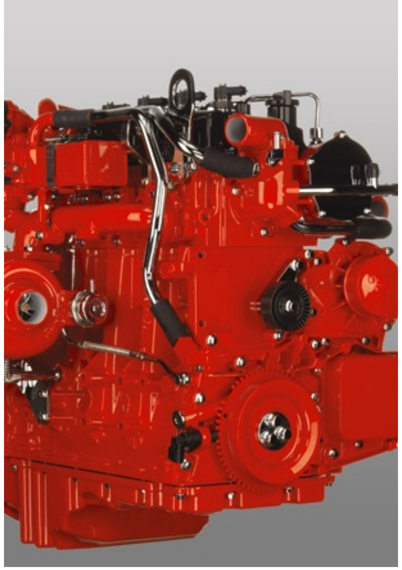
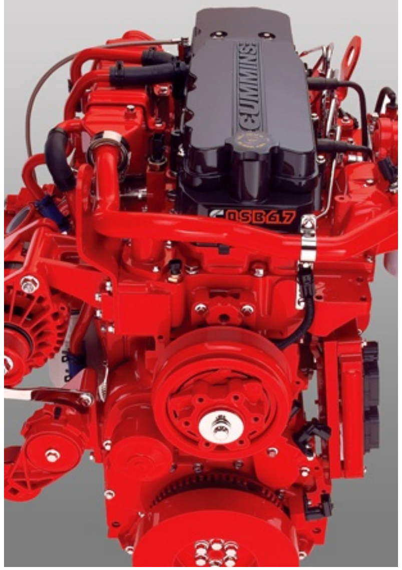
Cummins SuperTruck Program

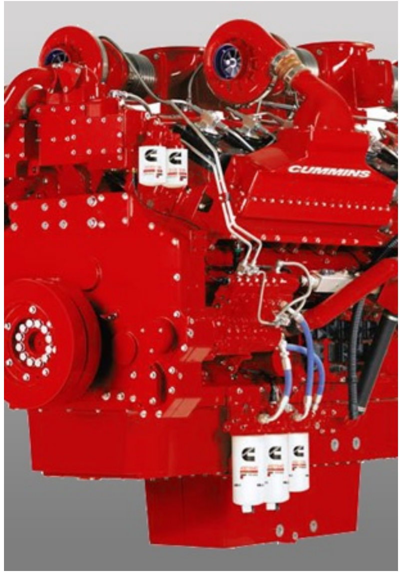
Technology and System Level Demonstration of Highly Efficient and Clean, Diesel Powered Class 8 Trucks

David Koeberlein- Principal Investigator
Cummins Inc.

May 16, 2013 **Project ID: ACE057**







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Relevance - Program Objectives
(DoE Vehicle Technologies Goals)

All Technologies must meet Current US EPA 2010
Emissions Standards and Transportation/Safety Standards

Objective 1: Engine Development

Engine system demonstration of 50% or greater BTE in a test cell at an operating condition indicative of a vehicle traveling on a road at 65 mph.

Objective 2: Vehicle Integration & Development

a: Tractor-trailer vehicle demonstration of 50% or greater freight efficiency improvement (freight-ton-miles per gallon) over a defined drive cycle.

b: Tractor-trailer vehicle demonstration of 68% freight efficiency improvement (freight-ton-miles per gallon) over a defined 24 hour duty cycle (above drive cycle + extended idle) representative of real world, line haul applications.

Objective 3: Engine Development

Technology scoping and demonstration of a 55% BTE engine system. Engine tests, component technologies, and model/analysis will be developed to a sufficient level to validate 55% BTE.

Baseline Vehicle and Engine: 2009 Peterbilt 386 Tractor
and Cummins 15L ISX Engine

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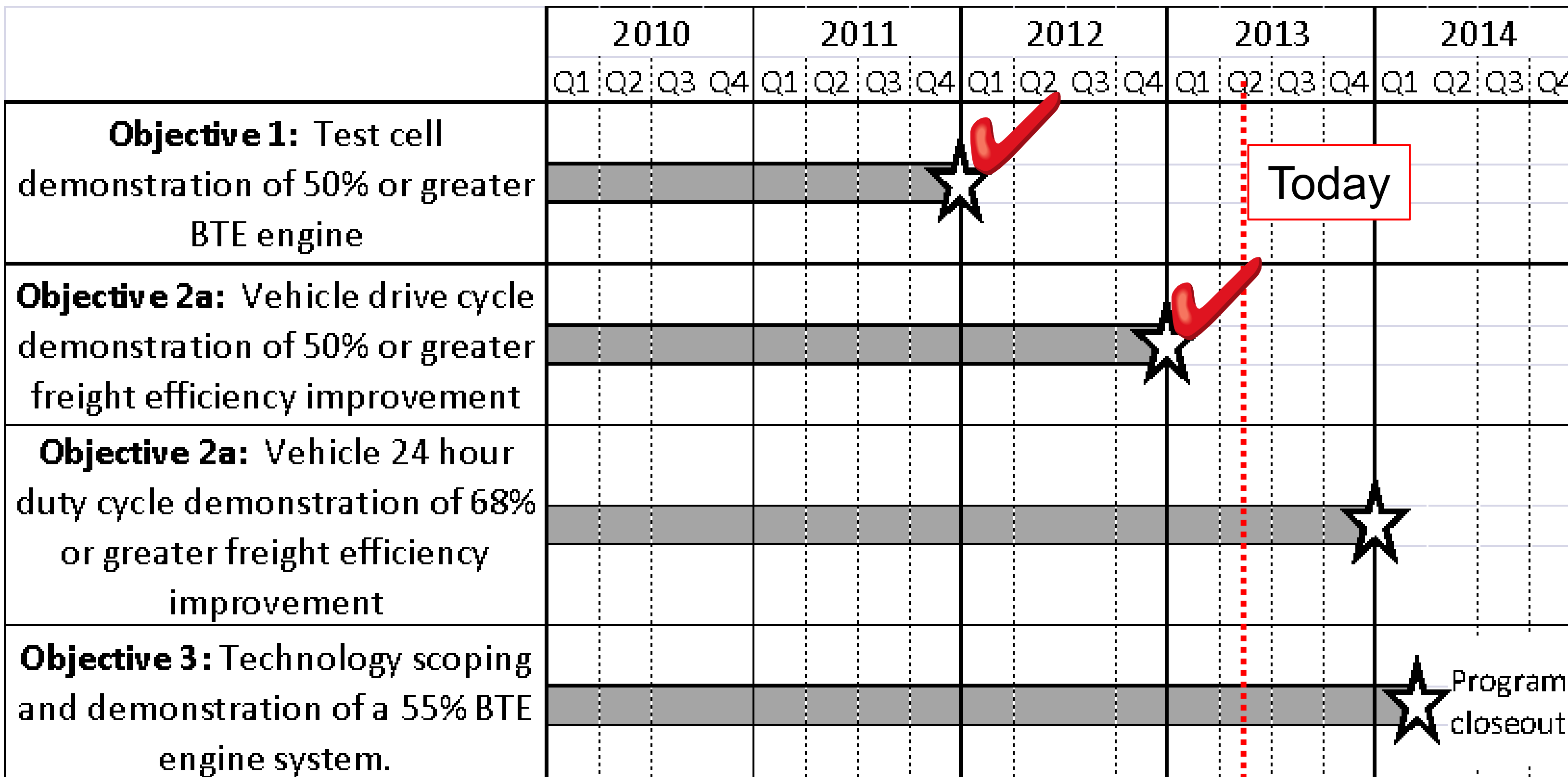
Overview - Program Schedule and Budget

Budget: DoE Share $38.8M (49%)
Contractor Share $40.3 M (51%)
$31 M total DoE share spend to date

4 Year Program: April 2010 to April 2014



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

Overview - Program Partners

Program Lead

Cummins Inc.

- Cummins Fuel Systems
- Cummins Electronics
- Cummins Turbo Technologies
- Cummins Emissions Solutions
- Cummins Filtration
- Modine
- Oak Ridge National Lab.
- Purdue University
- VanDyne SuperTurbo Inc.

Peterbilt Motors Company

- Eaton
- Delphi
- Modine
- Utility Trailer Manufacturing
- Bridgestone
- Goodyear
- U.S. Xpress
- Dana
- Bergstrom
- Logena
- Bendix

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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

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

- ARRA Goal: Create and/or Retain Jobs

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

Projections (2013)

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

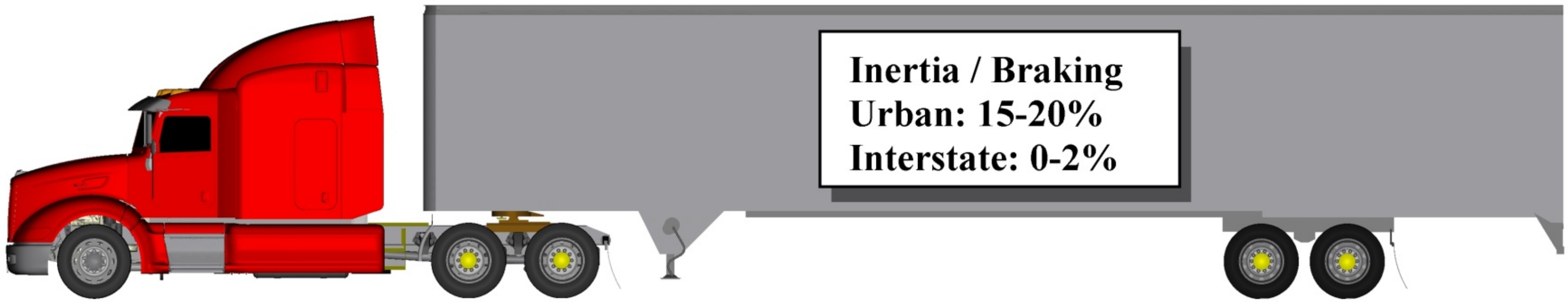
- ARRA Goal: Spur Economic Activity
  - Greater than $62M total spend to date
- Goals align with VT Multi-Year Program Plan 2011-2015
  - Advanced Combustion Engine R&D (ACE R&D):
    - 50% HD engine thermal efficiency by 2015 (ref: VT MYPP 2.3.1)
  - Vehicle and Systems Simulation and Testing (VSST):
    - 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

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



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.

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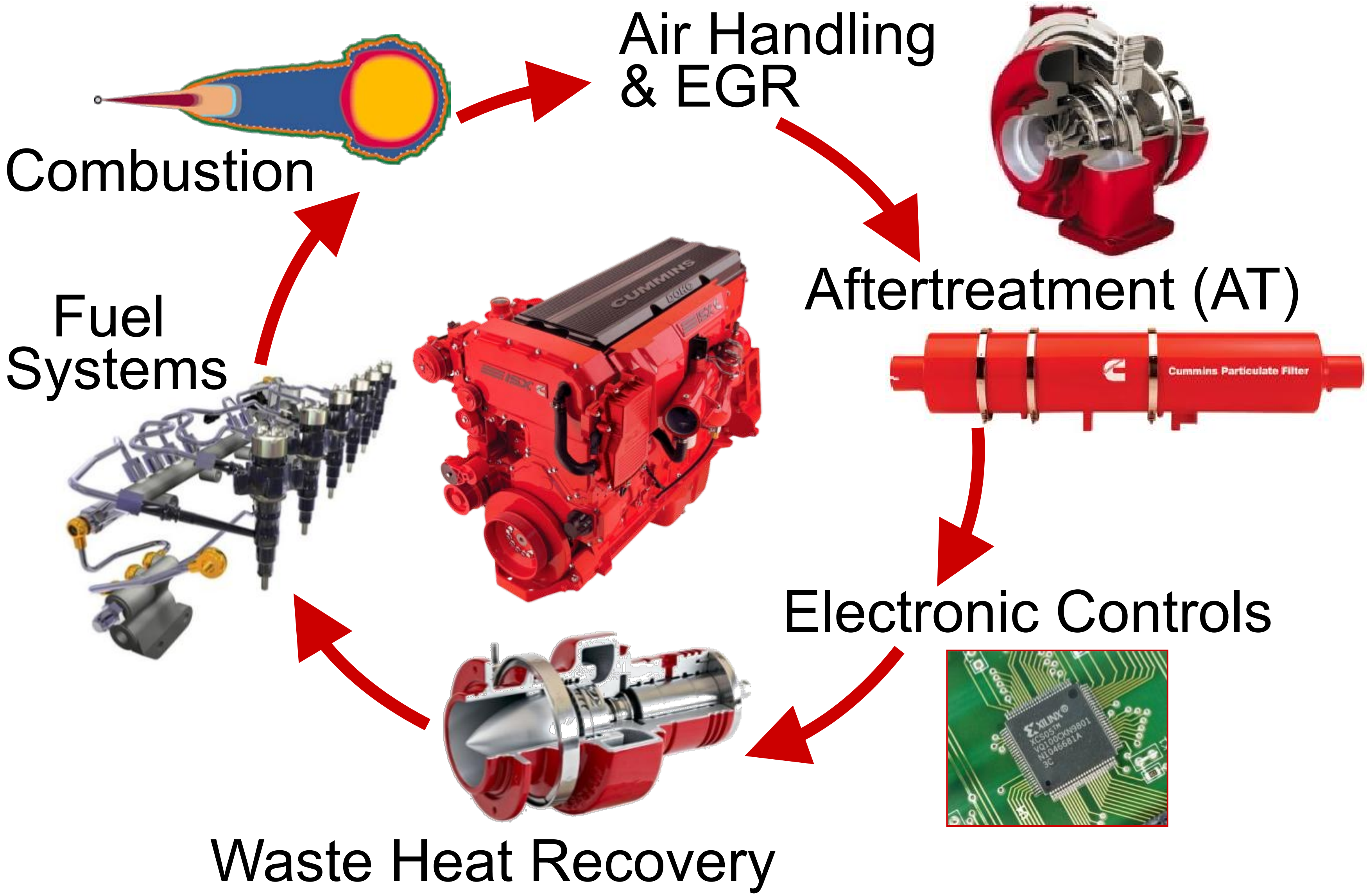
Approach - Integration of Cummins Component Technologies



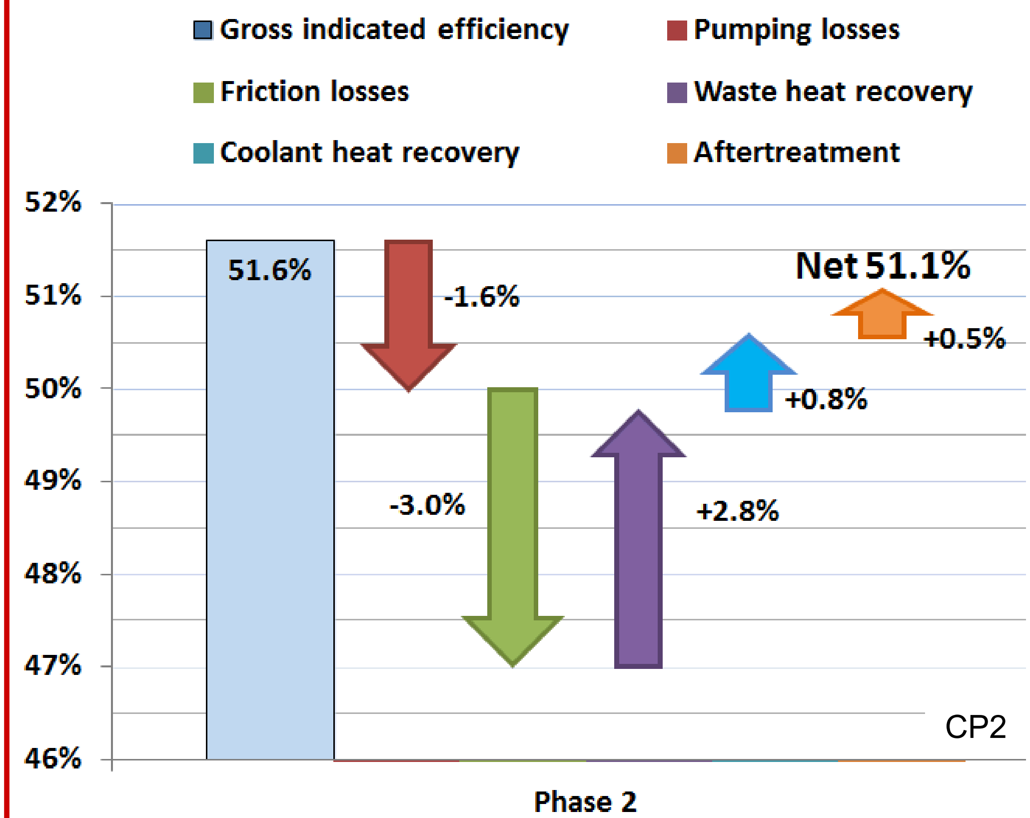
Technical Accomplishments – 50+% Thermal Efficiency Gains

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

Gas flow improvements
- Lower dP EGR loop
- Turbocharger efficiency

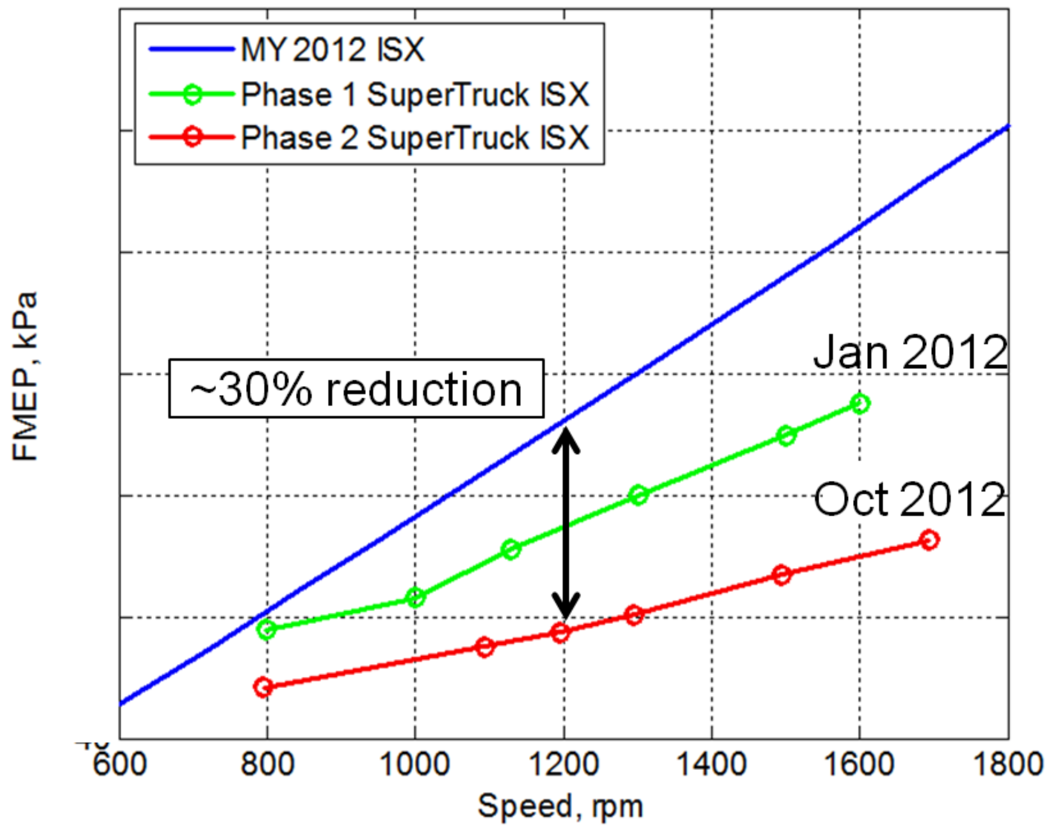
Parasitic reductions
- Shaft seal
- VF Lube pump & viscosity
- Geartrain
- Cylinder kit friction
- Cooling & fuel pump power

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



Reference: Objective 1

Engine Friction & Parasitic Reduction



- Mechanical efficiency improved
  - Improvements should be witnessed across speed/load map
    - Greatest efficiency improvements in the lower load portions of map

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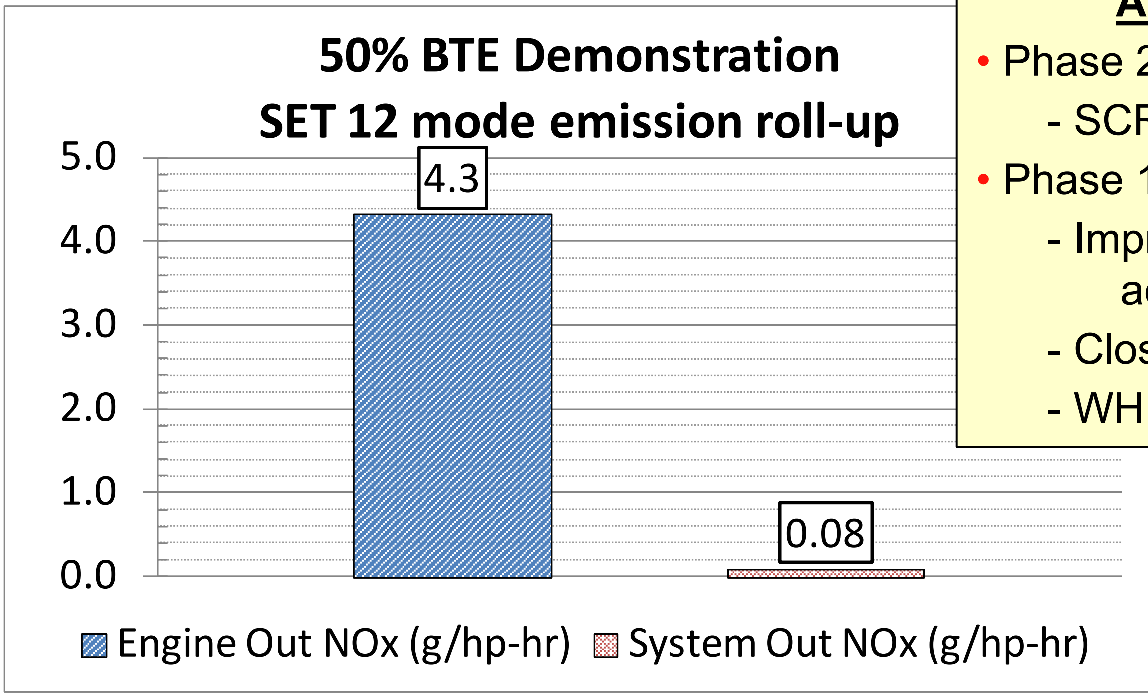
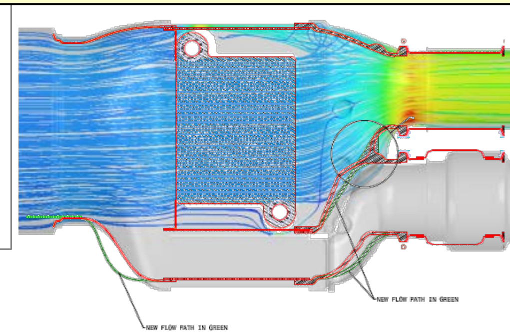
Technical Accomplishment – Supplemental Emission Test (SET) Weighted Modal Cycle NOx Emissions



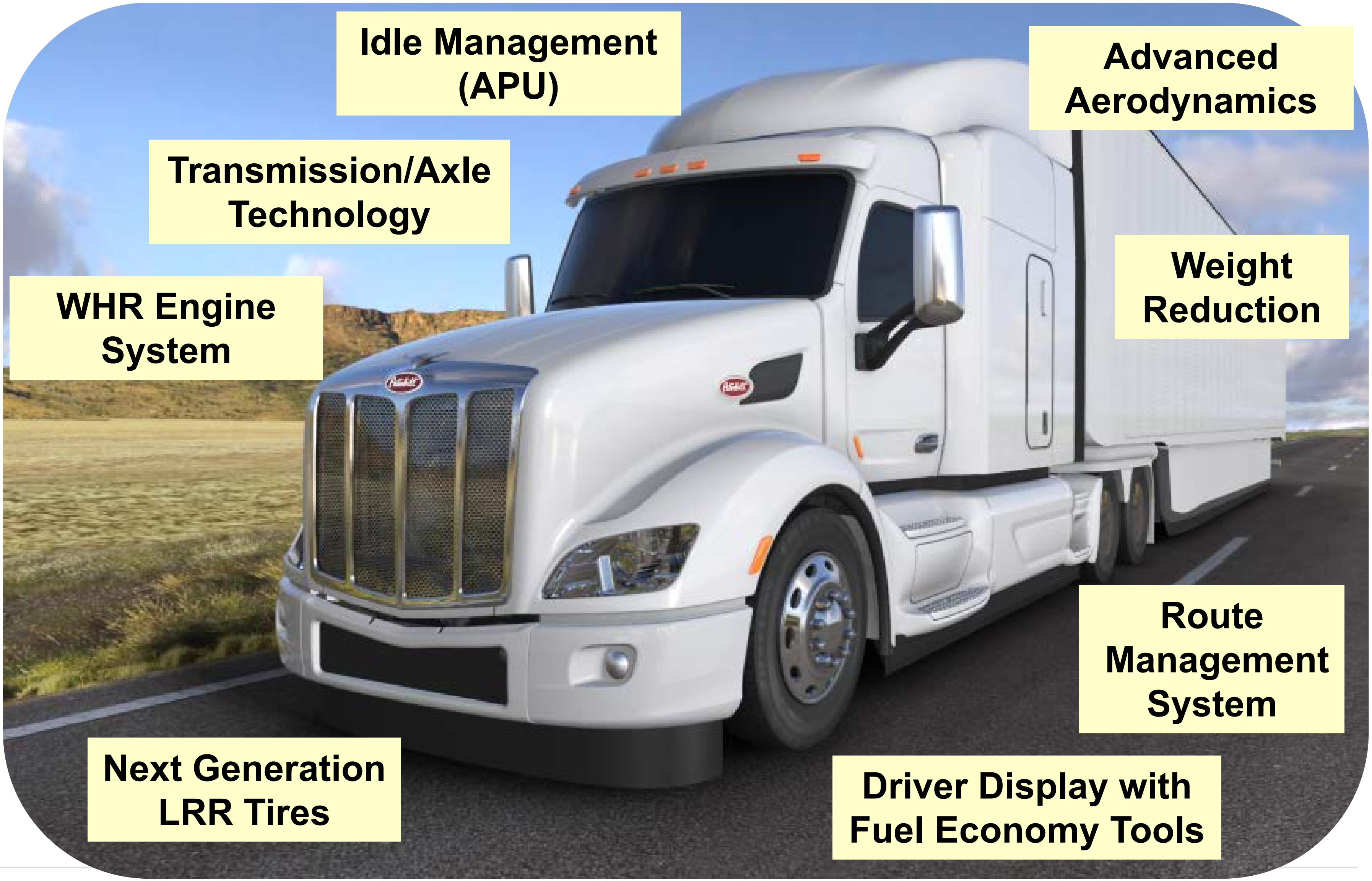
Aftertreatment Progress

- Phase 2 50% Aftertreatment changes:
  - SCR catalyst formulation
- Phase 1 50% improvements:
  - Improved design of NOx sensing across face of catalyst
  - Close loop control
  - WHR heat exchanger integration



- System capability to proceed forward to calibration to prevailing 2010 emissions of 0.2 g/(hp-hr).
- Next process step is calibrating for the RMCSET and FTP cycle with the Demo 2 truck engine during Q1 2013.

Freight Efficiency Enabling Technologies



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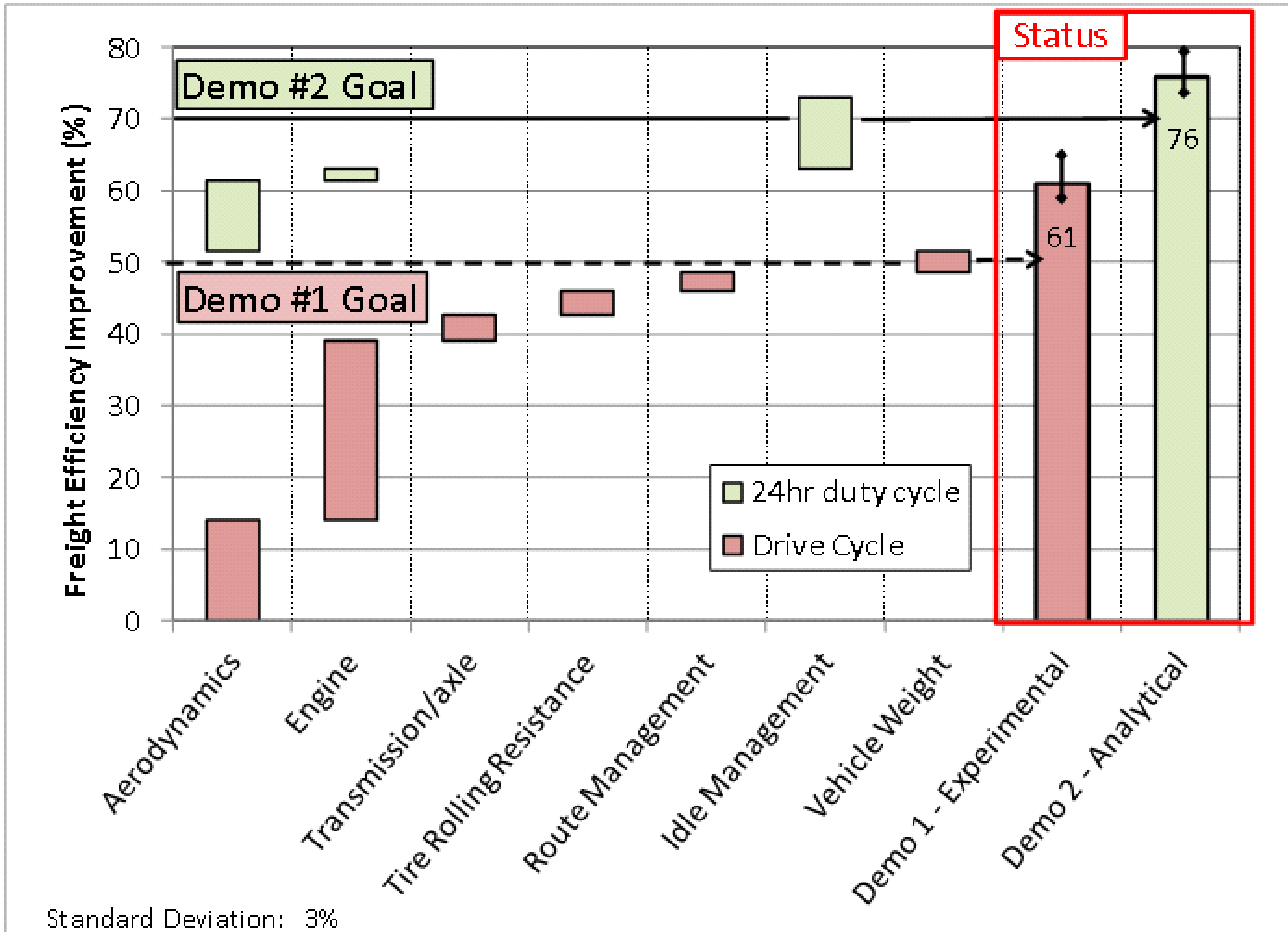
Technical Accomplishment – Freight Efficiency Test Results

Reference: Objective 2

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

Technical Accomplishment – Freight Efficiency Status



Reference: Objective 2

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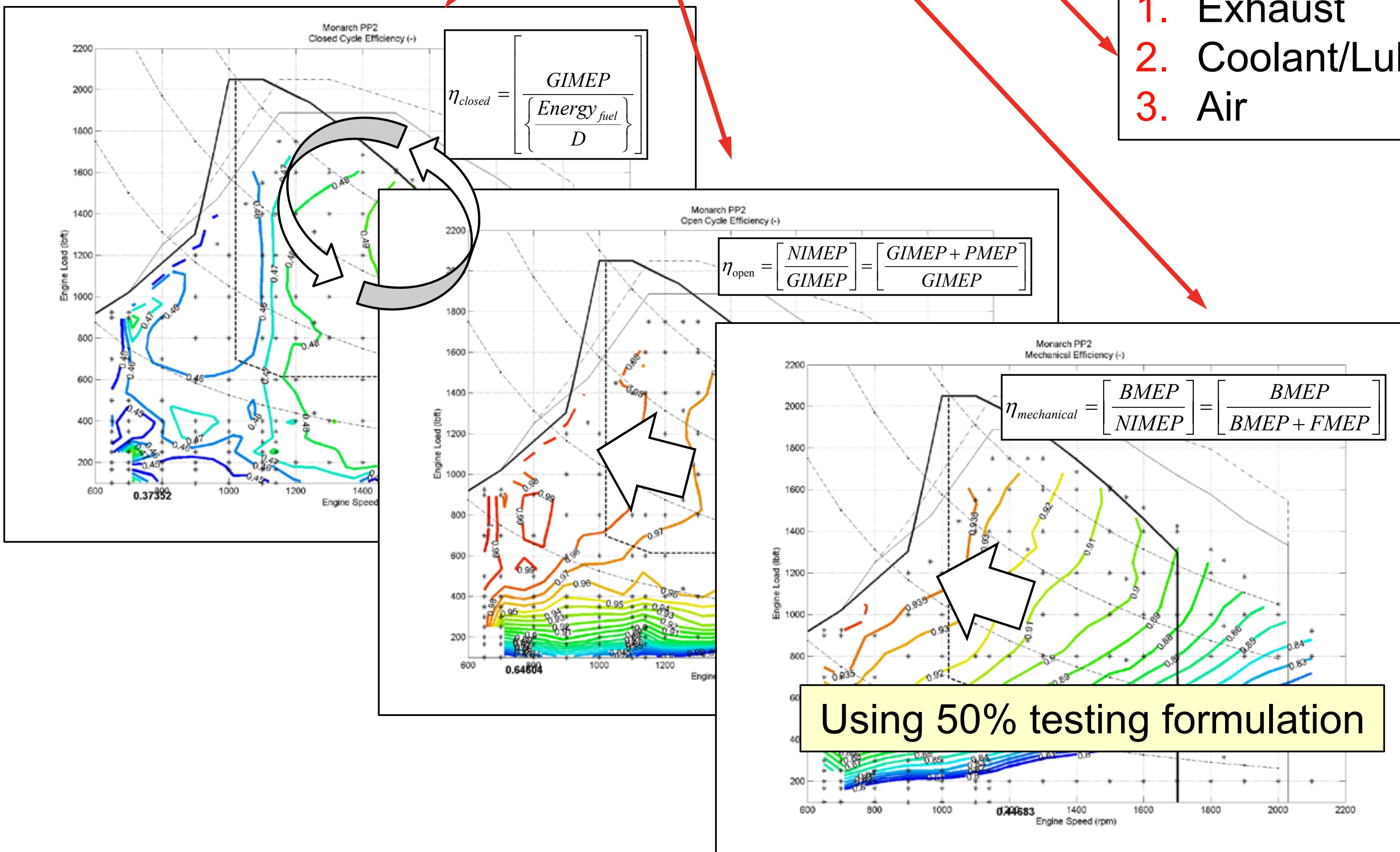
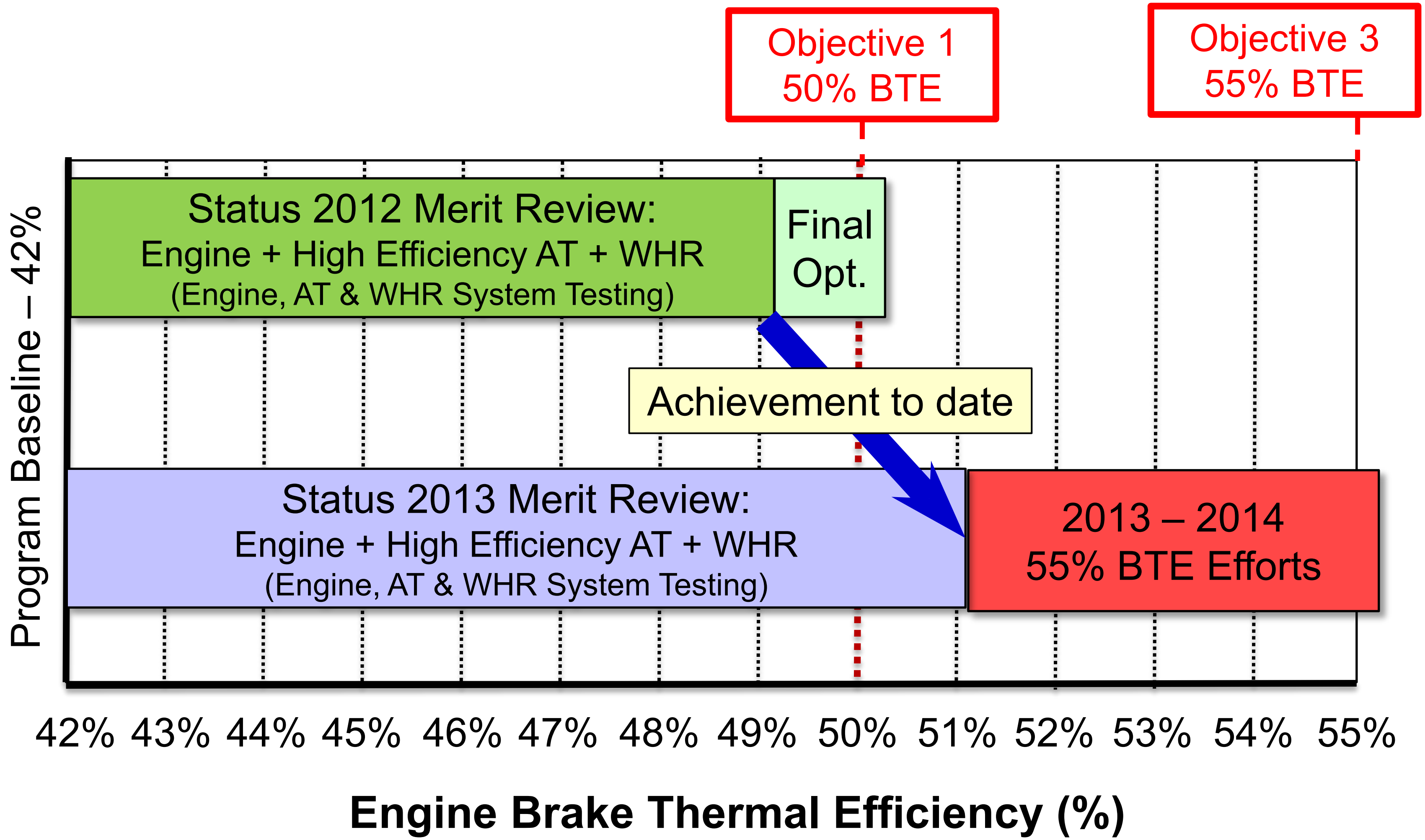
Approach – 55% Thermal Efficiency

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

1. Exhaust
2. Coolant/Lube
3. Air



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



*WHR - Cummins Organic Rankine Cycle Waste Heat Recovery

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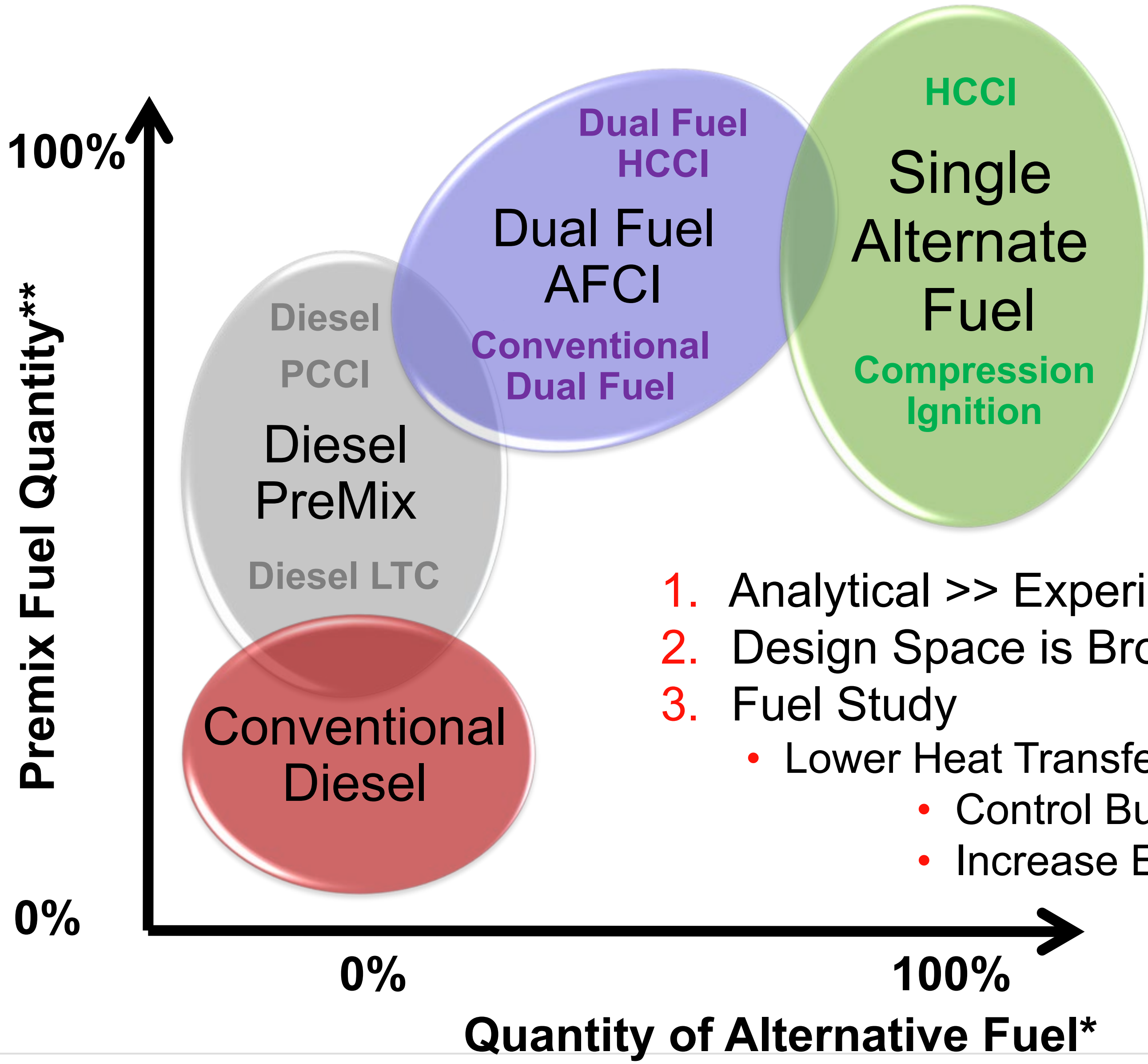
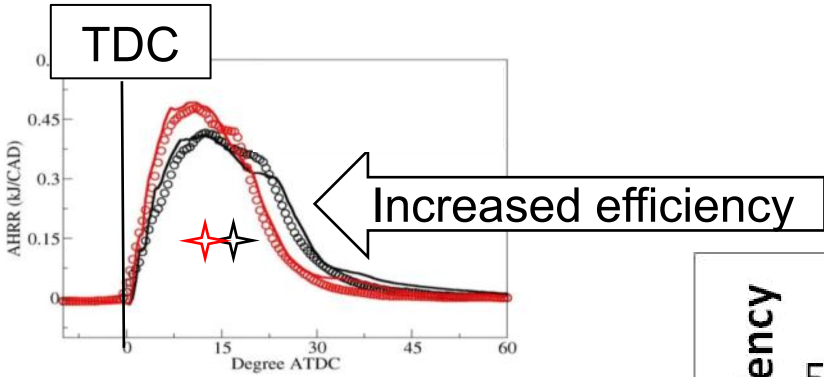
Approach – 55% Engine Technology Scoping - Fuels



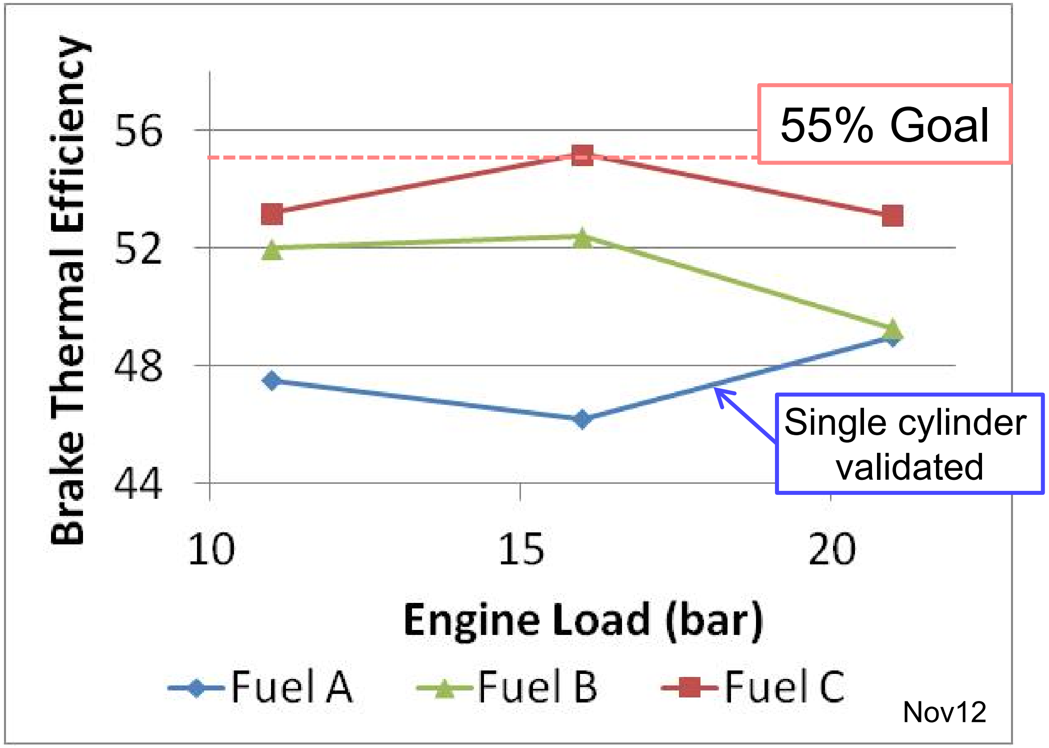
1. Analytical >> Experimental
2. Design Space is Broad
3. Fuel Study
   - Lower Heat Transfer
     - Control Burn Duration
     - Increase Effective Expansion

Technical Accomplishment – 55% Engine Analytical Data



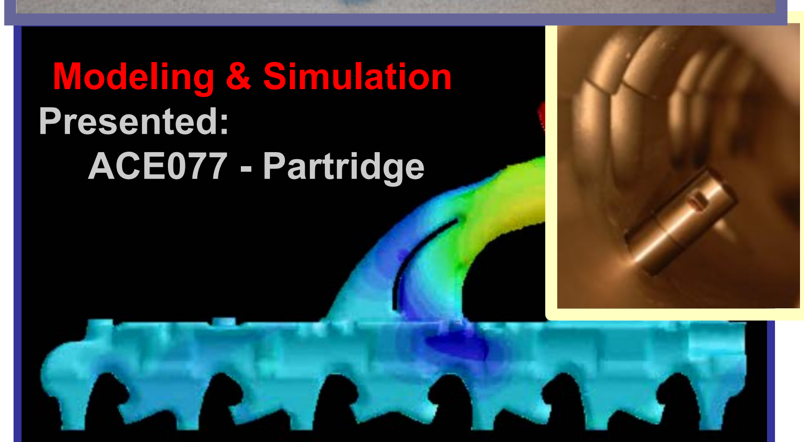
2013 advancement plan

- Combustion design
- Air handling system matching
- Cycle simulation
- WHR integration
- Targeted engine tests
    - Correlate to simulation

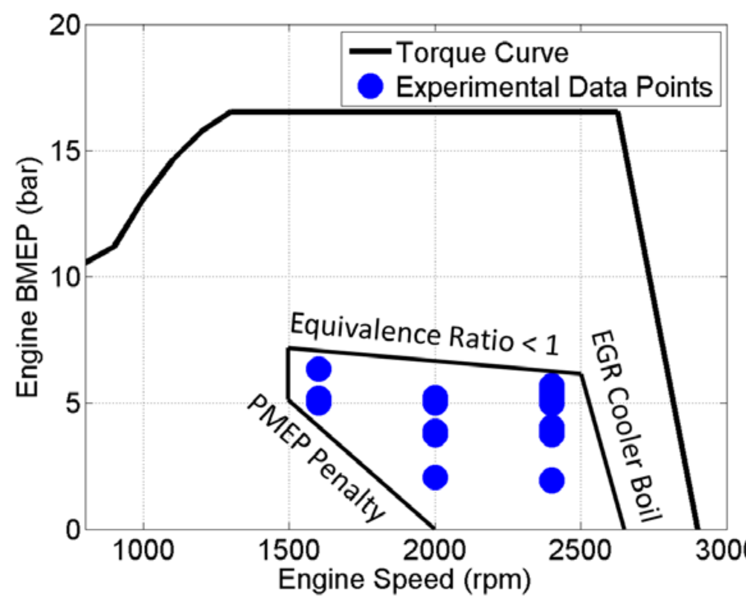


Collaborations– ORNL & Purdue Participation

- ORNL
  - Sensing methods for:
    - Combustion uniformity studies
      - High response spatial & temporal EGR variation study
      - Enables validation of CFD and analysis led design
      - Experimental testing complete
        - » Dec 2012



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



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Milestones and Technical Accomplishments

- March 2012 to March 2013 – **Technical Accomplishments**
  - √ Demonstrated 50+% BTE (Objective 1)
  - √ Demonstrated 61% freight efficiency improvement (Objective 2a)
  - √ Completed wind tunnel and vehicle testing of Waste Heat Recovery
  - √ Tested advanced transmission
  - √ Performance tested SOFC APU
  - √ Path-to-Target analysis for a 55% thermal efficient engine
- March 2013 to March 2014 – **Future Work**
  - Engine "vehicle" calibration and optimization work
  - APU technology study – investigate alternatives to SOFC
  - Build and test for Vehicle Demonstration #2 (Objective 2b)
    - Vehicle freight efficiency on 24hr cycle
      - Hotel load APU testing
  - End user testing of Tractor – Trailer Aerodynamics Solution
  - 55% analysis and demonstration tests (Objective 3)

Summary

- Program remains on schedule
  - Meeting the ARRA and DoE VT MYPP goals
- Demonstrated a 50+% BTE engine system
- Demonstrated a 60+% vehicle freight efficiency improvement
- Analytical roadmaps updated with experimental component data
- Vehicle packaging and integration proceeding without major issues
- 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 lab and vehicle tests (Objective 2b)
  - Tractor-Trailer aerodynamic aids (Objective 2a)
- Developed framework and analysis for 55% thermal efficiency
- Developed working relationship with excellent vehicle and engine system delivery partners

Technical Back-Up Slides

Approach – Freight Efficiency Path to Target

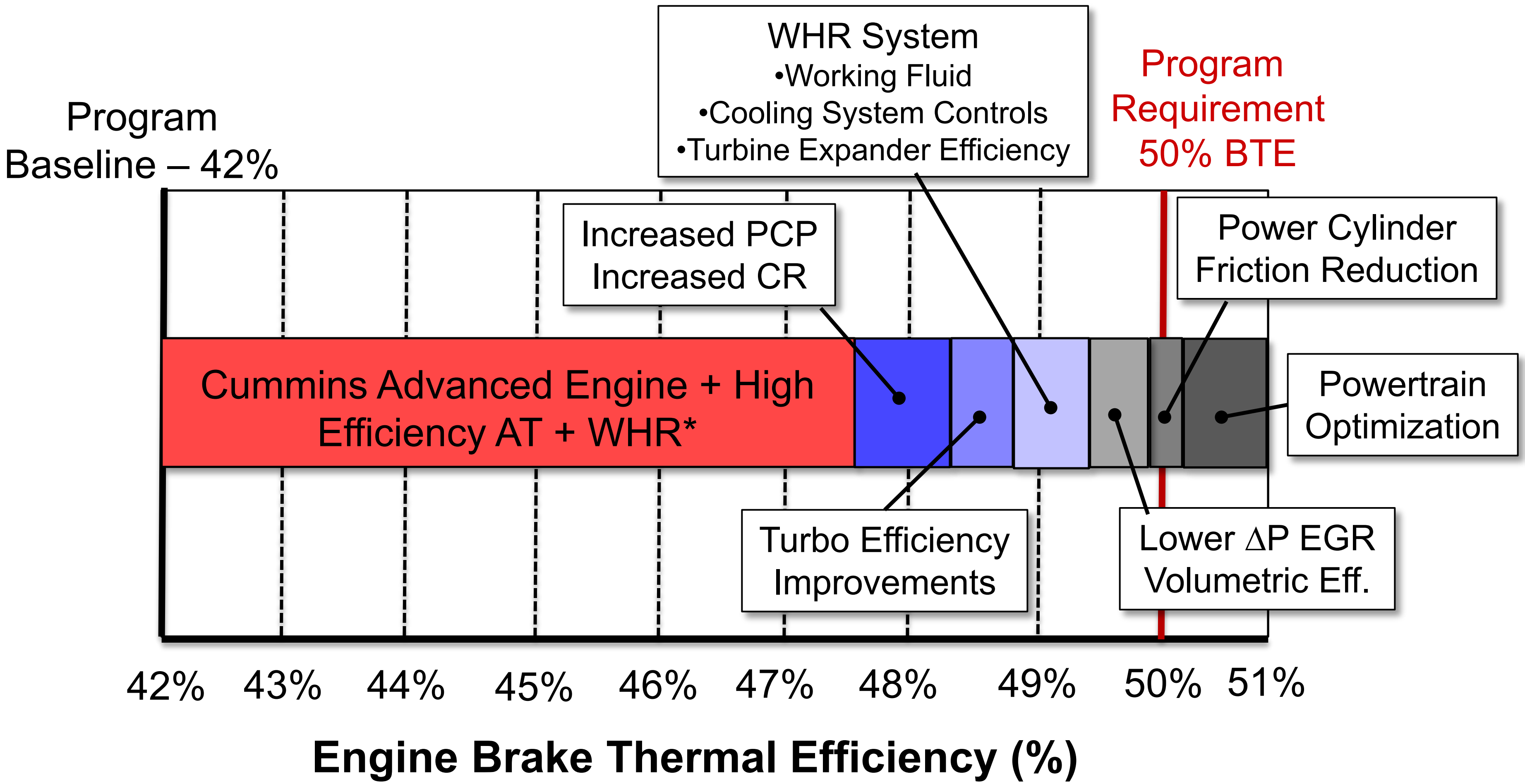
	Drive Cycle Vehicle Demonstration	24 Hour Duty Cycle Vehicle Demonstration
Technology	Freight Efficiency Improvement (%)	Freight Efficiency Improvement (%)
Vehicle Aerodynamics	14%	24%
Engine	25.5%	27%
Transmission/ Axles	3.5%	3.5%
Rolling Resistance	3.5%	3.5%
Route Performance Management	2.5%	2.5%
Idle Management	N/A	10%
Vehicle Weight	3%	3%
Total	**52%**	**73.5%**
Target	**50%**	**68.5%**

Ref: 2011 AMR - Stanton

Improvements – Technical Accomplishments

(Based on Analysis and Engine Component Testing)

Engine System Meets US EPA 2010 Emissions Regulation



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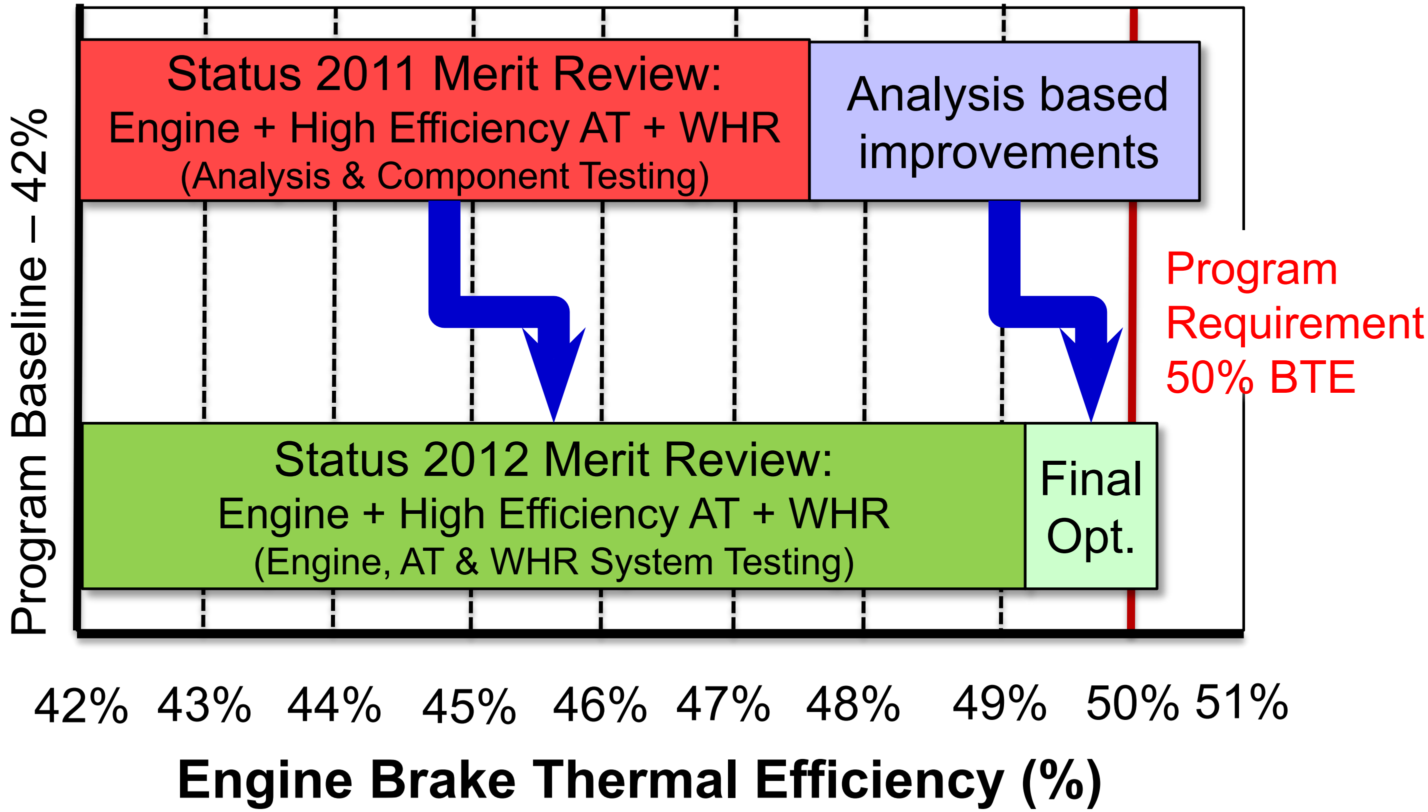
Technical Accomplishments - Improvements
(Based on Engine, AT & WHR Testing)

Engine System Meets US EPA 2010 Emissions Regulation



$$\eta_{brake} = \eta_{ig}\eta_{oc}\eta_{m} + \Delta_{WHR}$$

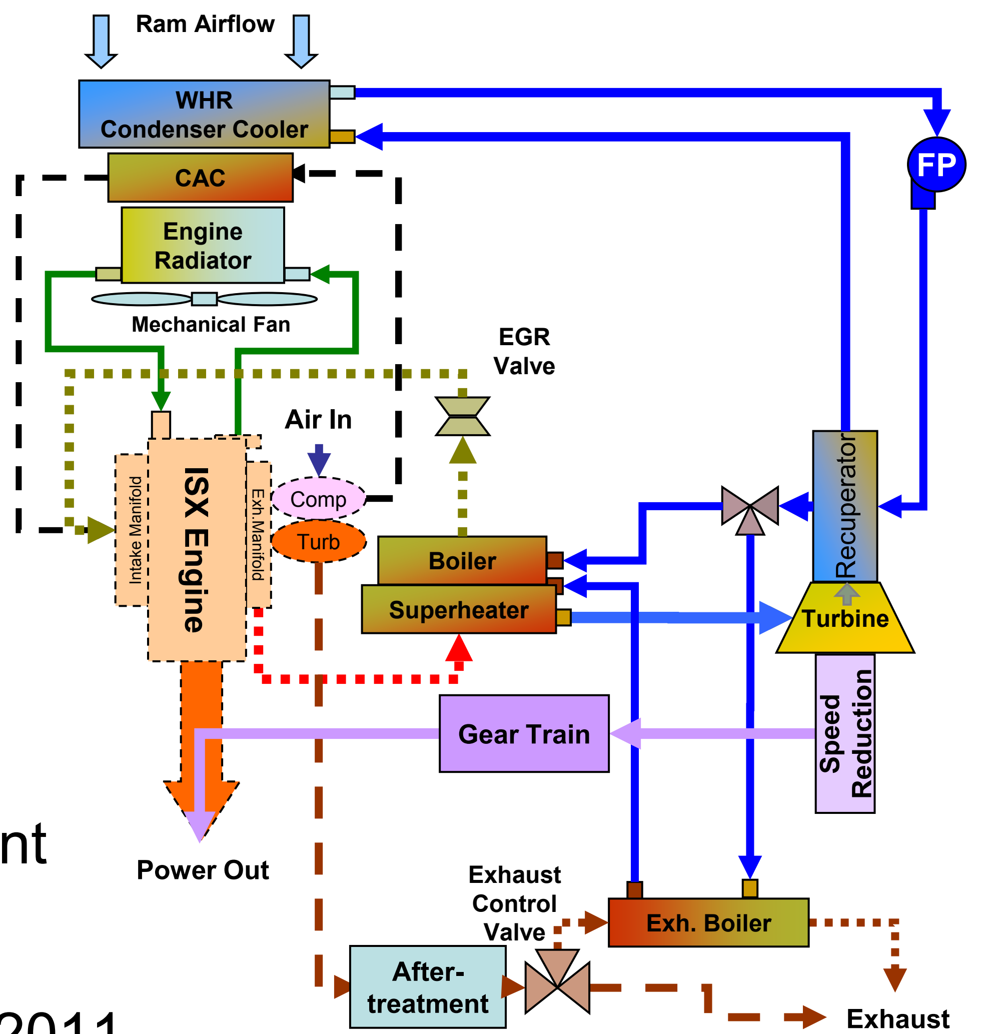
- Engine demonstration showed improvements in all terms

*WHR - Cummins Organic Rankine Cycle Waste Heat Recovery

Ref: 2012 AMR - Koeberlein

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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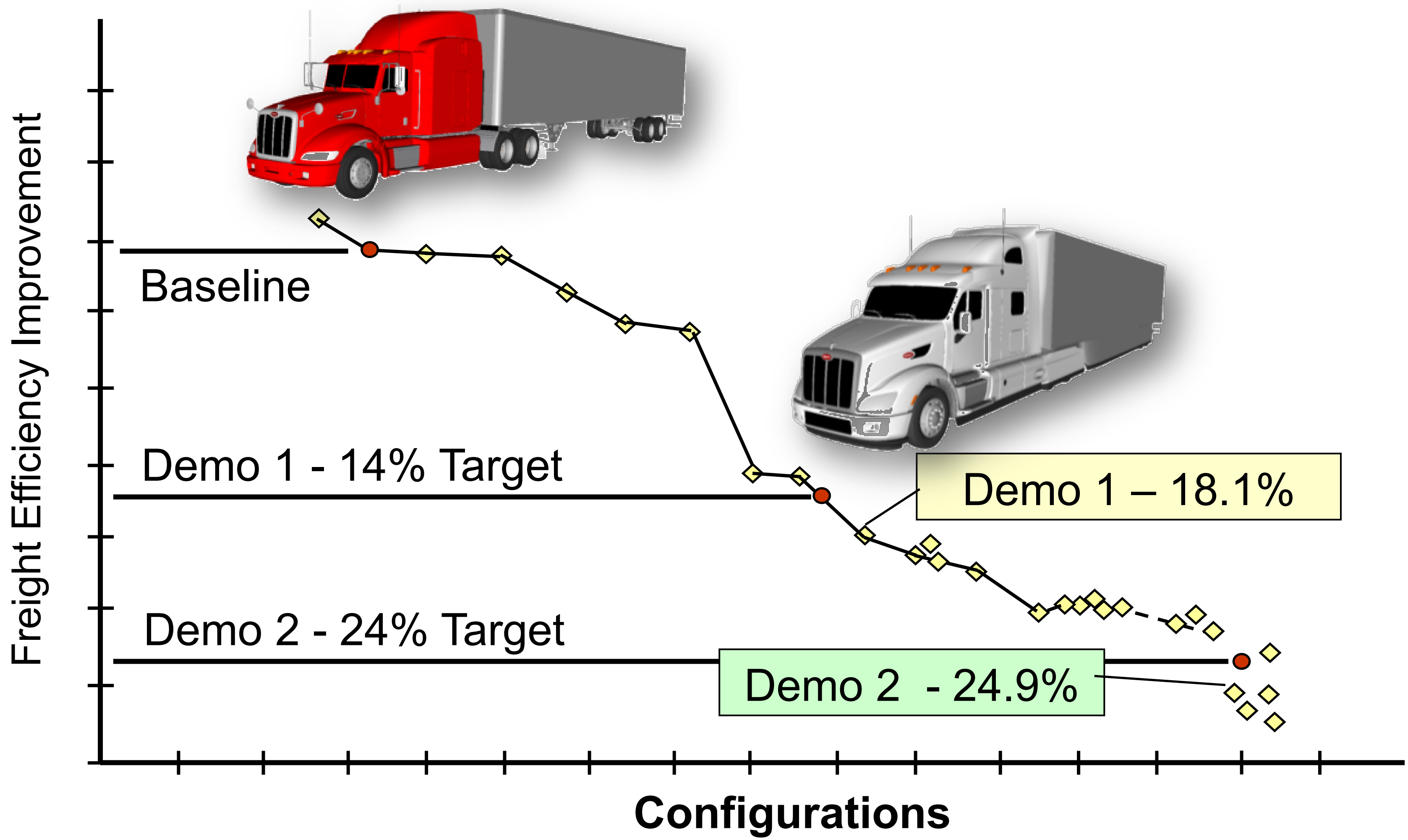
Vehicle Freight Efficiency of Aerodynamic Drag Reduction



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

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Vehicle Weight Reduction – Freight Efficiency Improvement

>3% Freight Efficiency Improvement With Vehicle Weight Reduction