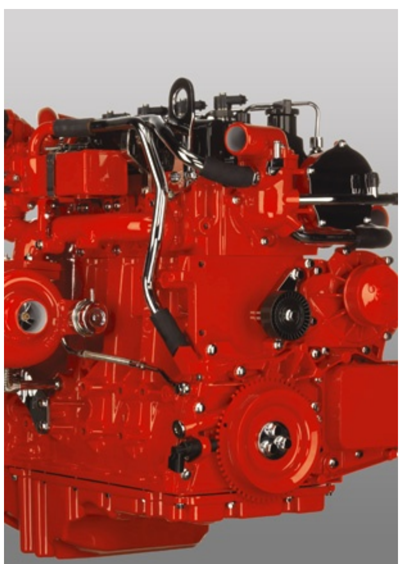
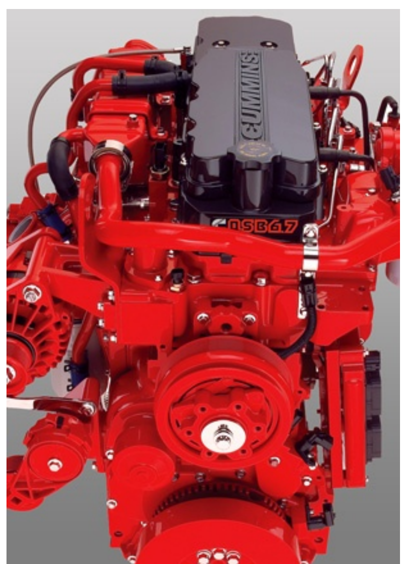
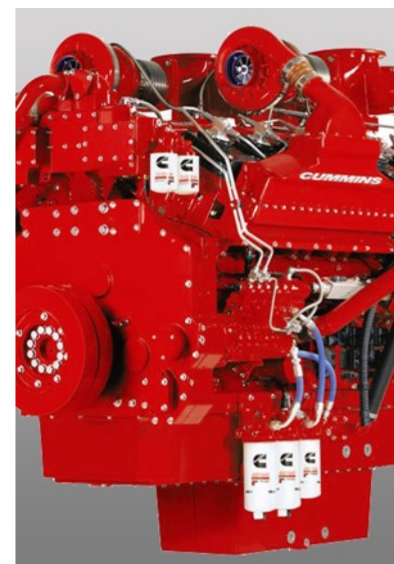
Cummins SuperTruck Program

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

David Koeberlein- Principle Investigator
Cummins Inc.

May 17, 2012 **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

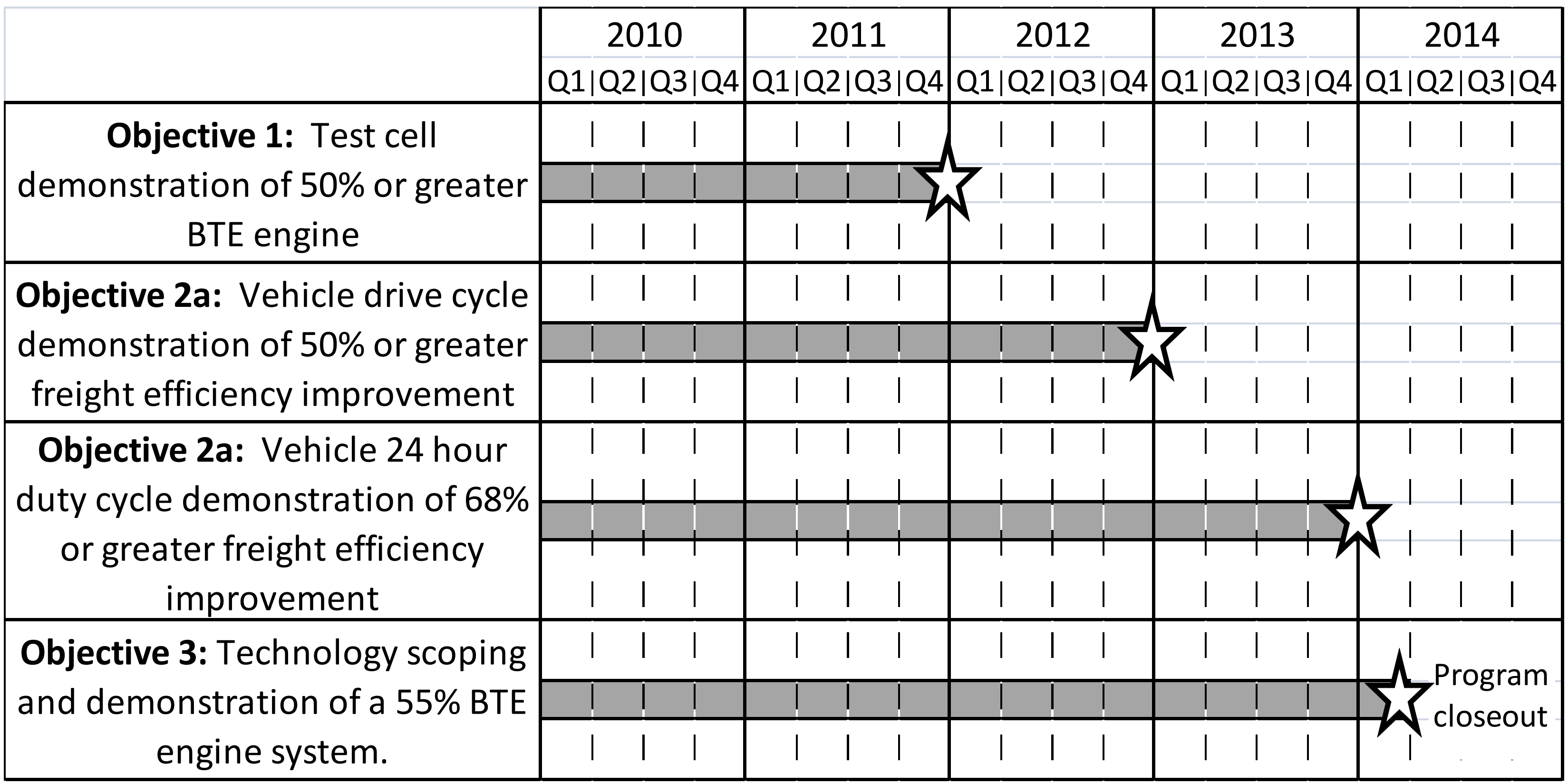
Technology scoping and demonstration of a 55% BTE engine system. Engine tests, component technologies, and model/analysis will be developed to a sufficient level to validate 55% BTE.

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

Overview - Program Schedule and Budget

Budget: DoE Share $38.8M (49%)
Contractor Share $40.3 M (51%)
$20.2 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 2012 AMR presentation ARRA-087

Overview - Program Partners

Program Lead

Cummins Inc.

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

Peterbilt Motors Company

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

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 integrated with VVA
VanDyne SuperTurbo	Turbocompounding/ Supercharging
Utility Trailer	Lightweight Trailer Technology
Dana	Lightweight Drivetrain Technology
Bergstrom	HVAC
Garmin	Driver interface/display
Logena	Network interface

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

- ARRA Goal: Create and/or Retain Jobs

			Projections	
Year	2010	2011	2012	2013
Full Time Equivalent	75.5	85	70	45

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

- ARRA Goal: Spur Economic Activity
  - Greater than $40M 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

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Approach – Vehicle Energy Analysis

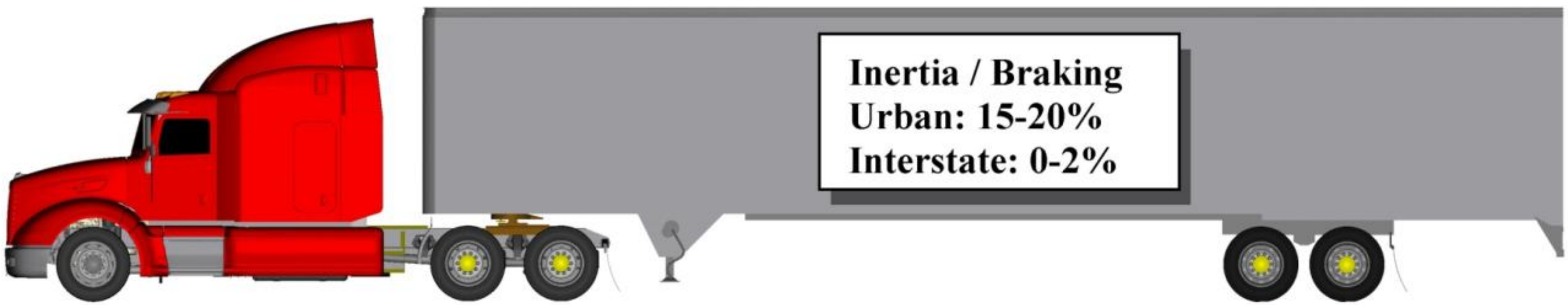
Analysis of 27 Drive Cycles for Class 8 Vehicles
with a Variety of Seasons (Summer, Winter, etc.)

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

Cummins

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

Peterbilt



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

Analyze: Where is the energy going? Identify priority.

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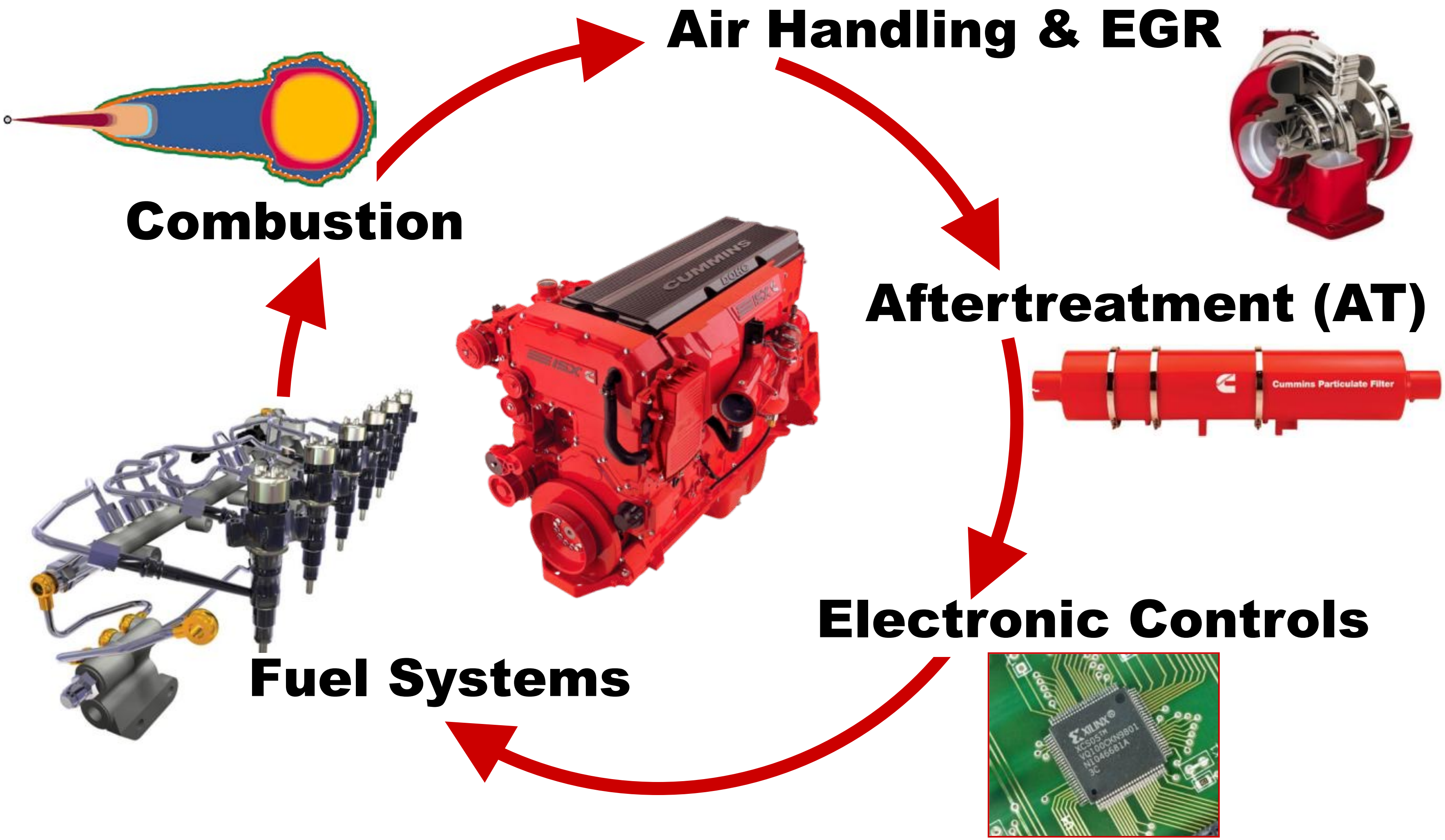
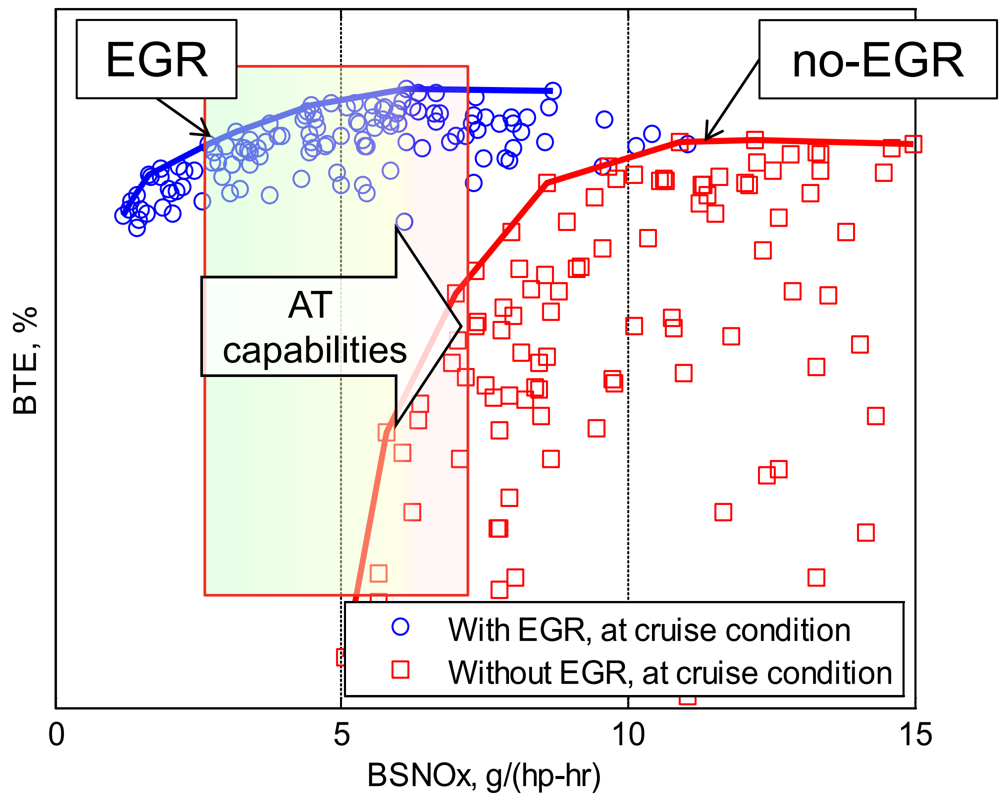
Approach - Integration of Cummins Component Technologies



Technical Accomplishment – Engine architecture decision

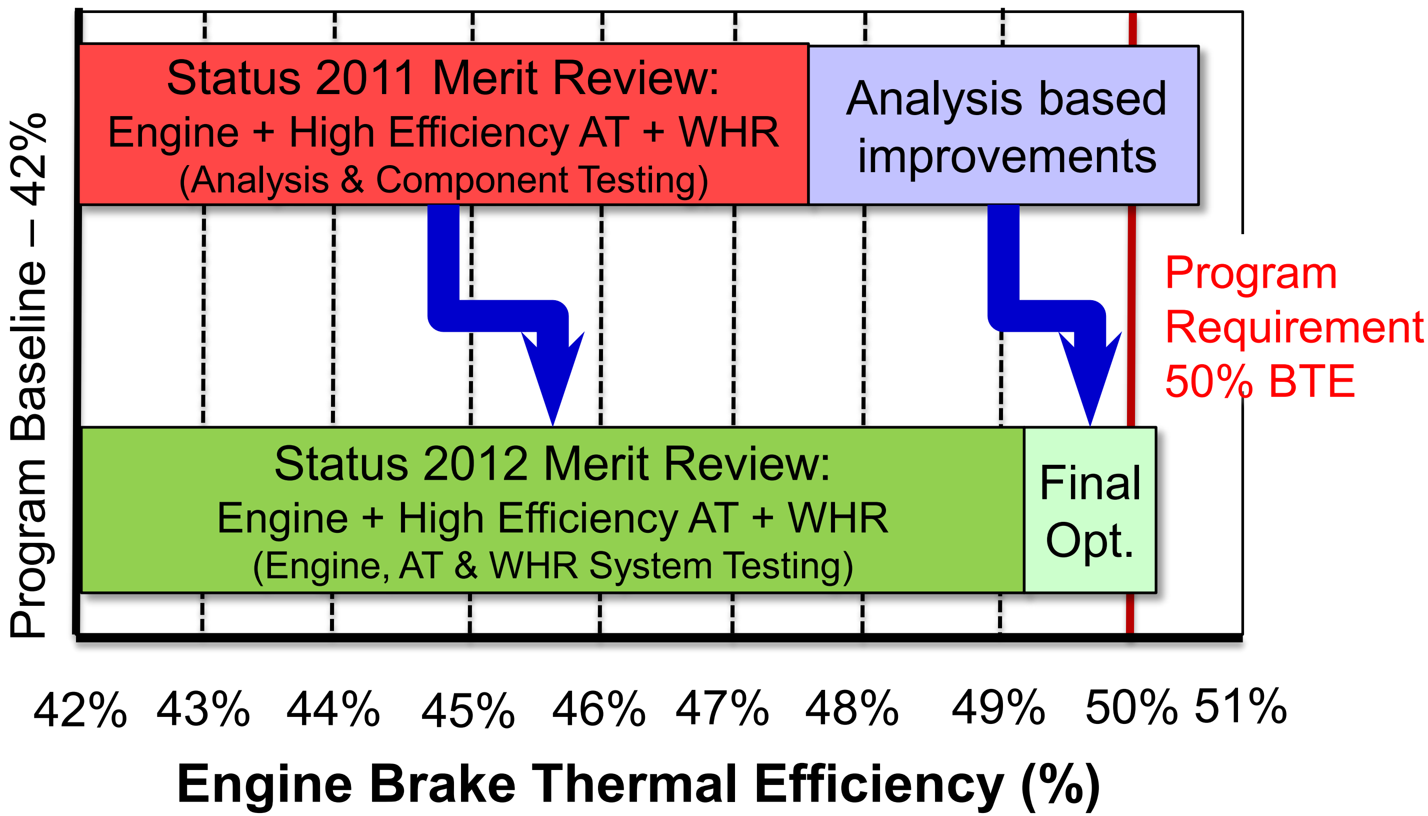
Question: Does a no-EGR engine architecture provide increased efficiency at lower system cost?



- Cummins data indicates an EGR solution yields best efficiency
- A unique no-EGR AT system design achieved compliance
- System cost analysis not favorable for no-EGR architecture

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

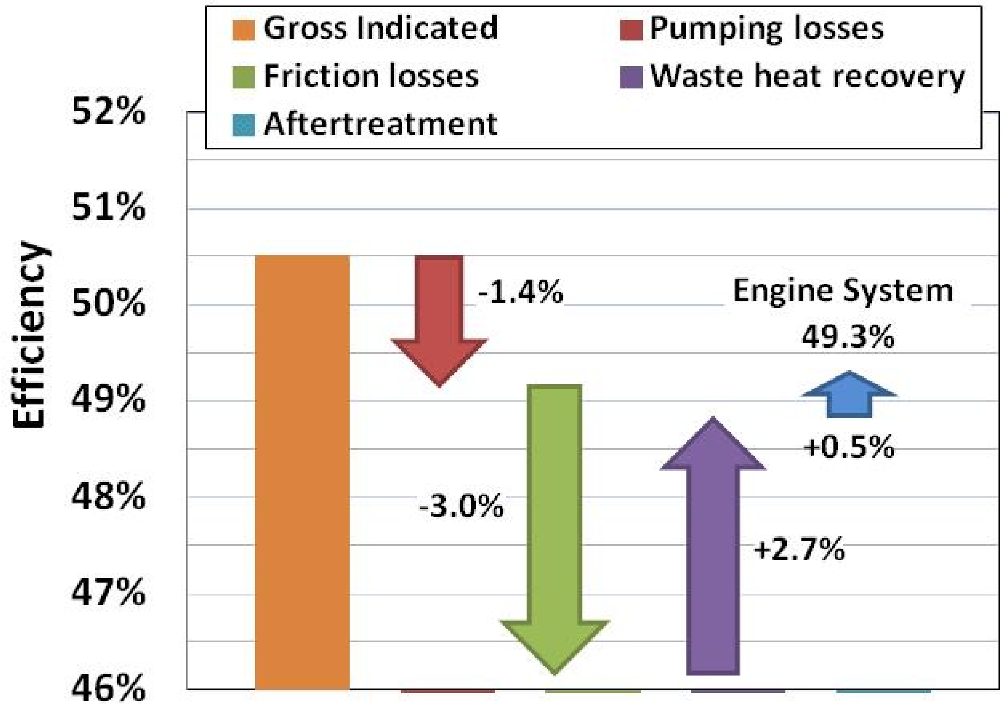
Technical Accomplishments – 50% Thermal Efficiency Gains

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

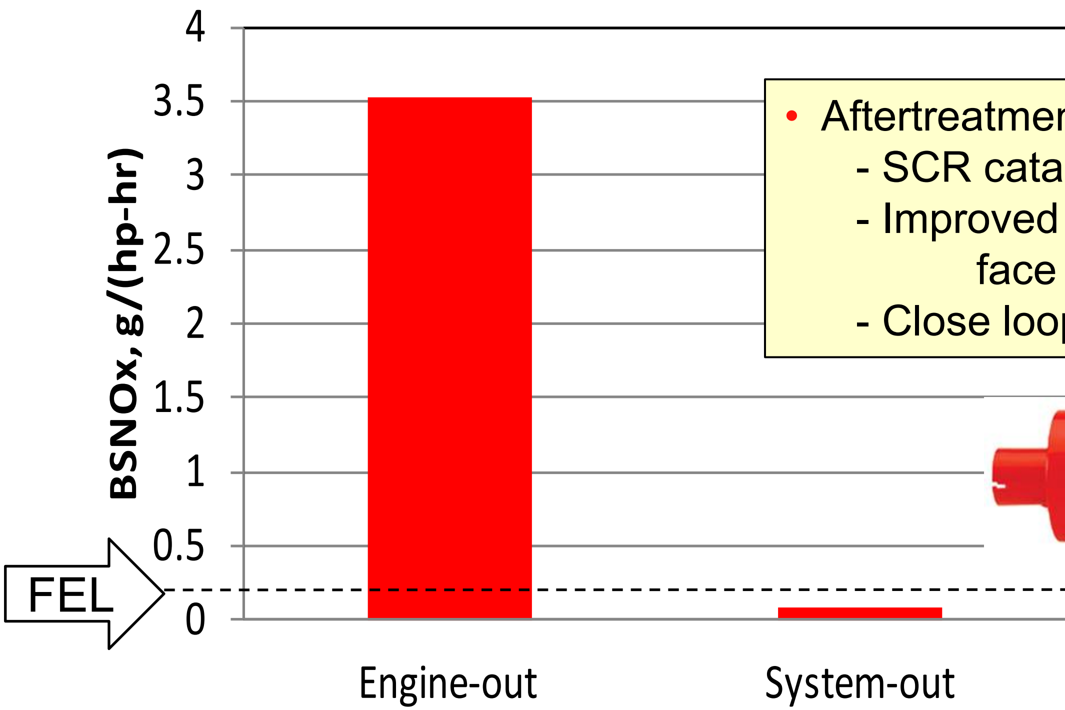
Gas flow improvements
- Lower dP EGR loop
- Turbocharger match

Parasitic reductions
- Cylinder kit friction
- Cooling pump power

WHR system
- EGR boiler/superheater
- Exhaust boiler
- Recuperator



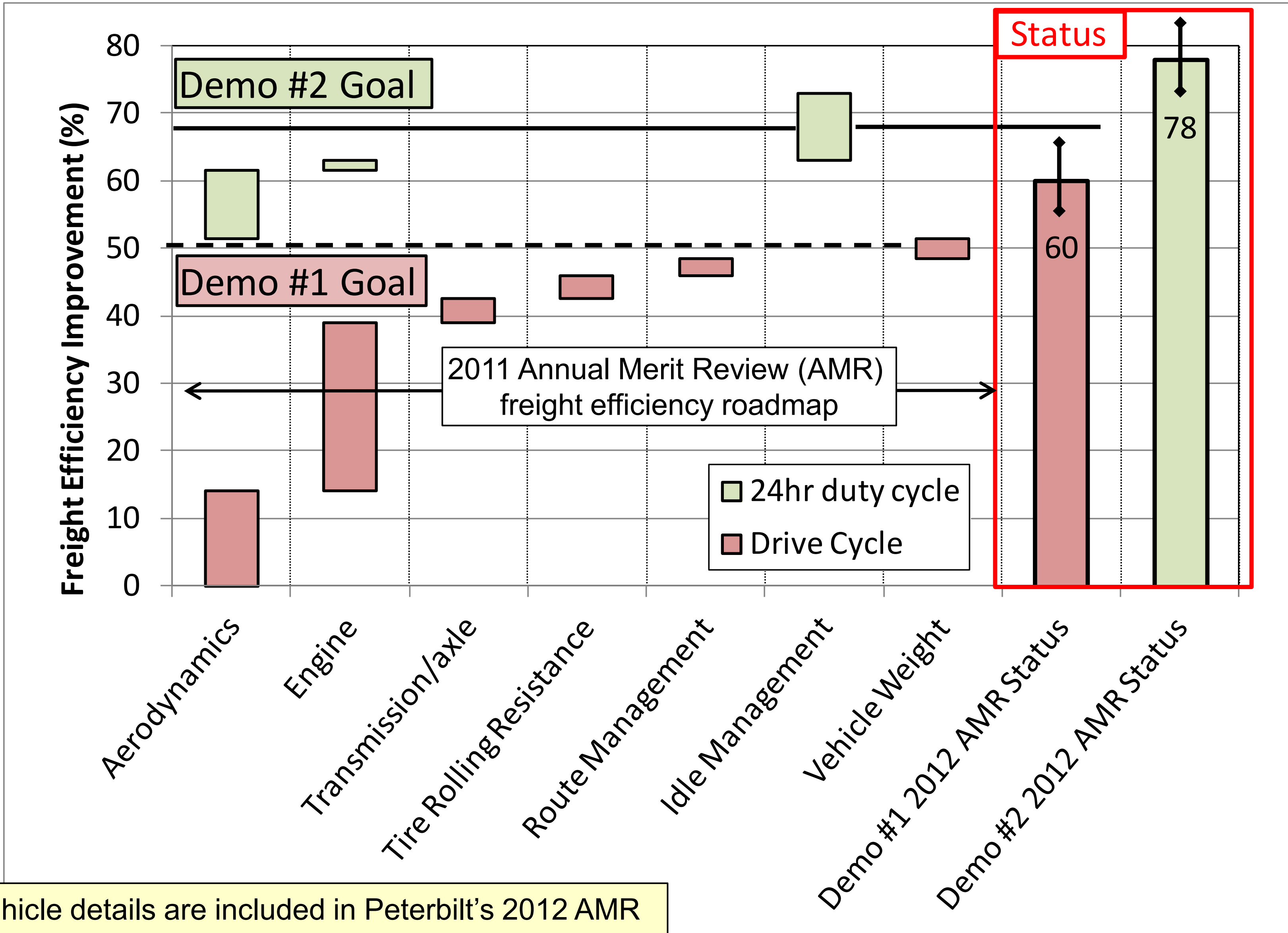
Technical Accomplishment – Supplemental Emission Test (SET) Weighted Modal Cycle NOx Emissions



- Aftertreatment effectiveness gain by:
  - SCR catalyst size optimization
  - Improved design of NOx sensing across face of catalyst
  - Close loop control

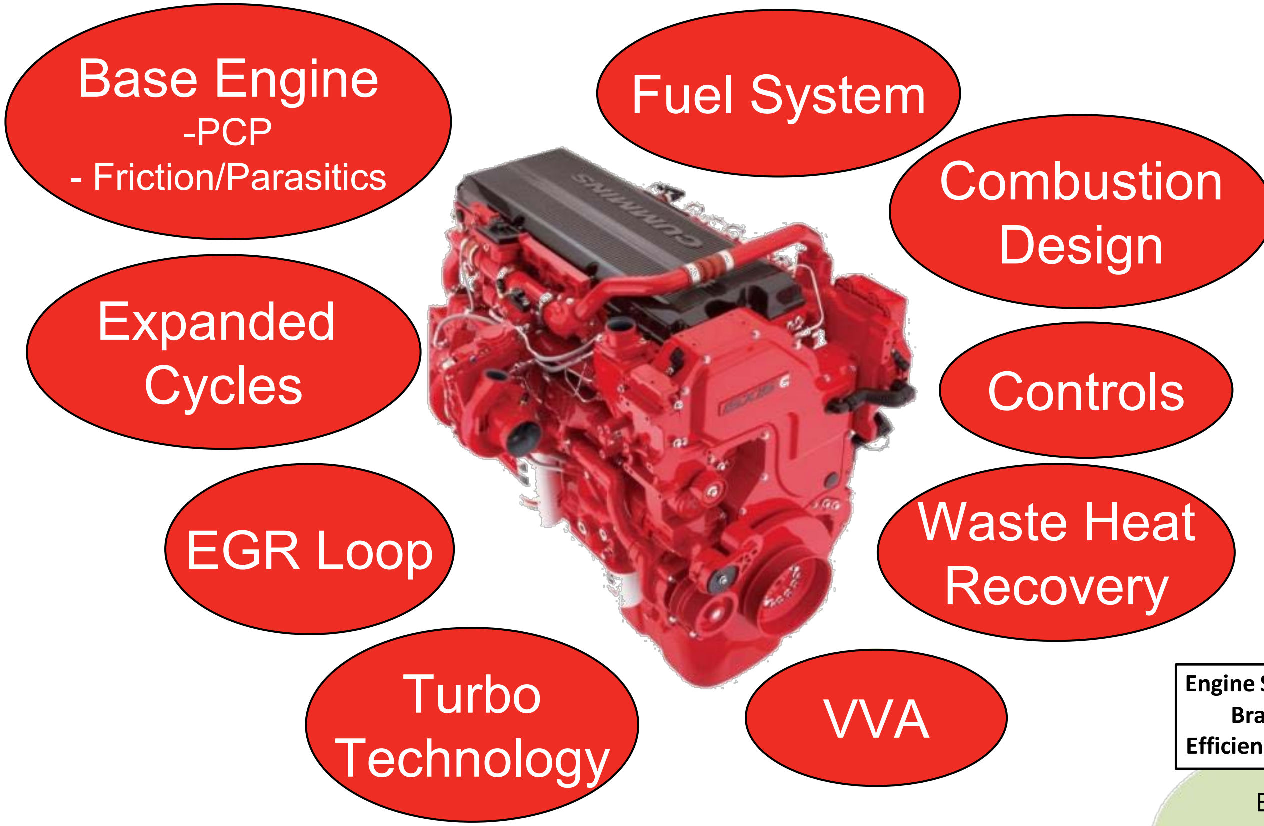
- Compliance to prevailing emissions 0.2 g/(hp-hr) demonstrated
- FTP requires additional calibration effort with optimized components

Technical Accomplishment – Freight Efficiency Status



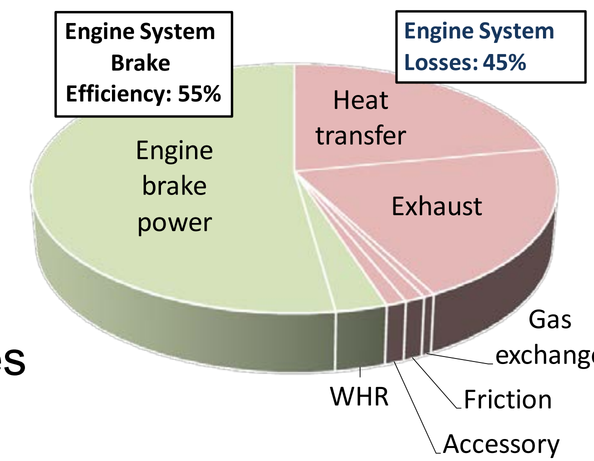
Vehicle details are included in Peterbilt's 2012 AMR presentation ARRA-087

Technical Accomplishment – 55% Engine Technology Scoping



2012 plan

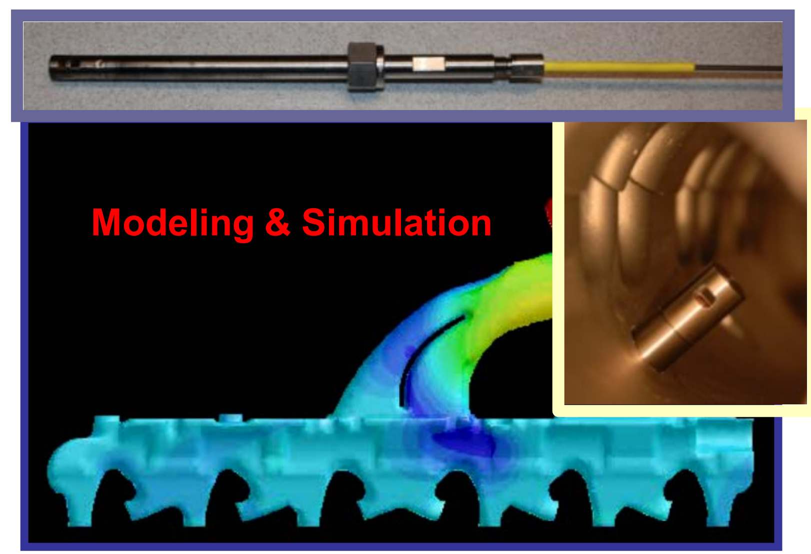
- Combustion system design
- Engine system simulation of roadmap technologies
- Targeted engine tests – correlate to simulation



Collaborations– ORNL & Purdue Participation

- ORNL
  - Sensing methods for:
    - Combustion uniformity studies
      - Spatially and high response temporally resolved EGR variation and its minimization
      - Enables validation of CFD and analysis led design
    - AT performance studies
      - Enhanced SCR understanding to improve models & control methods fundamental to high efficiency AT

- Purdue University
  - Engine control for variable intake valve diesel
    - Effective Compression Ratio estimator model
    - Control-Oriented low temperature combustion timing model
    - Oxygen fraction [O2] estimator



Milestones and Technical Accomplishments

- March 2011 to March 2012 – **Technical Accomplishments**
  - Analysis of Path to Target for Engine and Vehicle Efficiencies
  - Demonstrated the interim milestone toward 50% or greater BTE
  - Aerodynamic aid fabrication and initial vehicle testing
  - Initial vehicle tests of Cummins Waste Heat Recovery System
  - Initial testing of Advanced Transmission
  - Performance assessment of SOFC APU
- March 2012 to March 2013 – **Future Work**
  - Engine calibration and optimization work
  - Vehicle Testing of Advanced Transmission
  - Testing of Tractor – Trailer Aerodynamics Solution
  - Build and test for Vehicle Demonstration #1 (Objective 2a)
  - Design freeze for Vehicle Demonstration #2 (Objective 2b)
  - Initial vehicle calibration of Second Generation SOFC APU
  - 55% scoping analysis and targeted tests (Objective 3)

Summary

- Program remains on schedule
  - Meeting the ARRA and DoE VT MYPP goals
- Roadmaps updated for freight efficiency and 50% engine efficiency
- Studied alternative engine system architectures
  - Established an EGR engine architecture direction
- Demonstrated an interim milestone toward 50% or greater BTE
- Vehicle packaging and integration proceeding without major issues
- Build and testing of sub-systems are on the planned schedule
  - Cummins Waste Heat Recovery vehicle testing (Objective 2a)
  - Advanced transmission dynamometer and vehicle test (Objective 2a)
  - Solid Oxide Fuel Cell 2nd design iteration lab tests (Objective 2b)
  - Tractor-Trailer aerodynamic aids (Objective 2a)
- Developed working relationship with excellent vehicle and engine system delivery partners

Technical Back-Up Slides

Approach – Freight Efficiency Path to Target

Technology	Drive Cycle Vehicle Demonstration Freight Efficiency Improvement (%)	24 Hour Duty Cycle Vehicle Demonstration 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

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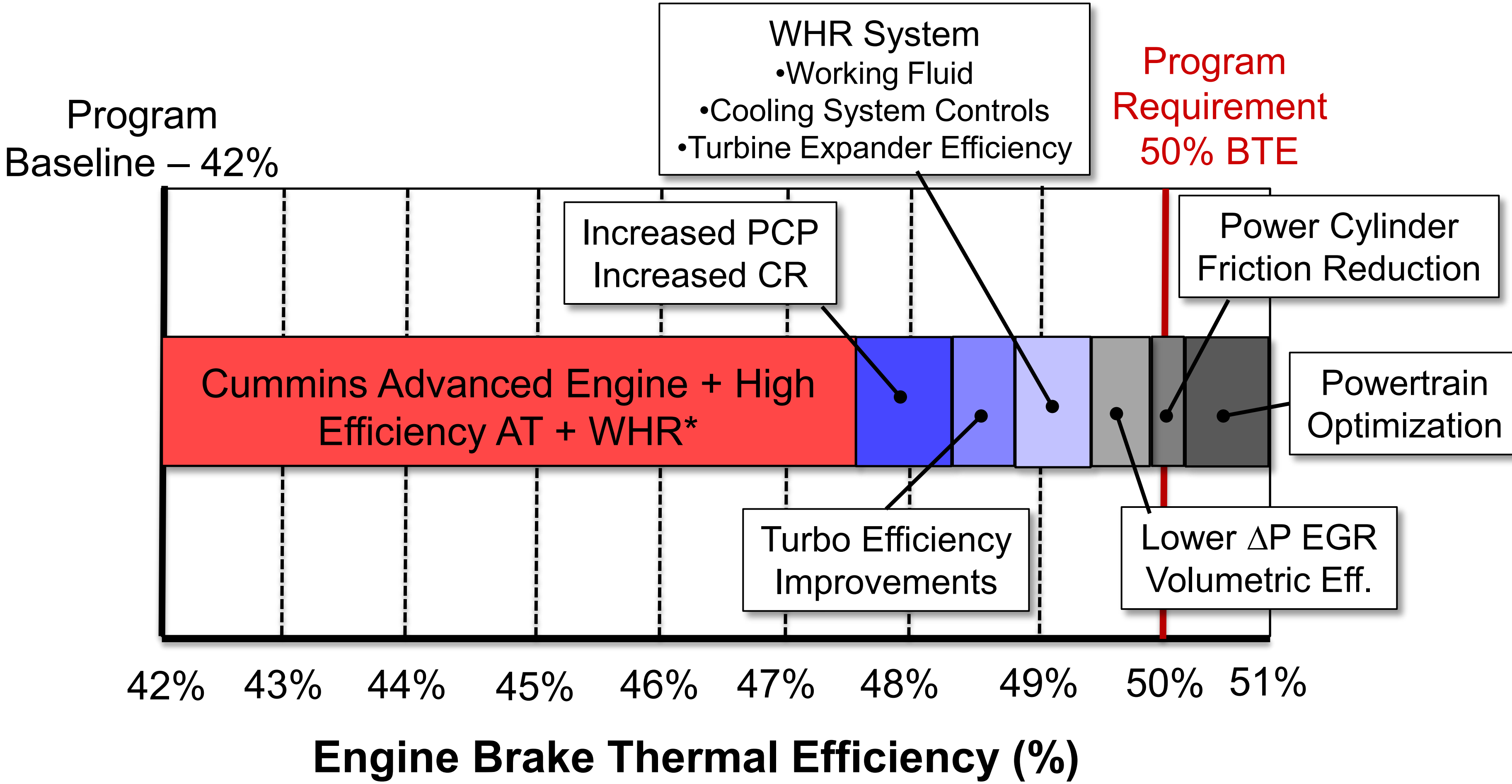
Improvements – Technical Accomplishments

(Based on Analysis and Engine Component Testing)

Engine System Meets US EPA 2010 Emissions Regulation



Ref: 2011 AMR - Stanton

*WHR - Cummins Organic Rankine Cycle Waste Heat Recovery

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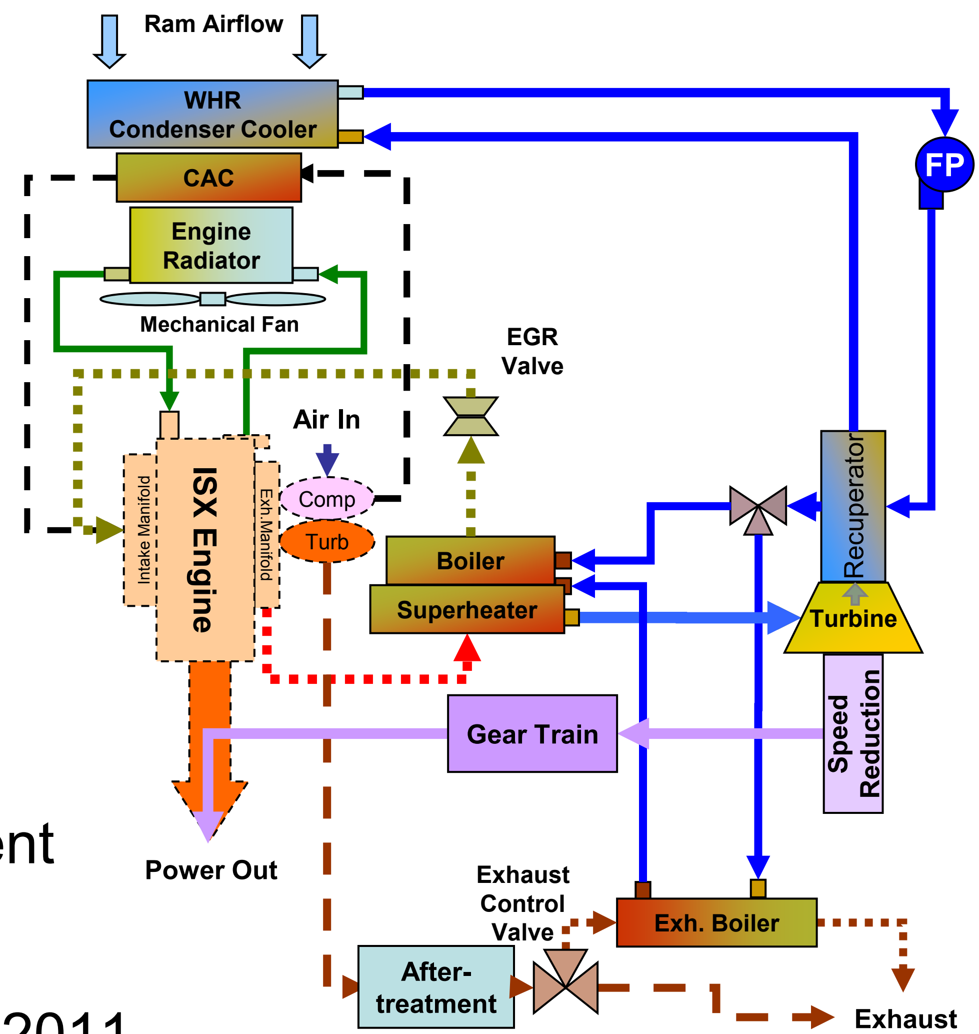
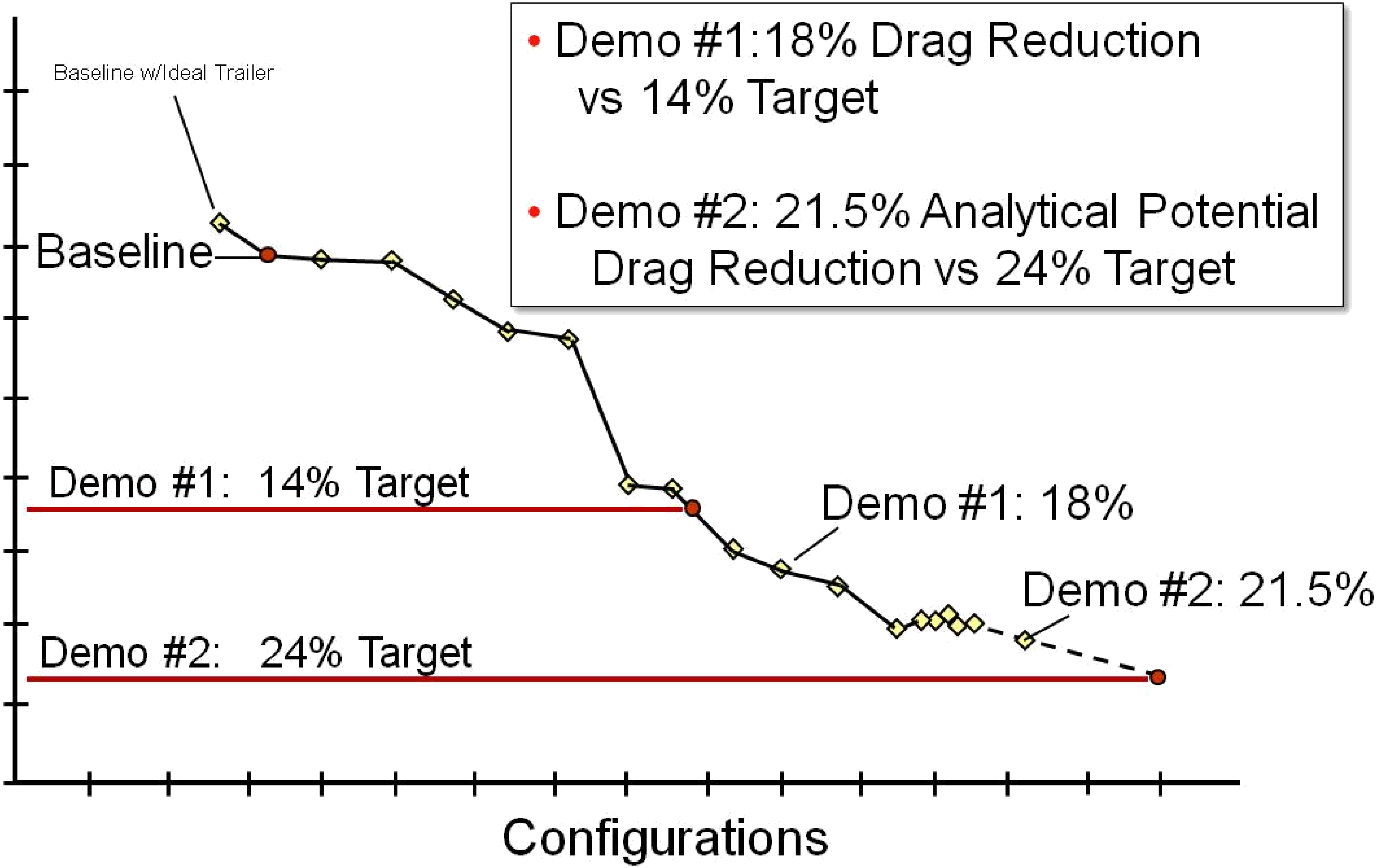
Cummins Waste Heat Recovery

- 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



Vehicle Aerodynamic Results

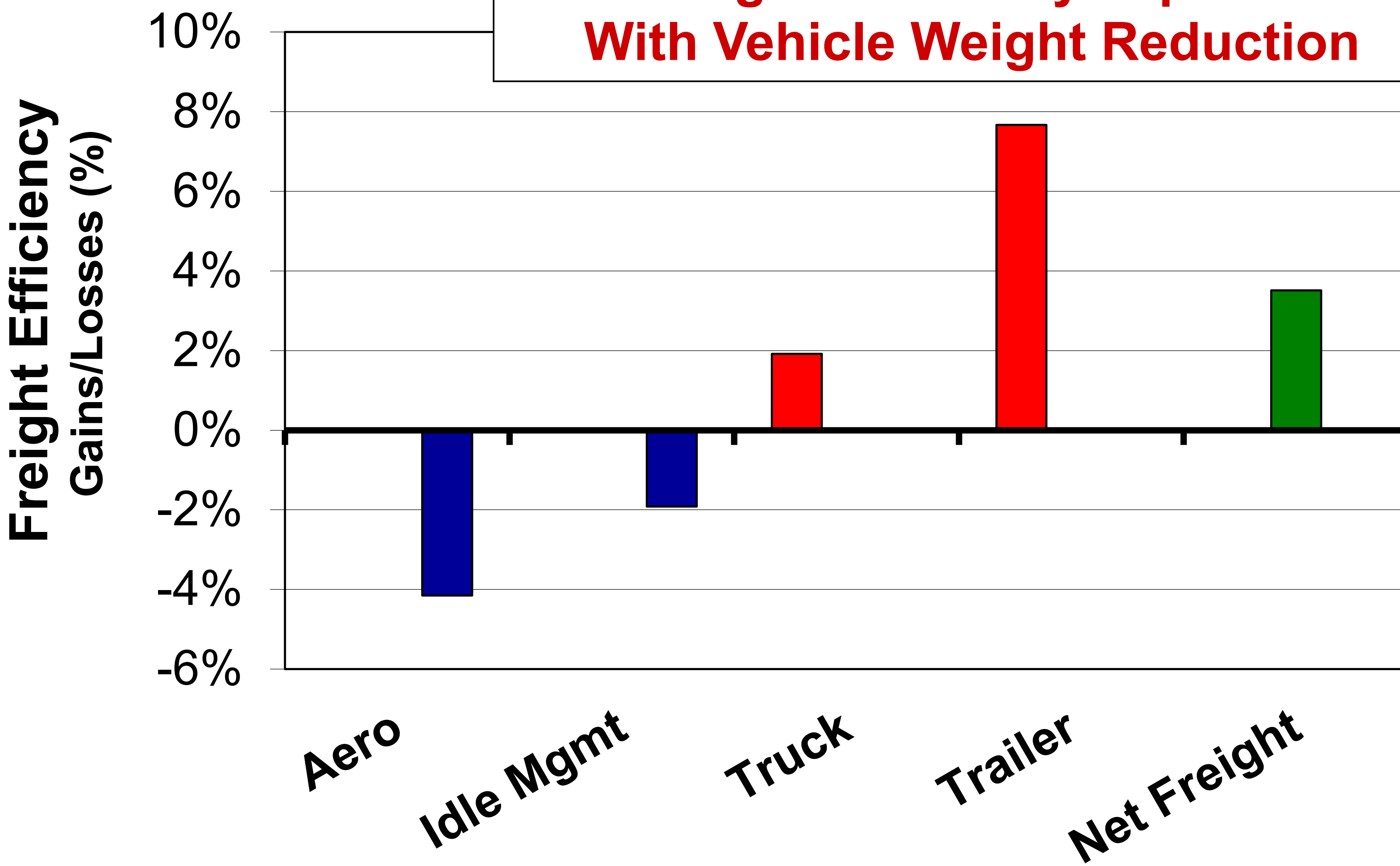
- Demo #1:18% Drag Reduction vs 14% Target
- Demo #2: 21.5% Analytical Potential Drag Reduction vs 24% Target



* 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

>3% Freight Efficiency Improvement With Vehicle Weight Reduction



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