SuperTruck – Development and Demonstration of a Fuel-Efficient Class 8 Tractor & Trailer

Engine Systems

DOE Contract: DE-EE0003303

NETL Project Manager: Ralph Nine

Program Investigator : Dennis W. Jadin, Navistar

DOE MERIT REVIEW

WASHINGTON, D.C.

May 17, 2012

National Energy Technology Laboratory
Department of Energy

Project ID: ACE059

Outline

NAVISTAR Advanced Technologies

- Program Overview
  - ❖ Partners
  - ❖ Scope of Work
  - ❖ Barriers and Technology Roadmap
- Technical Approach
  - ❖ Approach criteria
  - ❖ Time line
- Technical Accomplishments
  - ❖ Progress to date
  - ❖ Combustion, Air Systems, Base Engine, WHR
  - ❖ Fuel Reactivity Engine
- Future Work

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Goals and Objectives

Demonstrate 50% improvement in overall freight efficiency of a combination Tractor-Trailer
- 30/50% improvement achieved through tractor/trailer technologies
- 20/50% improvement achieved through Engine technologies

Attain 50% BTE Engine
Demonstrate path towards 55% BTE Engine

Barriers

Achieving 50% freight efficiency while balancing Voice of Customer Needs
Packaging of hybrid drive unit and Waste Heat Recovery Systems
Maintaining tractor weight while adding new systems
Availability of Suitable Battery Technology

Budget

DOE recently approved new budget periods / phases >>>>

Budget Period	Start Date	End Date
1	10/01/10	08/31/12
2	09/01/12	09/30/13
3	10/01/13	06/30/14
4	07/01/14	03/31/15
5	04/01/15	09/30/15

An increased level of resources planned in budget periods 2 & 3 will accommodate project deliverables in periods 4 & 5.

Total Project Funding:	DOE	$37,328,933
	Prime Contractor	$51,801,146
DOE Funding Received :		$ 13,393,868

Program Overview

Engine Partnerships

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Test Facilities
Partners

Oct-11 | Oct-13

Phase I | **Phase II** | **Phase III-IV**

Navistar
BEHR

Combustion
Emissions
Fuel System
Head
CR

Turbocompounding

VVA *ORC*

Base Engine

50% BTE Demo

Federal Mogul

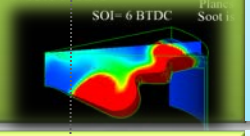
Friction Reduction
Accessories

Friction Benchmark

BOSCH

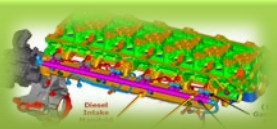
High-injection pressure capability

CFD-Testing benchmarks



Higher CR capability

ANL
WISCONSIN RESEARCH CONSULTANTS



Engine Design
Controls

Fuel Reactivity Testing

Advanced Engine Technologies

55% BTE Demo

AMR 2012

Barriers (Challenges)

And Technology Roadmap

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Key: ✓ high confidence to contain
✸ working on improving solution

System	Barriers (challenges)	Technology Roadmap
Engine & Vehicle	• **Cost effective** • **Robust** (controls, durable) • **Reduced weight**	Rely on analysis to select technology ✓ Technology to road cycle selection ✓
Engine	• **High combustion efficiency with low in-cylinder emissions (NOx, PM)**	Improve Fuel Injection/Air Systems ✓ Advanced Combustion Regimes ✸ Reduced friction, advanced accessories ✓
Engine	• **Modest bottoming cycle efficiency** • **Simplified aftertreatment**	Advanced designs ✓ Optimum integration to engine ✸ Close collaboration with suppliers ✓
Engine	• **High-efficiency combustion range**	Understanding of chemical kinetics ✸ Introduce combustion feedback ✓
Engine	• **Non optimum fuel formulation**	Introduce reactivity control ✓

Scope of Work

Technology Development and Concept Readiness (Phase II)

1 October 2011 – 30 September 2013

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completed In progress

Task	Description		Status
2.1-1	**Engine and vehicle model**	Integrate engine model to vehicle	50%
		Updating engine mode with ORC	50%
2.1-2	**Advanced Diesel Combustion**		
	Fuel System to 2900bar with Comb Fbk	Complete	100%
	WHR-TUCO	Complete	100%
	WHR-ORC	Procurement 5/12. Testing 9/12.	20%
	VVA	Procurement 5/12. Testing 6/12	40%
	Aftertreatment	Running NOx reduction cat (0~50%)	70%
	Friction reduction and electrification	Accessories are being benchmarked	60%
	Control System	Platform is built and tested	100%
2.1-3	**Fuel Reactivity Engine**		
	Lab/Engine/Controls Design and Build	Completed Engine and DAQ install	100%
	Testing	Began combustion characterization	20%
2.5	**Concept Readiness**		-
	Demo 50%/55% BTE targets		-

Approach

Selection Criteria Towards 50% BTE

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BTE > 50%

20%

4. WHR

3. Friction Accessories

2. Air System

1. Combustion

Base efficiency

Leverage Technologies

- Electrical Turbocompounding
- Rankine Cycle
- Low Friction components
- Variable Oil Pump
- Variable Speed Water Pump
- VVA
- Turbo optimization
- Increased PCP
- Optimum timing
- Higher Injection Pressure

Optimize Integration Criteria

Efficiency gain

Weight

(Ton-mile/gallon)

Cost

(payback)

Evaluation at Fully Loaded Drive Cycle
(65,000 lb vehicle weight)

Approach

Optimum Roadmap Towards 50% BTE

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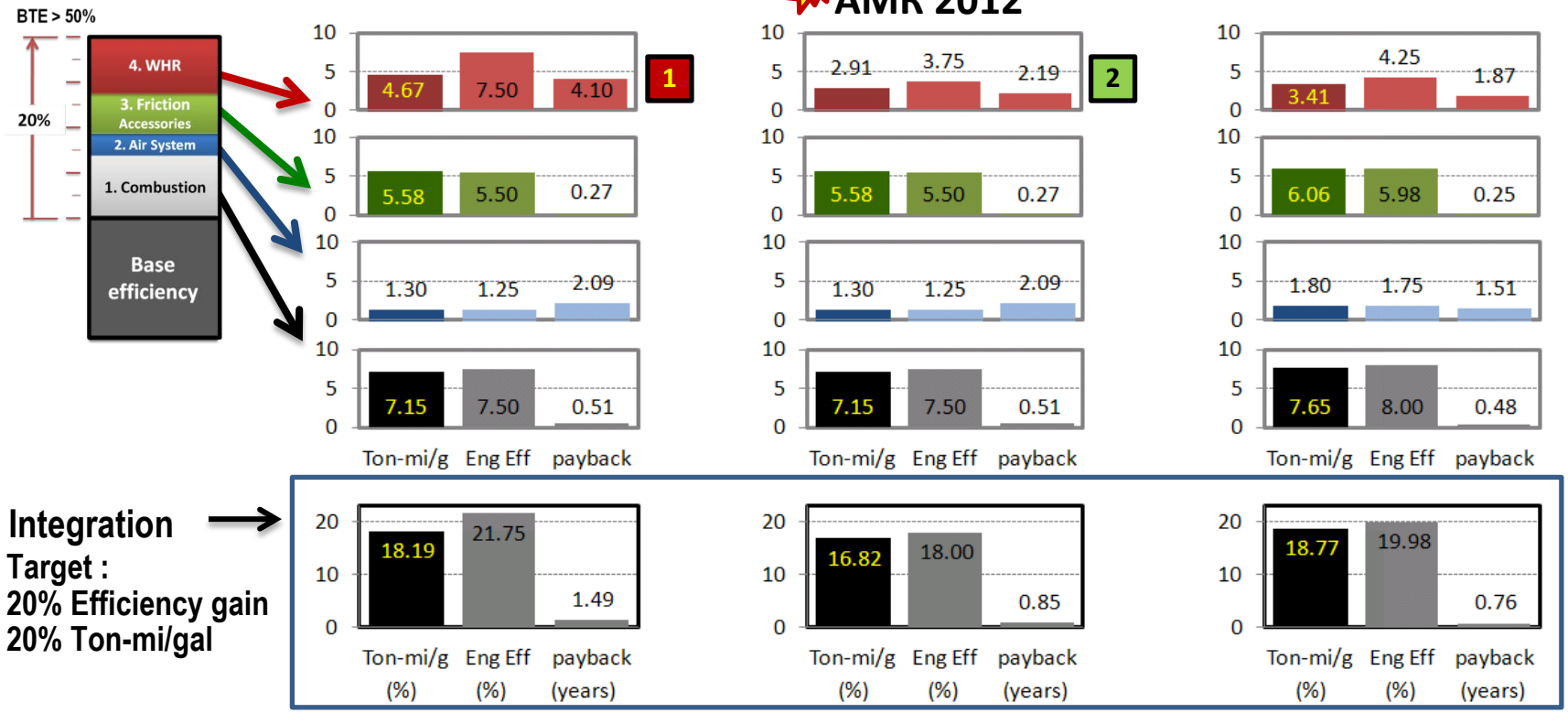
AMR 2012



Approach

Base Engine with all technologies

1

Concerns:
Longer payback
Complexity from ORC

Down selection
Based on current tests and present projections

2

WHR limited to
Electric Turbocompounding

Down selection
With next generation hardware upgrade

20% engine η gain ~ 50% BTE
~19% freight efficiency gain

Approach

Timeline and Tuning Engine Technology Build

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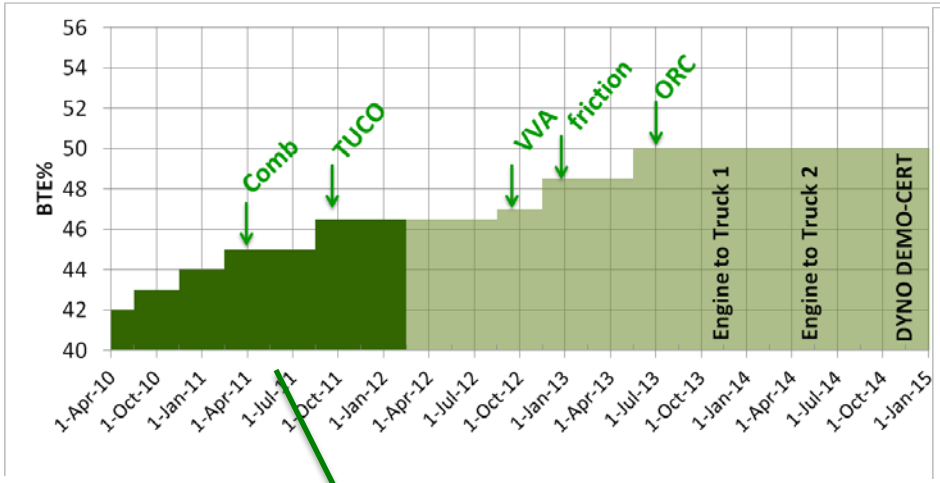
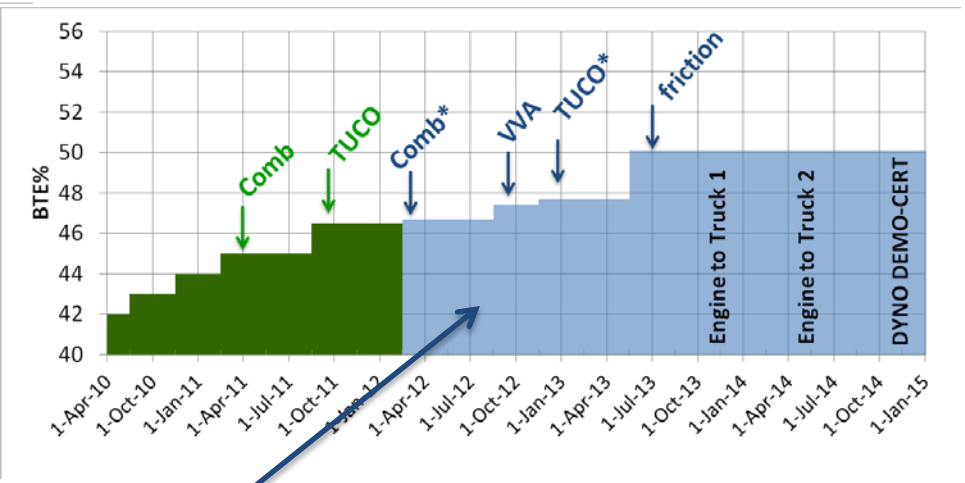
Original Plan



Updated Plan



Phase I (completed)

- ✓ Combustion raised 3% BTE
- ✓ Turbocompounding raised 1.6% BTE
- ✓ Current dyno demo at 46.5% BTE

Phase II (current)

- ✓ Continue comb development
- ✓ Continue Turbocompounding
- ✓ Preparing for VVA
- ✓ Preparing for friction package

Note:
ORC development will be on dynamometer only

Accomplishments

Progress to Date

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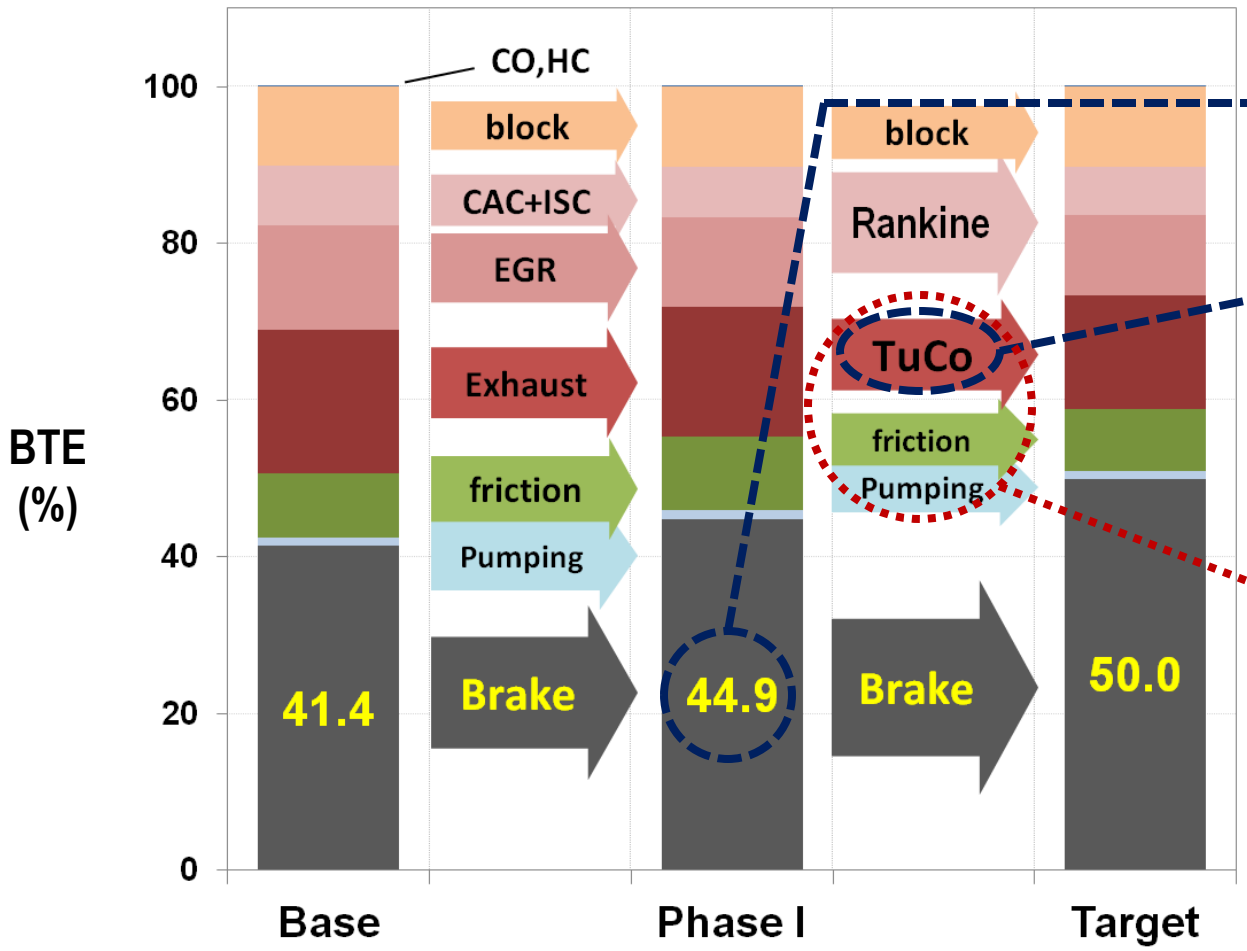

To date

Combustion improvements ~45%

Turbocompounding ~47%

Currently

Improved TuCo
Friction Reduction
Accessories
Air systems

50%

Results shown at road load condition

Accomplishments

1. Combustion Efficiency

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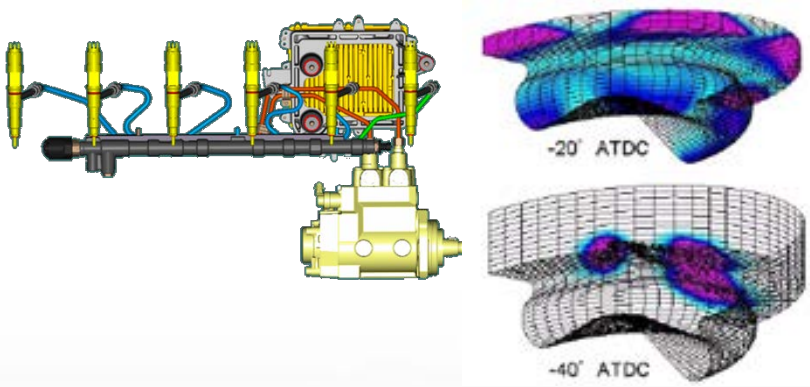
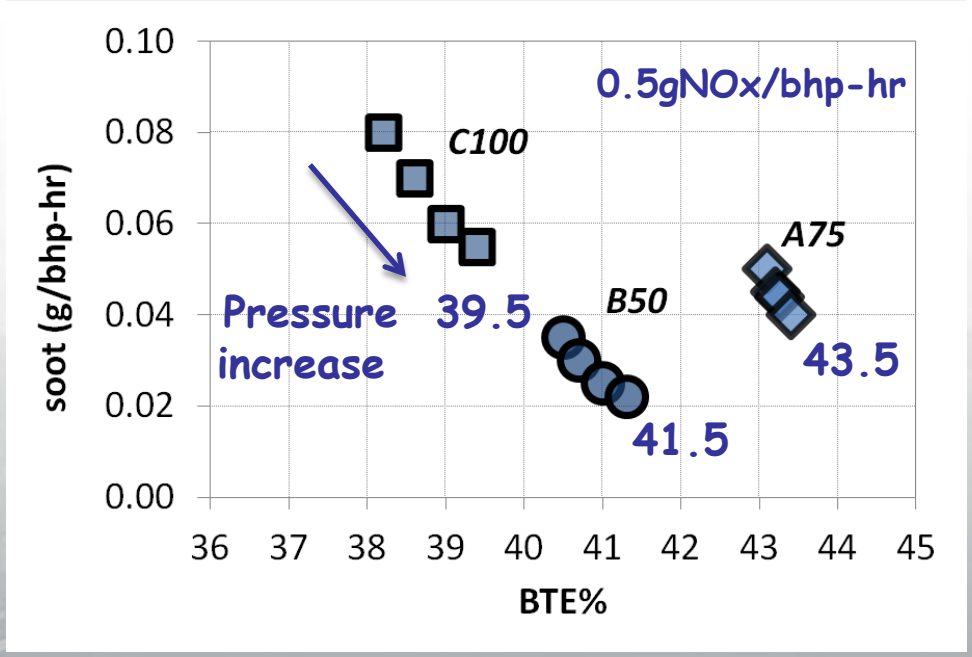
Comprehensive CFD for comb matching
Improved injection system efficiencies
Increased injection pressure
Optimum NOx-PM-BTE





Results:

- ✓improve BTE across N-range
- ✓reduces soot across N-range

Ref.
D. Jadin, AMR 2011
W. de Ojeda, DEER 2011

Accomplishments

2. Air System

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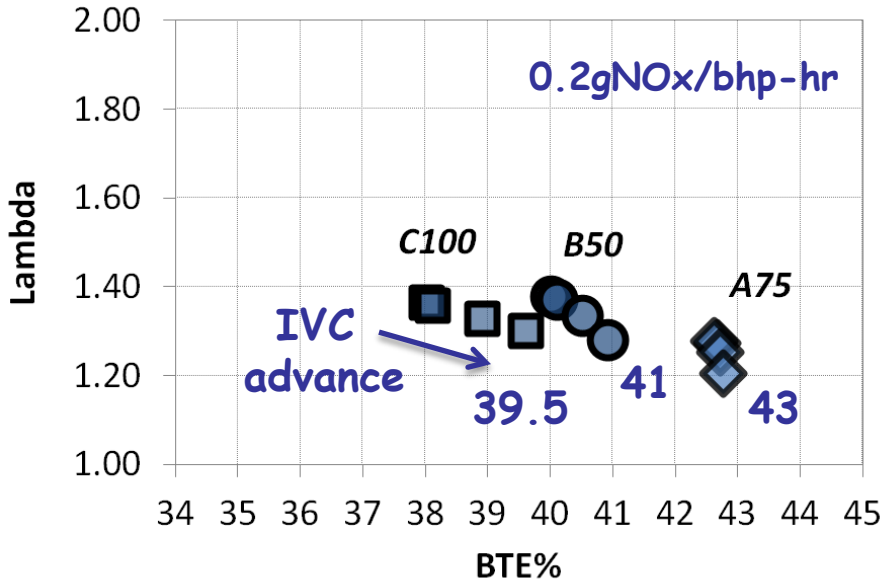
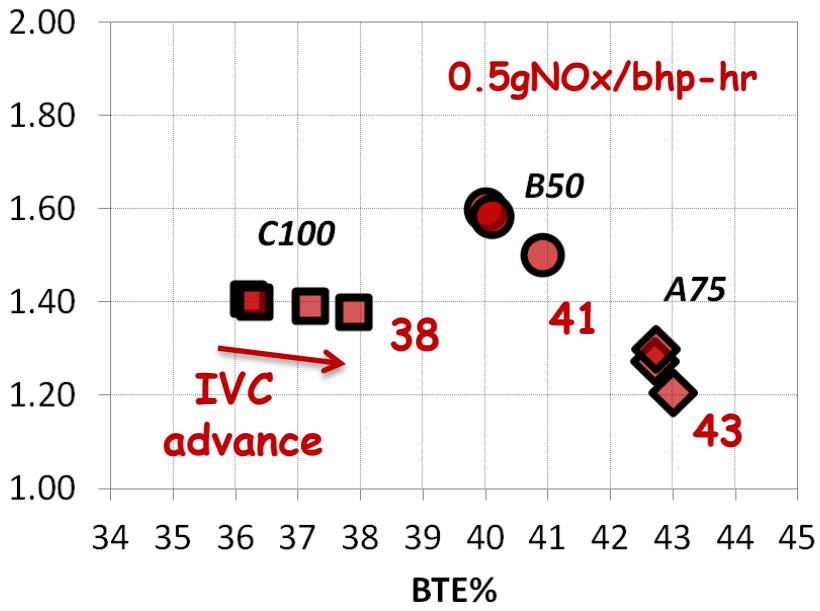
MAXXFORCE™ Engine will incorporate a Variable valve actuation device:
-Control over combustion temperatures
-Improved turbo matching

Results

- ✓ Thermodynamic gains across NOx range
- ✓ BTE across a wide range of speeds





Data based on simulation

Accomplishments:

3. Base Engine

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- ✓ **Three major engine categories: Power cylinder, power transfer, crankcase**
- ✓ Performance categories addressed: friction, peak cyl pressure, thermal management
- ✓ Target BTE improvement of **1.5 - 2.0%** or more percent

		status	Target	Current Projection (BTE GAIN)
Power Cylinder	Pistons	**on engine stand**	**0.5**	**0.5**
	Rings	**on engine stand**		
	Connecting Rod	**on engine stand**		
	Cyl Liner	**on engine stand**		
	Cooling Jets	under development		
Power Transfer	Crankshaft	under development	**0.6**	**0.6**
	Main Bearings	**on engine stand**		
	Rod Bearings	**on engine stand**		
	Camshaft	**on bench stand**		
	Stem Seals	under development		
Crankcase	Lube Pump	**on engine stand**	**0.9**	**0.9**
	Coolant Pump	**on bench stand**		

Accomplishments:

4. Waste Heat Recovery

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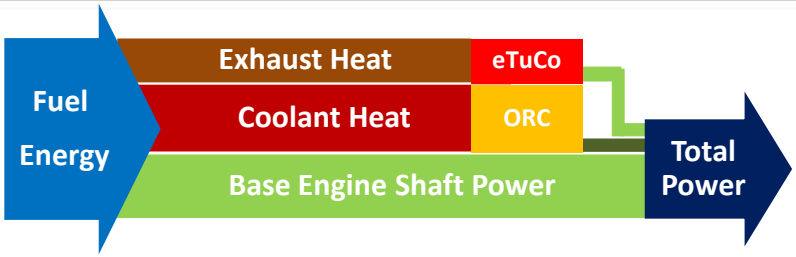

1. Turbo-compounding (eTuCo)

- ✓ Completed Gen. 1 cell testing and system optimization
- ✓ Completed Gen. 1 transient calibration for vehicle operation
- ✓ Installed Gen. 1 system on Mule #2 for vehicle testing
- ✓ Completed Gen. 2 optimization and rematch study for demo trucks

2. Rankine Cycle (ORC)

- ✓ Finalized working fluid selection (Ethanol + denaturant)
  - ❖ Still looking for the optimum fluid
- ✓ Finalized system configuration using high temp. coolant through the condenser
- ✓ Completed designs for heat exchangers (with Behr), expander, and pump
- ✓ Hardware delivery on target for May 2012 system build

Accomplishments:

4. Waste Heat Recovery

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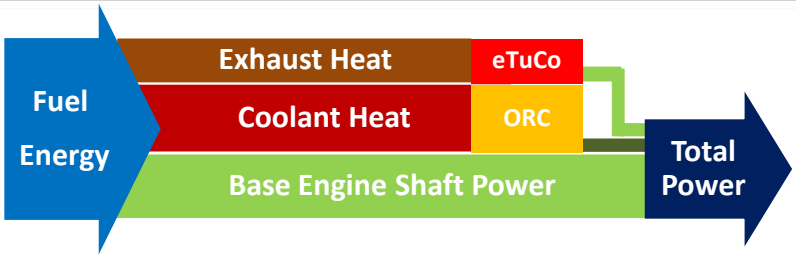

Performance Measures	TuCo		ORC		Total
– USSET DC BSFC improvement	3.1%		5.8%		8.9%
– A75 BTE improvement	1.3%		2.0%		3.6%
– Ton-mpg improvement	2.1%	+	2.3%	=	4.4%
– B100 PTC HR reduction	3.4%		0%		3.4%
– System weight	114 kg		271 kg		385 kg
– System cost	$		$$$		$$$$
– Data Source	Test Data + GT-P Model Rematching		Model		

Accomplishments:

4a. Waste Heat Recovery (eTurbo-compounding)

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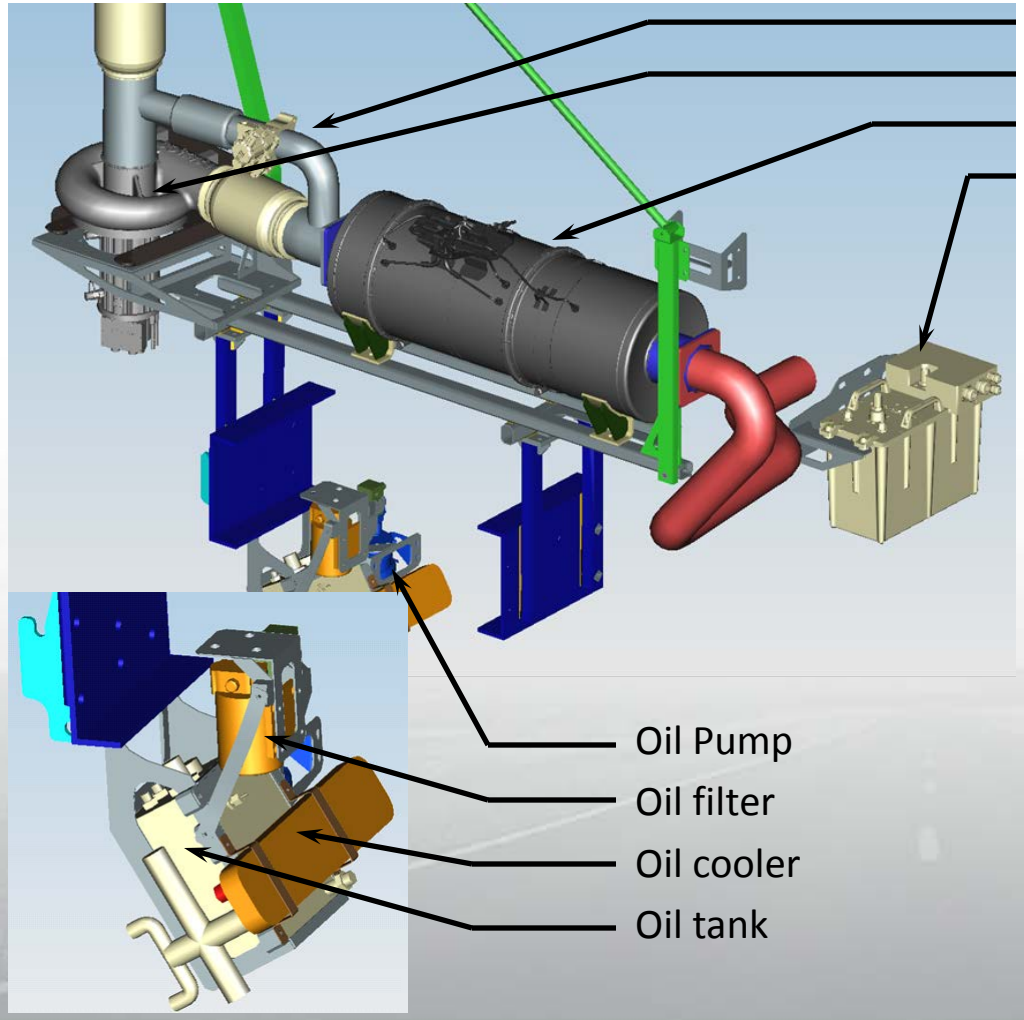

Mule Truck #2 eTuCo System Installation

Accomplishments:

4b. Waste Heat Recovery (Organic Rankine Cycle)

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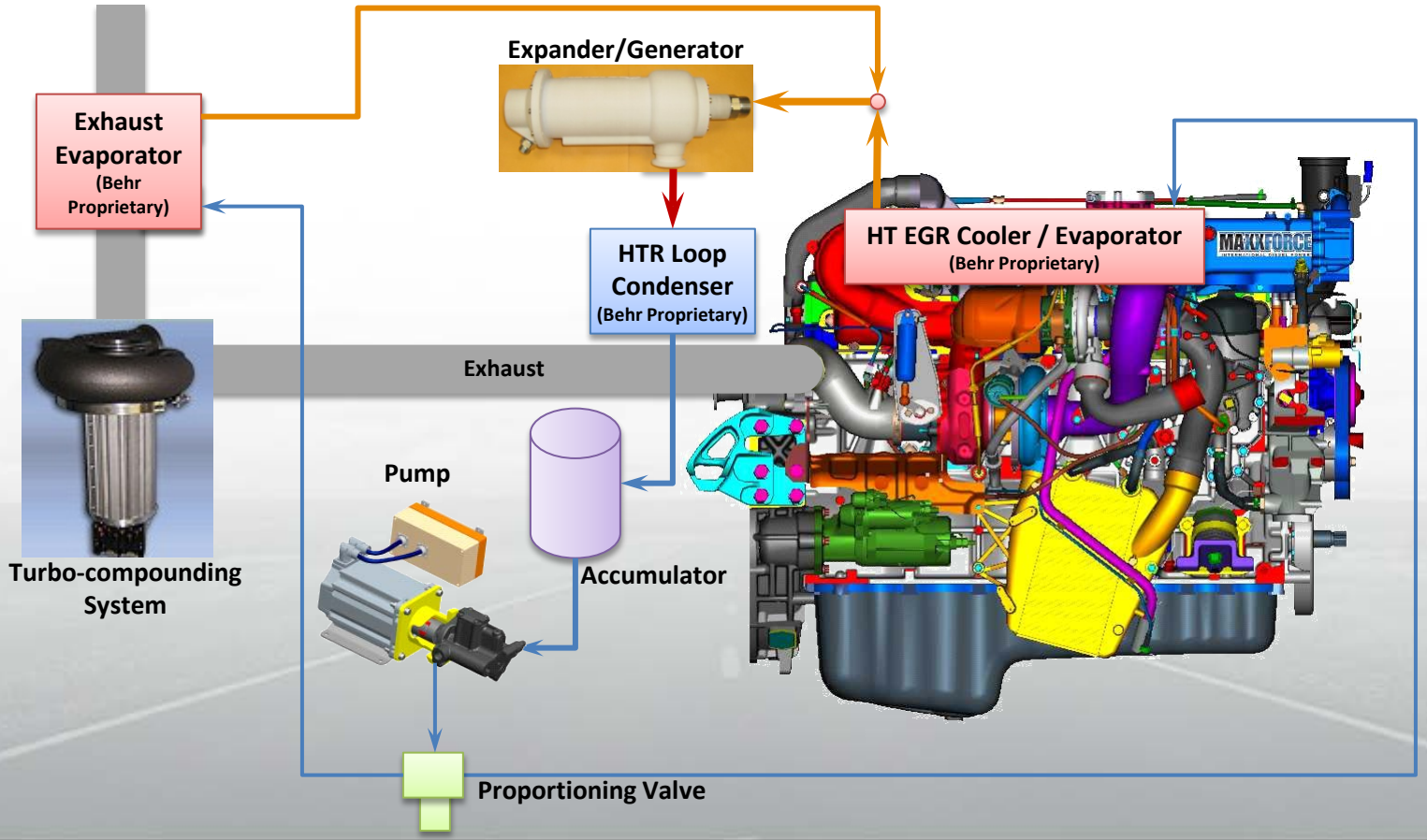
- Rankine Cycle System Configuration



Accomplishments

55% BTE Target with Dual Fuel Engine

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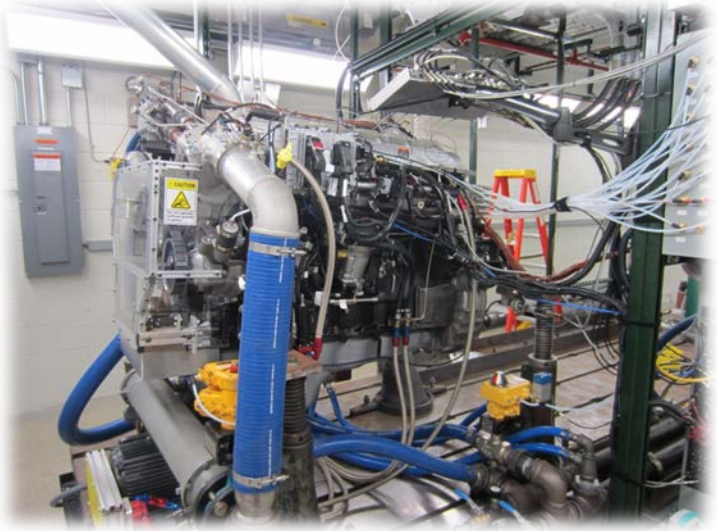
completed In progress Not started

Task	Team
Lab and Dynamometer Ready Engine and control , install Instrumentation , DAQ	**NAV** **ANL**
Combustion Simulation (Phase 1)	**WERC**
Diesel Baseline	**ANL**
Phase 0 Build and initial testing **Calibrate WERC models**	ANL NAV
Phase I VVA + VGT Builds **WERC modeling**	ANL NAV
Phase II Added Fuel Reactivity	NAV
Phase III Piston Optimization	NAV
Phase IV Turbocompounding	NAV
Phase V Base improvements	NAV

→ Ref. W de Ojeda (DEER 2011)

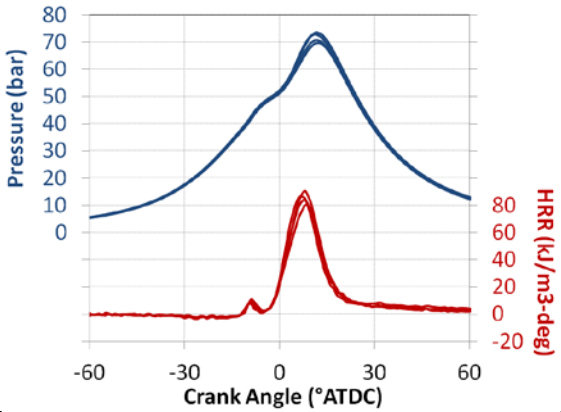
→ Initial testing underway at Argonne Facility



Engine setup at Argonne facility, Darien, IL

Early results are very encouraging

BMEP:	**5.8 bar**
BTE gain	**> 3% over baseline**
NOx:	**0.06 g/hp-hr**
Smoke:	**0.04 FSN**
Gasoline%:	**75%**



Accomplishments

55% BTE Target Roadmap

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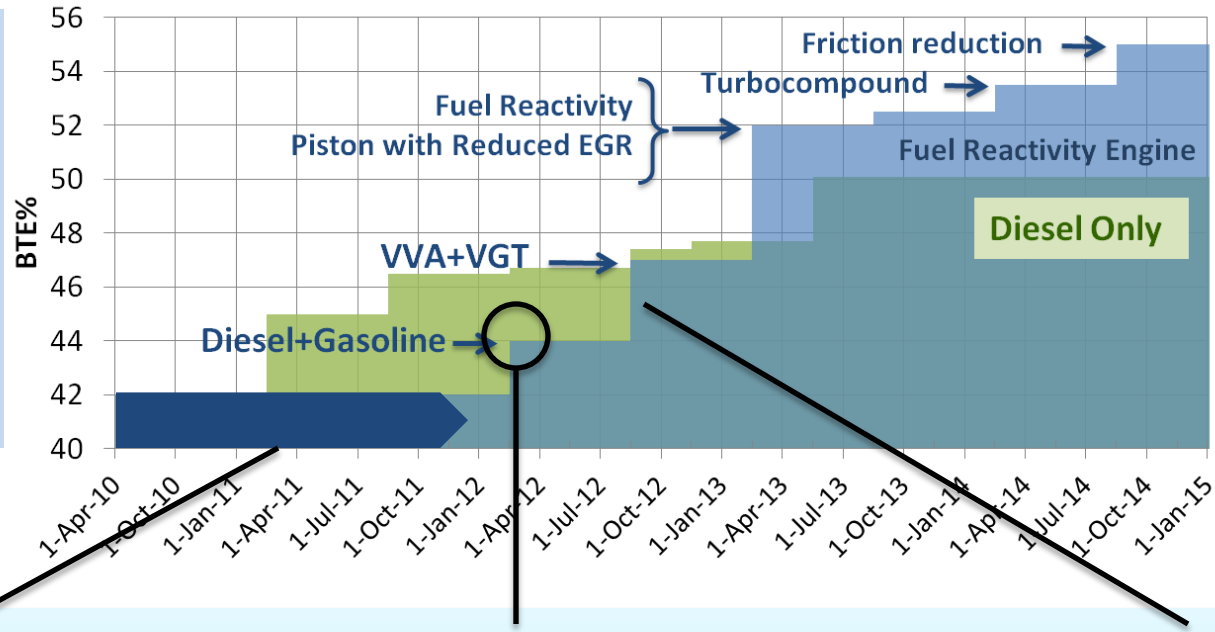
55% remains a bold goal for experimental work

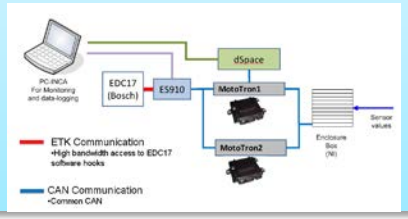


55% fuel reactivity engine

50% high efficiency Diesel

Completed:

- ✓Engine Build
- ✓Lab readiness
- ✓Control system layout



Initial results are very encouraging

BMEP:	5.8 bar
BTE gain	> 3% over baseline

Near zero emissions:

NOx:	0.06 g/hp-hr
Smoke:	0.04 FSN

Leverage technologies from the High Efficiency Diesel platform

- VVA
- Two-Stage Turbocharger
- EGR system
- Turbocompounding
- Friction reduction and accessories

Remaining Activities for 2012

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Main activities:

- VVA installation and benchmarking in test cell
- Deploy next generation Electrical Turbo-compounding and integrate with VVA
- Benchmark the ORC system in test cell
- Initiate friction reduction in dedicated engine and facility
- Fuel Reactivity testing

Project Summary

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I. To date the following technologies have been incorporated:

- ✓ **On engine combustion, leading to a growth in BTE from 42 to 45%:**
  - Extended peak cylinder pressure capability (190→220 bar)
  - Higher injection pressure (2200→2900 bar)
- ✓ **On heat recovery, leading to a further increase to 46.5%:**
  - Electrical turbo-compounding with advance air system
  - Transferred to vehicle

II. Current preparations include:

- ✓ **Nearly all base components** procured with expectation to meet **1.5-2.0% BTE gain**
  - Preparing for a systematic engine benchmark:
- ✓ **VVA engine** is nearly complete for benchmark

III. Advanced 55% BTE demonstrator is operational at ANL