Cummins SuperTruck Program

Technology and System Level Demonstration of Highly Efficient and Clean, Diesel Powered Class 8 Trucks

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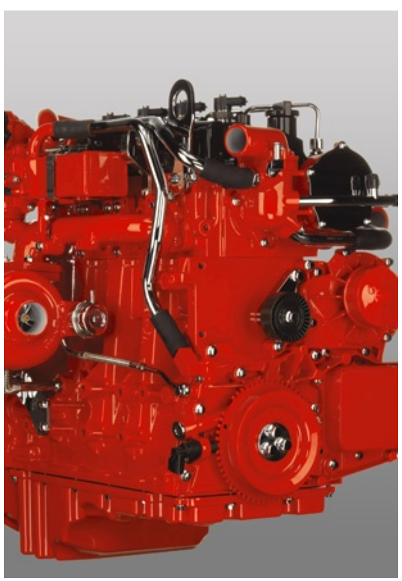
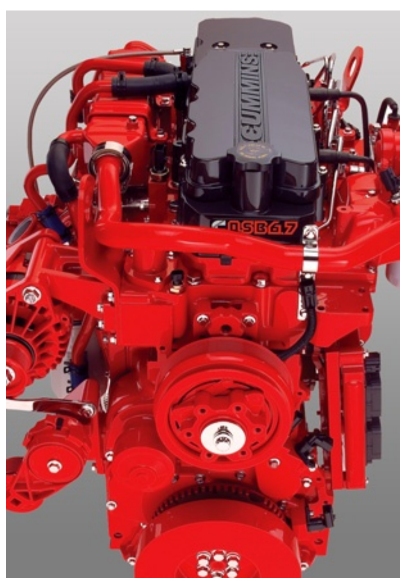
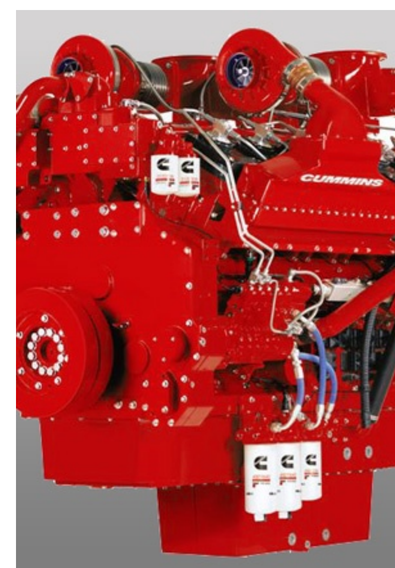
Cummins Inc.

June 20, 2014 **Project ID: ACE057**



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Overview

	OBJECTIVES	Timeline 4 1/2 year program: April 2010 thru September 2014 2010 / 2011 / 2012 / 2013 / 2014
Engine	**1:** Test cell demonstration of 50% or greater BTE engine	
Vehicle	**2a:** Vehicle drive cycle demonstration of 50% or greater freight efficiency improvement	
Vehicle	**2b:** Vehicle 24 hour duty cycle demonstration of 68% or greater freight efficiency improvement	
Engine	**3:** Technology scoping and demonstration of a 55% BTE engine system.	

Today

Period

Program closeout

Budget:

- Total: $77,662,230
  - DoE share* $36,335,608
  - CMI share* $36,335,608

  * actuals as of 12/31/2013

Peterbilt partner details are included in Peterbilt's 2014 AMR presentation ARRA-081

Partners:

- Cummins – Program Lead & Engine
  - Modine
  - Oak Ridge National Lab
  - Purdue University
  - Peterbilt – Vehicle Integrator
    - Peterbilt Partners

Overview – Program Barriers

- Engine Downspeed (Reduced Engine Speed)
  - ✓ Powertrain component response
  - – Closed cycle efficiency gains
- High Conversion Efficiency NOx Aftertreatment
  - ✓ Fuel Efficient Thermal Management
- ✓ Vehicle and Engine System Weight Reduction
- ✓ Underhood Cooling with Waste Heat Recovery
- Powertrain Materials
  - ✓ Increased Peak Cylinder Pressure with Cost Effective Materials for Block and Head
  - – Thermal Barrier Coatings for Reduced Heat Transfer
- ✓ Trailer Aerodynamic Devices that are Functional
- Parasitic power reductions

More vehicle specific details are included in Peterbilt's 2013 AMR presentation ARRA-081

Relevance - American Recovery and Reinvestment Act (ARRA) & VT ARRA Goals

- ARRA Goal: Create and/or Retain Jobs

					Projections
Year	2010	2011	2012	2013	2014
Full Time Equivalent	75.5	85	60	46	17

States: Indiana, Texas, Michigan, Wisconsin, Tennessee, Illinois, California, Colorado, New York

- ARRA Goal: Spur Economic Activity
  - Greater than $72.6M total spend to date (ref: thru Dec 2013)
- Goals align with VT Multi-Year Program Plan 2011-2015
  - Advanced Combustion Engine R&D (ACE R&D):
    - 50% HD engine thermal efficiency by 2015 (ref: VT MYPP 2.3.1)
  - Vehicle and Systems Simulation and Testing (VSST):
    - Freight efficiency improvement of 50% by 2015 (ref: VT MYPP 1.1)
- Invest in Long Term Economic Growth
  - Freight transport is essential for economic growth
    - Commercial viability assessment

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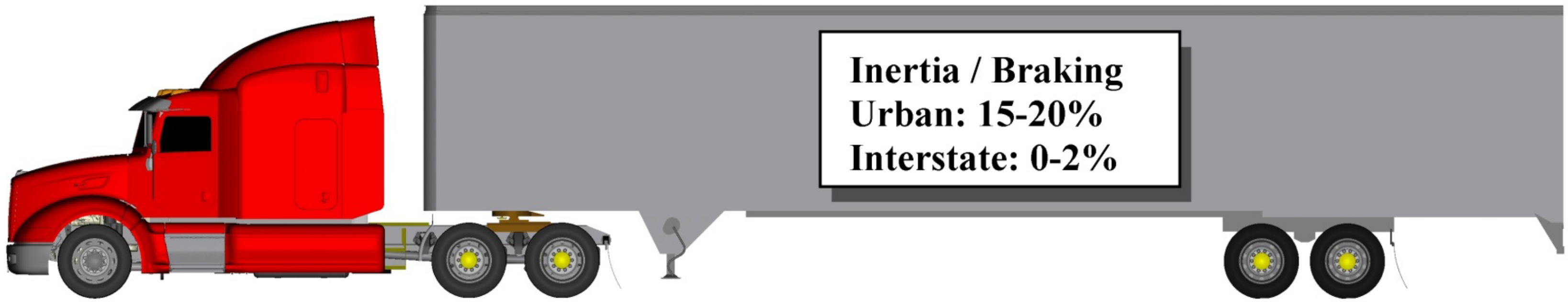
Approach – Vehicle Energy Analysis

Analysis of 27 Drive Cycles for Class 8 Vehicles
with a Variety of Seasons (Summer, Winter, etc.)

1 — Engine Losses
Urban: 58-60%
Interstate: 58-59%
Cummins

2 — Aerodynamic Losses
Urban: 4-10%
Interstate: 15-22%
Peterbilt



Inertia / Braking
Urban: 15-20%
Interstate: 0-2%

5 — Auxiliary Loads
Urban: 7-8%
Interstate: 1-4%
Delphi & Bergstrom

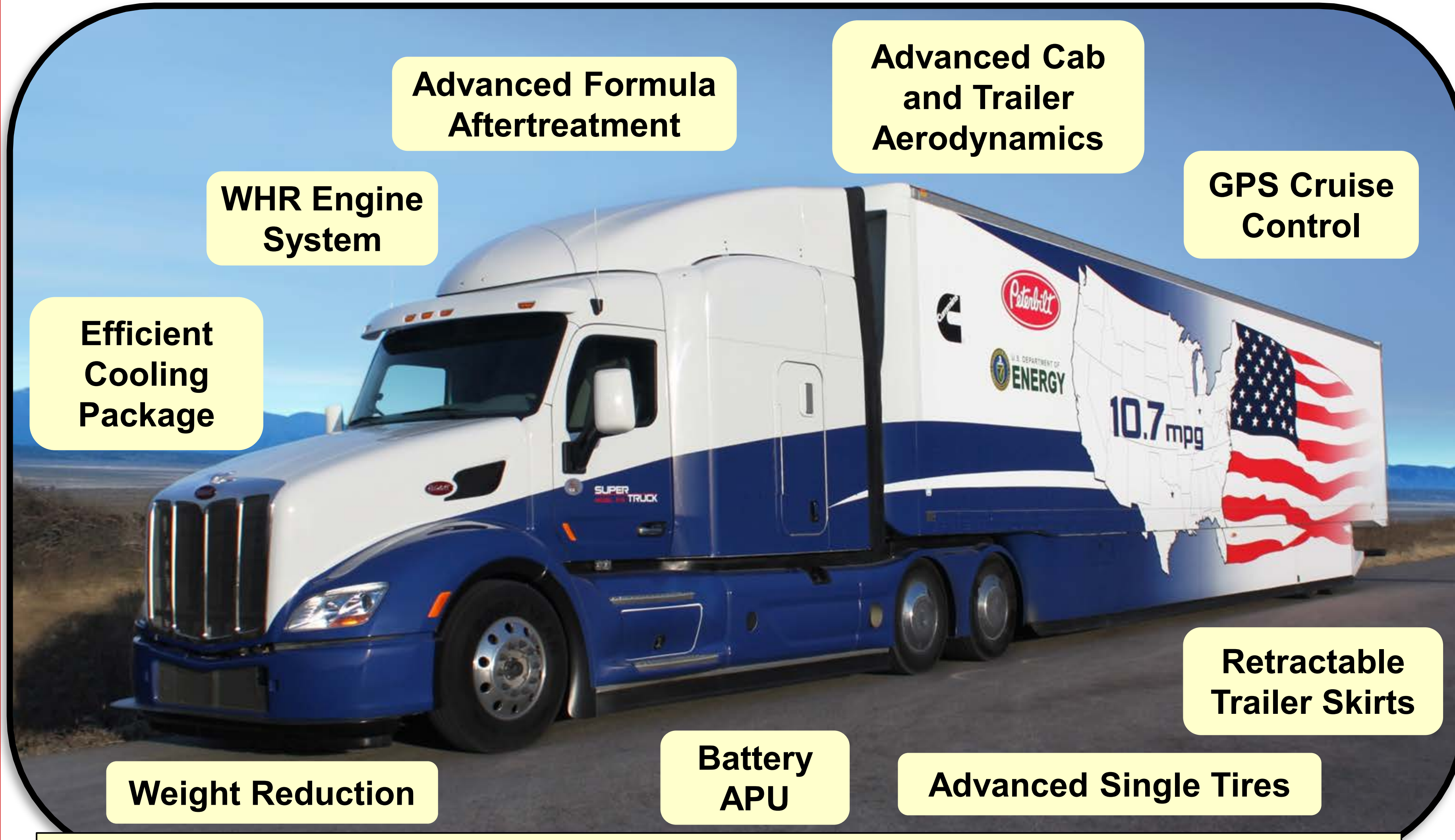
4 — Drivetrain
Urban: 5-6%
Interstate: 2-4%
Eaton & Dana

3 — Rolling Resistance
Urban: 8-12%
Interstate: 13-16%
Bridgestone & Goodyear

Weight Reduction

Analyze: Where is the energy going? Identify priority.

Technical Accomplishments - Freight Efficiency Enabling Technologies



Reference: Objective 2

- Vehicle details are included in Peterbilt's 2013 AMR presentation ARRA-081

Technical Accomplishment –
24 hour Freight Efficiency Test Results

86% Freight Efficiency Improvement

75% Fuel Efficiency Improvement

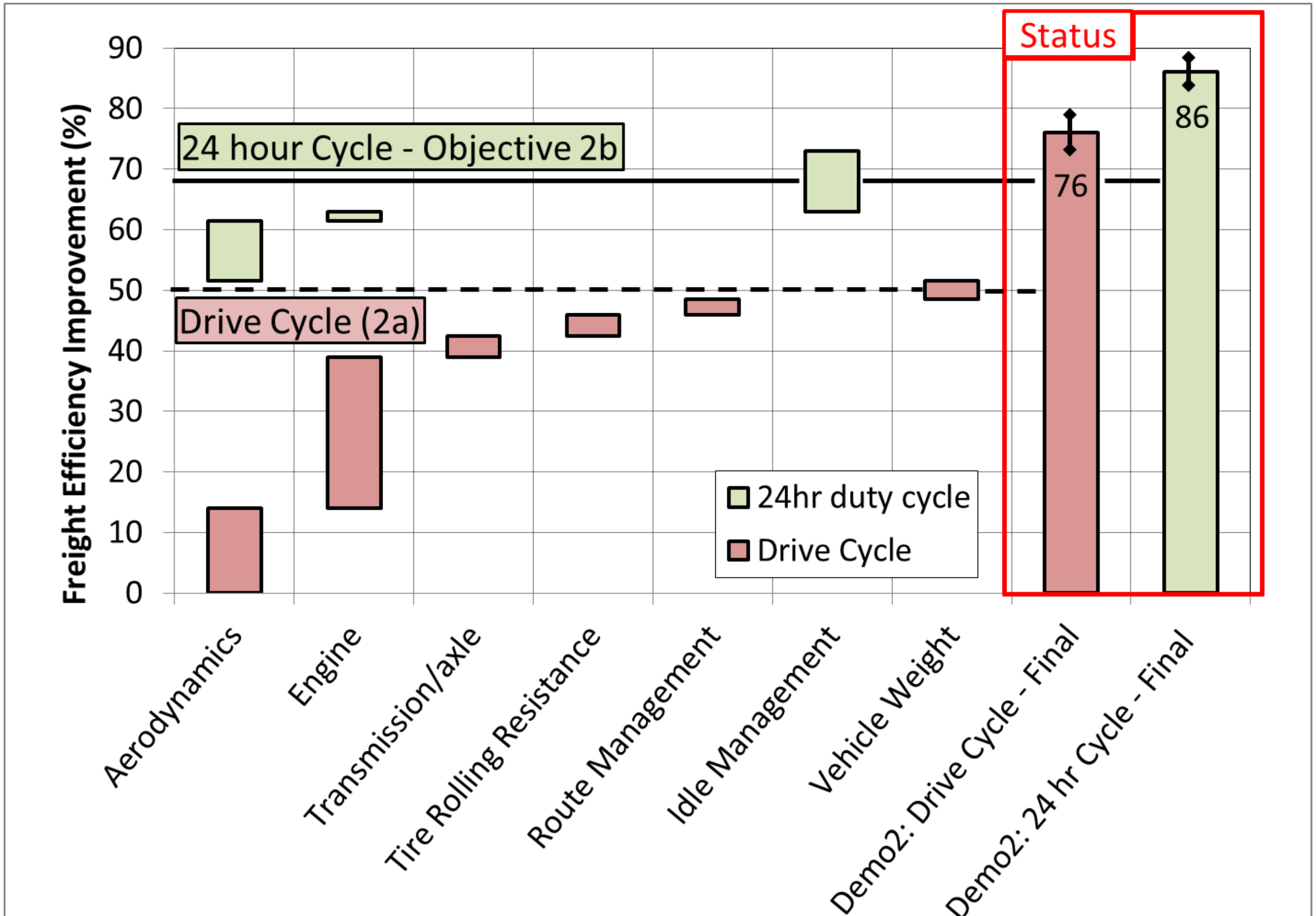
43% CO_2 Reduction

SuperTruck @ DoE Headquarters – 19Feb2014

Reference: Objective 2

- Vehicle details are included in Peterbilt's 2013 AMR presentation ARRA-081

Technical Accomplishment – Freight Efficiency Status



Reference: Objective 2

- Vehicle details are included in Peterbilt's 2013 AMR presentation ARRA-081

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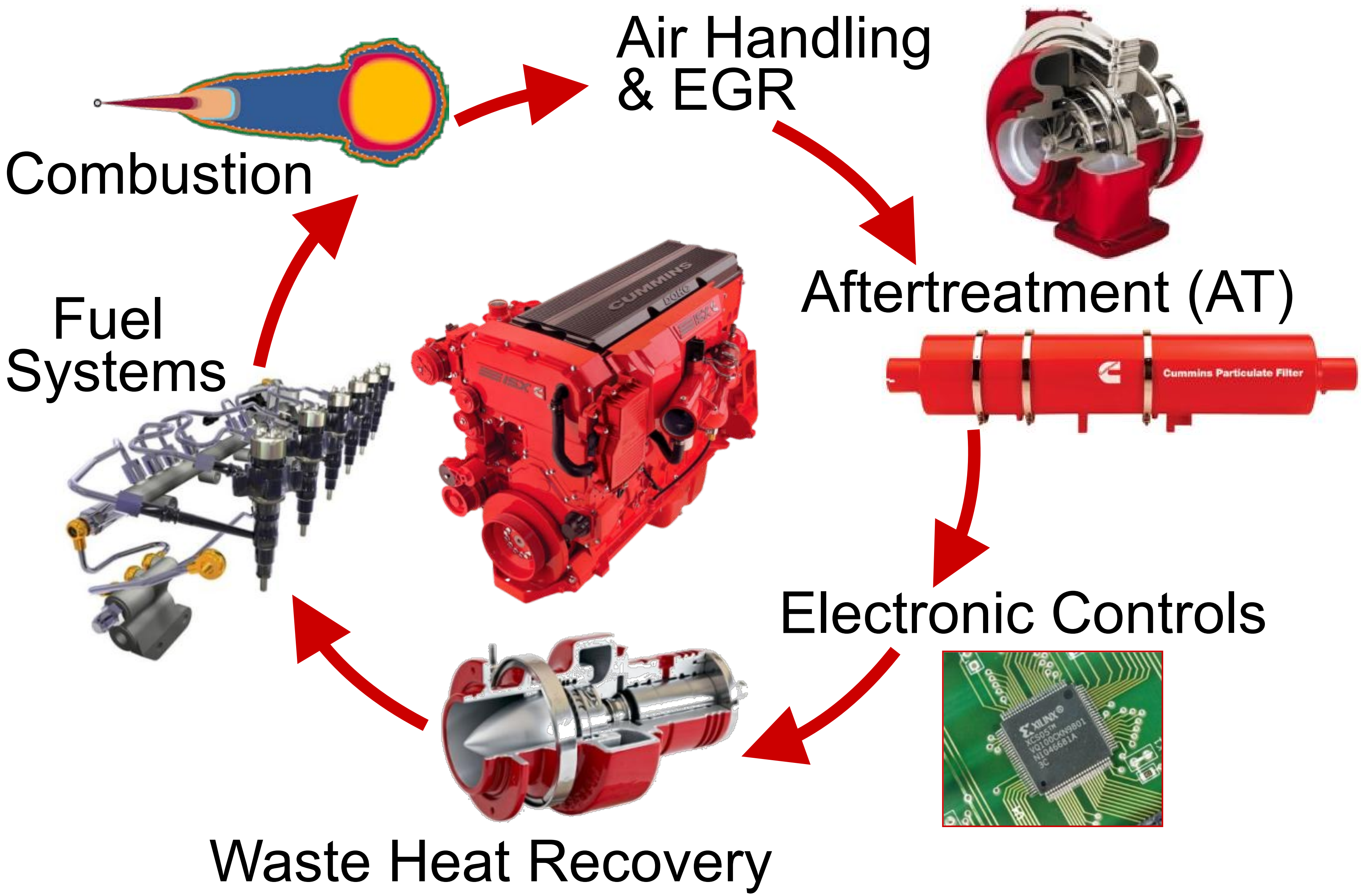
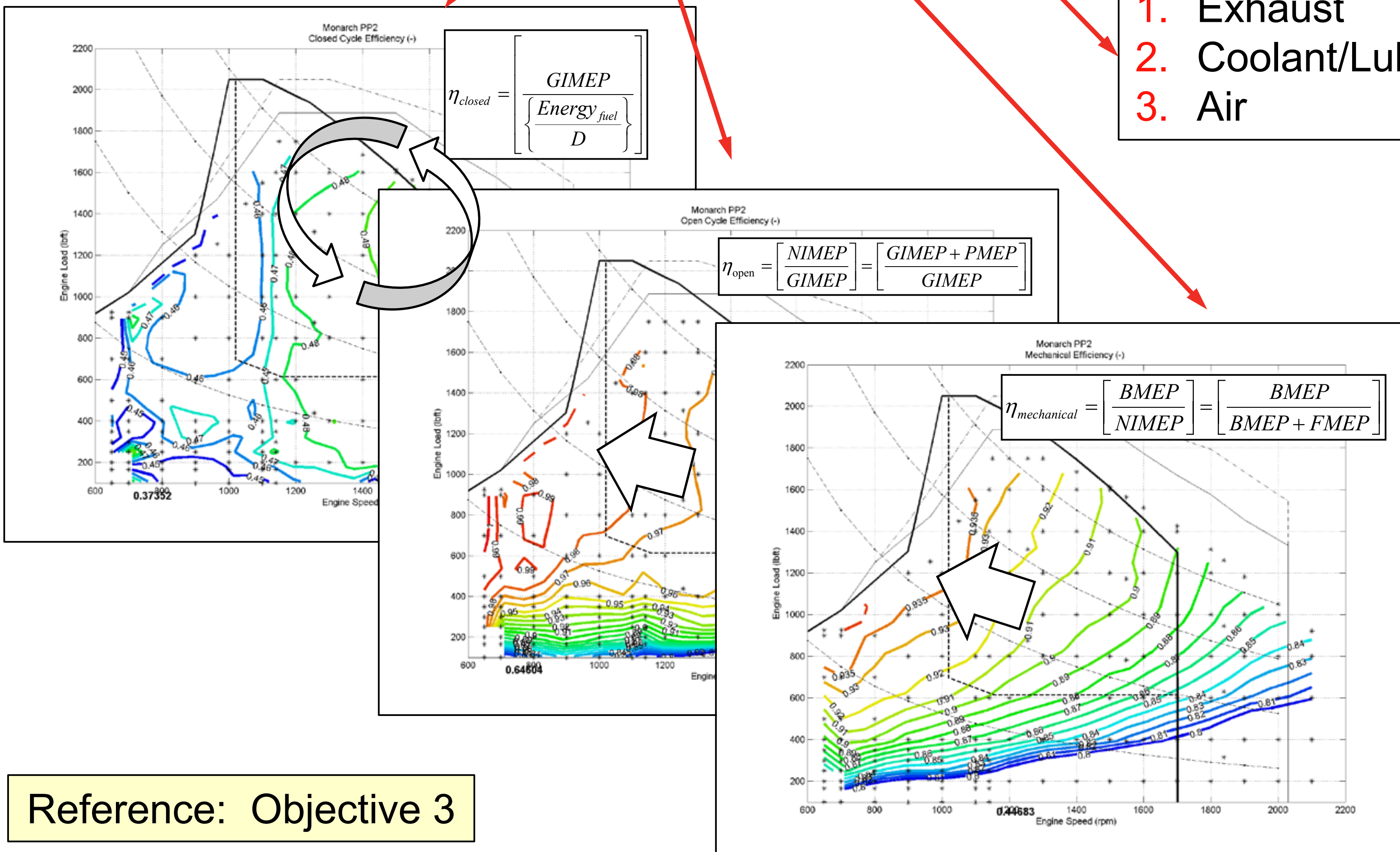
Approach - Integration of Cummins Component Technologies



Approach – 55% Thermal Efficiency

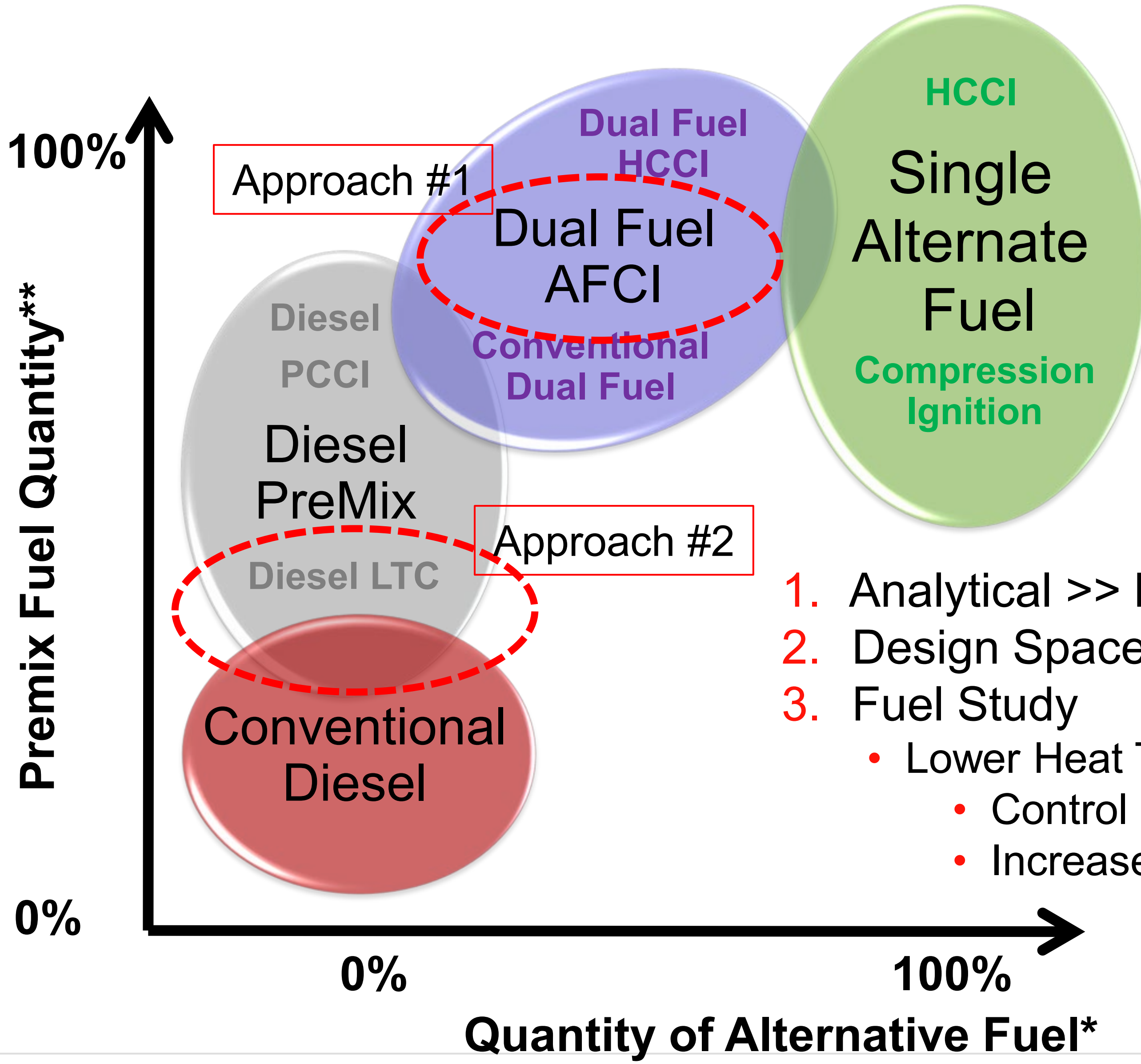
$$\eta_{thermal} = \eta_{closed} * \eta_{open} * \eta_{mechanical} + WHR$$

1. Exhaust
2. Coolant/Lube
3. Air



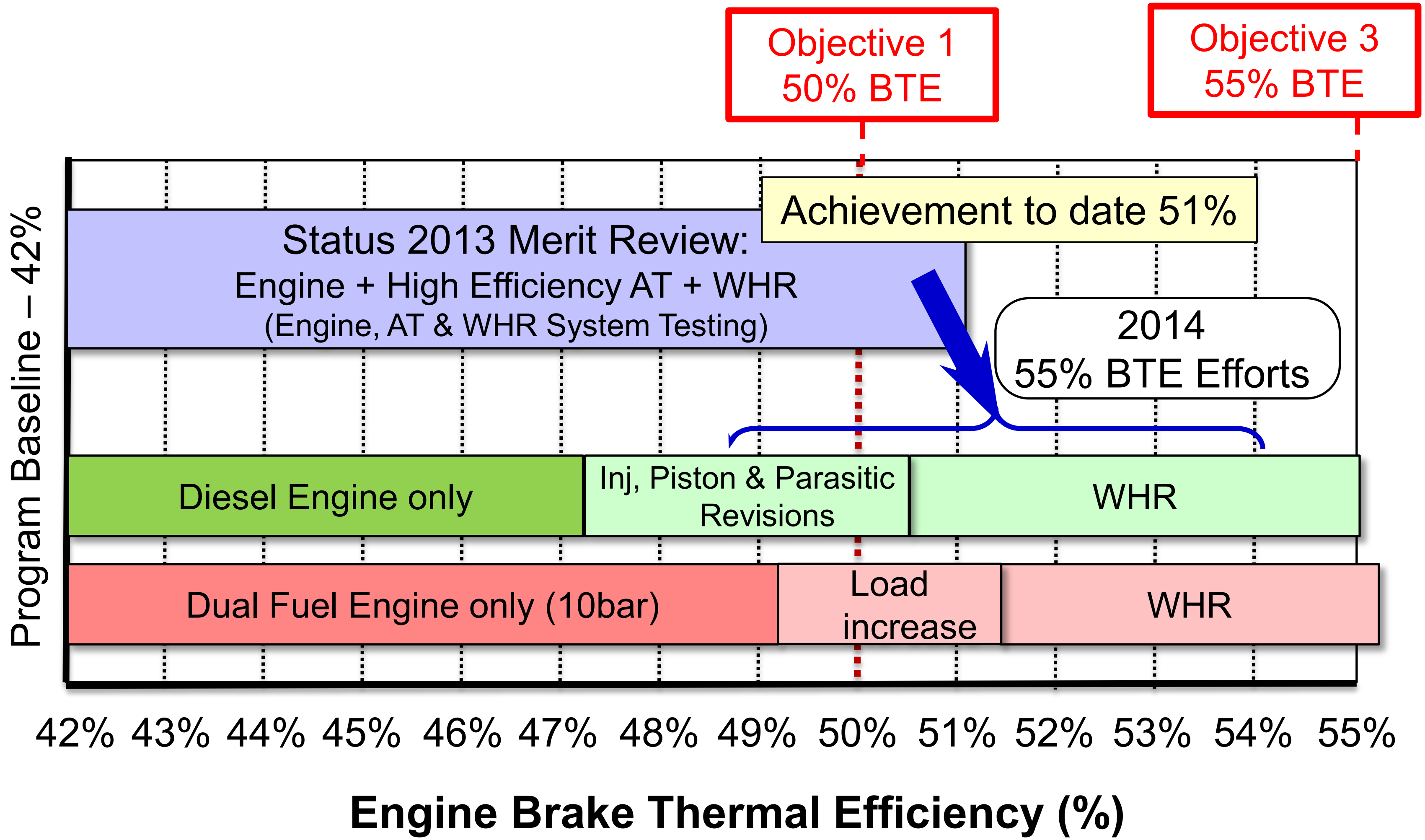
Reference: Objective 3

Approach – 55% Engine Technology Scoping - Fuels



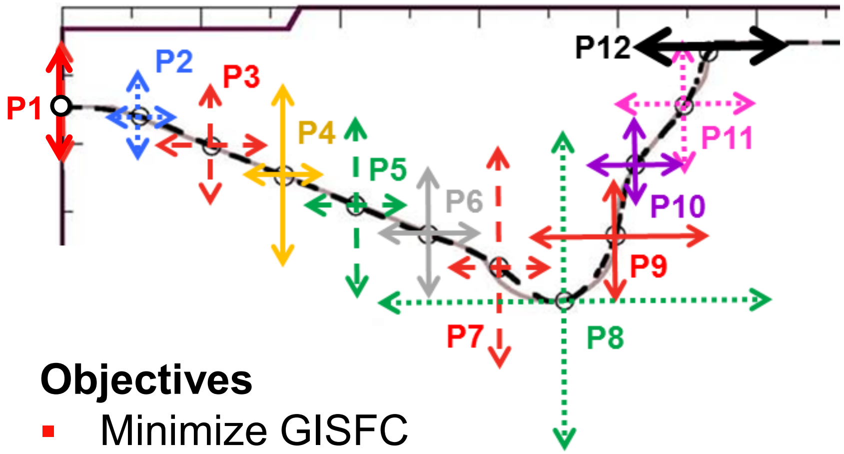
1. Analytical >> Experimental
2. Design Space is Broad
3. Fuel Study
   - Lower Heat Transfer
     - Control Burn Duration
     - Increase Effective Expansion

Technical Progress - Improvements
(Based on Engine, AT & WHR Testing)



*WHR - Cummins Organic Rankine Cycle Waste Heat Recovery

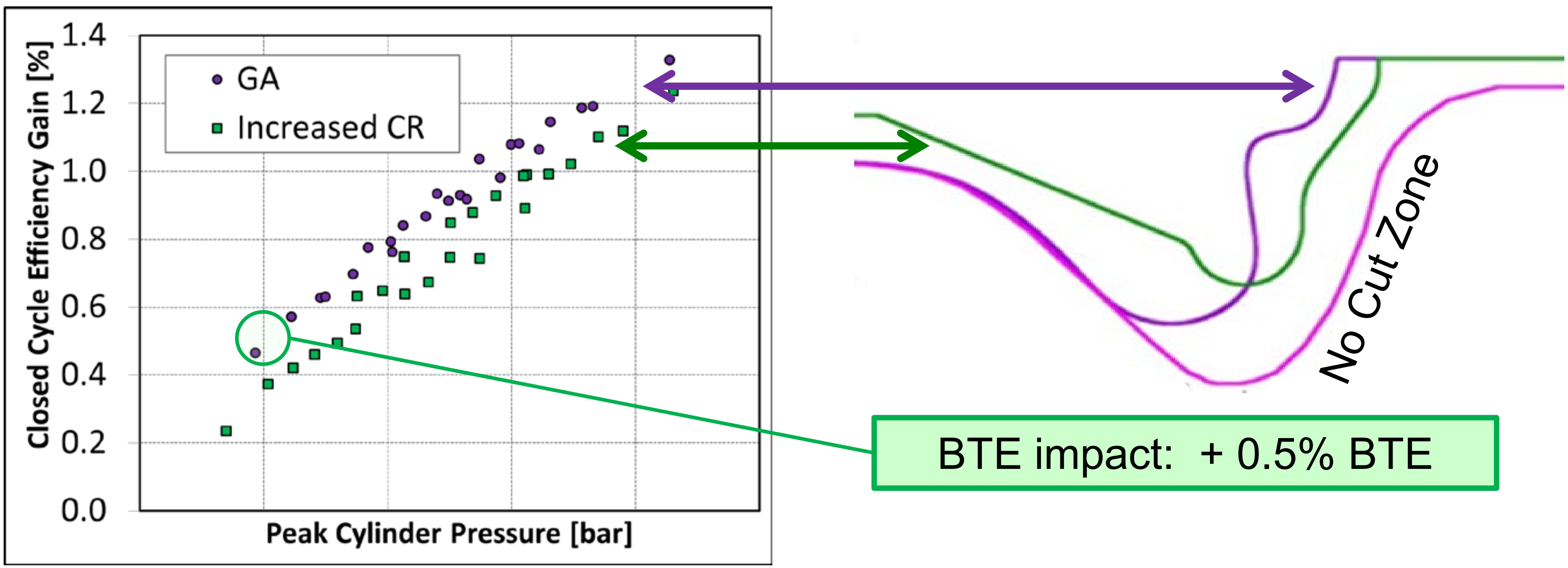
Technical Progress
Optimized Piston Bowl – Genetic Algorithm



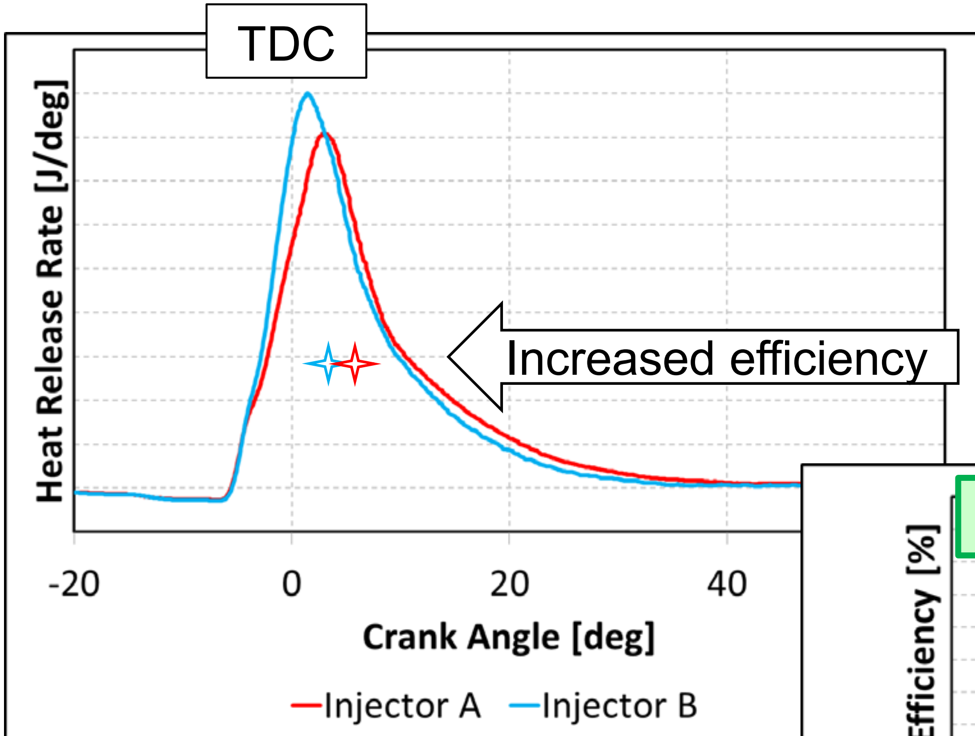
- 131 bowl generations computed
  - Compression ratio increase
- Optimized profile outperformed

Objectives

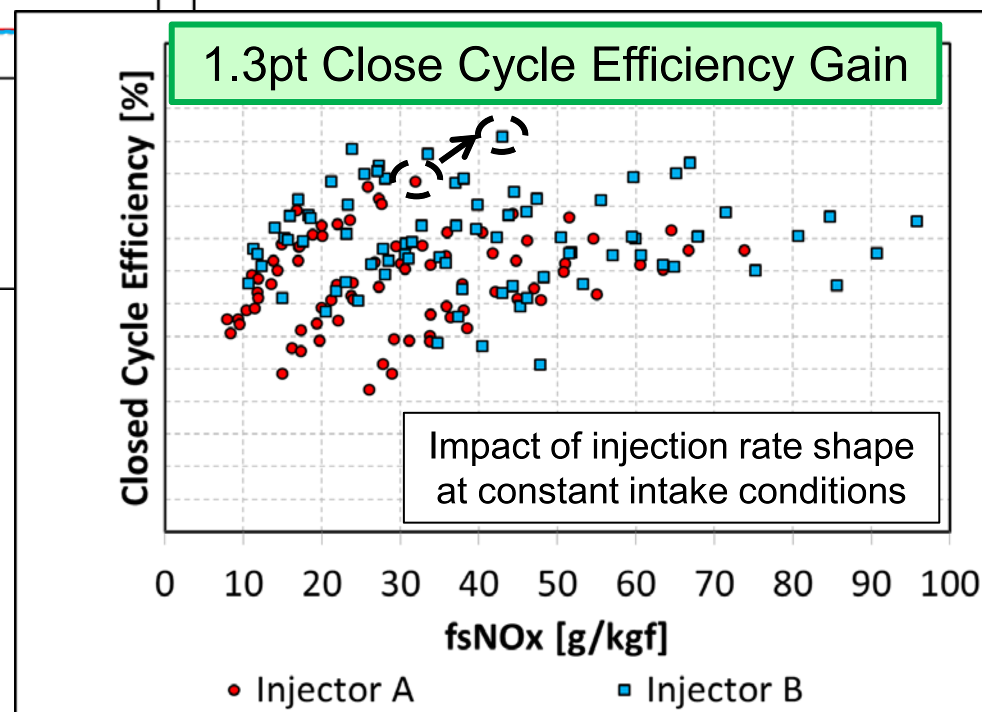
- Minimize GISFC
- Constrain NOx, PM, Peak Cylinder Pressure



Technical Progress
Optimized Injector – Single Cylinder Engine



- Injection rate shape revised with injector specification
  - Controls combustion heat release rate



- Seeking to minimize combustion duration
- Seeking to control combustion phasing for optimum efficiency

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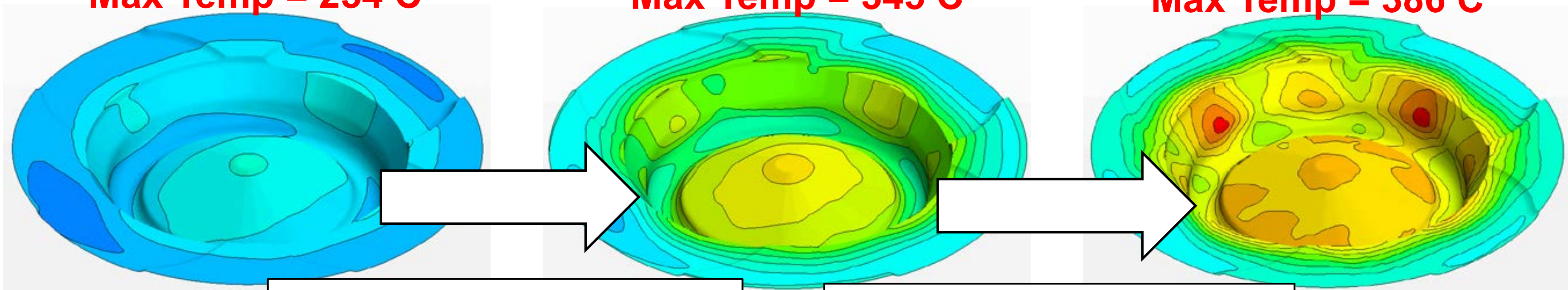
Technical Progress – Piston Thermal Solutions

Base Piston: Max Temp = 254 C

Piston A: Max Temp = 345 C

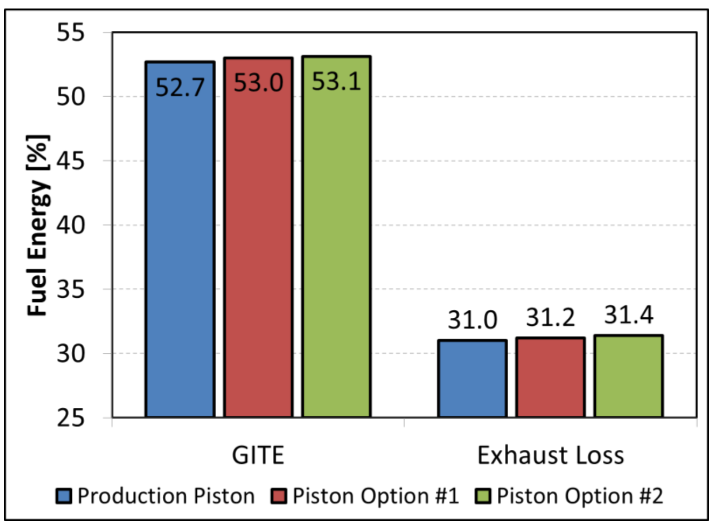
Piston B: Max Temp = 386 C

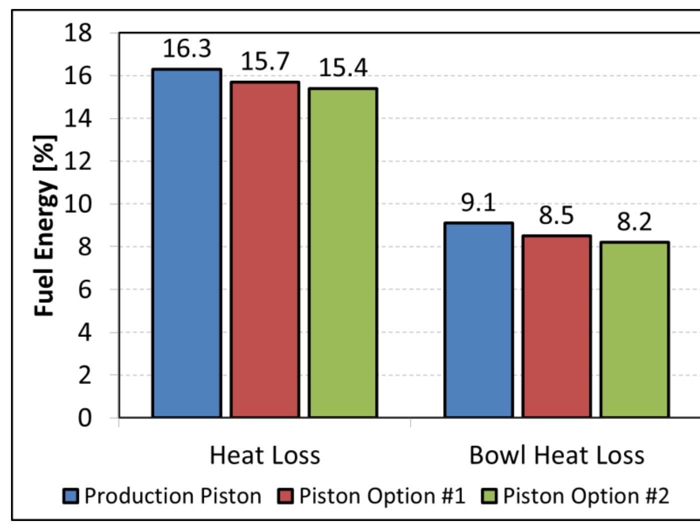


0.6 pt heat loss reduction
0.3 pt GITE improvement

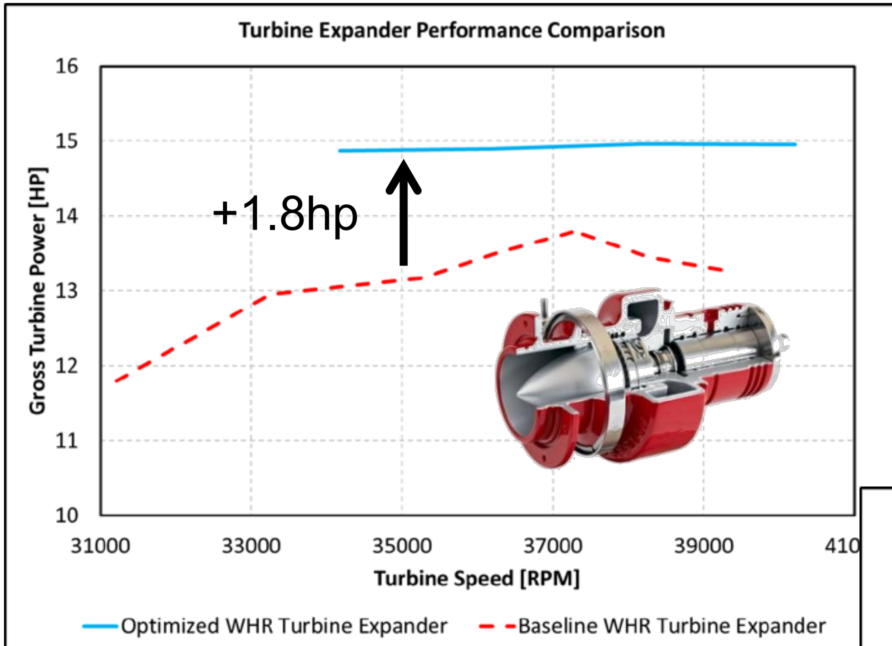
0.3 pt heat loss reduction
0.1 pt GITE improvement

BTE impact: + 0.8% BTE





Technical Progress –
Improved WHR Turbine Expander & Parasitic Reductions

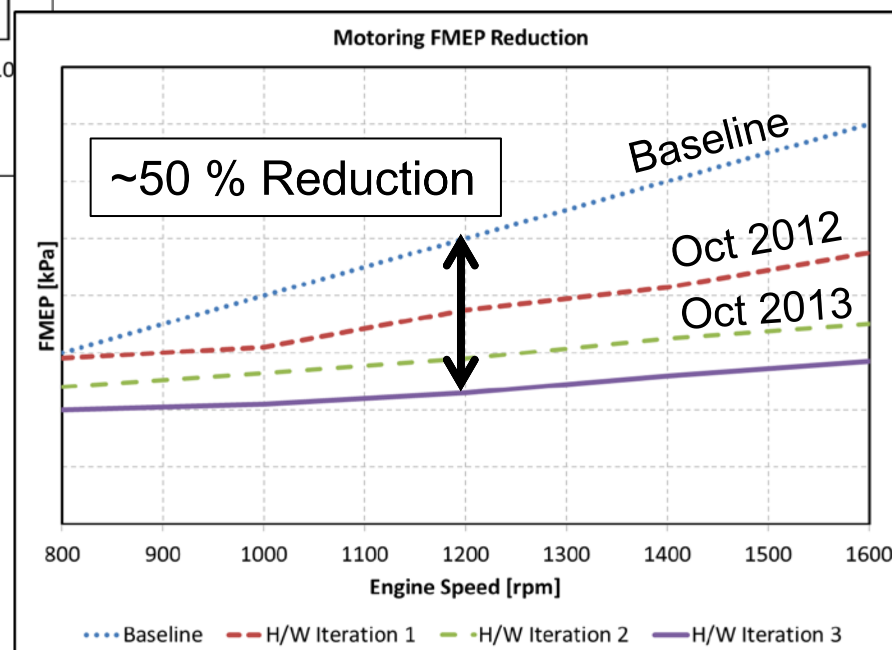


- Improved turbine efficiency
- System heat exchanger architecture arrangement
  - Pre-heat of low pressure loop

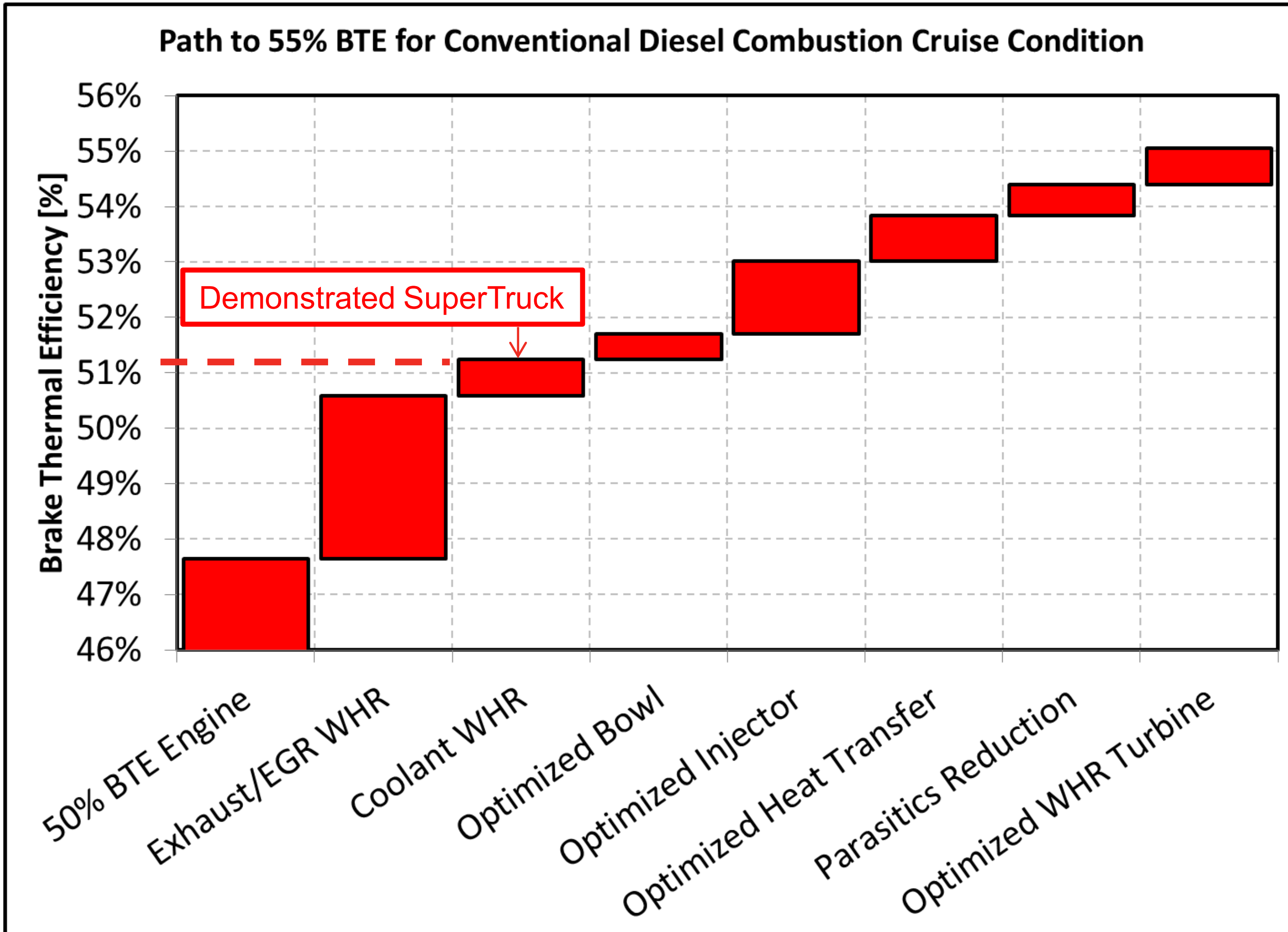
BTE impact: + 0.7% BTE

- Friction and Parasitic reduction
  - Piston/ring pack/liner changes
  - Piston cooling flow reduction
  - Main & rod bearing

BTE impact: + 0.6% BTE



Technical Progress
Conventional Diesel Path to 55% BTE



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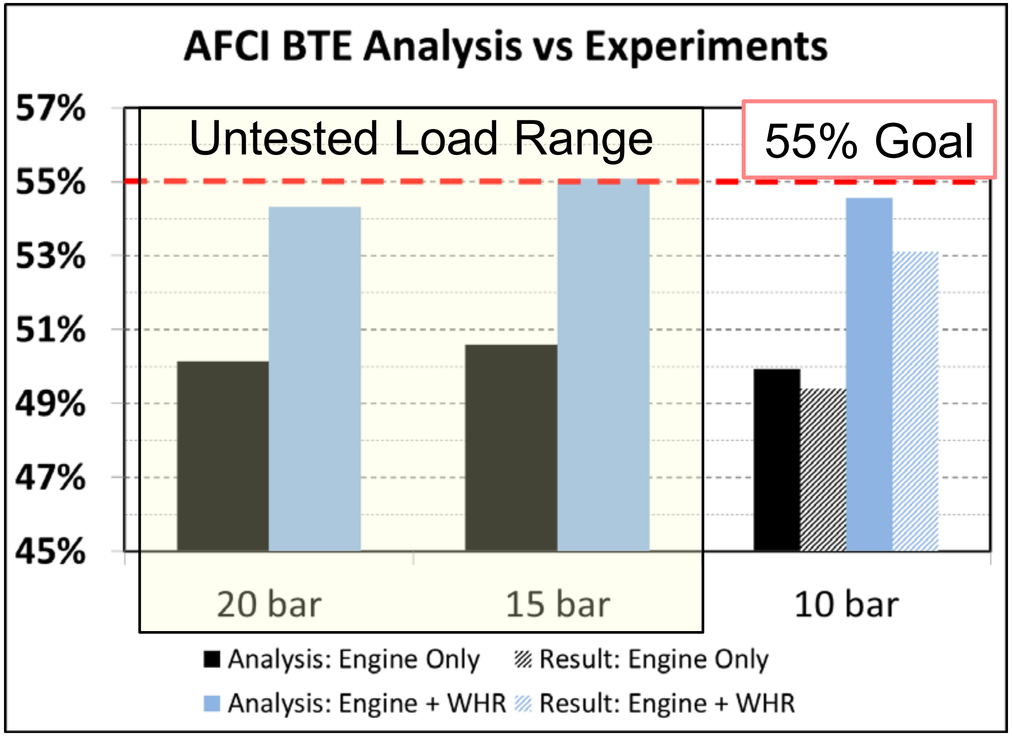
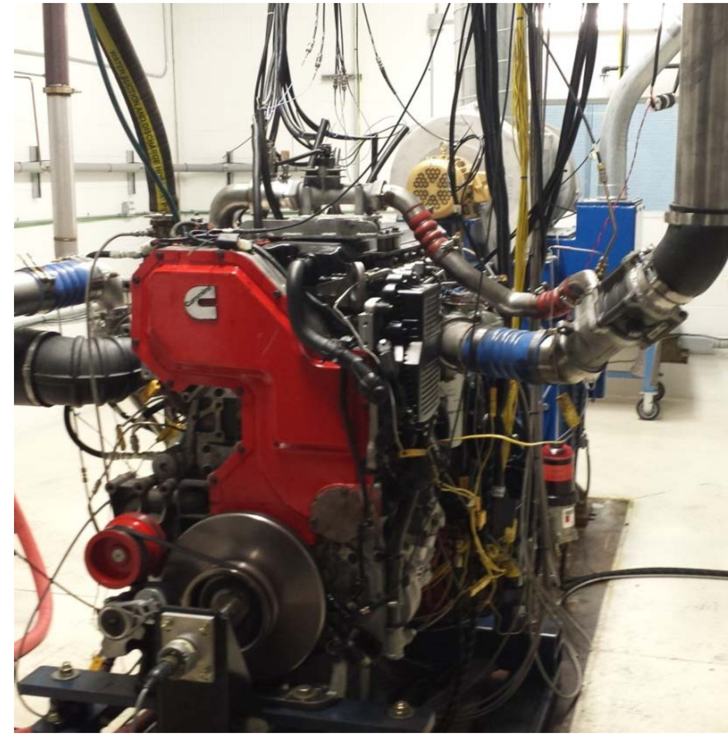
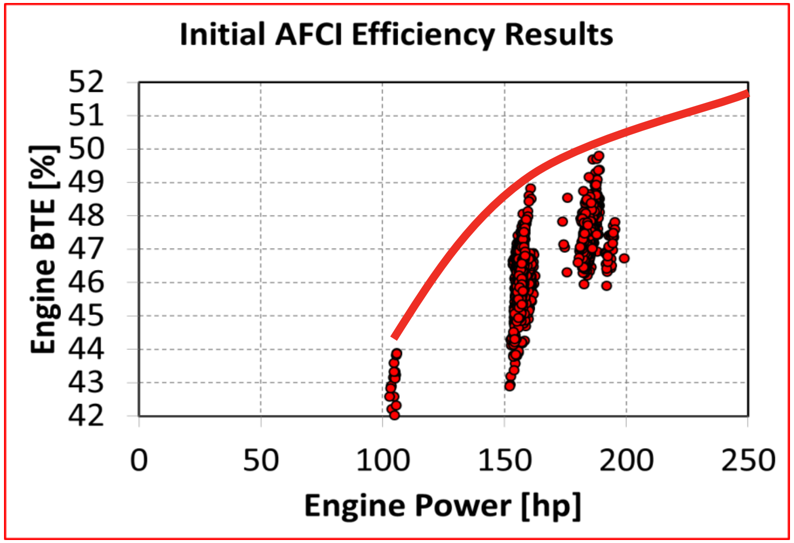
Technical Progress - Alternate Fuel Compression Ignition (AFCI) – Analysis to Experiment Status



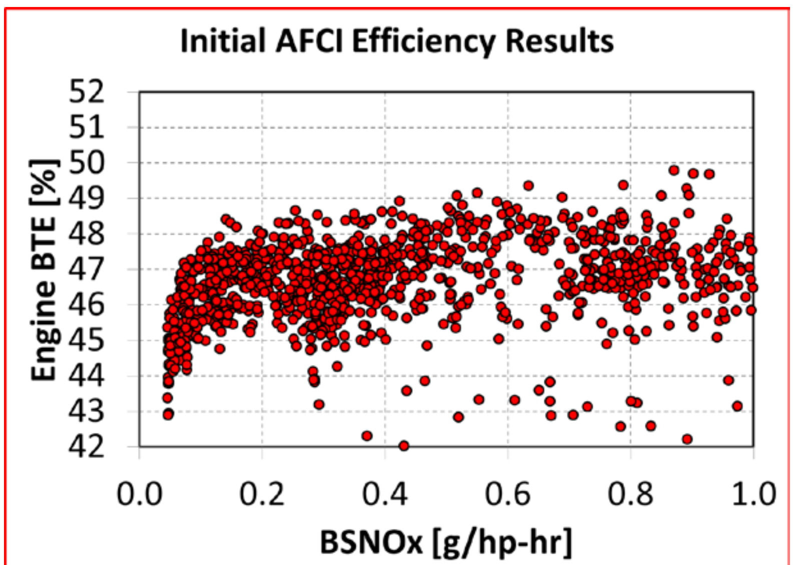


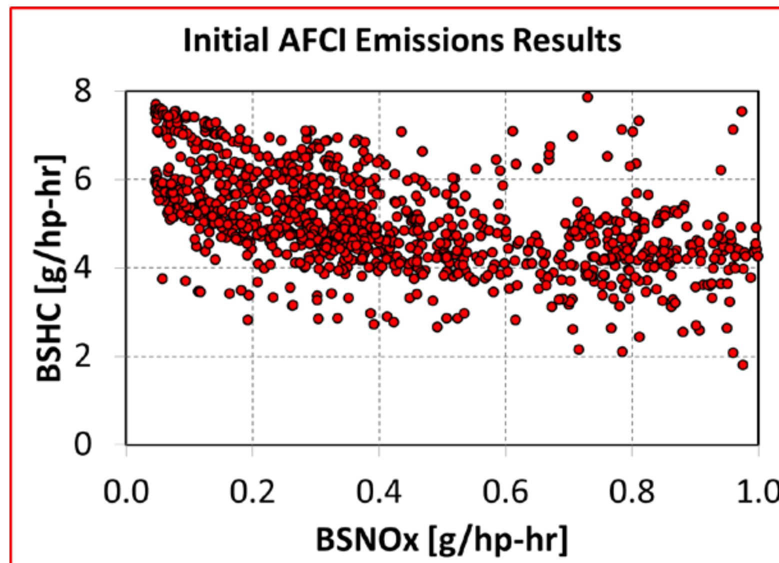
- Experiments align to analysis
  - Analysis showed peak efficiency between 14 to 16bar
  - Temperature sensitivities observed
    - Control system compensation algorithms helpful to manage cyl-cyl variation
    - ORNL probe test for residual gas & Tivc
- WHR estimates revised to experimental heat availability

Technical Progress
AFCI Efficiency and Emission Capability



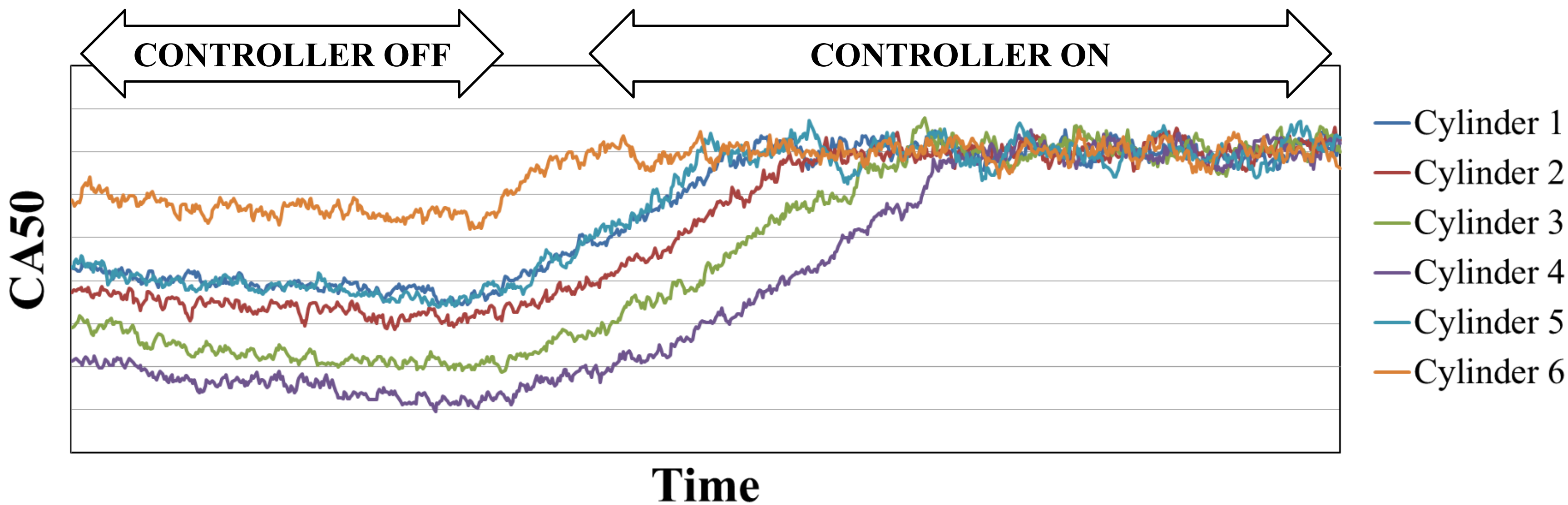
- Demonstrated AFCI engine efficiency of 49.4% BTE
- NOx emission low
- HC emission reasonable for DOC formulations





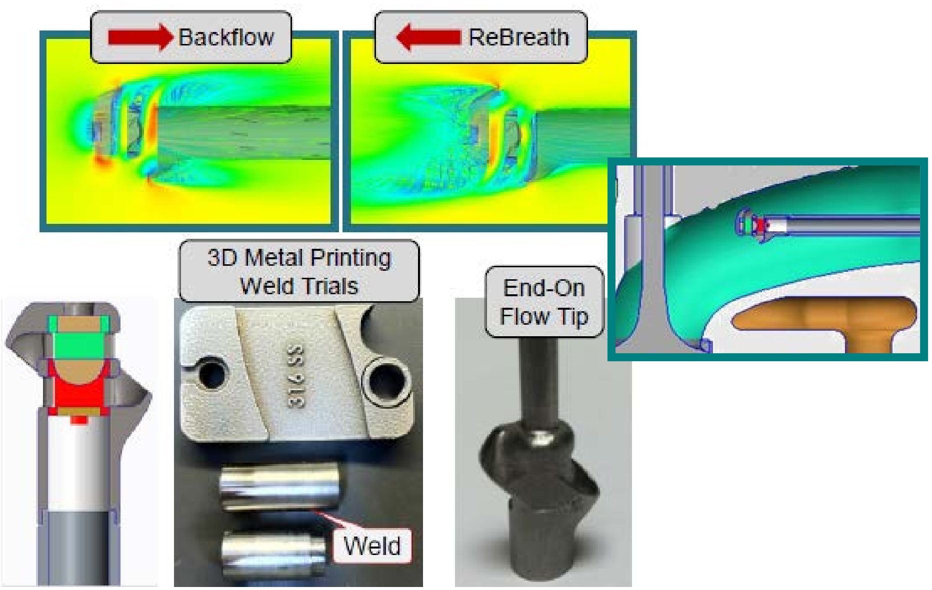
Technical Progress
AFCI Combustion Phasing Control

- Combustion phase control system developed
  - Cylinder-to-Cylinder & Cycle-to-Cycle controller
  - Enables independent control
    - Maximized overall multi-cylinder engine capability
    - Robustness to cylinder-to-cylinder and cycle-to-cycle variations



Collaborations– ORNL & Purdue Participation

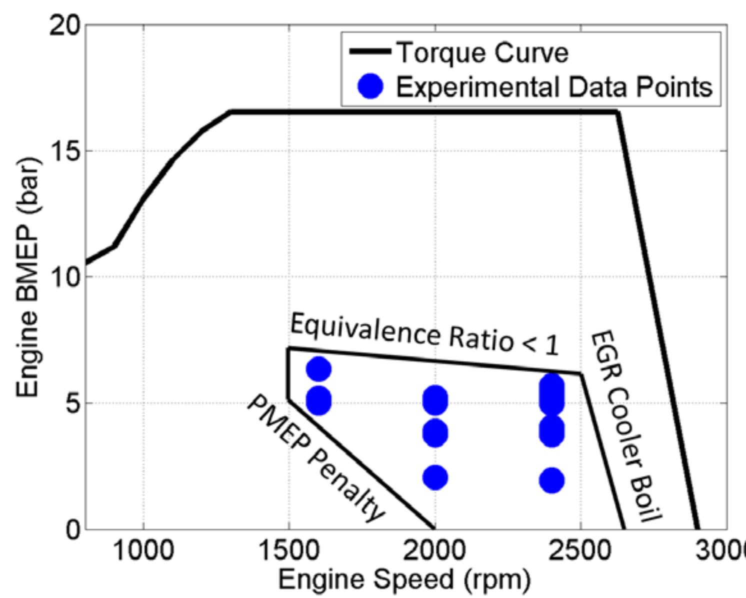
- ORNL
  - Sensing methods for model development and validation of:
    - Tivc determination
      - EGR fraction
      - Residual fraction



Modeling & Simulation

Presented: ACE077 - Partridge

- Purdue University
  - Completed diesel PCCI study
    - Explore range expansion
  - Diesel engine VVA
    - Commissioned intake & exhaust VVA test bed
    - VVA functional analysis



Reviewer Comments and Responses

Many complimentary comments:

- *Project had accomplished objectives on time to date*
- *Observed a large project team, incorporating laboratories, industry and universities.*

Recommendations:

- *Cautioned that the 55% goal approach relied upon HCCI and dual fuel, where these two technologies have not been experimentally proved to be BTE improvement friendly technologies. The reviewer warned that while dual fuel showed some promising feature, high pumping loss and stability control for transient operation was too tough to overcome. Both technologies suffered high HC emissions. The contractor should demonstrate the technical feasibility with preliminarily convincing data at the current level.*
  - Comments: We are taking both a conventional diesel and a dual fuel approach. Our analysis path last year had identified a viable path with dual fuel. Over the course of last year, our efforts toward advancing conventional diesel has shown a viable conventional diesel path.
- Cautioned that reliance on dual fuel was risky for a 55% goal, partially due to high HC and CO emissions for cold start.
  - Comments: Dual fuel would start on diesel. Emission and speciation sampling during our dual fuel testing has shown HC emission that are reasonable for effective and efficient conversion with a conventional diesel oxidation catalyst (see 2014 slide 20).
- *The reviewer commented that Slide 20 only showed two key partners for technical progress (i.e., ORNL and Purdue University), while Slide 7 showed a large number of partners. The information was kind of misleading in terms of collaboration and coordination.*
  - Comments: As the prime PI, I try to give a program perspective of the overall related partnerships, i.e. 2013 Slide 7, however, the details of this presentation focused more detail on those collaborations and partnerships pertinent to our engine related activities, i.e. 2013 slide 20.

Milestones and Technical Accomplishments

- March 2013 to March 2014 – **Technical Accomplishments**
  - √ Demonstrated 86% freight efficiency improvement (Objective 2b – 24hr)
    - √ 75% fuel economy increase
  - √ Demonstrated 76% freight efficiency improvement (Objective 2a – Drive)
    - √ 66% fuel economy increase
  - √ Demonstrated Li-Ion Battery & SOFC capability
  - √ Completed wind tunnel and vehicle testing of Waste Heat Recovery
  - √ Validated an advanced transmission efficiency model
  - √ Path-to-Target analysis for a 55% thermal efficient engine
    - √ Demonstrated AFCI 'engine only' efficiency of 49.4% BTE @ 10bar (Objective 3)
- March 2014 to September 2014 – **Future Work**
  - – 55% BTE path to target roll-up analysis (Objective 3)
    - Targeted verification testing

Summary

- Program remains on schedule
  - Meeting the ARRA and DoE VT MYPP goals
- Demonstrated a 50+% BTE engine system (Objective 1)
- Demonstrated a 70+% vehicle freight efficiency gains (Objective 2a & 2b)
  - Analytical roadmaps updated with experimental component data
  - Built and tested sub-systems
    - Cummins Waste Heat Recovery vehicle testing (Objective 2a)
    - Advanced transmission dynamometer and vehicle test (Objective 2a)
    - Solid Oxide Fuel Cell APU in lab and vehicle tests (Objective 2b)
    - Li-Ion battery APU (Objective 2b)
    - Tractor-Trailer aerodynamic aids (Objective 2a)
- Developed framework and analysis for 55% thermal efficiency
  - Completed analytical roadmaps for both diesel and dual fuel approaches
  - Completing targeted engine tests to validate roadmaps
- Developed working relationship with excellent vehicle and engine system delivery partners

Technical Back-Up Slides

Participants – Who's doing what
Roles and Responsibilities

Participant	Responsibility
Cummins Inc.	• Prime contractor • Team coordination • Engine system • Vehicle system analysis
Peterbilt Motors Co.	• Vehicle Build Coordination • Vehicle Integration • Tractor-Trailer Aero • Freight efficiency testing
Cummins Turbo Technology	Turbomachinery & WHR power turbine
Cummins Fuel Systems	Fuel system
Cummins Emissions Solutions	Aftertreatment
Eaton	Advanced transmission
Delphi	Solid Oxide Fuel Cell idle management technology
Bendix	Reduced weight brake system and drive axle control

Participant	Responsibility
Bridgestone & Goodyear	Low rolling resistance tires
Modine	WHR heat exchanger & vehicle cooling module
U.S. Xpress	• End User Review • Driver Feedback • Commercial Viability
Oak Ridge National Laboratories	Fast response engine & AT diagnostic sensors
Purdue University	• Low temp combustion • Control models • VVA integration
VanDyne SuperTurbo	Turbocompounding/ Supercharging
Utility Trailer	Lightweight Trailer Technology
Dana	Lightweight Drivetrain Technology
Bergstrom	HVAC
Logena	Network interface

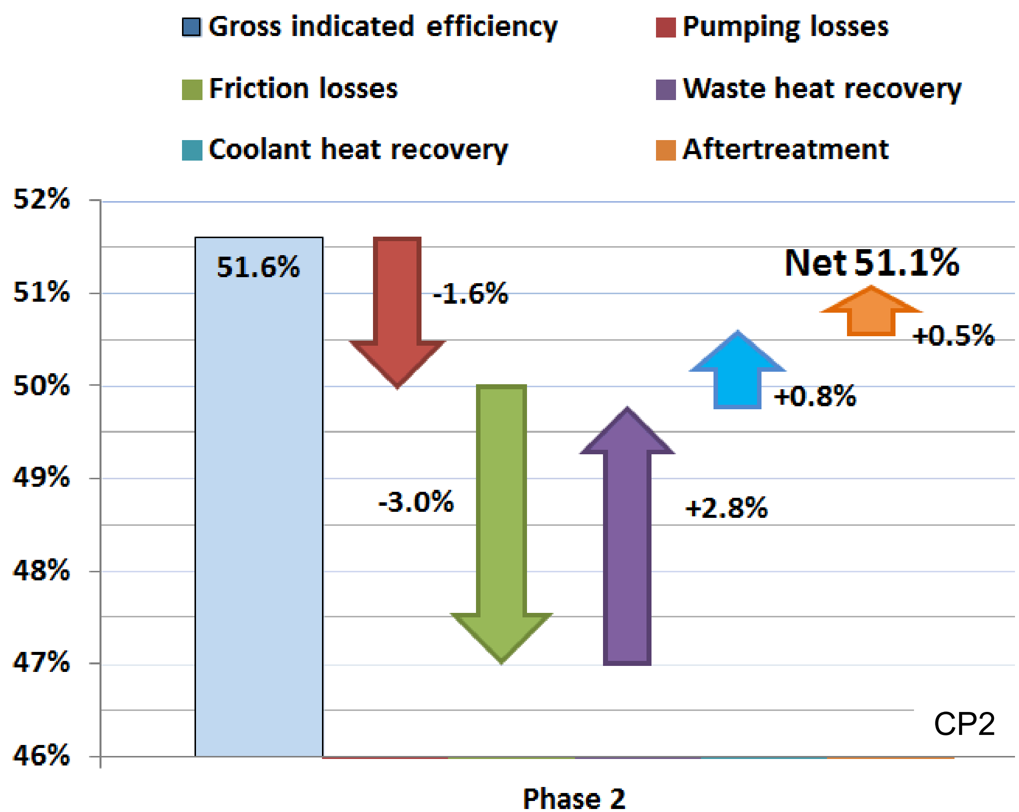
Technical Accomplishments – 50+% Thermal Efficiency Gains

Gross indicated gains
- Comp. ratio increase
- Piston bowl shape
- Injector specification
- Calibration optimization

Gas flow improvements
- Lower dP EGR loop
- Turbocharger efficiency

Parasitic reductions
- Shaft seal
- VF Lube pump & viscosity
- Geartrain
- Cylinder kit friction
- Cooling & fuel pump power

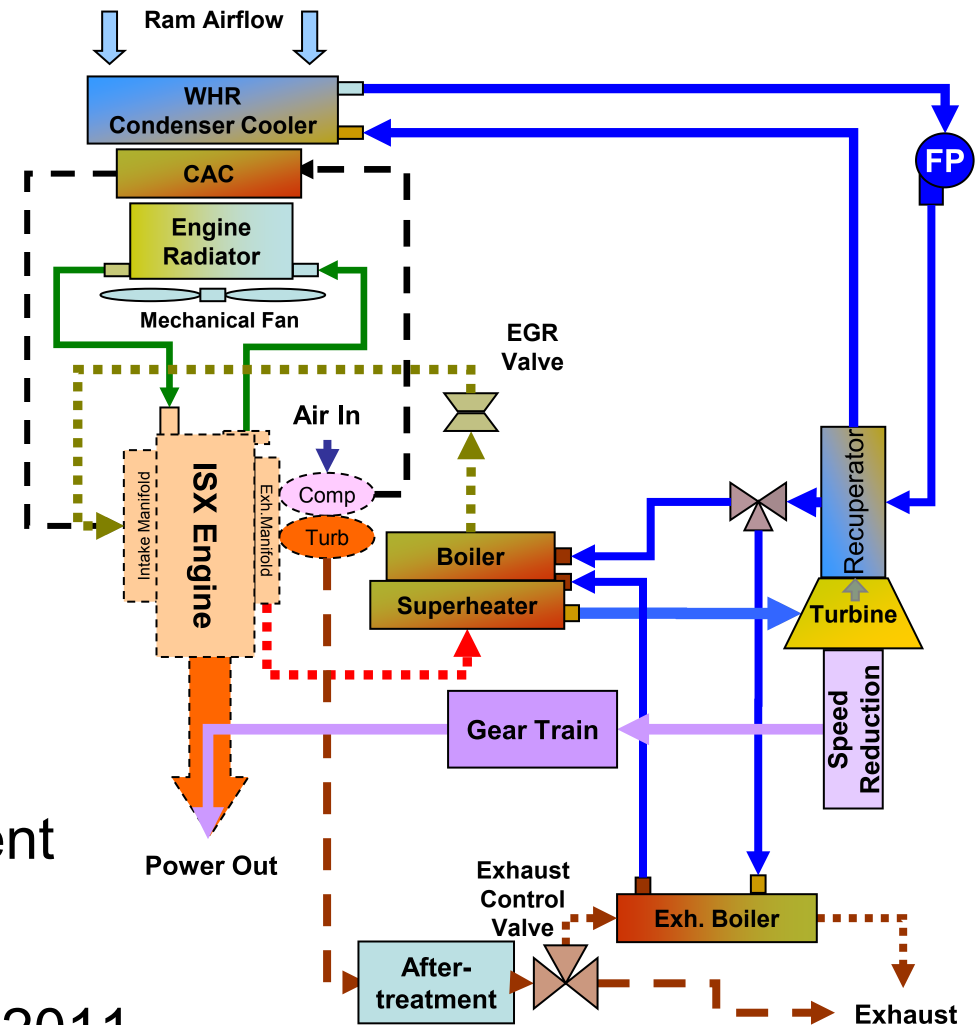
WHR system
- EGR, Exhaust, Recuperator
- Coolant & Lube



Reference: Objective 1

Cummins Waste Heat Recovery

- Organic Rankine Cycle
- Recovery of:
  - EGR
  - Exhaust heat
- Mechanical coupling of WHR power to engine
- Low global warming potential (GWP) working fluid refrigerant
- Fuel Economy improvement goal of ~6%
- 1st vehicle installation Sep2011



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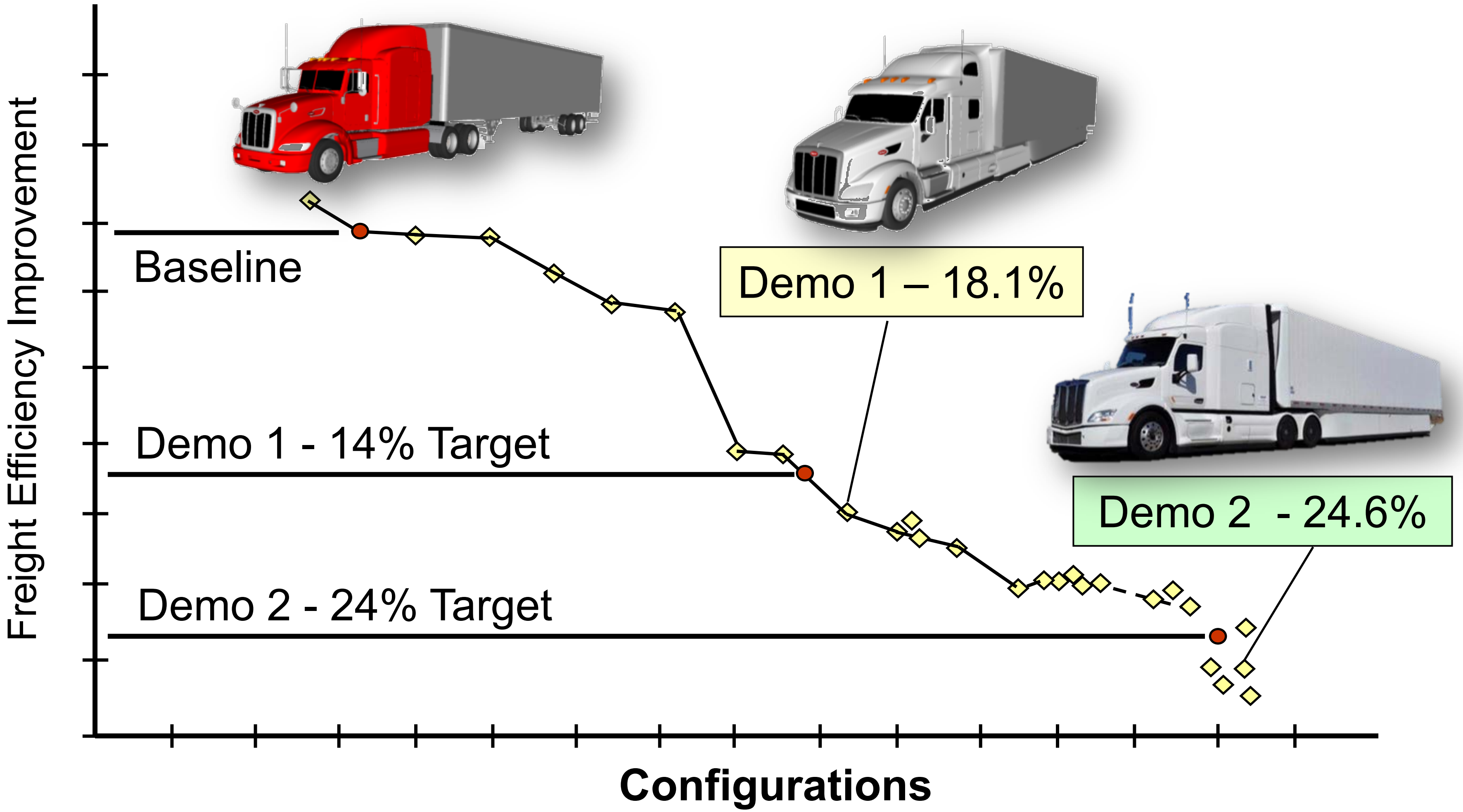
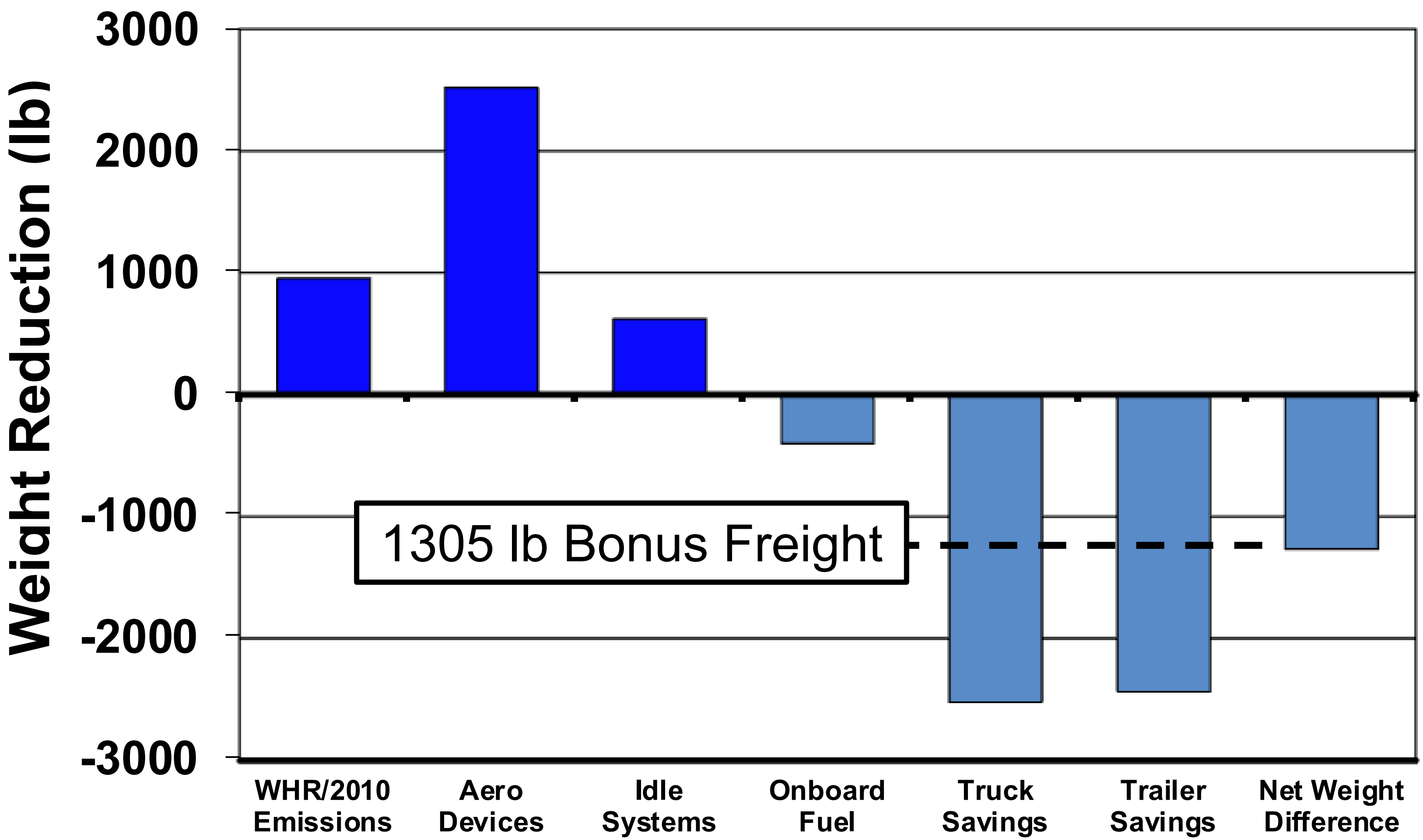
Vehicle Freight Efficiency of Aerodynamic Drag Reduction



* Cd's Shown Are Adjusted to SAE J1252 Baseline Using
% Average Deltas From 0 and 6 Degree CFD Runs

Vehicle Weight Reduction – Freight Efficiency Improvement



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