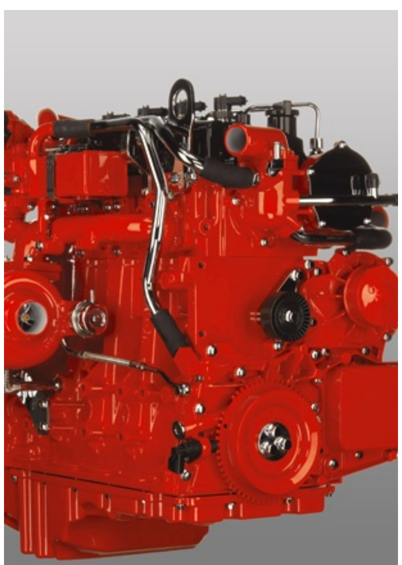
Cummins SuperTruck Program

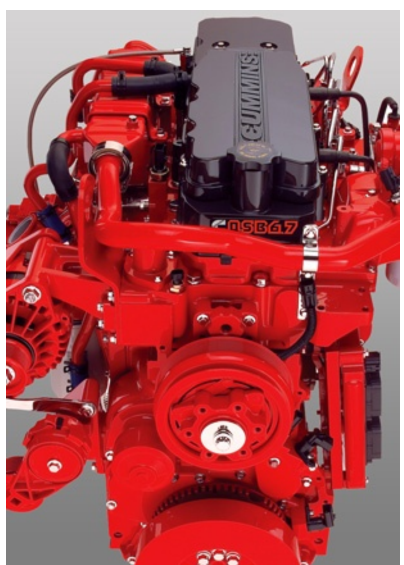
Technology and System Level Demonstration of Highly Efficient and Clean, Diesel Powered Class 8 Trucks

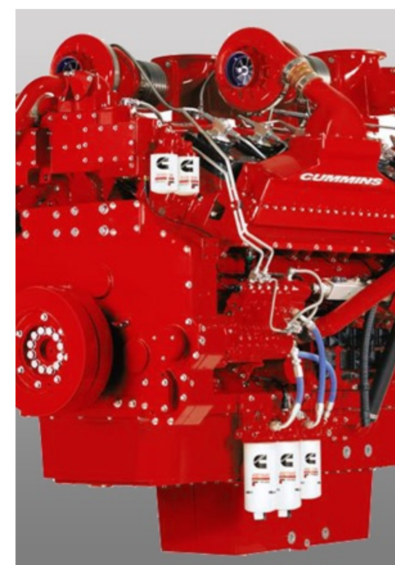
David Koeberlein- Principal Investigator

Cummins Inc.

June 12, 2015 **Project ID: ACE057**

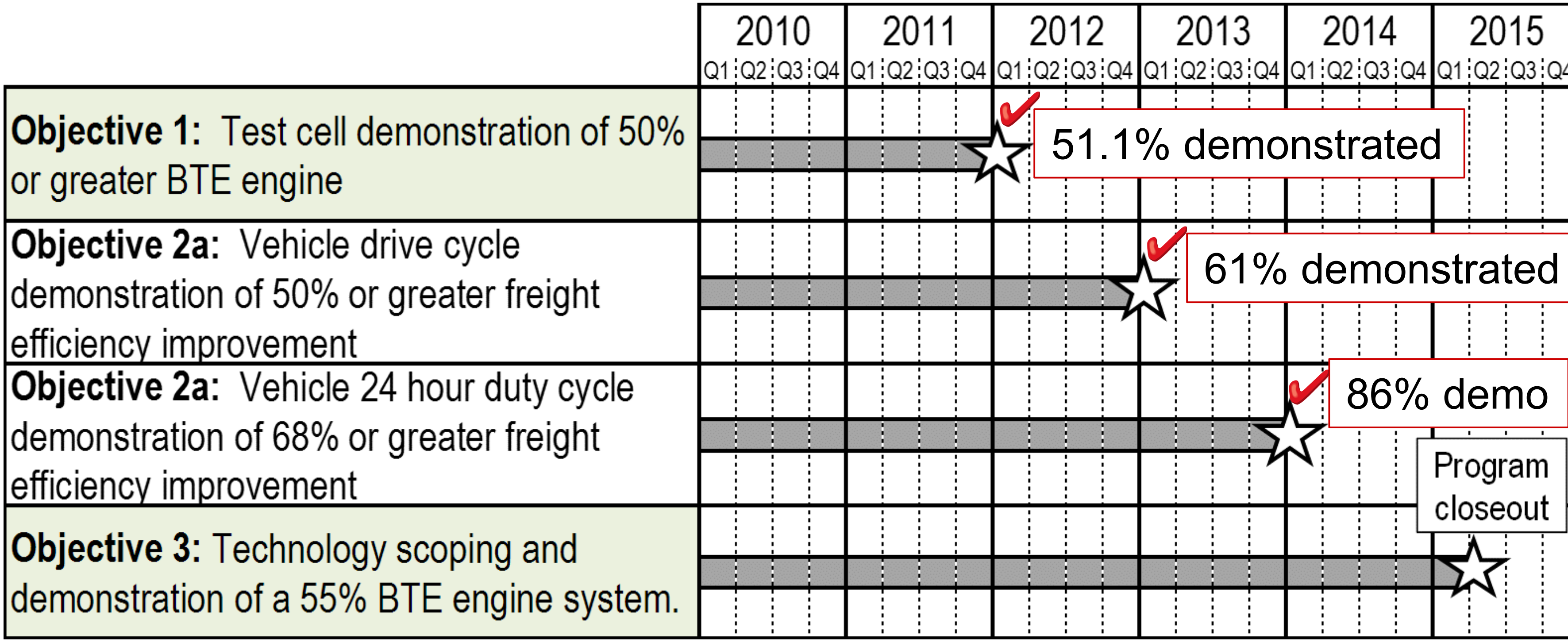






This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview



Budget:

- Total: $78,049,716
  - DoE share* $38,831,115
    CMI share* $39,218,601
    * actuals as of 12/31/2014

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

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

- ARRA Goal: Create and/or Retain Jobs

Year	2010	2011	2012	2013	2014	2015 (Projections)
Full Time Equivalent	75.5	85	60	46	14	3

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

- ARRA Goal: Spur Economic Activity
  - Greater than $78M total spend to date (ref: thru Apr 2015)
- 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

Innovation You Can Depend On

Approach – Vehicle Energy Analysis

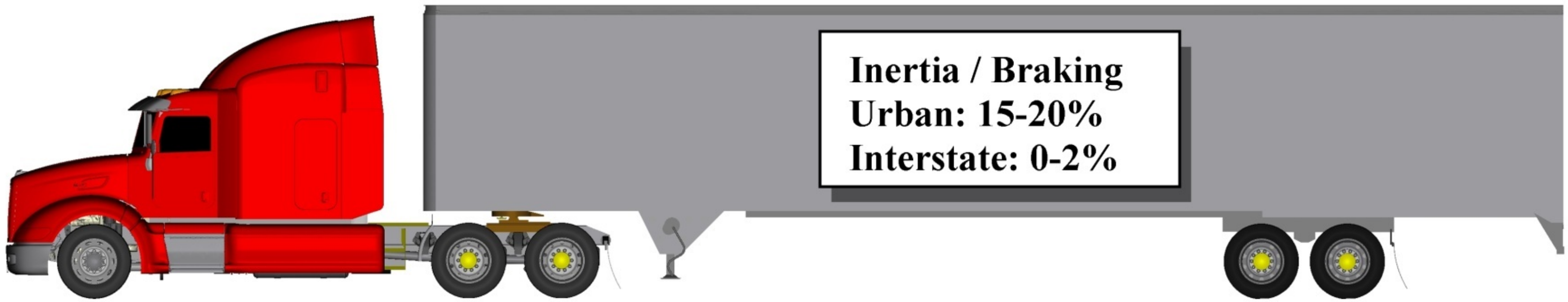
Analysis of 27 Drive Cycles for Class 8 Vehicles
with a Variety of Seasons (Summer, Winter, etc.)

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

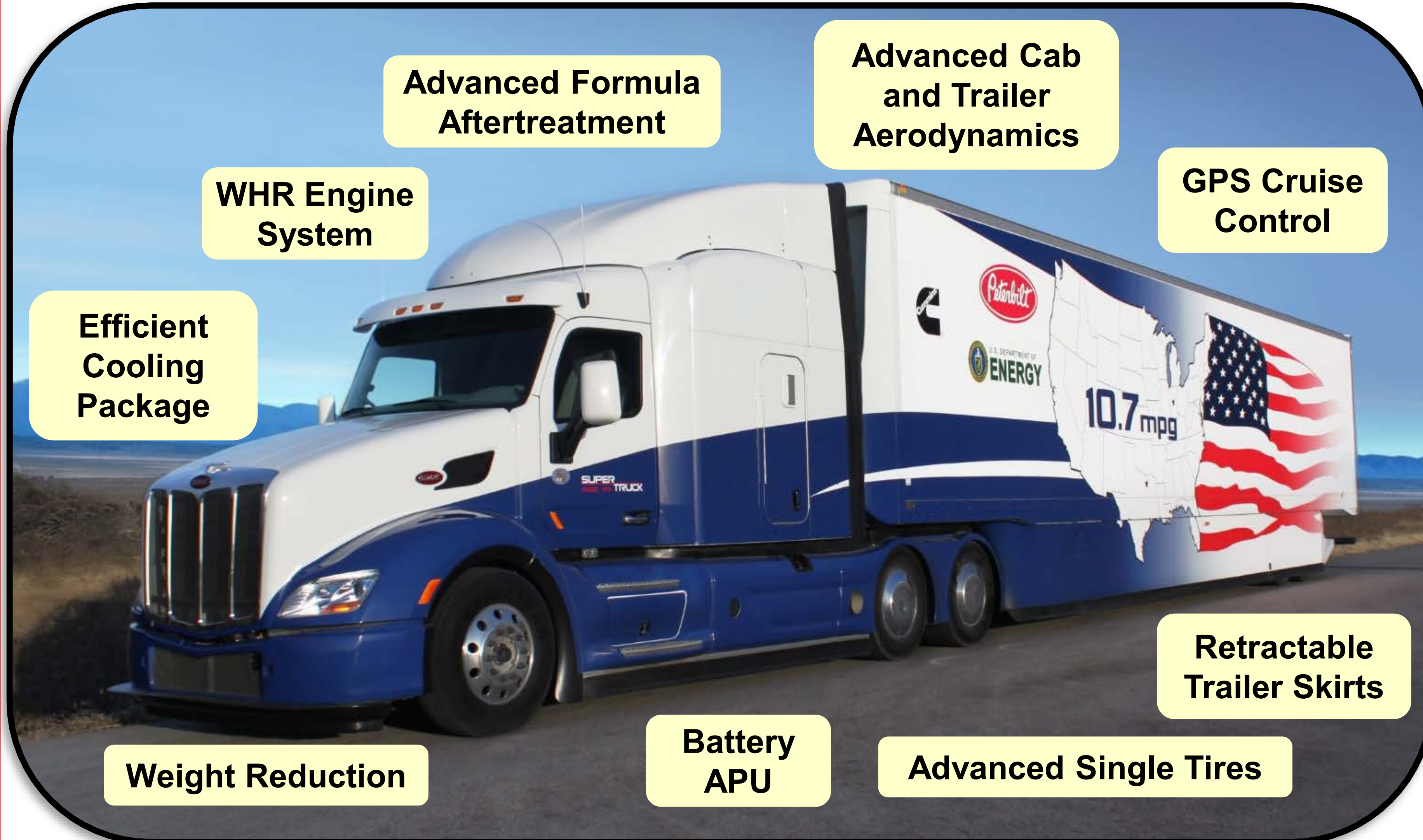
Weight Reduction

3
Rolling Resistance
Urban: 8-12%
Interstate: 13-16%

Bridgestone & Goodyear

Analyze: Where is the energy going? Identify priority.

Technical Accomplishments - Freight Efficiency Enabling Technologies



Technical Accomplishment:
2012 Drive Cycle Freight Efficiency Test

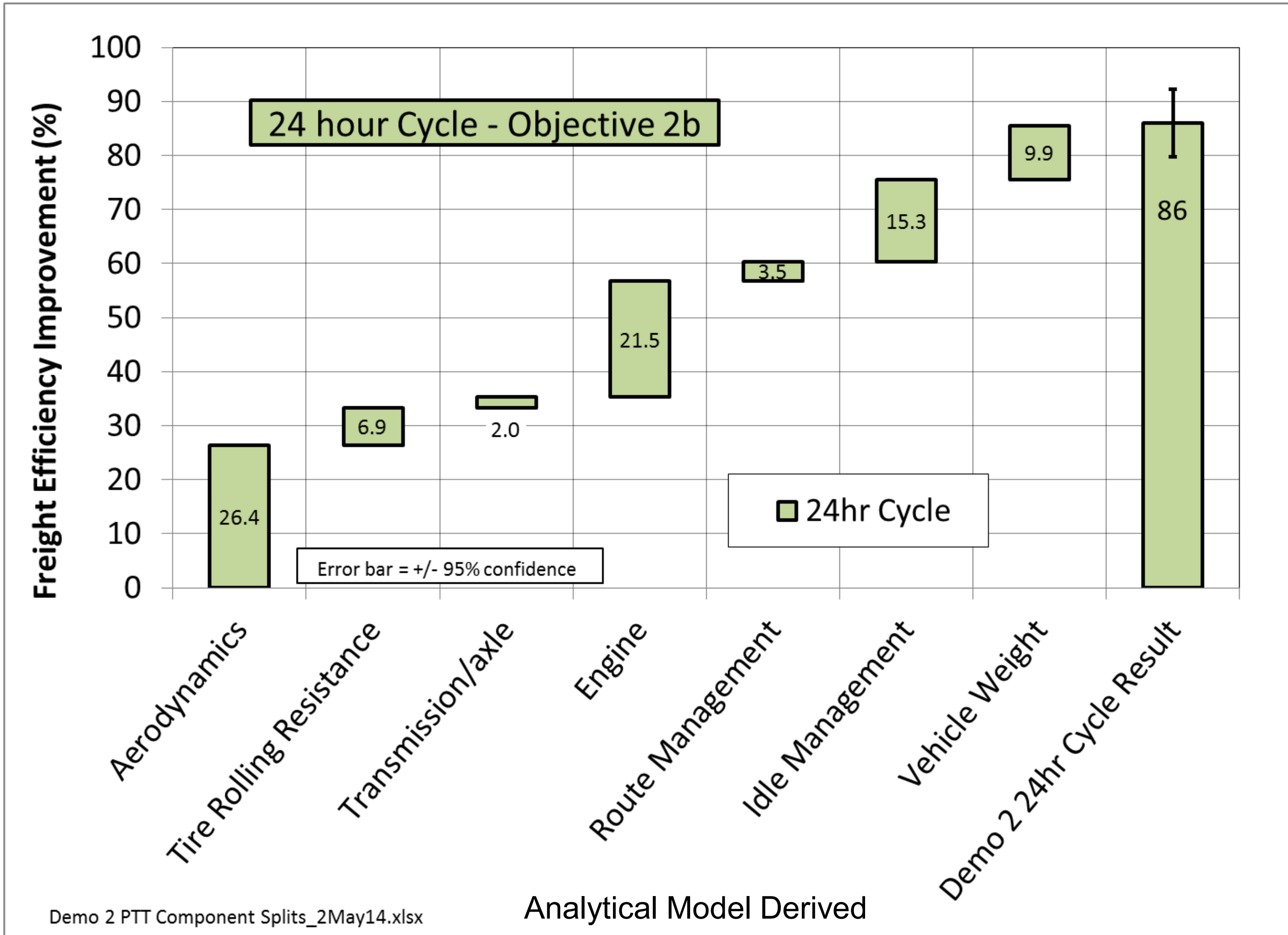
	GVW	Freight	MPG (Range)	(Ave) FTMPG Improvement	(Ave) MPG Improvement
587 Demo 1	65k	32,705	9.3-10.2	**61%**	**54%**
		+1434			

Technical Accomplishment:
2013 24 hr Drive Cycle Test Results

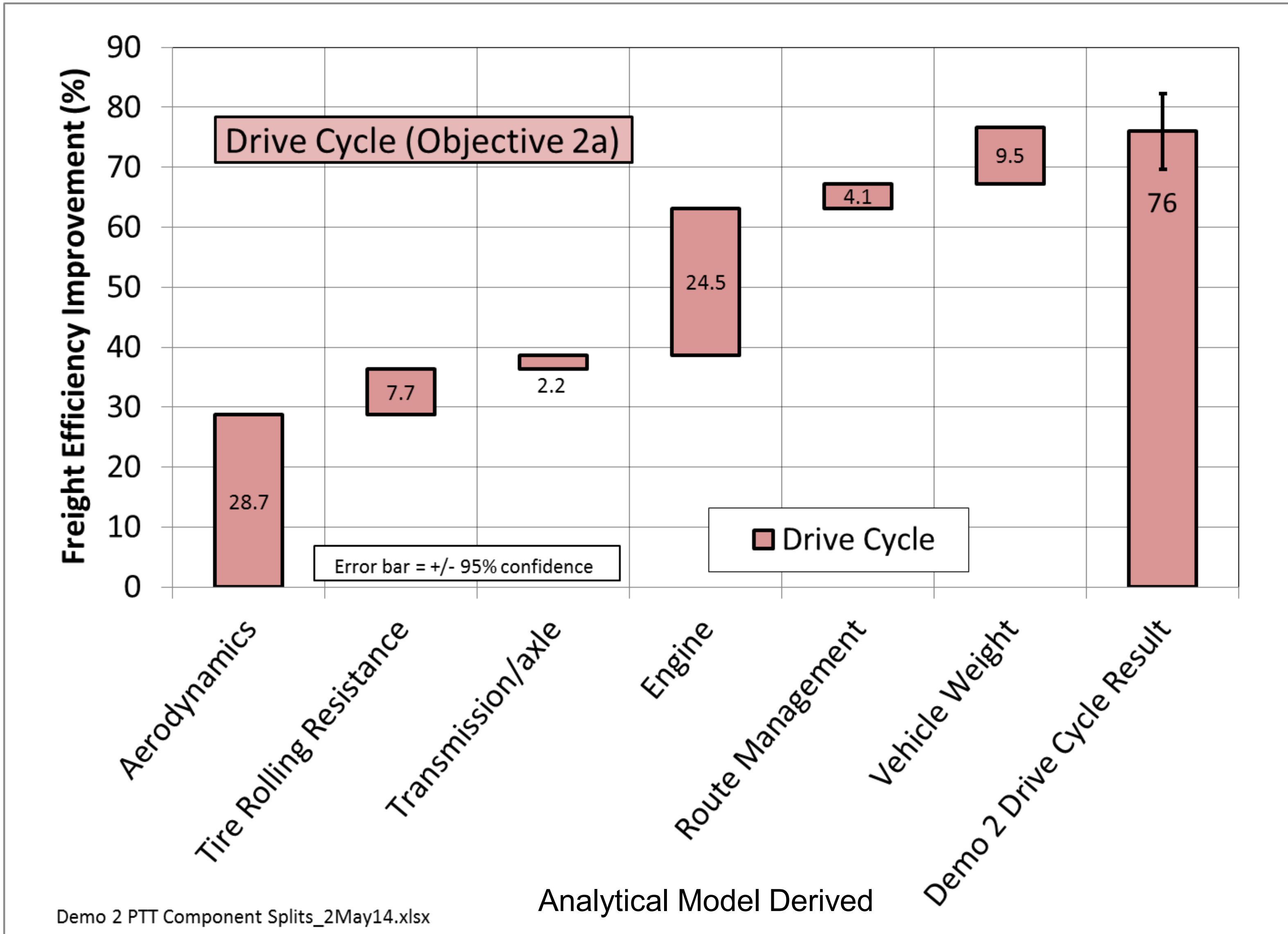
	GVW (lb)	Freight (lb)	MPG (Range)	(Avg) FTMPG Improvement	(Avg) MPG Improvement
579 Demo 2	65k	32,576	9.4-9.5	86%	75%
		+1305			

Goal: 68%

Technical Accomplishment – 24 hour Cycle Freight Efficiency Bridge

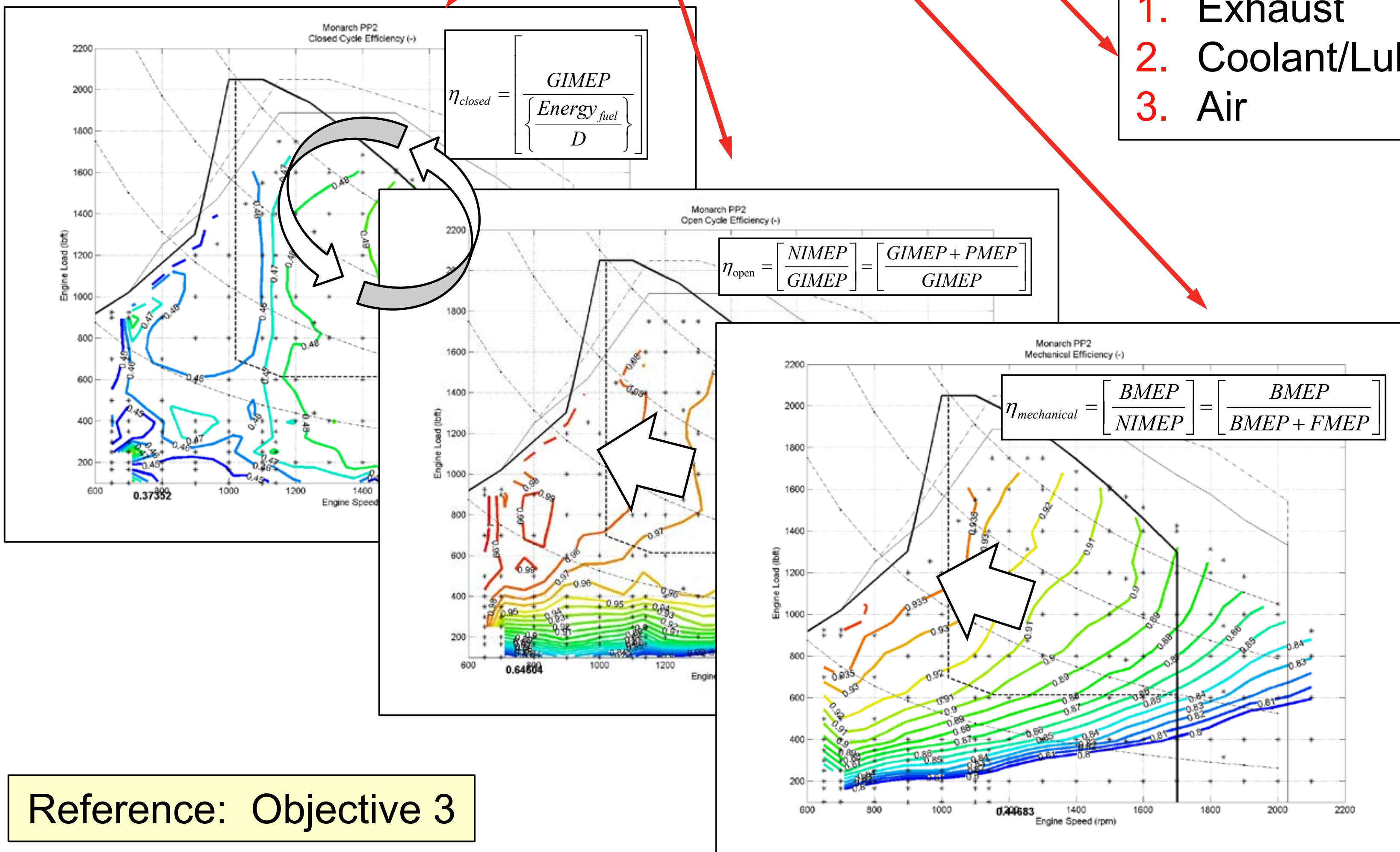


Technical Accomplishment – Drive Cycle Freight Efficiency Bridge



Approach – 55% Thermal Efficiency

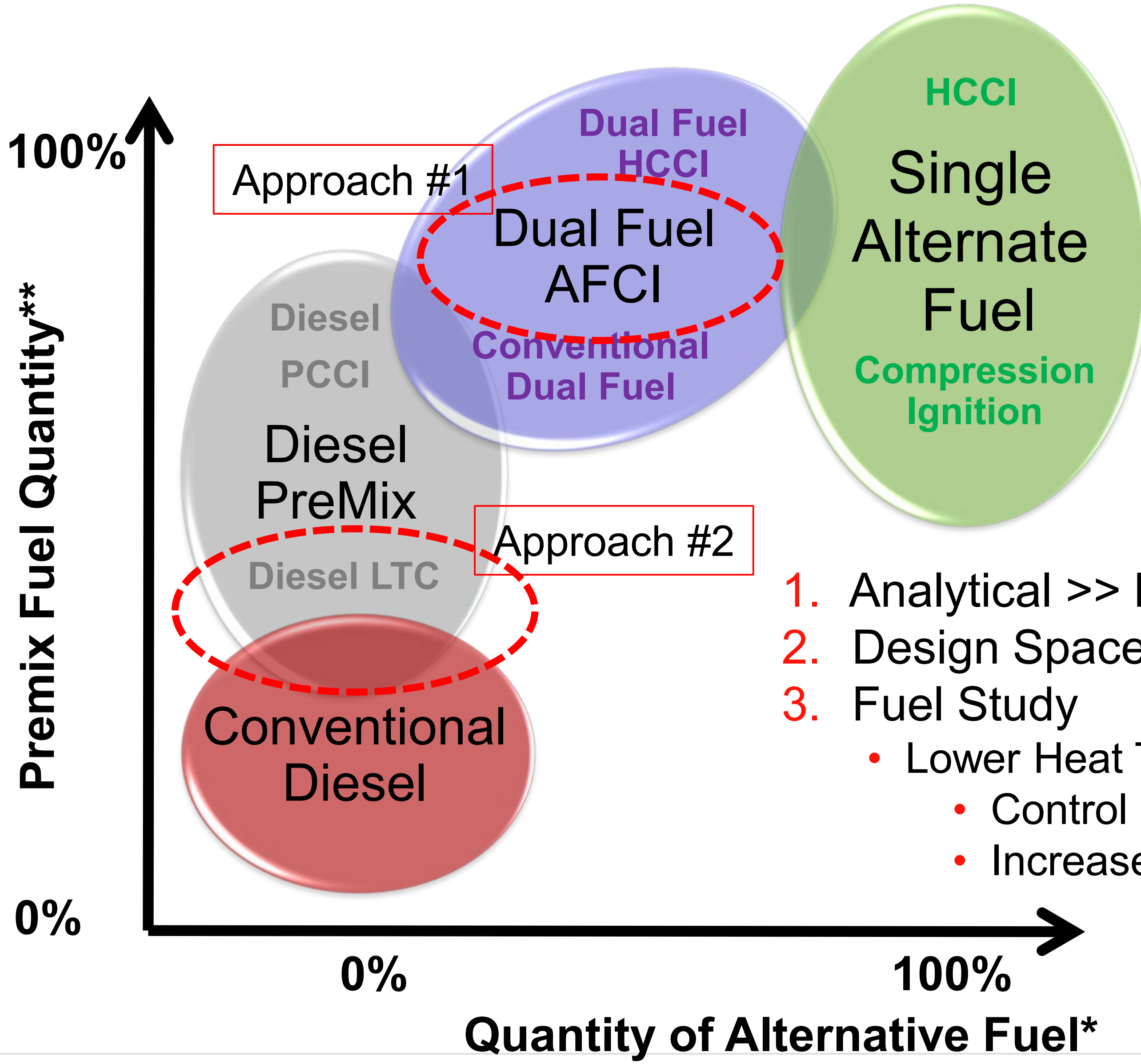
$$\eta_{thermal} = \eta_{closed} * \eta_{open} * \eta_{mechanical} + WHR$$



1. Exhaust
2. Coolant/Lube
3. Air

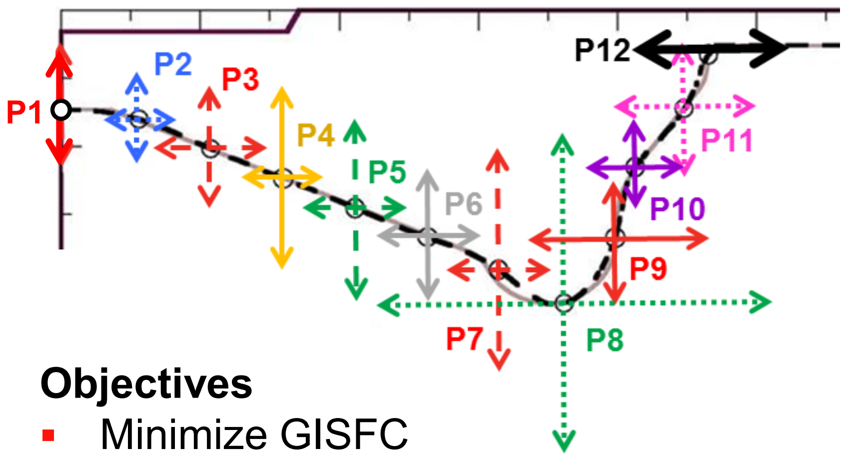
Reference: Objective 3

Approach –
55% Engine Technology Scoping - Fuels



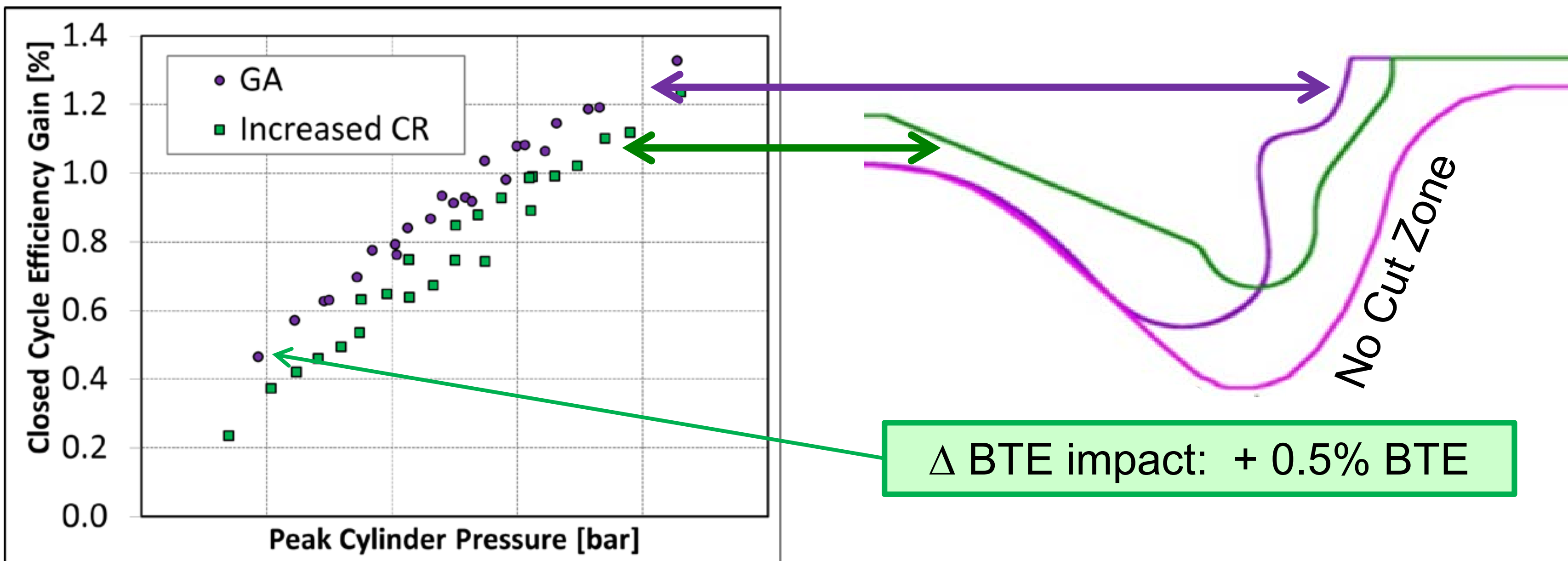
1. Analytical >> Experimental
2. Design Space is Broad
3. Fuel Study
   - Lower Heat Transfer
     - Control Burn Duration
     - Increase Effective Expansion

Technical Progress
Optimized Piston Bowl – Genetic Algorithm



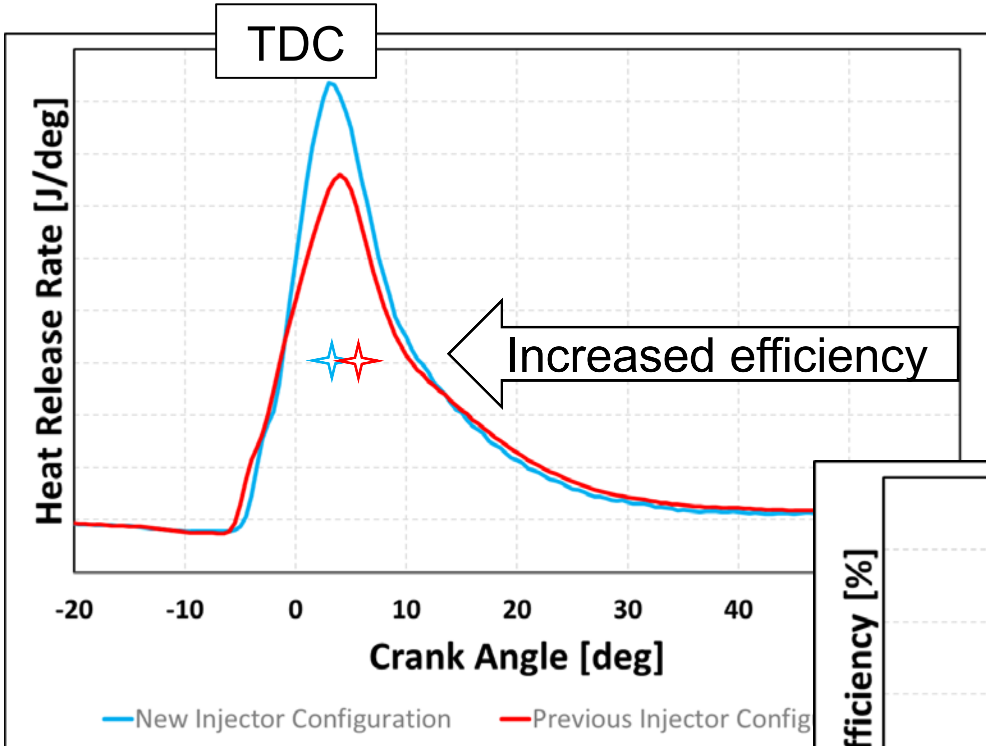
- 131 bowl generations computed
  - Compression ratio increase
- ➢ Optimized profile outperformed

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

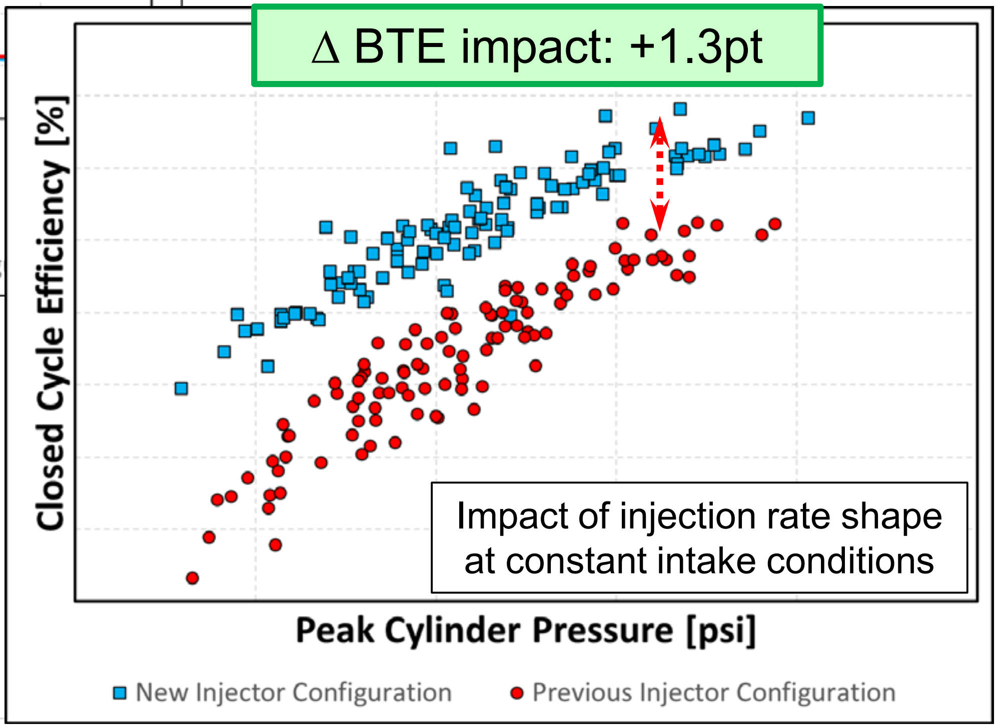


Δ BTE impact: + 0.5% BTE

Technical Progress
Optimized Injector – Single Cylinder Engine Results



- 3rd injector design completed
  - Robust cavitation design
  - Heat release improvements shown
  - Injector shot-shot work remains



- Single cylinder engine results show up to 2pt closed cycle efficiency gain
- Multi-cylinder results show ~1.3pt closed cycle gains
  - Air handling enhancements needed

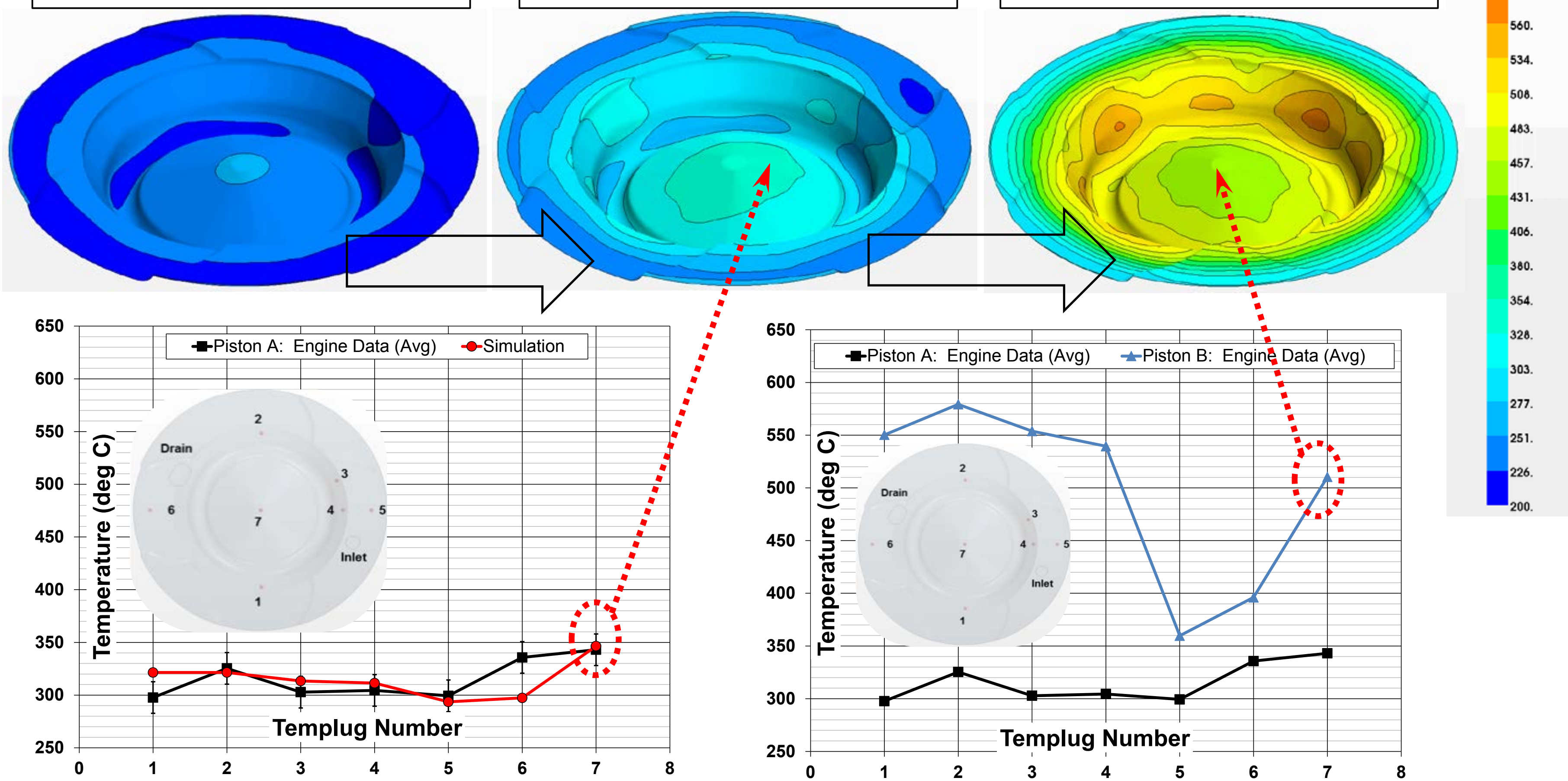
Innovation You Can Depend On

Technical Progress –
Piston Thermal Solution Validation Results

Base Piston:
Max Temperature = 254º C

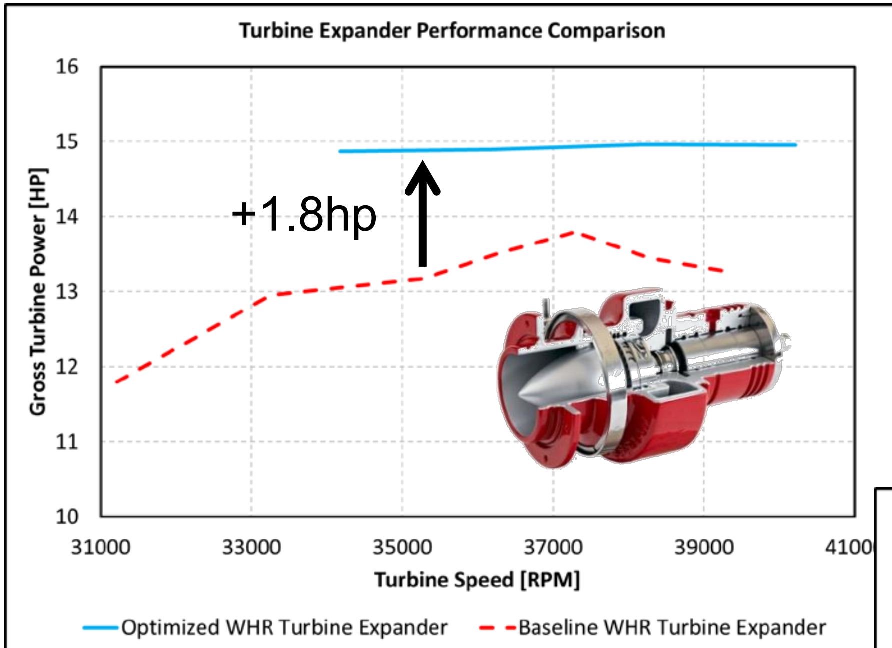
Piston A:
Max Temperature = 345º C

Piston B:
Max Temperature = 574º C



Net Cycle Δ BTE impact: + 1.7%
Includes open and closed cycle gains

Technical Progress –
Improved WHR Turbine Expander & Parasitic Reduction Results

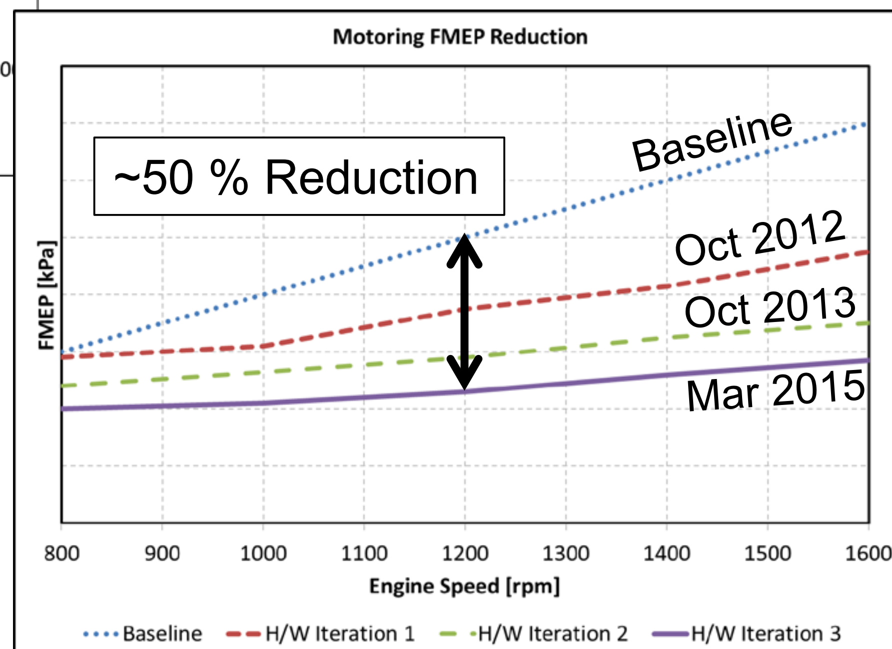


- Improved turbine efficiency
- System heat exchanger architecture arrangement
  - Pre-heat of low pressure loop

Total BTE contribution: 3.6%
Δ BTE impact: + 0.7% BTE

- Friction and Parasitic reduction validated on multi-cylinder engine
  - Piston/ring pack/liner changes
  - Piston cooling flow reduction
  - Fuel pump parasitic reduction
  - Lube pump improvements

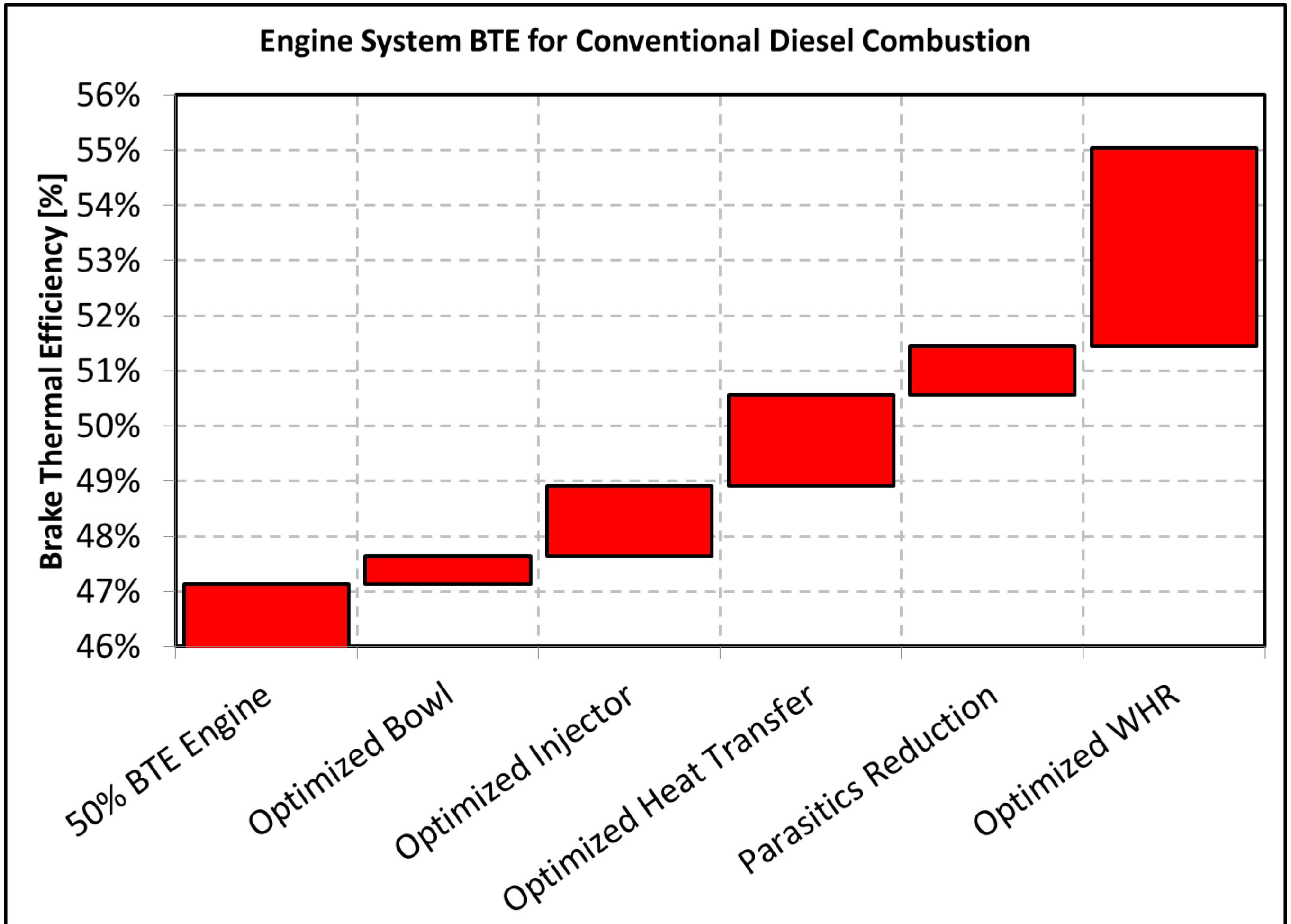
Δ BTE impact: + 0.9% BTE



Innovation You Can Depend On

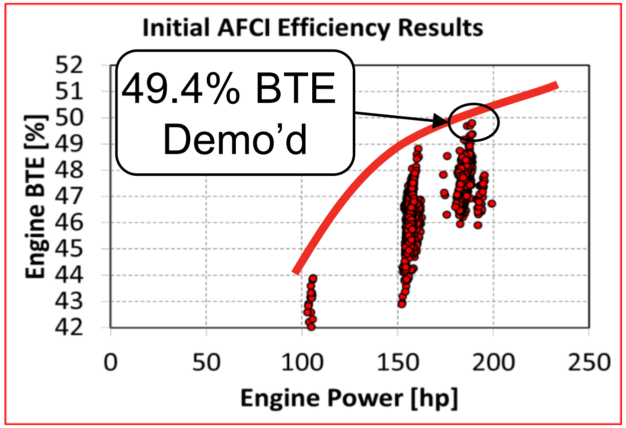
Technical Progress
Conventional Diesel Path to 55% BTE

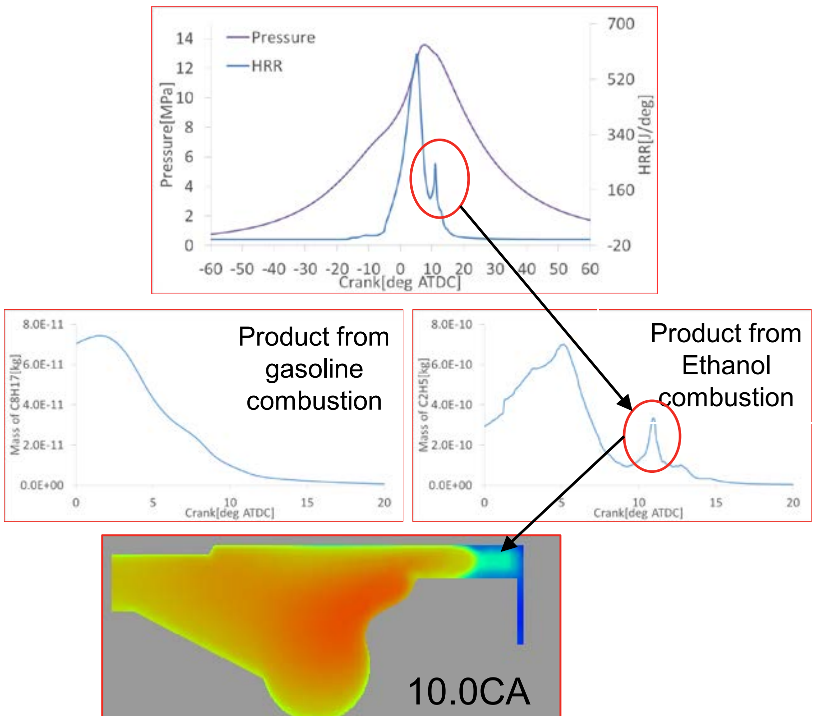
- Completed Cycle Simulation of technologies 'as a system'
  - Inputs to cycle simulation are result of Combustion CFD/Thermal Conjugate analysis, single cylinder engine data, injector flow rate data, multi-cylinder motoring friction data



Innovation You Can Depend On

Technical Progress
AFCI Auto-Ignition Investigation



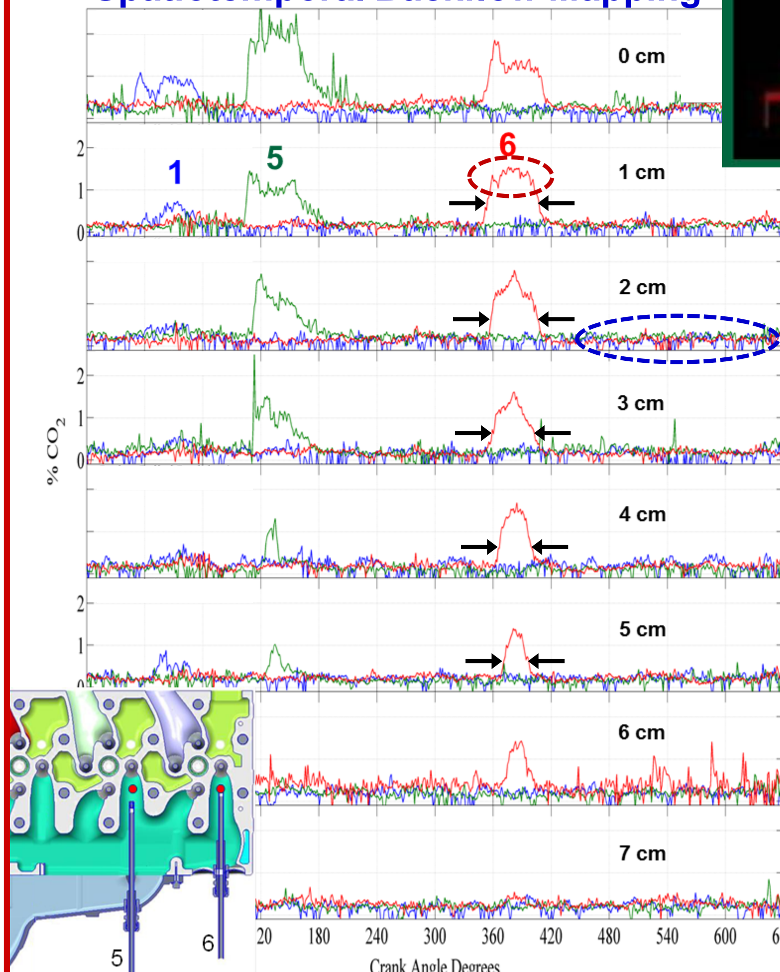


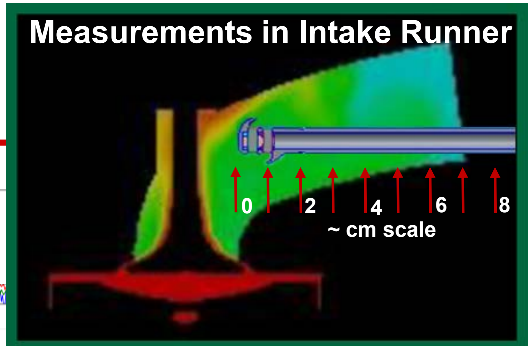
1. Dual fuel approach showed load limitation @ 10 bar BMEP
   - Engine cylinder component design efforts to lower 'hot spot' temperatures were not successful in increasing load capacity.
2. A new version of Comb CFD analysis tool identified auto-ignition source
   - Abnormal heat release around 10 CA is mainly caused by the auto-ignition of Ethanol at the piston top
3. AFCI work continues with a dual fuel DoE sponsor contract
   - Objective is for a 50% petroleum reduction, not a high BTE engine

Collaboration & Technical Progress:
Backflow, Uniformity & Temperature Test

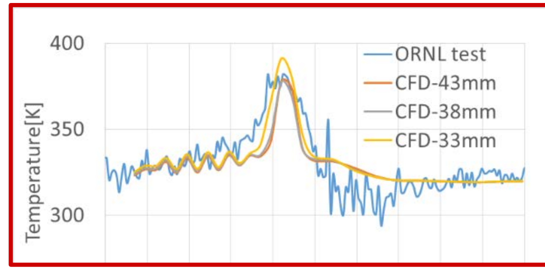
ORNL/CMI Multi-Cylinder Test
September 22-26, 2014
Presented: ACE077 - Partridge

Spatiotemporal Backflow Mapping





CFD EGR Probe Comparison



- Charge components directly measured
  - EGR-Air (baseline)
    - EGR-Air uniform temporally & cyl-to-cyl
  - Combustion-residual backflow (pulse)
  - Temperature
- Flat pulse indicates uniform backflow dilution
  - Dilution factor relates backflow to cylinder residual
  - Backflow ≈ 20.8% residual + 79.2% fresh EGR-air
- Width indicates backflow penetration depth
  - Use in Cylinder-Charge model
- Measured backflow wider than CFD
  - Flow in probed port much slower than modeled
- Many details & insights for assessing
  - Hardware, system, models, control

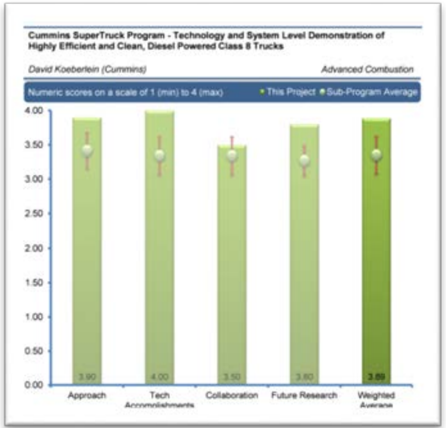
Collaborations – SuperTruck Program

Engine Development ⇔ **Vehicle Development**

- Cummins Subsidiaries
  - Fuel Systems
    - Injector & Fuel pump
  - Electronics
    - WHR & AT controls
  - Turbo Technologies
    - WHR turbine & Turbocharger
  - Emissions Solutions
    - Truck AT system
- Modine
  - WHR heat exchanger design
- Oak Ridge National Lab.
  - Advanced lab sensors & controls
- Purdue University
  - PCCI combustion modelling
  - VVA modelling
- VanDyne SuperTurbo Inc.
  - Turbocharger/Supercharger system
- Numerous other contributors

- Eaton
  - Transmission
- Modine
  - Vehicle cooling module
- Goodyear
  - Tires
- USXpress
  - Customer operation & interface feedback
- Dana
  - Driveshaft & axle system
- EXA
  - Aerodynamic analysis
- Bergstrom
  - Cab & Electric Sleeper HVAC system
- Bendix
  - Axle system control & brake drum material cert
- Numerous other contributors

Reviewer Comments and Responses



Many complimentary comments:

- *The reviewer observed a fundamentally sound, very advanced, and technically complete approach to improving BTE to meet the program goals.*
- *The reviewer observed that the project exceeded engine and vehicle goals by large margins. Credibility and analyses would likely lead to the success in meeting 55% BTE. The reviewer noted a very impressive breakdown of opportunities and preliminary results.*

Recommendations:

- *The reviewer questioned why only two partners were used in this program (i.e., ORNL and Purdue University). The reviewer stated that there were no tangible results demonstrated with these two partners in Slide 21.*
  - Comments: The program utilized numerous partners and collaborations to achieve the goals. Technical backup slide 26 sought to identify other program contributors. Peterbilt utilized Eaton and Delphi and Cummins utilized Peterbilt, ORNL, Purdue, Modine and VanDyne as sub-recipients. However, there are numerous other partners who contributed advanced technologies with individual components. It's difficult in the allotted presentation space to recognize those with which we couldn't have done it without them. Hopefully, this years' slides help, as its not unnoticed or unrecognized.
- *The reviewer was looking at all the options. The reviewer stated not being sure the dual fuel approach to 55% BTE was worth it given only a small BTE advantage and the infrastructure/complexity issues with dual fuel.*
  - Comments: We recognize the dual fuel HD truckstop E85 infrastructure availability issues, as well as the technical challenges, controls being critical. However, the engine related changes are not large, while offering low Nox emissions solutions and possibly diesel fuel system and AT system cost reductions with a dual fuel architecture. The key is, it is not a bi-fuel architecture.

Summary

- Program completed on schedule
  - Met the ARRA and DoE VT MYPP goals
- Demonstrated a 50+% BTE engine system (Objective 1)
- Demonstrated a 80+% 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

Innovation You Can Depend On

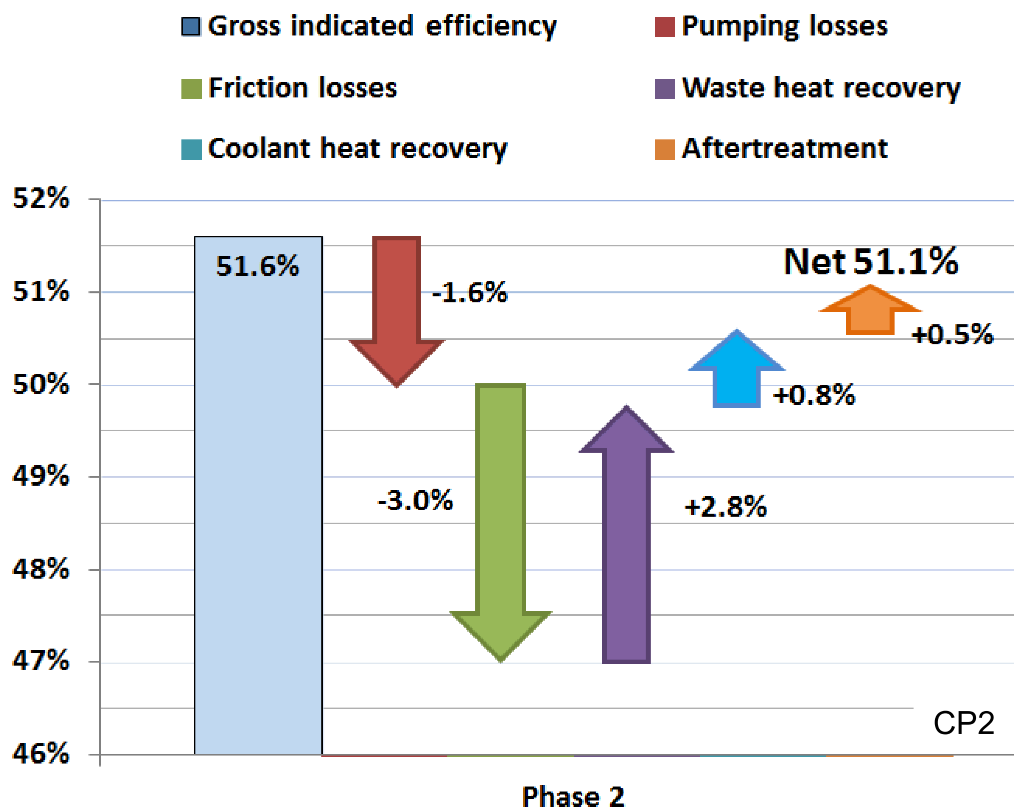
Technical Accomplishments – 50+% Thermal Efficiency Gains

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

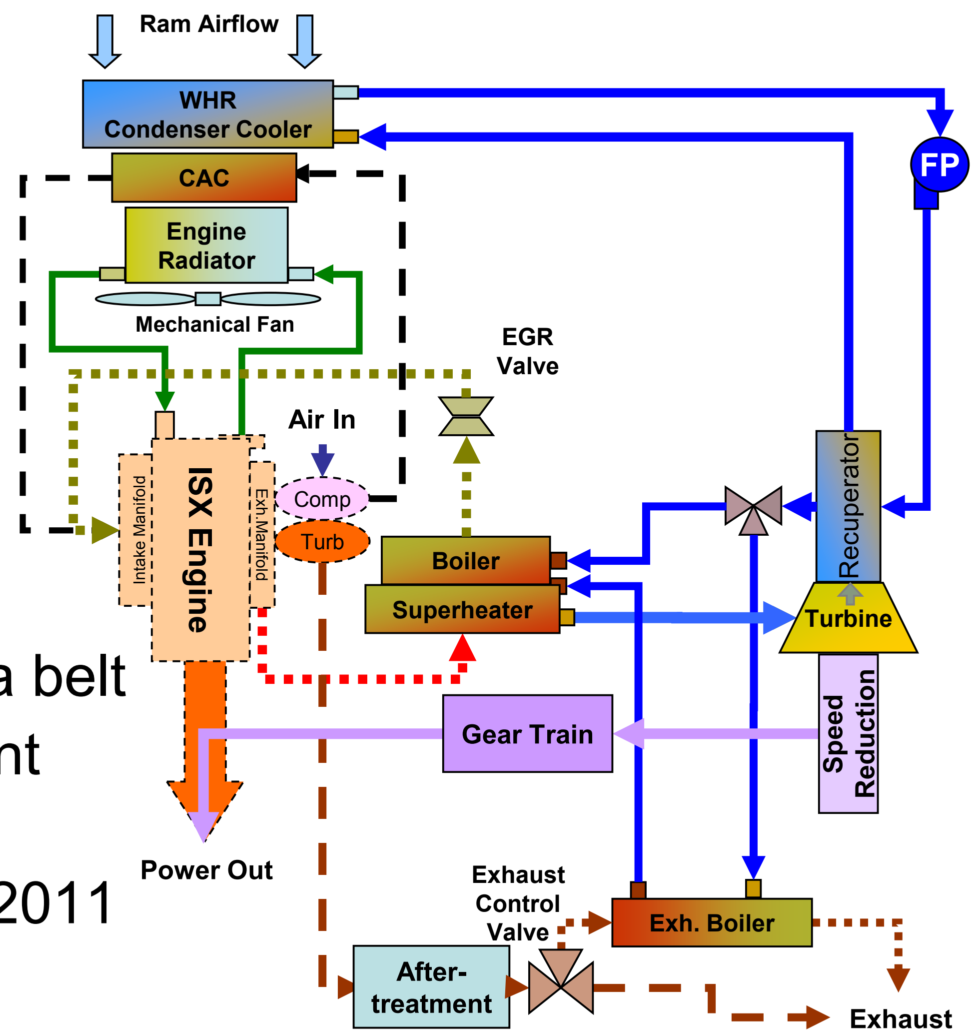
WHR system
- EGR, Exhaust, Recuperator
- Coolant & Lube



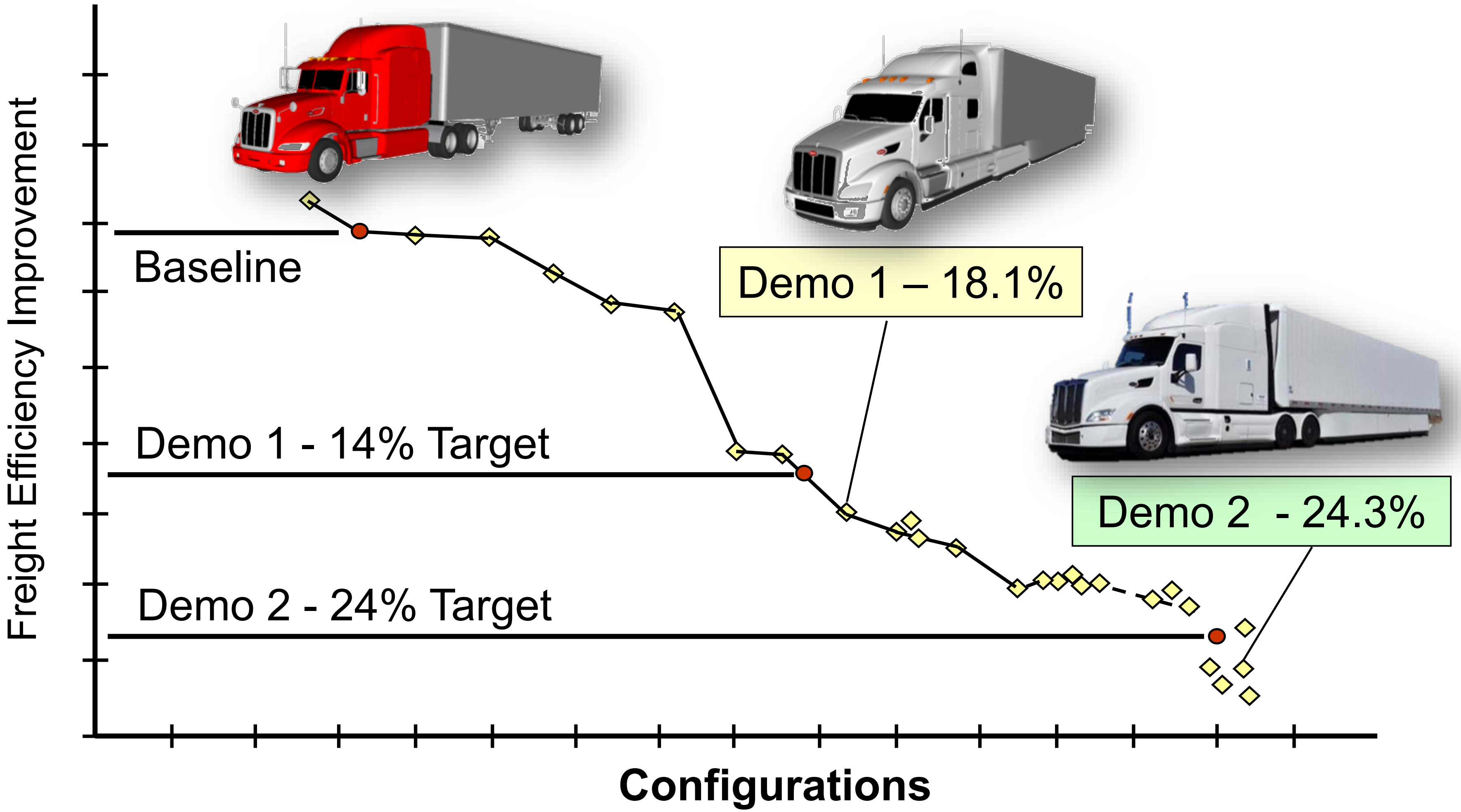
Reference: Objective 1

Cummins Waste Heat Recovery

- Organic Rankine Cycle
- Low GWP, non-flammable refrigerant working fluid
- Recovery of:
  - EGR
  - Exhaust heat
  - Coolant/Lube – optional
  - Charge air - optional
- Mechanical coupled WHR turbine power to engine via belt
- Fuel Economy improvement goal of ~4-5%
- 1st vehicle installation Sep2011



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