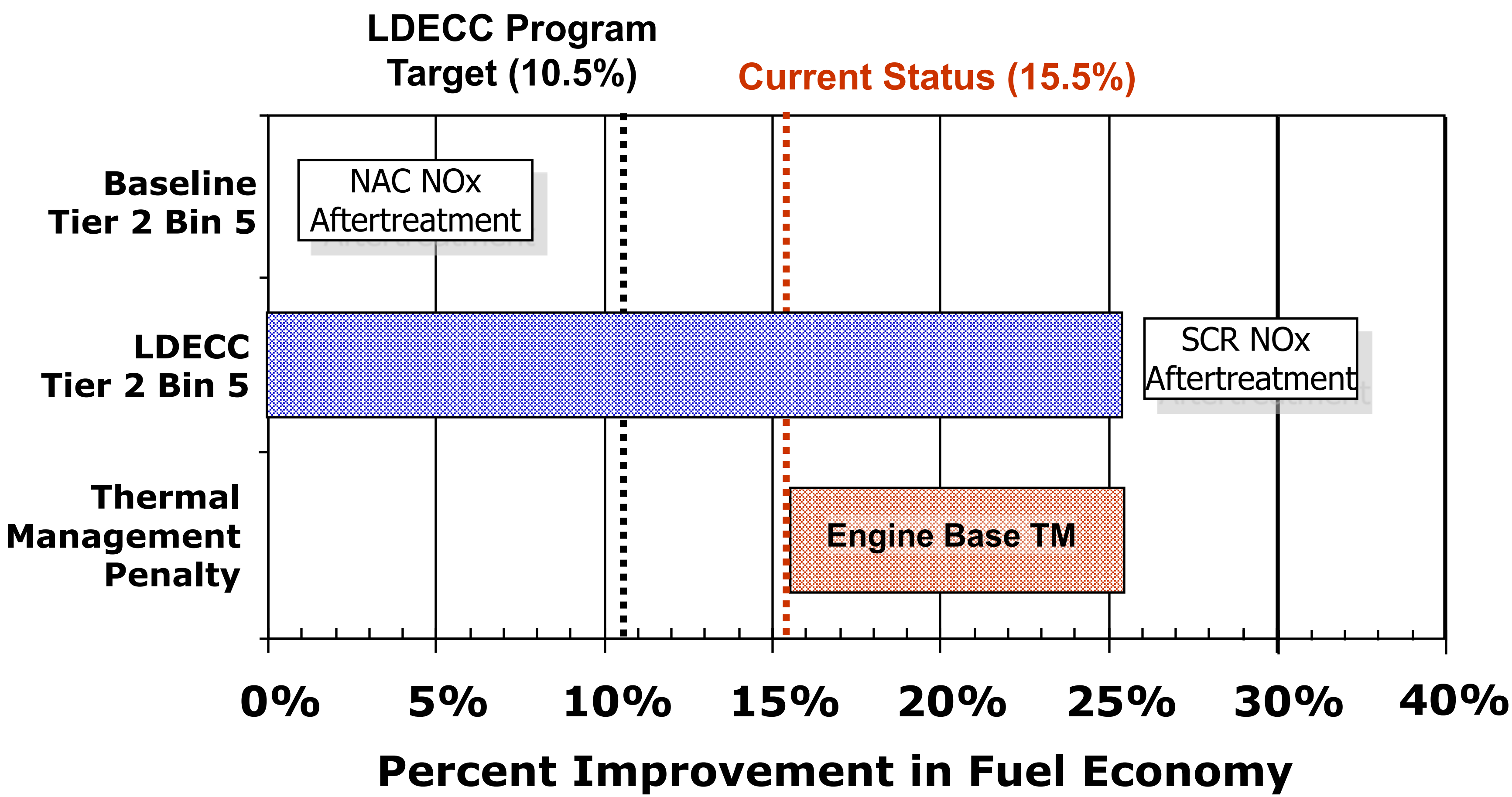
# High Pressure EGR System – SCR NOx AT




T = Turbine
C = Compressor
TB = Turbine Bypass
CB = Compressor Bypass
VG = Variable Geometry

# Fuel Economy Status – City Drive Cycle

Vehicle Test Weight = 5000 lb



# Benefits of Air Handling System Upgrades

- Decrease in pressure drop (before HPT and inter-stage section)
- Additional hardware for thermal management and US06 operation
  - EGR Cooler Bypass (EBV)
  - Variable Geometry Turbo (VGT)
- Addition of Inter-stage AT
- Reduce turbine by-pass valve leakage (0.6 mpg)

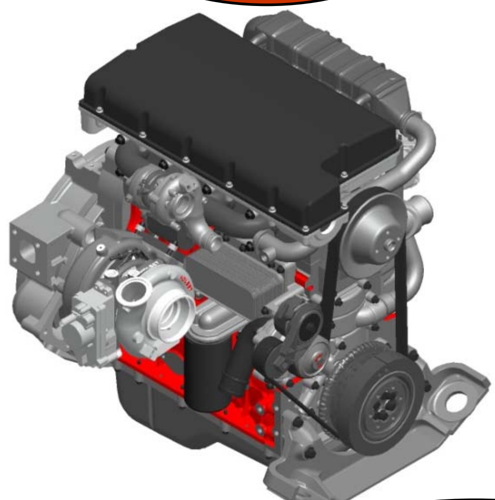
# Light Duty Technology Roadmap

**Fuel System**
- Precision Injection
-High Injection Pressure
-VSP
- Piezo

**Variable Valve Actuation**

**Advanced Combustion**
-Enhanced Early PCCI
-Lifted Flame Combustion

**Variable Intake Swirl**



**Controls**
-Closed loop combustion
- Charge air manager

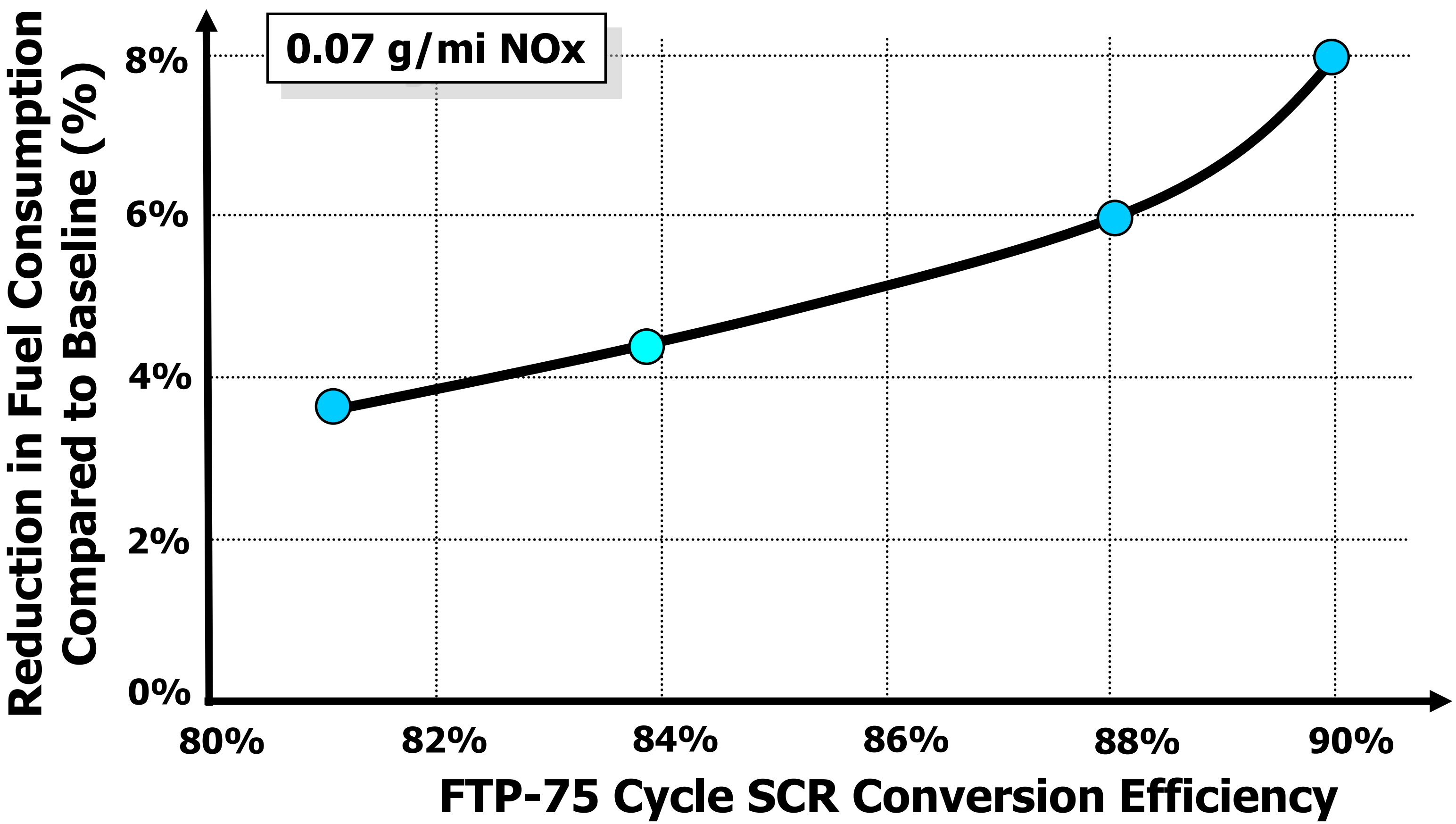
**Aftertreatment**
- Low Temperature SCR
- Low ΔP
- Low Soot Loading
- Partial Filter
-Interstage AT

**EGR Loop**
- Lower Pressure Drop
-Alternative Cooling
-2-loop Cooling
-HP/LP

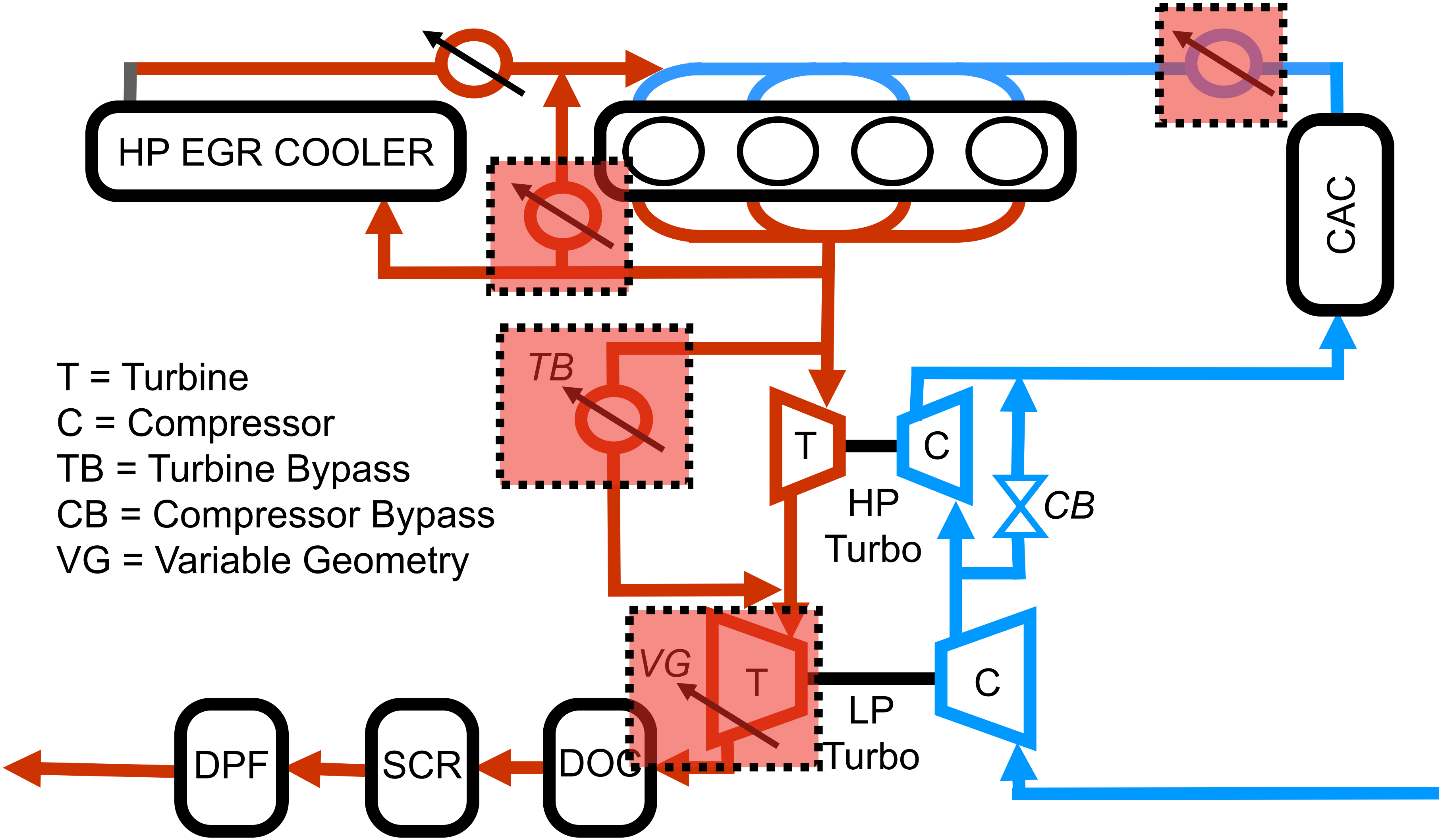
**Turbo**
-Two Stage
-HP Stage VGT

**Friction/Parasitics**
-Variable displacement pumps
-Piston
-Bearings
-Lube oil

# Achieving High SCR Conversion Efficiency



# Thermal Management Levers



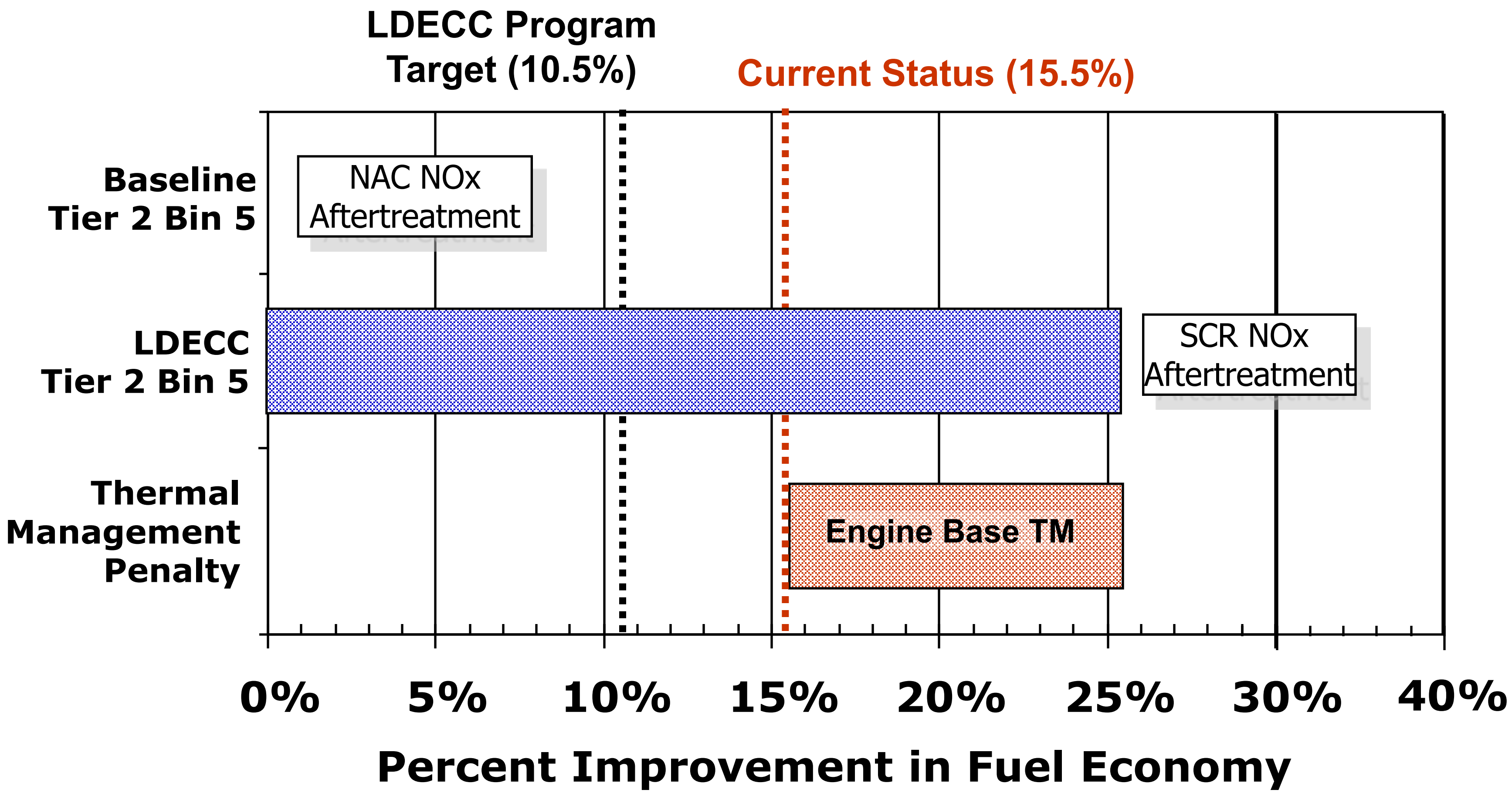

T = Turbine
C = Compressor
TB = Turbine Bypass
CB = Compressor Bypass
VG = Variable Geometry

# Thermal Management Levers

- Intake Throttle
- EGR By-Pass Valve (EBV)
- Turbine By-Pass Valve (TBV)
- Low Pressure VGT
- Fuel Injection Parameters
- Closed Couple Catalyst (CCC) Formulation
- Aftertreatment Insulation (Exhaust Manifold Design and Aftertreatment System)
- Fuel Reformer

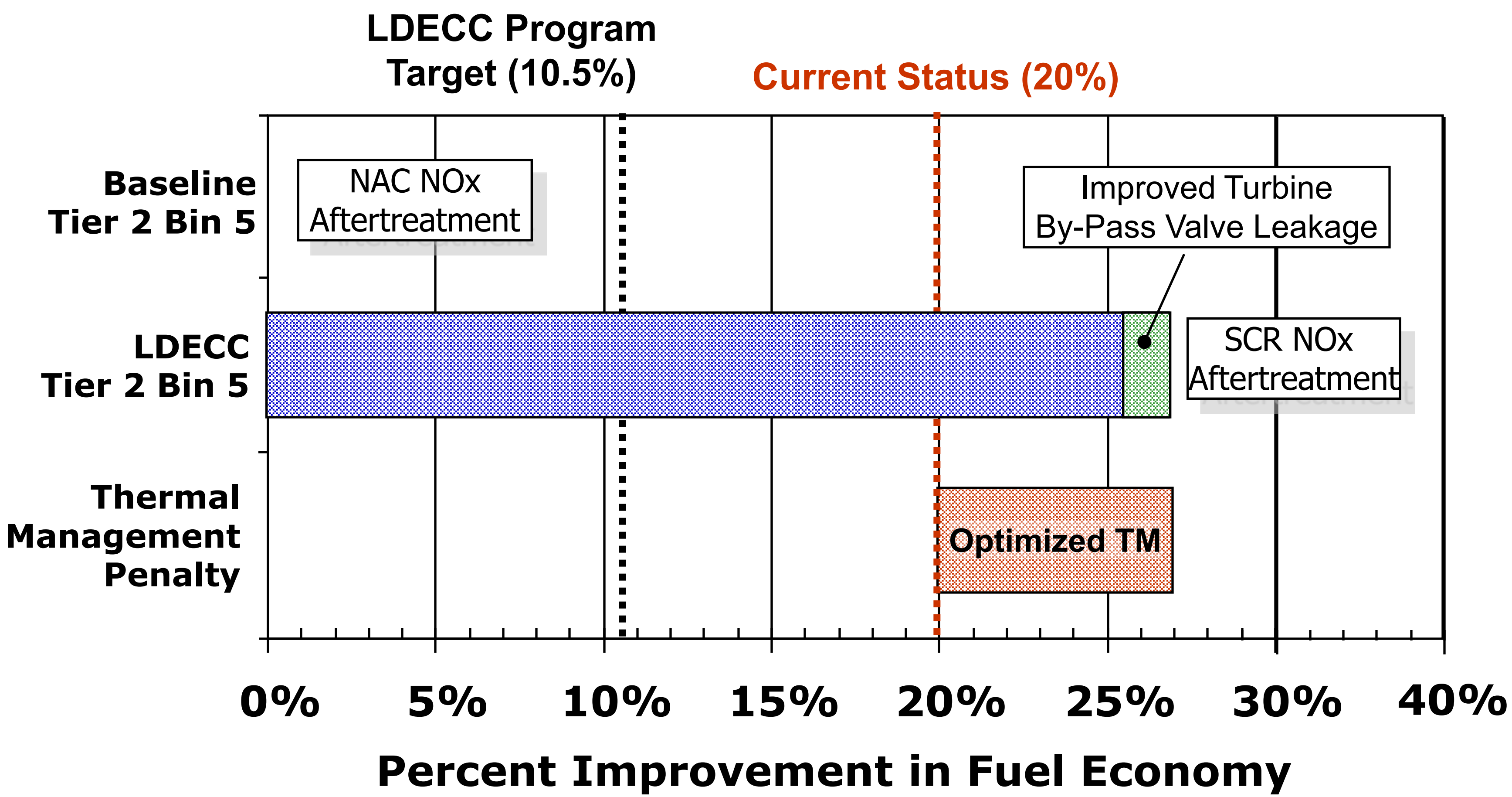
# Fuel Economy Status – City Drive Cycle

Vehicle Test Weight = 5000 lb



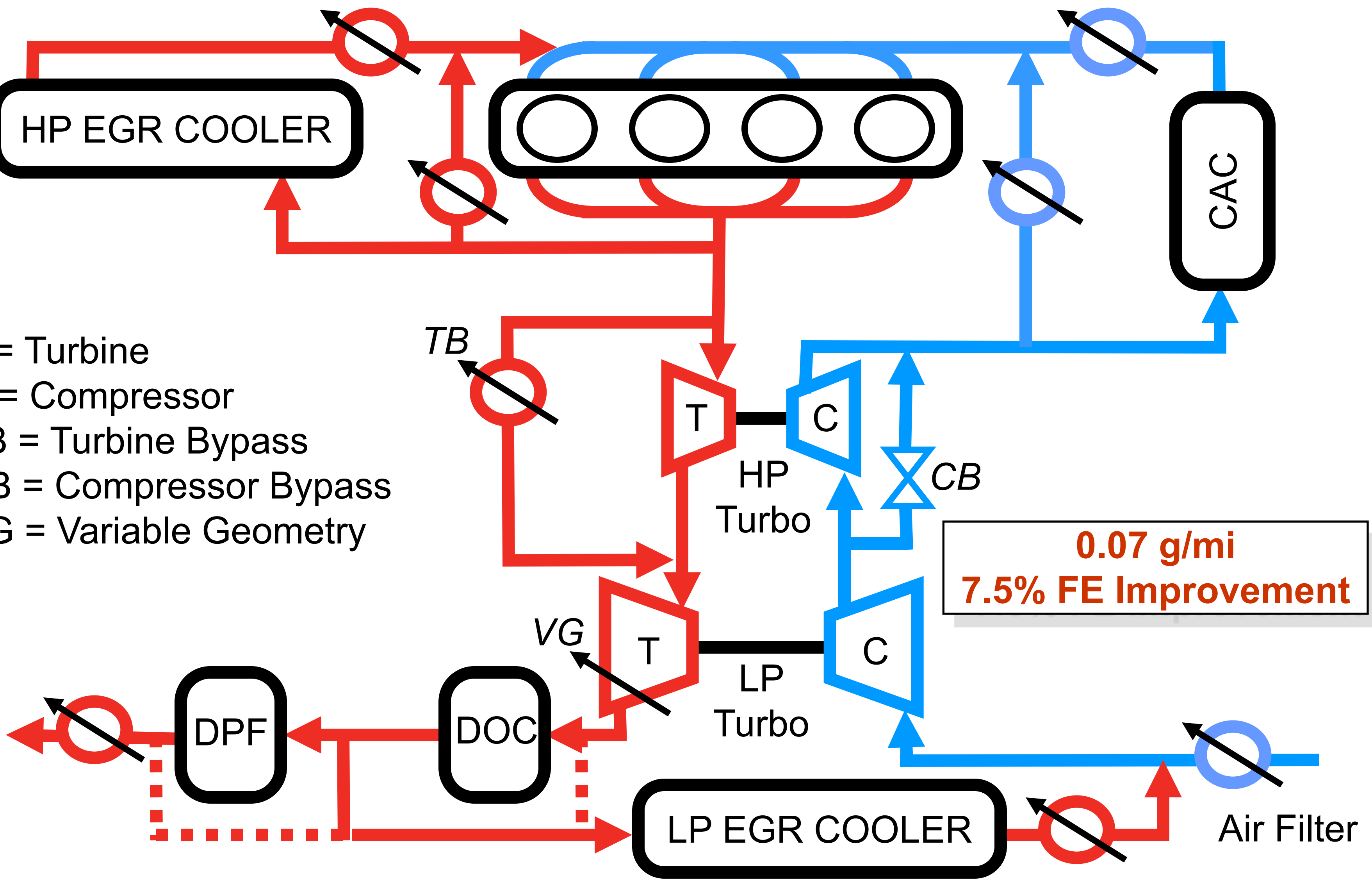
# Potential Fuel Economy Improvement with Optimized TM - Analysis

Vehicle Test Weight = 5000 lb



# In-Cylinder NOx Control
## (No NOx Aftertreatment)

# High Pressure/Low Pressure EGR System – In-Cylinder (no NOx AT)




T = Turbine
C = Compressor
TB = Turbine Bypass
CB = Compressor Bypass
VG = Variable Geometry

**0.07 g/mi**
**7.5% FE Improvement**

# Program Summary

- Program on schedule to conclude in November 2010
- Engine + aftertreatment components have been selected based on performance capability and product cost impact
- A 15.5% fuel economy improvement has been demonstrated with the SCR based architecture
  - Program emphasis is to reduce the fuel economy penalty associated with aftertreatment thermal management
    - Multiple options exist to reduce penalty from 10% to 7%
    - Balance fuel efficiency with product cost
- A 7.5% fuel economy improvement has been demonstrated with no NOx aftertreatment at 0.07 g/mi
  - Need additional NOx reduction to meet the design margin
  - Need additional 3% improvement in fuel economy to meet target
- Recent risk: meeting engine NVH requirements while minimizing impact on fuel economy
- Next steps are:
  - SCR - Selection of thermal management strategy
  - SCR and In-Cylinder - Final engine calibration while meeting NVH requirements