Light Duty Efficient Clean Combustion

2009 Semi-Mega Merit Review

Donald Stanton

Research & Technology

May 21, 2009

Project ID: ace_34_stanton

Agenda

- Project Goals and Objectives
- Project Partners
- Technical Approach and Enabling Technologies
- Master Schedule and 2009 Milestones
- Wrap-up and Questions

Project Goals and Objectives

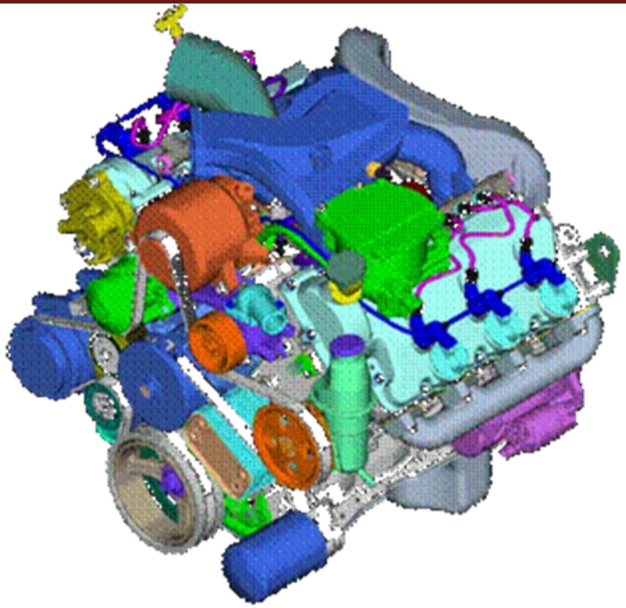
Goal

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



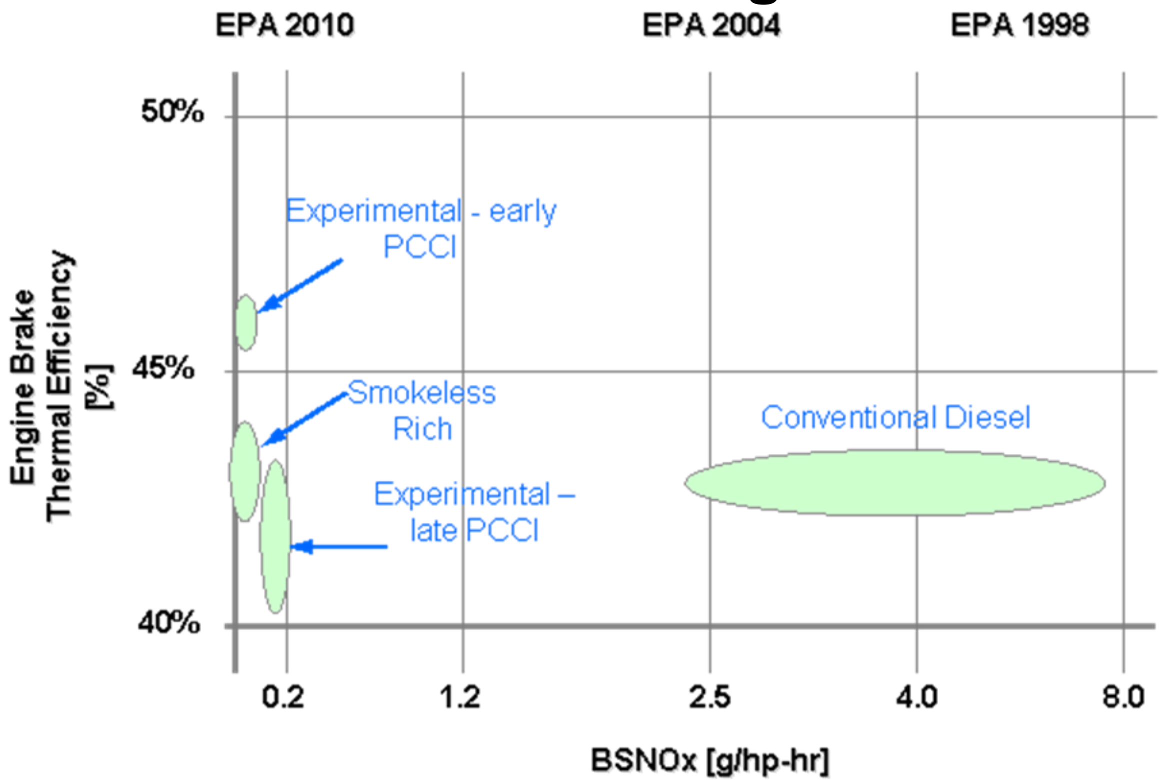
- Budget Period I – October 2007 thru December 2008
  - Applied Research & Exploratory Development
  - $834K DoE Funding and $834K Cummins Funding
- Budget Period II – January 2009 – September 2009
  - Advanced Development
  - $735K DoE Funding and $735K Cummins Funding
- Budget Period III – October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

Project Partners

- <u>Daimler-Chrysler</u>
  - Definition of Vehicle and Power-train Technical Requirements
  - Packaging Feasibility Study
  - Active Participant in Design Reviews and Program Updates
  - Provide Vehicle for Demonstration
- <u>BP</u>
  - Evaluation of Future Market Fuels
  - Supply of LDECC Fuel
  - Collaboration on the Evaluation of Fuel Sensing Technologies

Technical Approach

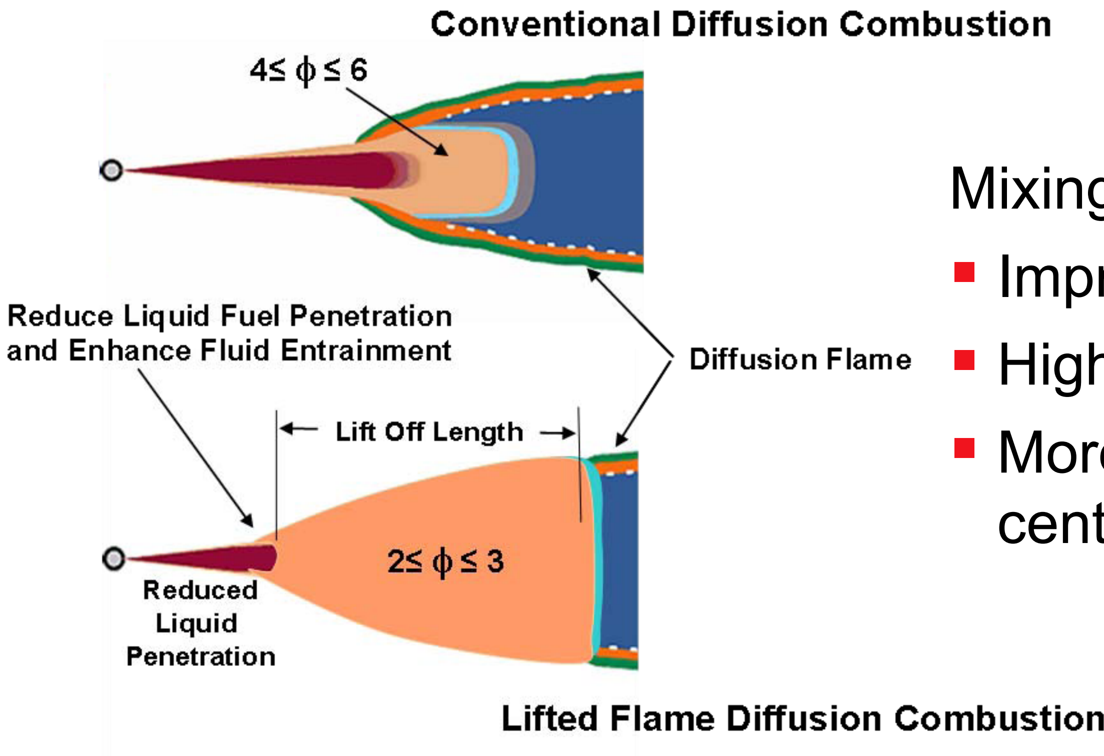
1. Expand Low Temperature Combustion Range



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

Technical Approach

2. Lifted Flame Combustion at High Loads



Mixing Enables:

- Improved NOx vs. PM
- Higher EGR tolerance
- More favorable combustion centroid

Transitioning to Lifted Flame Combustion at intermediate loads will avoid the high noise and cylinder pressures of early PCCI while maintaining excellent fuel economy

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

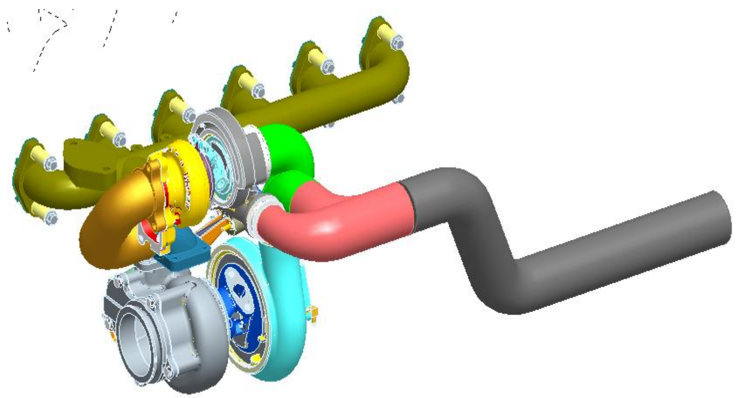
Enabling Technologies
Fuel Injection System

- High Fuel Injection Pressure
- Improved Small Quantity/Precision Injection Capability
- Increased Number of Injection Pulses
- Integration of FIE Controls with Closed Loop Combustion Controls

Enabling Technologies

Air Handling System

- High Capacity/High Efficiency EGR System
- Fast Response Air Handling Components
  - Variable valve actuation
    - Miller Cycle, Trapped Residual, A/T Regeneration
  - Variable swirl
  - Two stage turbocharger



Enabling Technologies
Control and Sensing Systems

- Closed Loop Combustion Control
  - Robust, production viable in-cylinder sensors
  - Piezo actuator feedback for fuel delivery and combustion phasing
- Fuel Quality Sensing
  - Robust, model-based adaptive control
- Charge Management Embedded Models
  - Improved transient charge control
- Drive Cycle Optimization

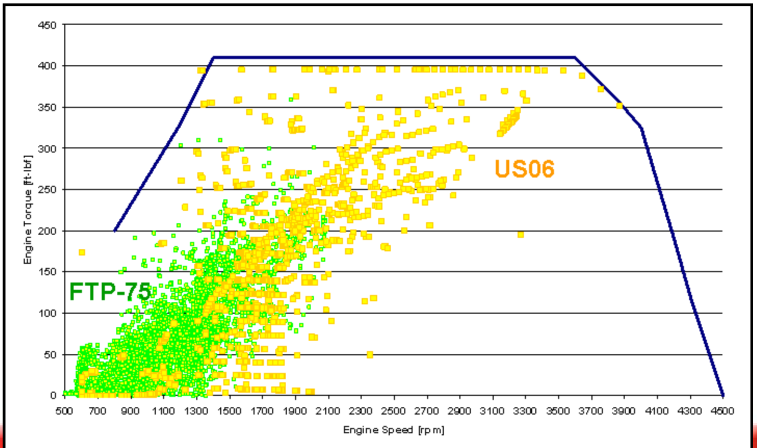
Enabling Technologies
Aftertreatment

- Diesel particulate filter
  - Reduced ΔP
  - Soot loading characteristics (ΔP linearity and hysteresis)
  - High temperature durability for fast regeneration
- High NOx Conversion Efficiency SCR
- Diesel oxidation catalyst formulation
- Aftertreatment configuration (order of the components)
- Thermal management strategy
  - Fuel injection strategies
  - VGT turbo operation
  - VVA

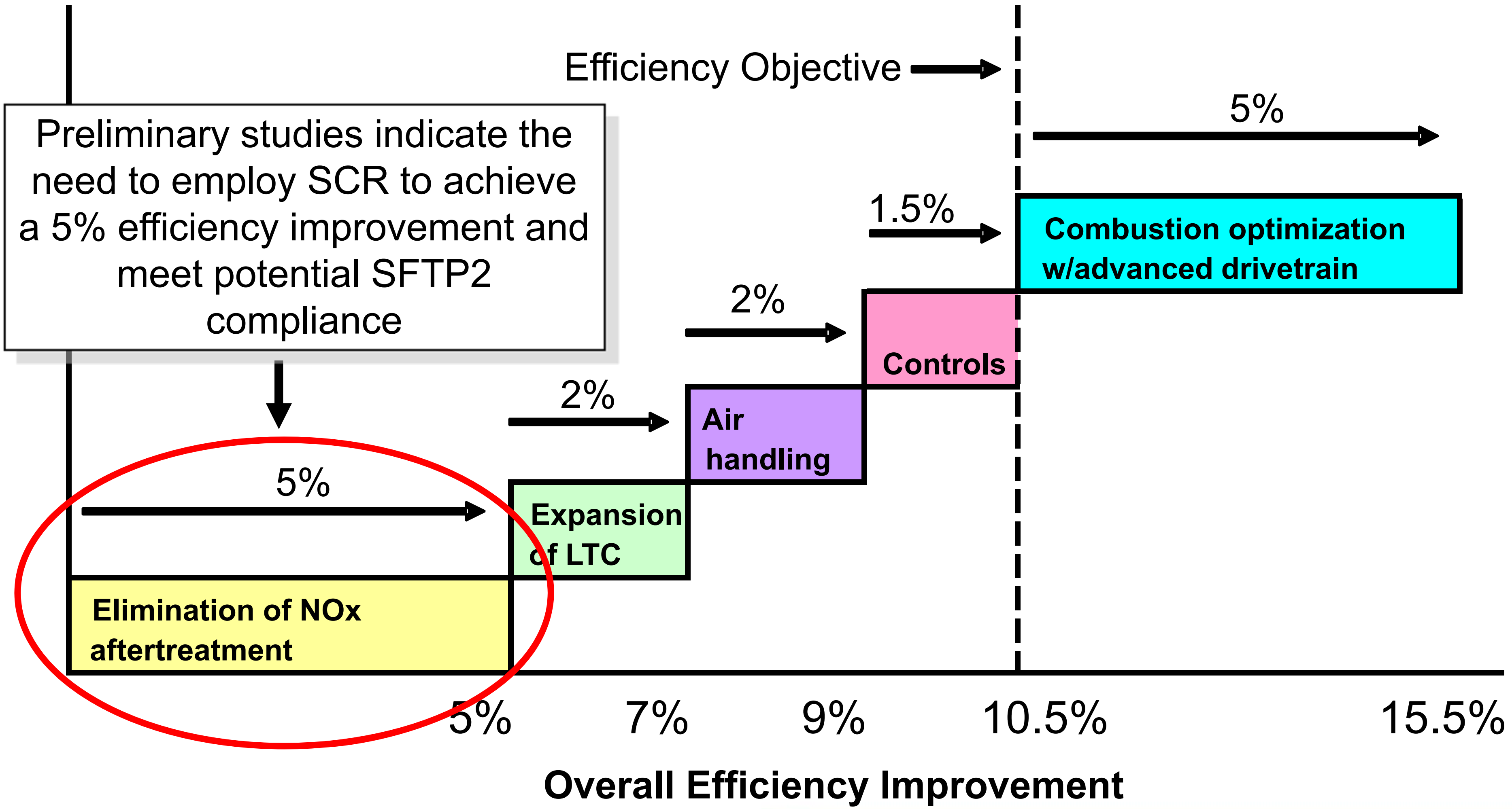
Impact of SFTP2 Emissions Compliance

- CARB is considering a revision to the SFTP certification (referred to as SFTP2)
- The impact of SFTP2 is unclear since there are several proposals
- More stringent emissions levels for US06 will have a significant impact on the chosen strategy for NOx compliance while meeting efficiency targets
- May drive the need for NOx aftertreatment
- Program will explore two strategies for NOx control
  - In-cylinder (no NOx aftertreatment)
  - High NOx conversion efficiency SCR system

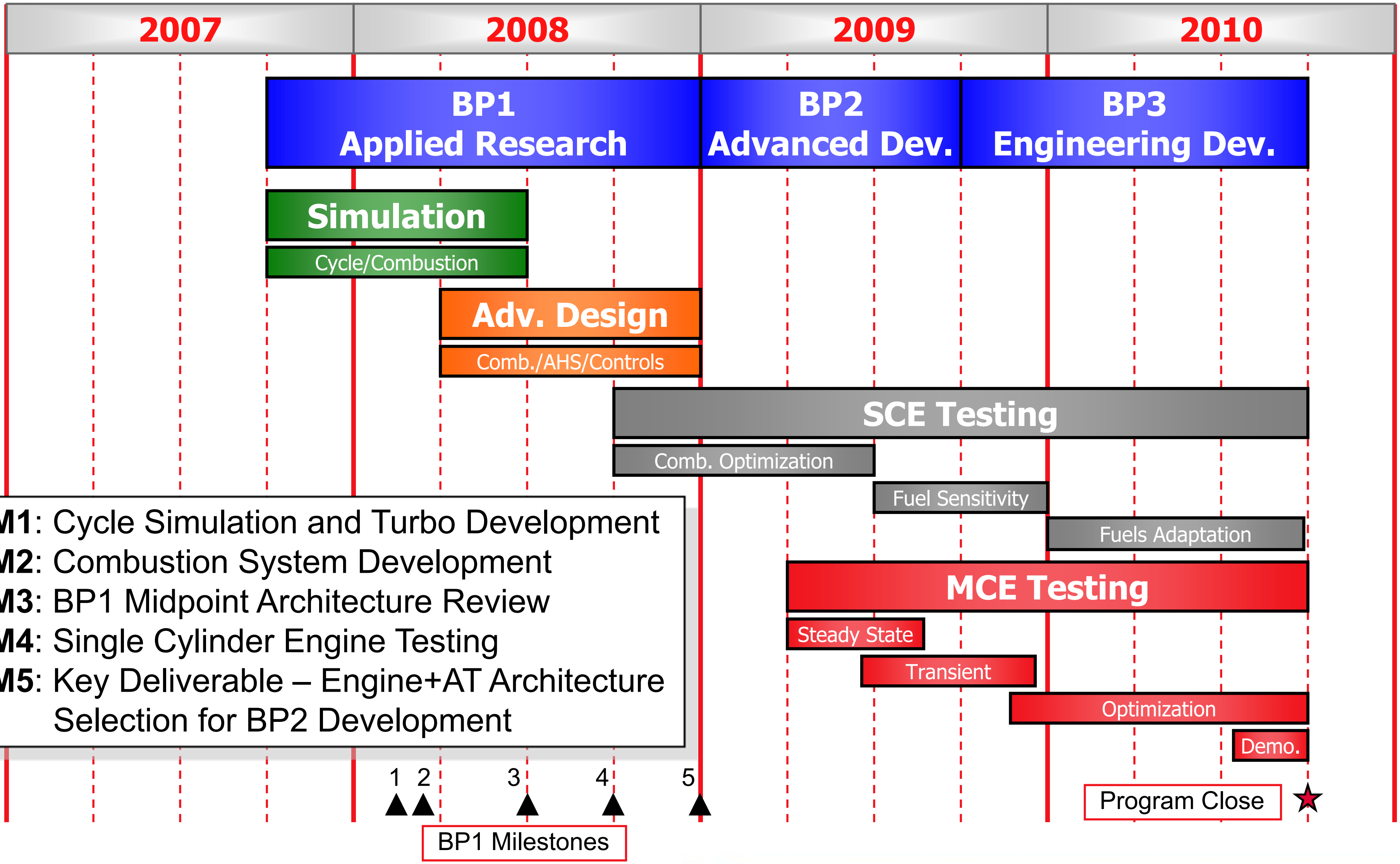
SFTP(120k) = 0.35*FTP75 + 0.28*US06 + 0.37*SC03



Path to Fuel Efficiency Target



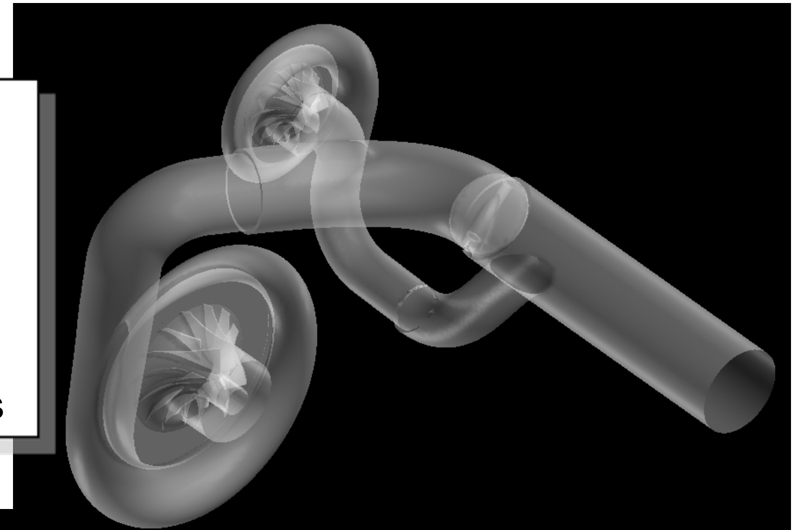
LDECC Master Schedule

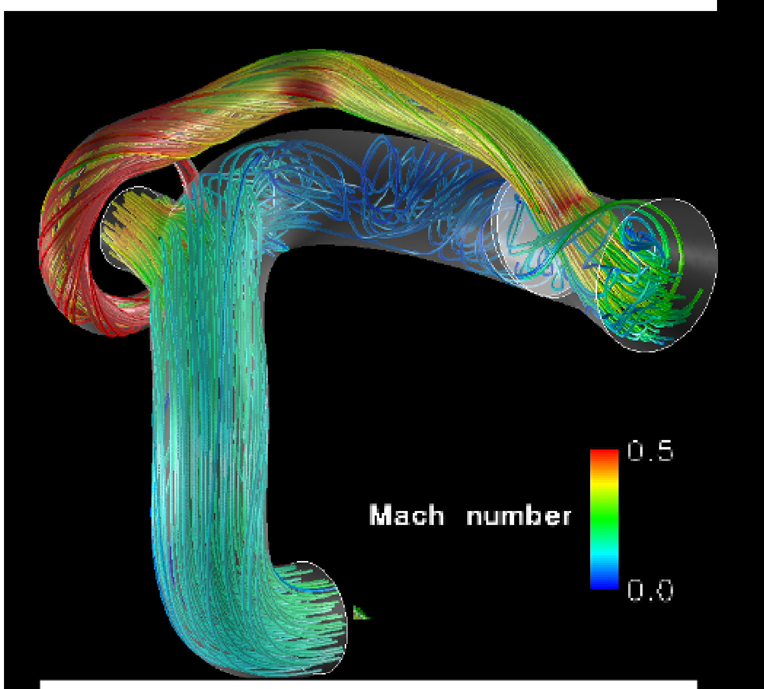


M1: Cycle Simulation and Turbo Development
M2: Combustion System Development
M3: BP1 Midpoint Architecture Review
M4: Single Cylinder Engine Testing
M5: Key Deliverable – Engine+AT Architecture Selection for BP2 Development

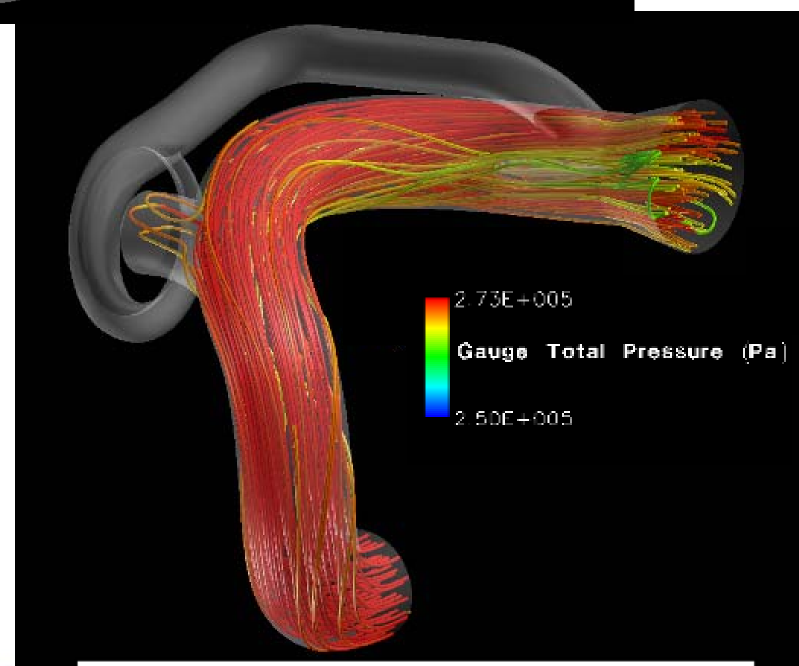
Sequential Turbomachinery Analysis

Optimization of the compact 2-stage, sequential turbo done with CFD
- Provide sufficient power density
- Minimize ΔP
- Deliver target A/F and EGR rates determined from single cylinder engine testing and GT-Power analysis



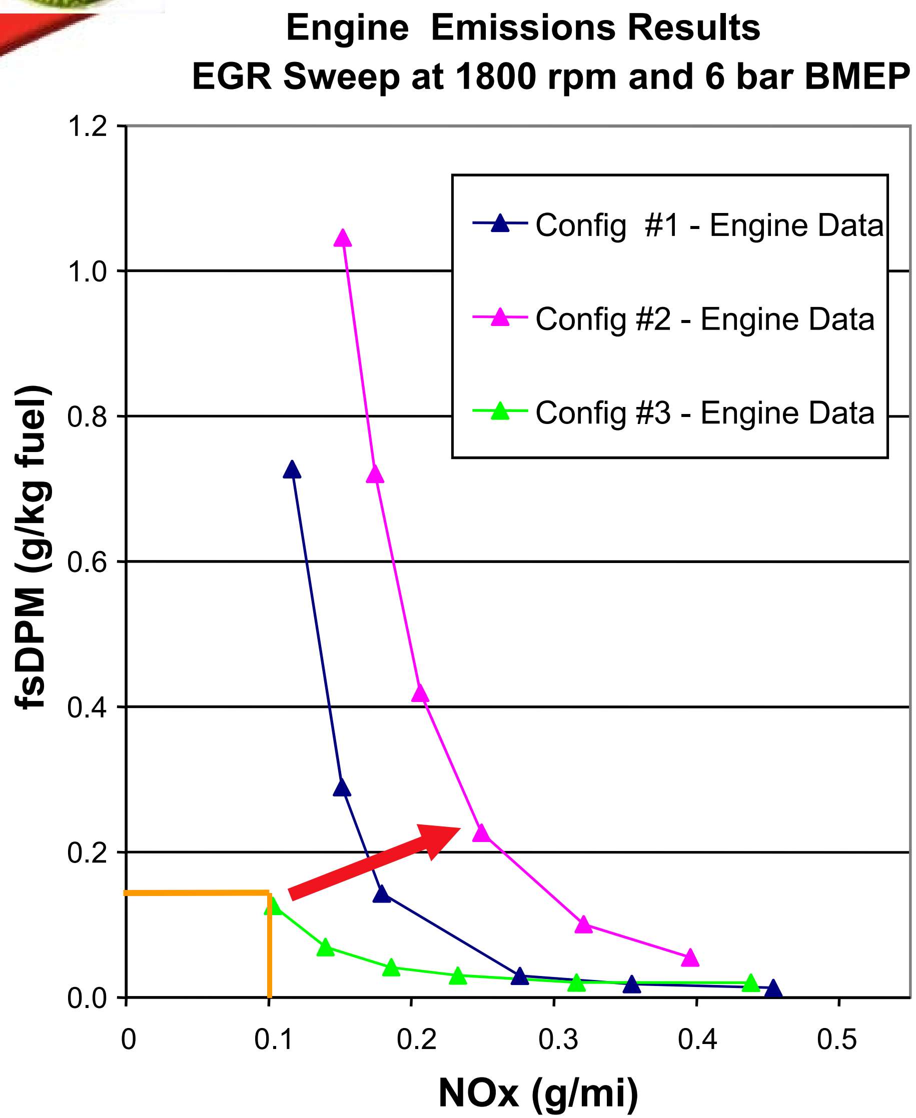


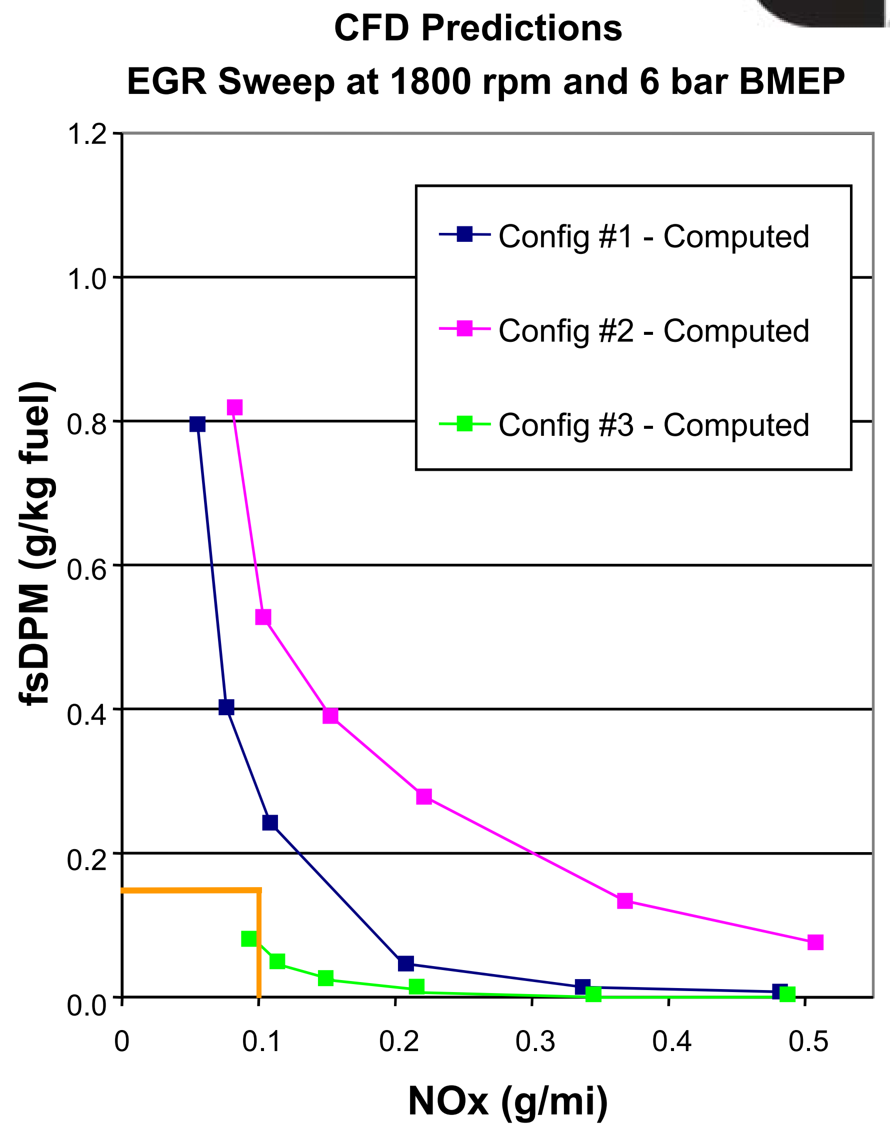
Compressor bypass valve closed



Compressor bypass valve opened

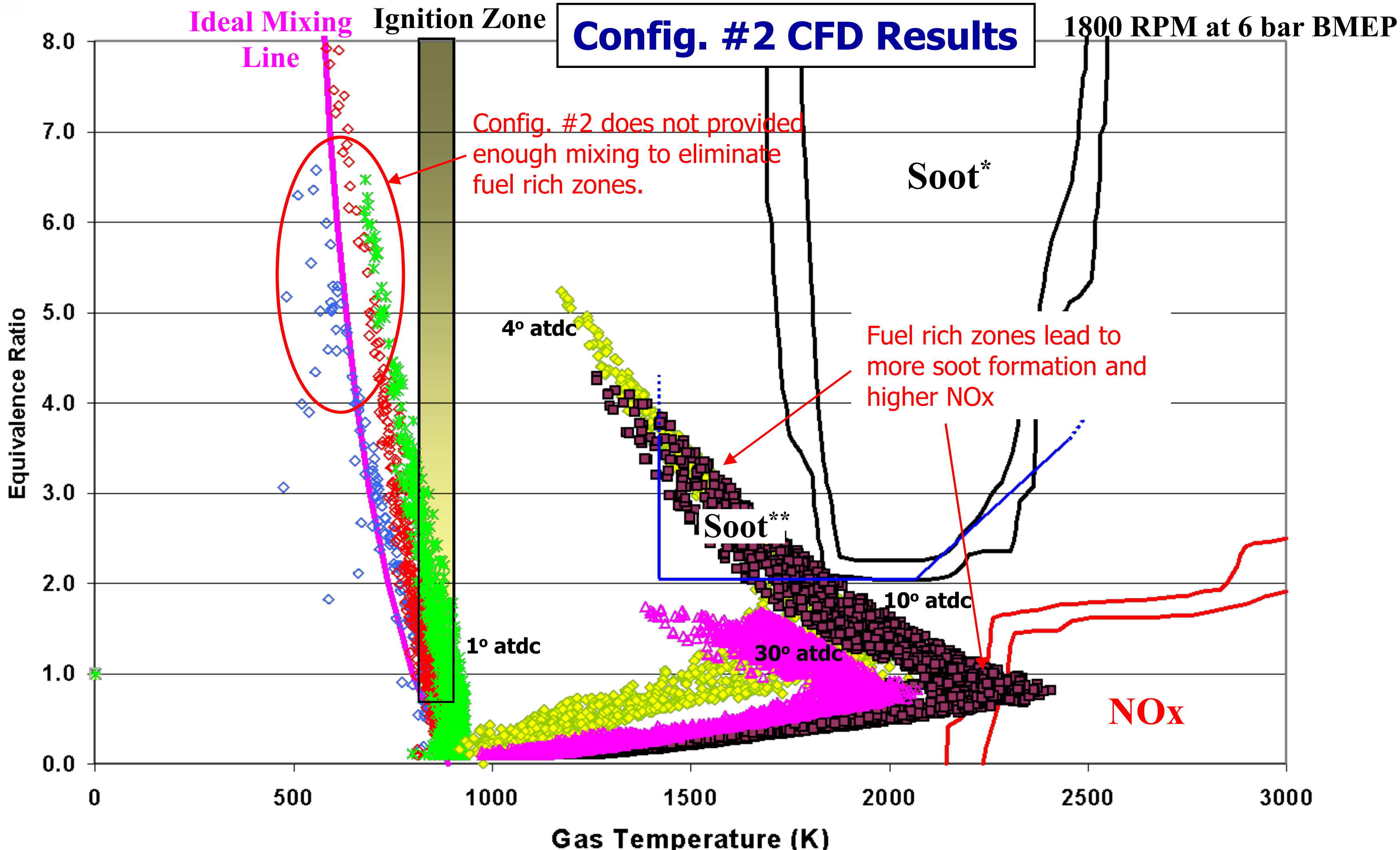
Combustion System Design for LTC





Note: Each configuration represents a unique piston bowl, injector nozzle, and intake swirl combination

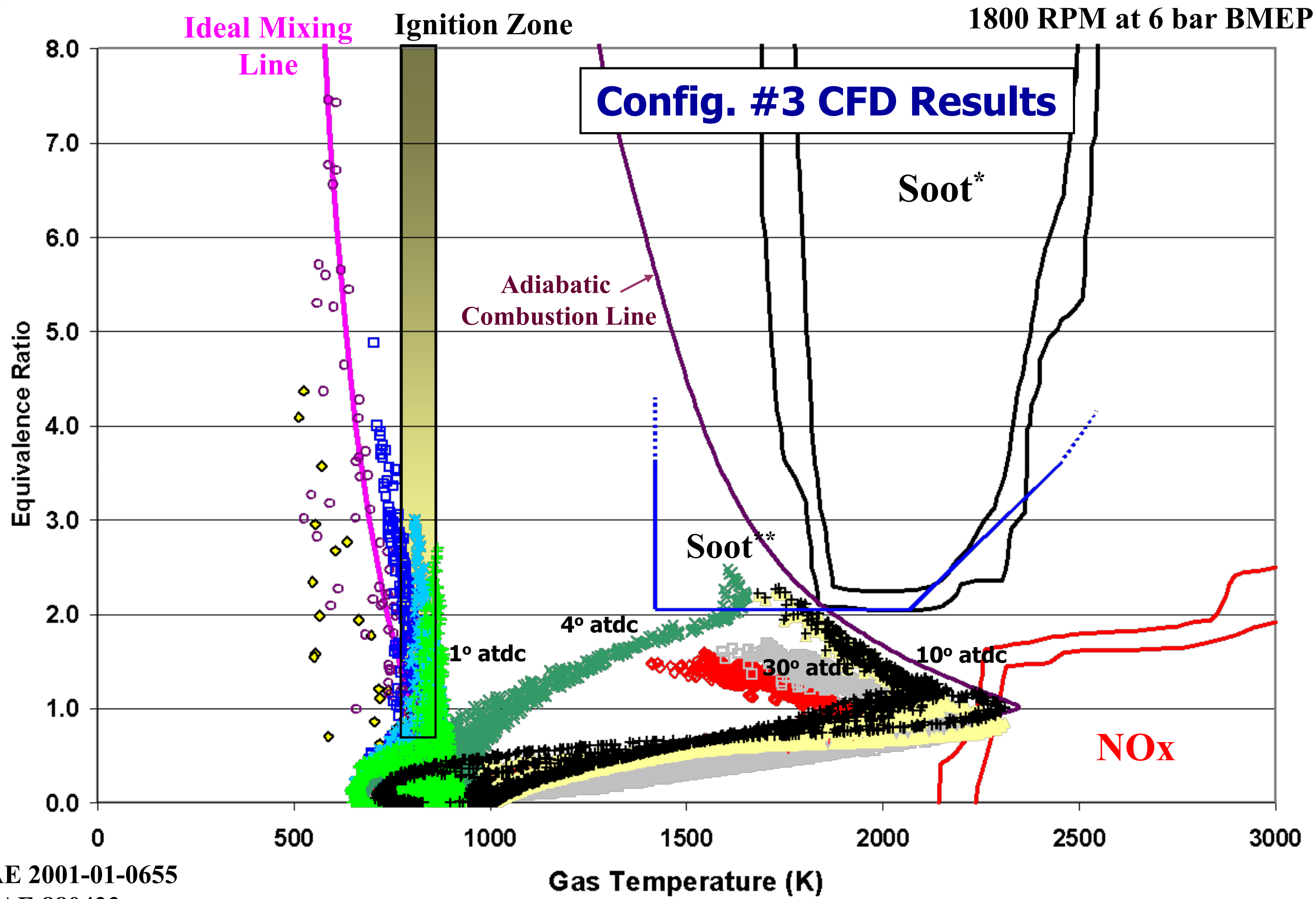
Evolution of the Combustion Process for Combustion System Configuration #2



*SAE 2001-01-0655

**SAE 880423

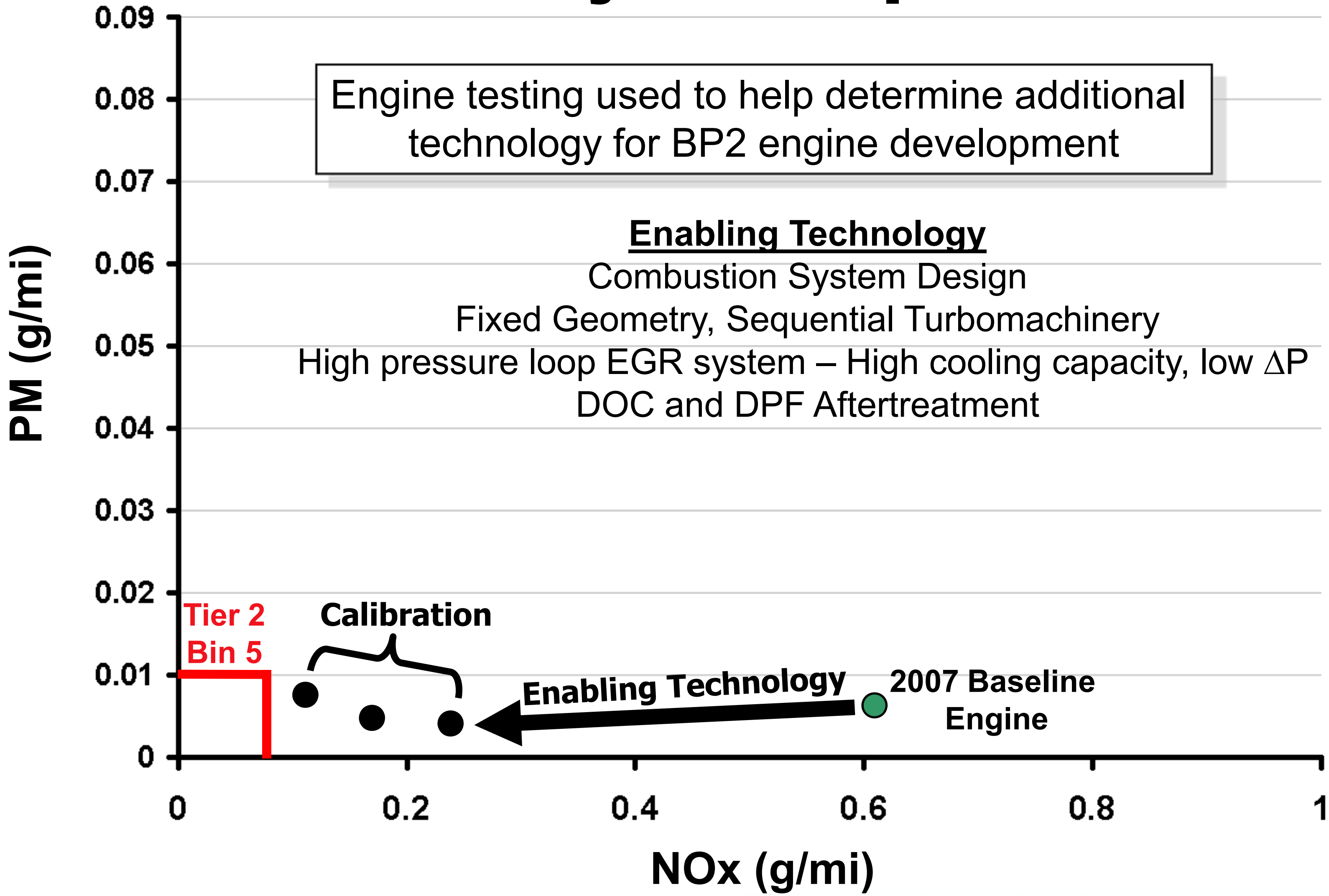
Evolution of the Combustion Process for Combustion System Configuration #3



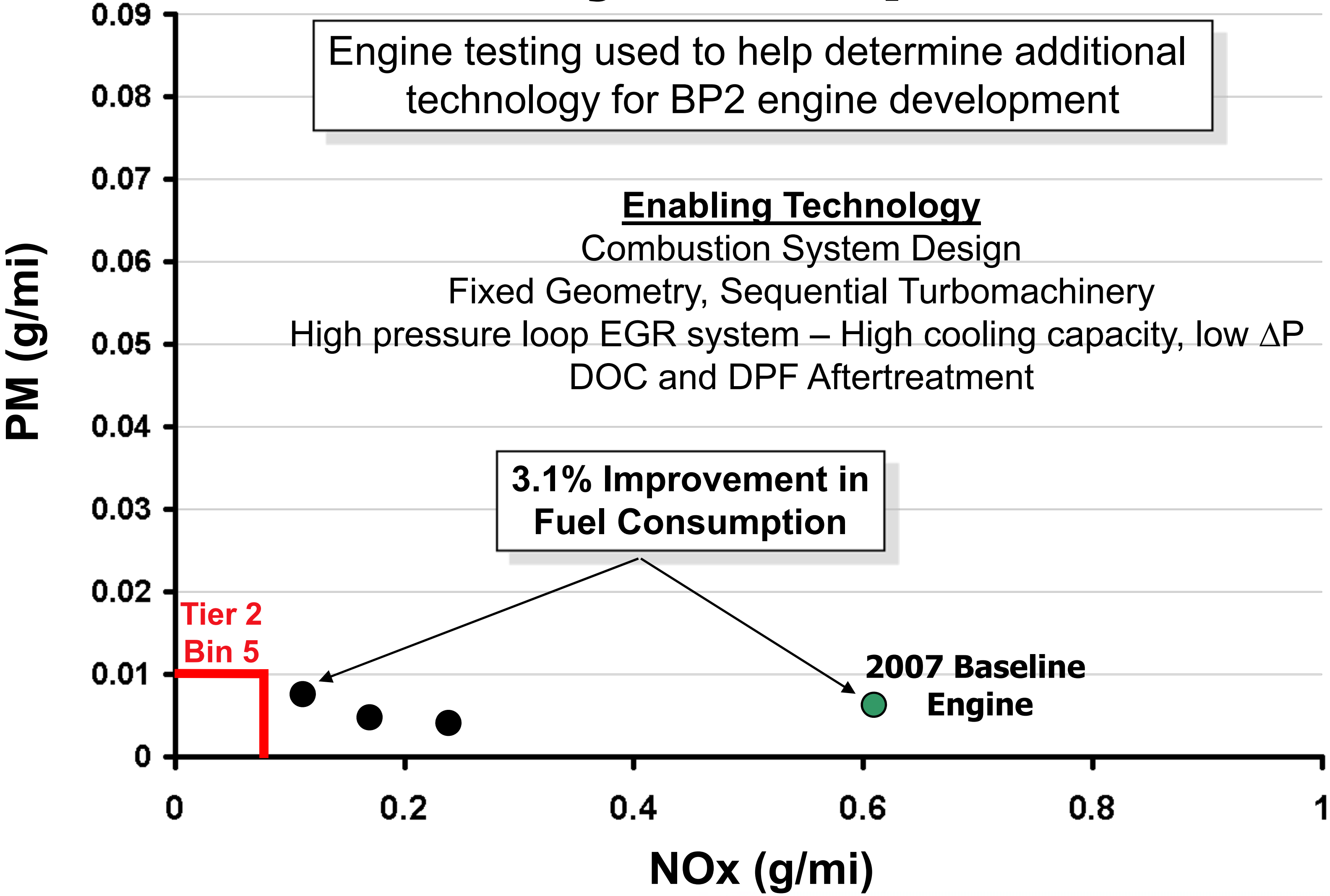
*SAE 2001-01-0655

**SAE 880423

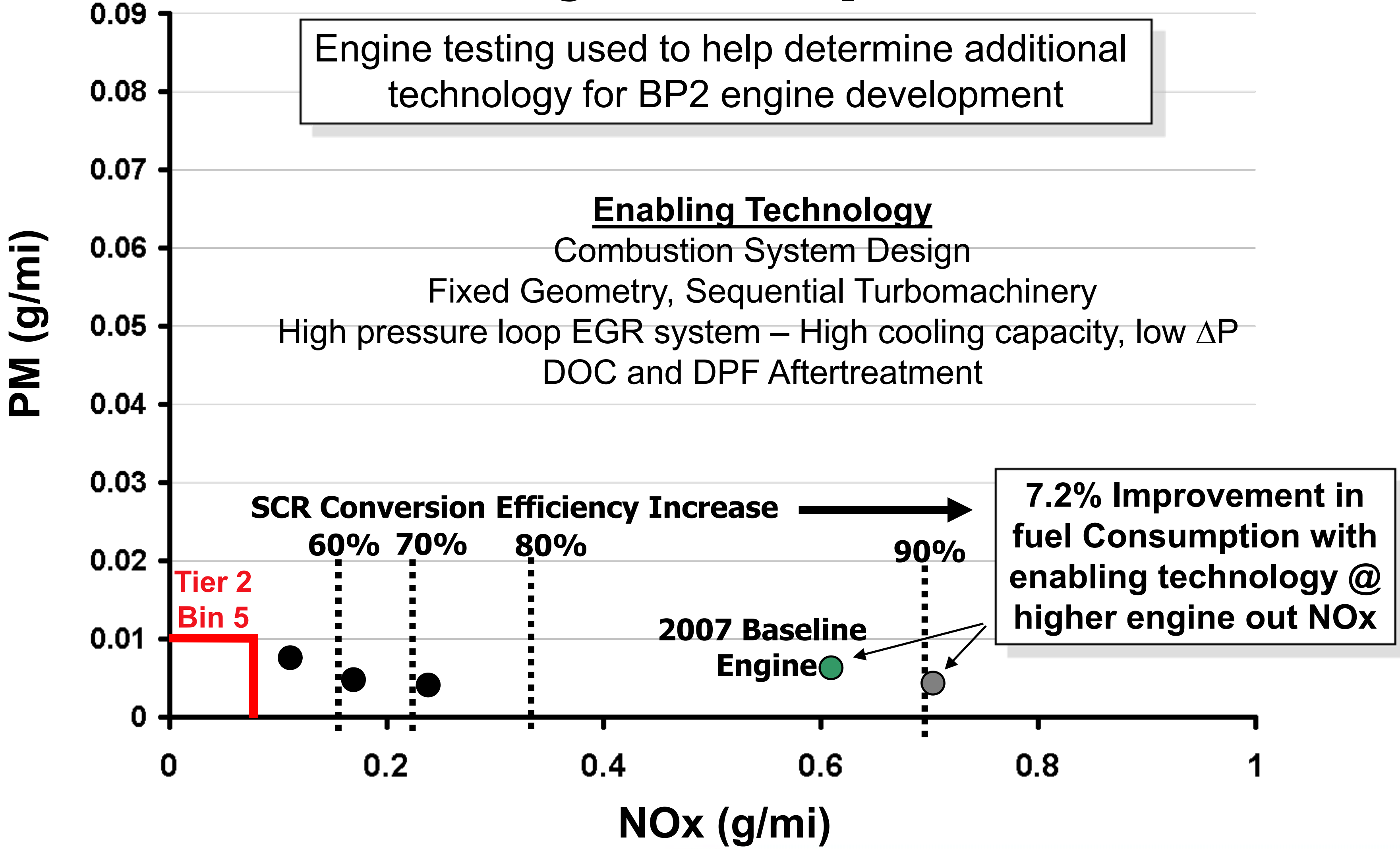
Current Status of Emissions and Efficiency Accomplishments



Current Status of Emissions and Efficiency Accomplishments



Current Status of Emissions and Efficiency Accomplishments



Light Duty Engine Architecture for BP2 Development

Fuel System
- >2200 bar injection pressure
- Up to 7 injection events

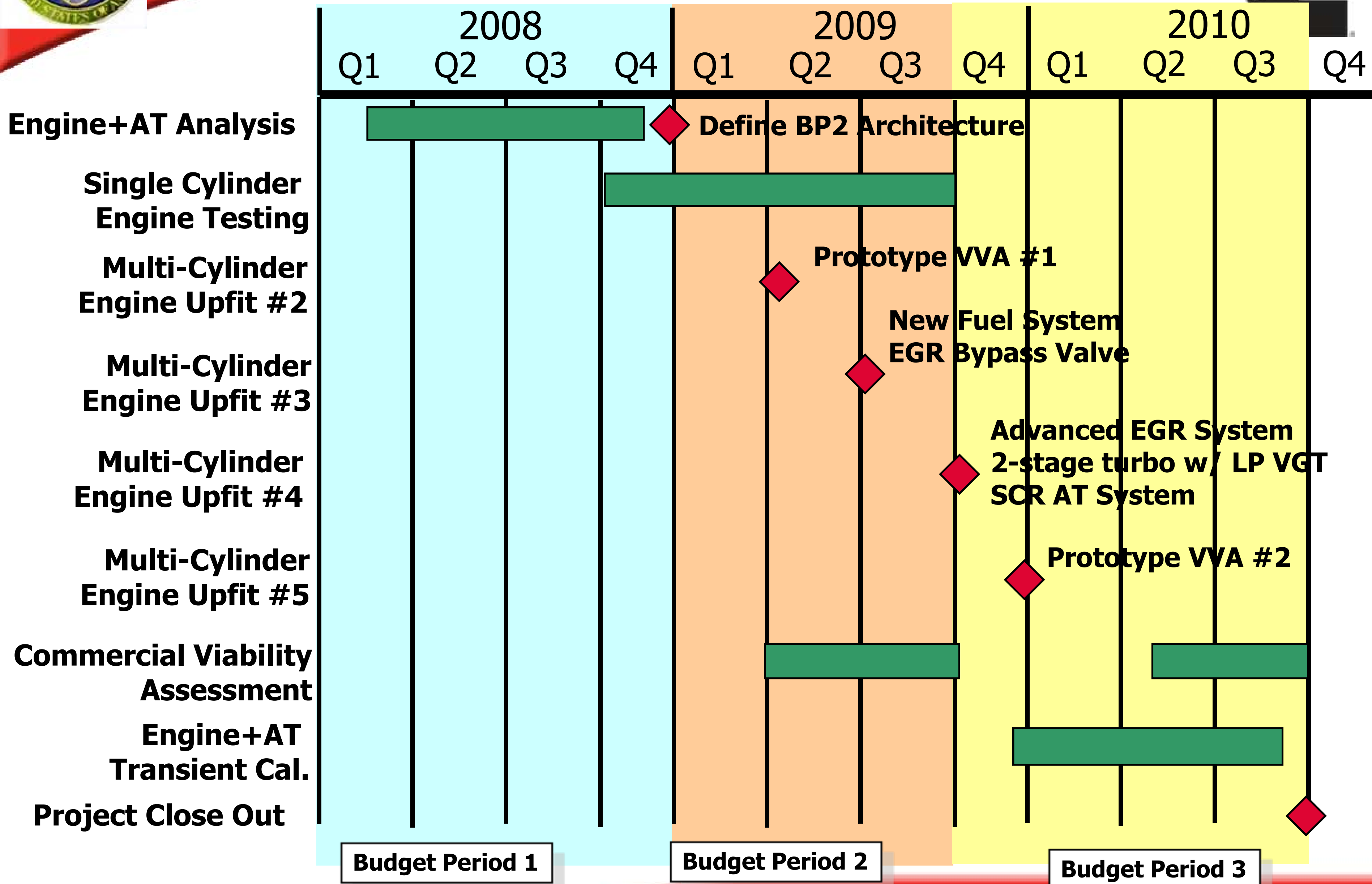
Air Handling
- 2-stage, sequential turbo with a LP stage VGT
- SOHC and DOHC VVA designs on-going

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

Multi-Cylinder Engine Build Schedule



2009 Milestone Descriptions

- **1: Closed Loop Combustion Control Strategy** 6/15/09
  A controls strategy will be developed that will adjust fuel injection parameters based on processing of the cylinder pressure signal to achieve optimal combustion phasing.
- **2: Steady State, Multi-Cylinder VVA Testing** 7/15/09
  Engine testing will be conducted using the first prototype VVA system. Miller cycle, trapped residual, and aftertreatment thermal management will be explored. The main outcome will be the definition of the required functionality for a product intent VVA system.
- **3: Lower Compression Ratio Combustion System** 8/1/09
  Analysis and single cylinder engine testing to determine the benefits of a combustion recipe with lower compression ratio. The goal is to determine if a lower compression ratio piston can help extend the early PCCI operating range without efficiency degradation.

2009 Milestone Descriptions

- **4: Engine Architecture Definition for BP3 Development** 11/15/09

  Engine architecture for Budget Period 3 evaluations will be selected based on estimates of contribution to efficiency improvements, and economic and technical feasibility. Project readiness evaluation and GO/NO GO review to continue with BP 3.

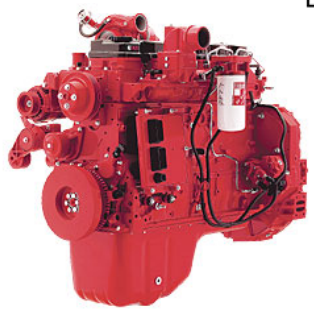
- **5: VVA System Control Strategy** 12/1/09

  Development of a VVA controls strategy. Integration of the VVA system controls will be done in two steps. First, the VVA controller will be incorporated into the engine air handling controls framework. Second, closed loop combustion control feedback will be added to the controls strategy

Commercial Viability

I4 Family of Engines

V8



4.5L

3.8L

2.8L

- LDECC technologies scale across all Cummins light duty diesel engines
- Key component technologies and subsystems are being developed by Cummins Component Business units (aftertreatment, turbomachinery, electronics, etc.) that are intended for production
- V8 engine will be the first opportunity for commercialization of LDECC technologies with North American OEMs.

Program Summary

- All program deliverables for BP1 have been met
- Program remains on schedule
- Key component technologies have been defined with development on-going
- Variable valve actuation remains the most challenging component technology to develop toward a commercially viable form
- Preliminary studies indicate the need to employ SCR aftertreatment to achieve the fuel efficiency target while meeting the potential SFTP2 emissions compliance
- Engine and aftertreatment architecture for BP2 development has been finalized
- Development effort underway to incorporate VVA and closed loop combustion control strategies

