High Fuel Economy Heavy Duty Truck Engine

2011 Annual Merit Review

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Mack Trucks, Inc. and
Volvo Powertrain North America

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ACE060

Overview

Timeline

October 2007 – October 2011

Barriers

Barriers addressed:

- Reduced engine efficiency due to NOx control
- Lack of cost effective and innovative advanced engine concepts
- Cost effective WHR systems

Budget

Total Project Funding

- DOE Share: 6.0 M USD
- Contractor Share: 12.0 M USD
  - Funding received in FY 08: 2.0 M USD
  - Funding received in FY 09: 1.6 M USD
  - Funding received in FY 10: 2.2 M USD

Partners

Project Lead:

Mack Trucks Inc., Volvo Powertrain N.A.

Collaborations:

- Volvo Powertrain Sweden
- Volvo Technology North America
- Ricardo, Inc.
- University of California Los Angeles
- Penn State University
- West Virginia University

Goals & Objectives - Relevance

- Reduce consumption of petroleum based fuel
- Reduce regulated emissions (HC, CO, NO_X, PM, and CO_2)

Objective 1:

Develop a highly efficient powertrain system to achieve reduction in CO2 emissions from a long haul truck by means of improved energy conversion and traction efficiency

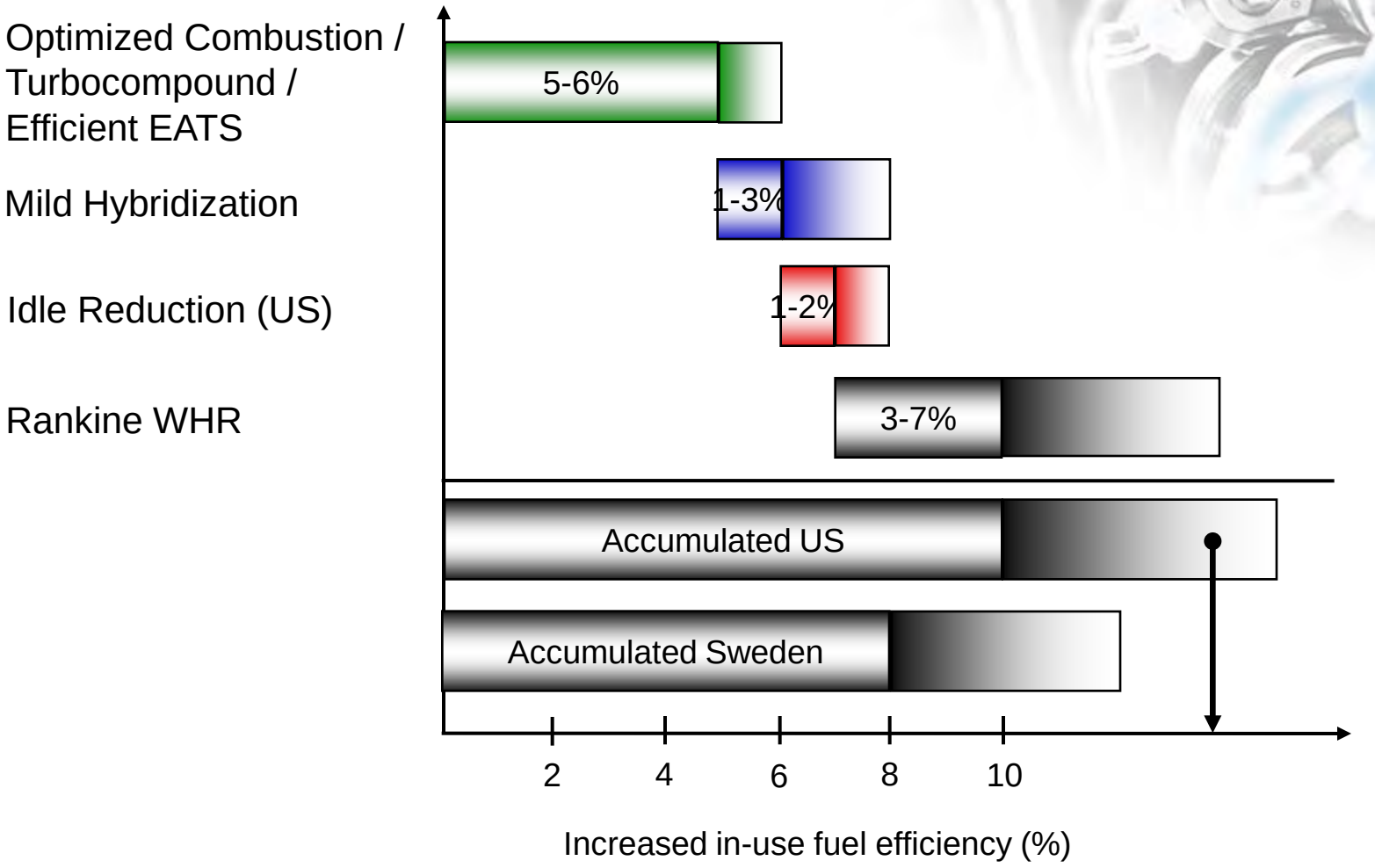
Objective 2:

Development of multi-fuel vehicles and drivetrains that are compatible with the long term use of combinations of fossil and bio-based diesel fuels.

Milestone Update (13/15)

Milestone Defined : 2010	Status
Result of concept simulations and choice of overall engine-driveline concept (month 6)	complete
Optimized turbocoumpound engine (month 12)	complete
Exhaust aftertreatment system (month 12)	complete
Simulation platform for waste heat recovery systems (month 12)	complete
Hybrid components requirement specification (month 6)	complete
Electric drive system requirement specification (month 10)	complete
Energy storage system requirement specification (month 11)	complete
Energy storage system control requirements (month 12)	incomplete
Functional specification of control system (month 10)	incomplete
Combustion performance evaluation including regulated and unregulated emissions for fuel matrix and categorization of market fuels. (month 12)	complete
Non-EGR combustion system optimized for biodiesel including evaluation of fuel consumption gain (month 12)	complete
Activity for aged catalyst materials and DPF oxidation rates measured for market fuels including RME, SME, synthetic diesel fuel and blends of fossil and biodiesel found on the market analyzed in synthetic gas bench. (month 6)	complete
DPF and catalyst sub models validated against measurements in synthetic gas bench (month 12)	complete
Fuel consumption and emissions improvement potential quantified for US10-based engine system equipped with additional sensors and running on cleaner fuels. (month 12)	complete
Fuel consumption, emissions and sensor information measured for no adaptive US10-based engine system equipped with additional sensors and running on reference fuel, market biodiesel fuel and engineered fuel. (month 12)	complete
Decision Gate: Whether a minimum of 10% fuel economy improvement is validated with analysis, modeling and component test as appropriate.	achieved

Approach / Strategy



Work Flow Plan

Realizable Powertrain concept for bio-diesel blends capable of reducing GHG with 10-20% for LH vehicles

Part A: Turbocompound / Rankine WHR
Engine Concept Development

Part B: Mild Hybrid
Concept Development

Part C: Bio-Fuel
Research, Bio Fuel Characterization

Complete Systems Assembly & **Vehicle verification**

Vehicle Demo US - Sweden

Phase 1 | Phase 2 | Phase 3 | Phase 4

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Technical Accomplishments & Progress

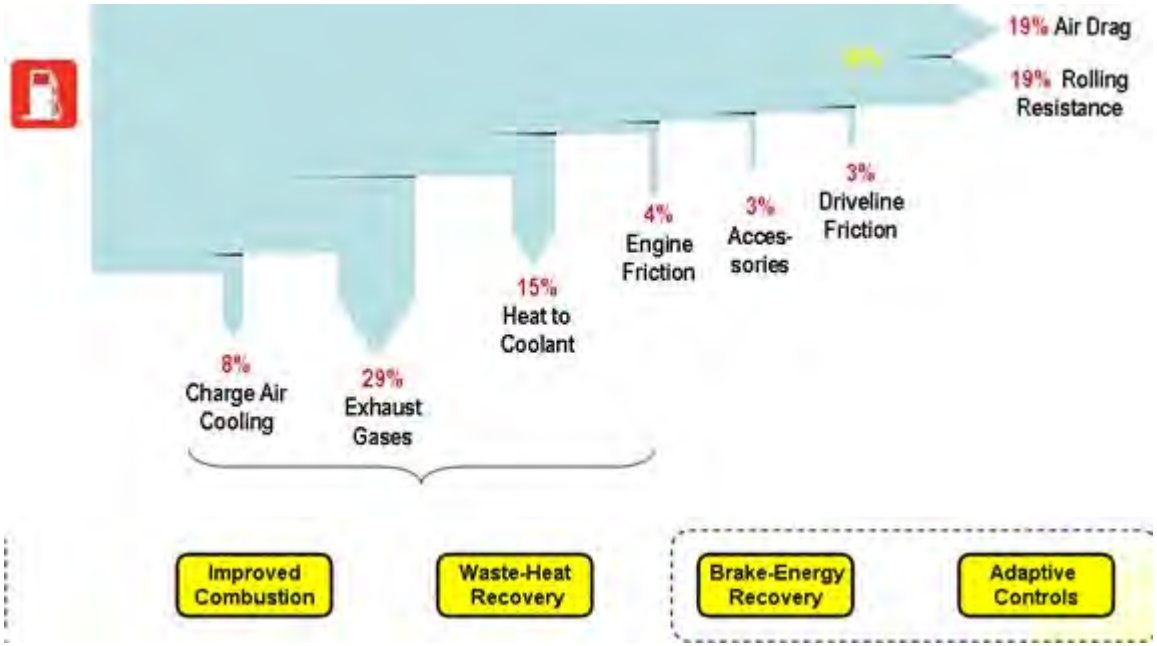
- Turbocompound design / transmission
  - Recovery mechanism investigation completed
  - System level engineering of WHR technologies
- Mild Hybrid Powertrain Development
  - Built tools to quantify efficiency of technology as a function of duty cycle/application
- Rankine Cycle Waste Heat Recovery (WHR)
  - System design finalized
  - System test planned 2011
- Optimized combustion
  - Designed novel piston bowl geometry
  - Optimized nozzle design and geometry
- Bio-diesel fuel investigation
  - Completed research regarding immediate impacts and short term durability

Previous Accomplishments

- Turbocompound:
  - Exhaust energy recovery
- Mild Hybridization:
  - Simulated clean electric power generation at stand-still
  - Vehicle simulation performed for 11 different duty cycles
- Rankine:
  - Basic layouts for WHR system developed and analyzed
  - Dynamic model of the system – heat transfer analysis
- Bio-Fuels
  - Systematic mapping of diesel-like bio-fuels regarding fuel injection, ignition and combustion
  - 4 oxygenated fuels tested for performance / efficiency

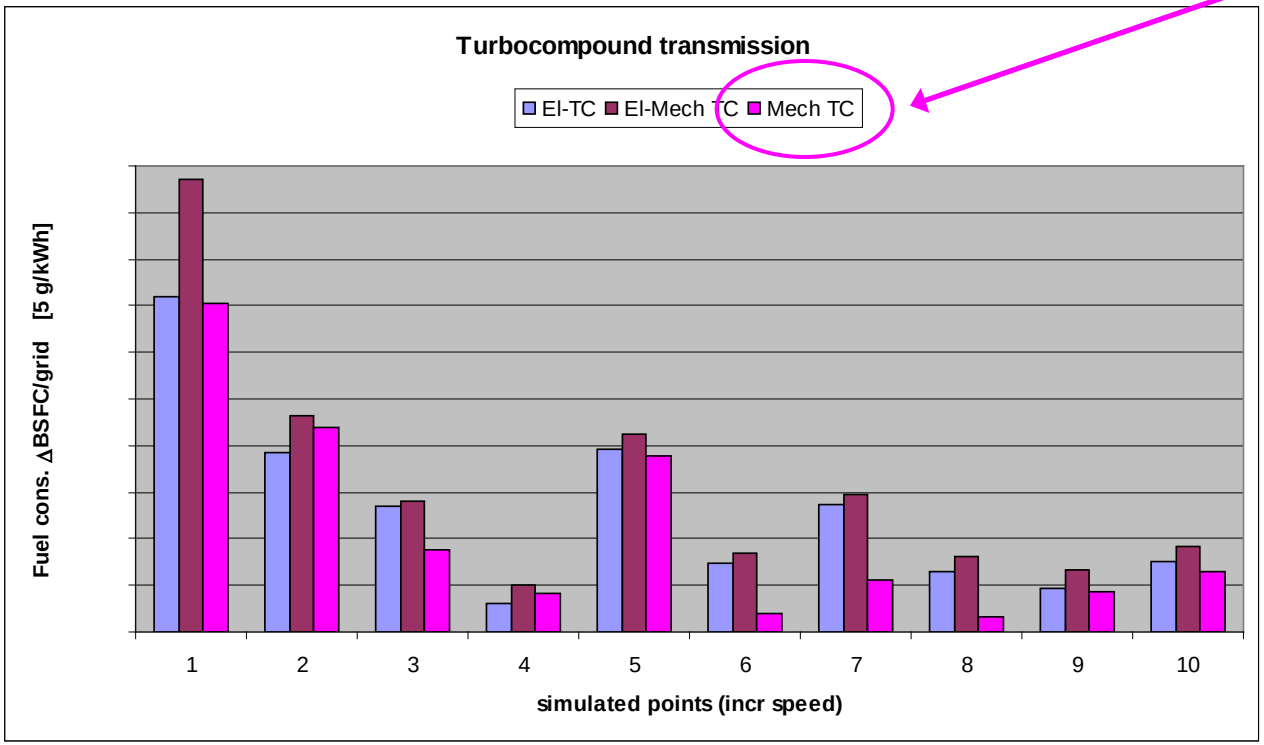
Turbocompound Engine Design-Accomplishments

- Optimized total engine system to maximize heat recovery and efficiency
  - Completed power conversion investigation
  - EGR system designed to minimize pumping losses
  - Matched turbine to optimize with improved combustion system



Turbocompound Transmission- Accomplishments

Three types of transmissions connecting the power turbine and engine crankshaft have been investigated – mechanical, electrical, and electromechanical

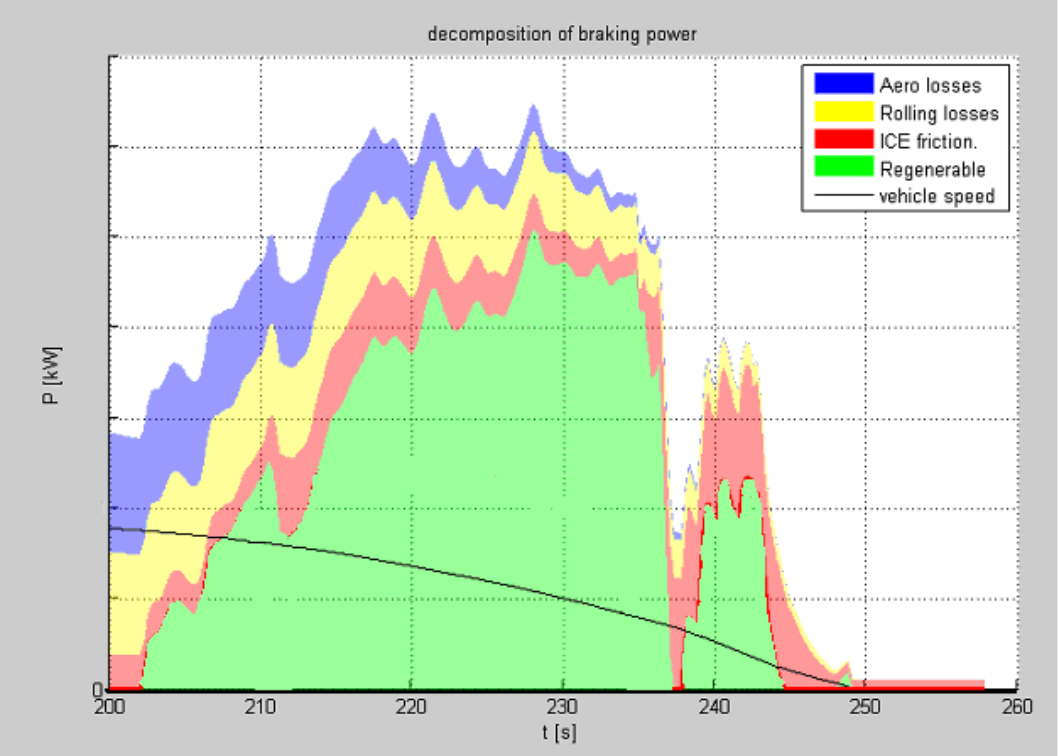


Fuel consumption results show fully mechanical transmission with fixed speed ratio to be most efficient

Electromechanical transmission does not give fuel economy improvement - work discontinued

Mild Hybridization- Accomplishments

- Completed system design for mild/micro hybrid
- Developed control strategies for hybrid including transmission
- Quantified and optimized Brake energy recovery / Engine start/stop
- Identified applications that would be suitable for Long Haul HEVs and conversely, applications for which Long Haul HEVs would not be acceptable.



Simulation performed to investigate theoretical recovery for mild hybrid, snapshot of customer duty cycle during deceleration.

Rankine Cycle Waste Heat Recovery- Accomplishments

- Thermodynamic simulations carried out to select the best system layout and choice of working fluid at cruise and full load operating points
- System simulation results that were considered in selection:

Attribute	Option 1	Option 3	Option 4	Option 5	Option 6
Available Power	-	-	-	+	+
EGR gas temp	+	-	-	-	+
Control	+	-	-	-	+
Heat rejection through condenser	+	-	-	-	=
System pressure drop	+	-	-	-	+
ORC system cost	+	=	-	=	=
Packaging	+	+	=	=	=
Safety	=	=	=	=	=

Parallel configuration comprised of EGR sub-cooler and an exhaust stack heat exchanger was selected

Concept for Rankine Cycle- Accomplishments

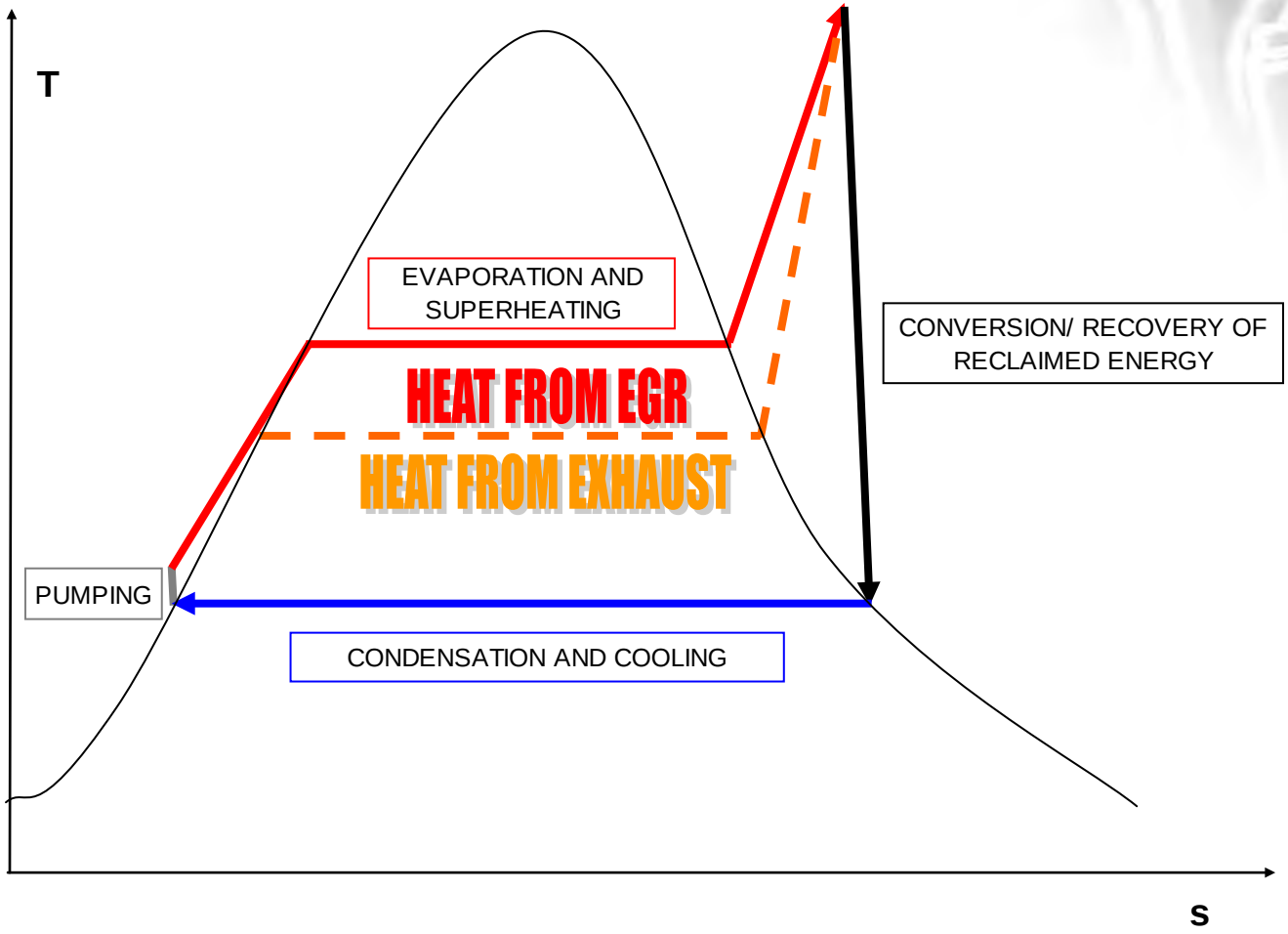
Most efficient and cost effective concept defined:

- Heat extracted from EGR (replace EGR cooler) and post exhaust aftertreatment system
- Parallel circuit design with an actuator capable of controlling the working fluid flow split between EGR and exhaust circuits
- Working fluid of water ethanol
- Piston expander
- Liquid cooled condenser

Investigated Alternatives:

Heat Sources	Working Fluid	Layout	Expander
EGR	~~Water~~	~~Option 1~~	Piston
~~Exh pre TC~~	~~Acetone~~	~~Option 3~~	~~Scroll~~
~~Exh pre EATS~~	~~Isobutane~~	~~Option 4~~	~~Turbine~~
Exh post EATS	~~R152a~~	~~Option 5~~	
~~Charge air cooler~~	~~Ethanol~~	Option 6	
~~Coolant~~	~~Water ammonia~~		
	~~R245fa~~		
	Water Ethanol		

Rankine Cycle
Waste Heat Recovery- Accomplishments



The additional heat available from the parallel circuit topology is evident in the addition of the Heat From EGR integrated area. 3-7% BSFC improvement possible

Bio-Diesel Fuel Evaluation- Accomplishments

- Single Cylinder Tests
  - Thermal efficiency, combustion characteristics, regulated / unregulated emissions, tradeoffs (NOx vs. Soot, FC vs. NOx)
- Particulate particle size distributions
  - Reduce soot with no adverse efficiency impact
- Effects or Deterioration on EATS
  - On road and chassis dynamometer testing
  - Short term EATS degradation study

Bio-Diesel Fuel Evaluation- Accomplishments

Testing

Test Plan:

- Three emissions tests and two periods of endurance running
- First baseline emissions test run on diesel fuel – remaining tests run on 20% biodiesel
- 67,000 miles on 20% biodiesel- internal testing

- Additional 1.6 million customer miles accumulated in a follow-up project

Focus is on two cycles – transient and cruise

	Phase T=Transient C=Cruise	Diesel to biodiesel	Biodiesel before and after endurance
Fuel mileage	T	No change	No change
	C	Slight reduction	No change
CO_2	T and C	Consistent with fuel mileage	Consistent with fuel mileage
CO	T	Reduced	No change
	C	No change	No change
THC	T and C	No change	No change
NO_x	T and C	Reduced	Reduced
PM	T and C	No change	No change

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Collaborations

- **Ricardo**
  - Rankine System design and simulation
  - Component procurement, integration and test
  - Control system development and provision
- **University of California Los Angeles (UCLA)**
  - Rankine WHR model generation
  - Transient system simulation, dynamic stability
- **Pennsylvania State University (PSU)**
  - Bio-fuel testing
- **West Virginia University (WVU)**
  - Powertrain optimization
- **Volvo Technology North America**
  - WHR system simulation integration
- **Volvo Powertrain, Sweden**
  - Collaboration on powertrain technology development

Future Progress

- Demonstrator software development for hybrid system
- Continue Waste Heat Recovery development into test phase
  - Improved design / packaging issues
- Continue injector modifications for greatest fuel economy
- Combine modified piston geometry with other FE hardware
- Improvements and testing of optimized fully mechanical turbocompound transmission
- Continuation of bio-fuel testing
  - More test mileage to see full “Useful Life”
  - Chemical makeup for biodiesel may be harmful to aftertreatment devices, even in low concentrations
- Integrate feasible technologies into demonstration vehicles in 2012

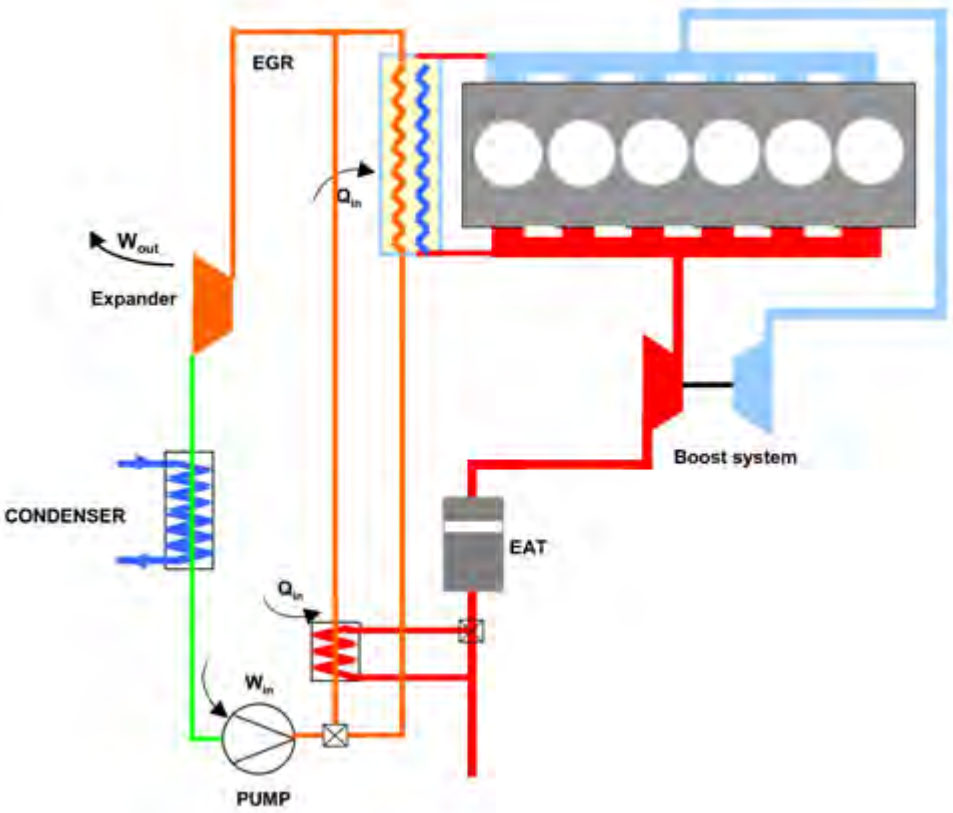
Summary

- **Relevance:** Design a highly efficient biodiesel tolerant powertrain system to significantly decrease fuel consumption and emissions
- **Approach:** Through engine concept, alternative fuel, and mild hybrid development: perform simulation and prototype testing to identify technology to meet petroleum based fuel consumption and engine emission reductions
- **Technical Accomplishments:** Developed and tested new and promising technologies. Anticipate to exceed project objectives for fuel economy on demonstrator chassis.
- **Collaborations:** Partner with Ricardo, UCLA and Volvo Technology for Rankine Development – PSU for bio-diesel studies – WVU and VPT Sweden for powertrain development
- **Future Progress:** Technologies considered viable will be tested as part of integrated demonstration vehicles in 2012

End of presentation.

Technical Back-Up Slides Follow

Rankine WHR parallel system topology explanation



- Parallel Rankine Geometry
  - Controlled for optimal distribution of WF
- EGR boiler
  - Cools EGR and recovers heat
  - Exhaust boiler
  - Post EAT (aftertreatment)
- Condenser- Direct vs. Indirect
  - Both being designed, cost and efficiency will determine technology