High-efficiency Engine Systems Development and Evaluation (ACE017)

K. Dean Edwards
Robert M. Wagner
Oak Ridge National Laboratory

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Gurpreet Singh, Ken Howden
Vehicle Technologies Program

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U.S. DEPARTMENT OF ENERGY

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Overview

Timeline

- Project start – October 2005
- Renewed focus began October 2010
- Ongoing

Budget

- FY2011 - $200k
- FY2012 - $200k

Barriers

- Project evolves to support DOE and industry partnerships in assessment of advanced engine and combustion technologies for improved efficiency
- Directly addresses barriers to achieving improved engine efficiency and understanding of advanced combustion regimes

Partners

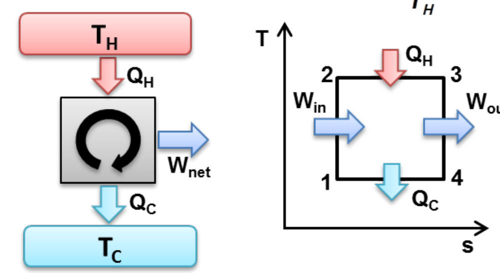
- Extensive interaction with industry, university, and National Laboratory partners
- Provided supporting analysis for understanding efficiency potential of ICEs to US DRIVE ACEC Tech Team

Objectives / Relevance

- **Evolves to support DOE and industry partnerships in assessment of advanced engine and combustion technologies for efficiency improvement in support of goal-setting activities**
- **In the previous evolution, successfully demonstrated DOE's 2010 efficiency goals for light-duty engines including a peak brake thermal efficiency (BTE) of 45%**
- **Renewed focus on analysis…**
  - » **Evaluating strategies to maximize brake efficiency of light-duty ICEs**
  - » **Understanding potential efficiency benefits of advanced combustion strategies such as RCCI**
- **Goal is to evaluate potential maximum efficiency limits of ICEs**
  - » **ICEs are open systems, therefore, thermodynamically, efficiency is NOT limited by Carnot efficiency**
  - » **Limited by non-ideal processes: friction, combustion irreversibility, heat loss, inefficient work extraction, etc**
- **Additional factors beyond the scope of current study further limit efficiency of production engines**
  - » **Cost, durability, emissions compliance, driveability and noise, power on-demand, material limits, etc**

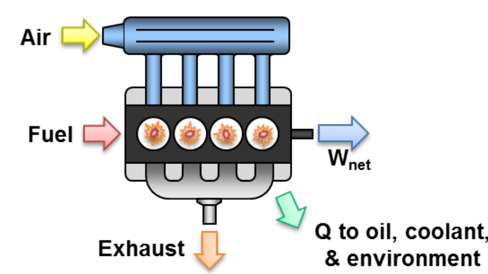
Closed-loop cycles must return working fluid to original state and thus are limited by Carnot efficiency

<u>Carnot heat engine</u> $\eta_{max} = 1 - \frac{T_C}{T_H}$



ICEs operate on an *open* cycle. Therefore, their maximum efficiency is limited by non-ideal, irreversible processes, NOT by Carnot efficiency

<u>Internal combustion engine</u> $\eta_{max} \cong 100\,\%$



Milestones

- **Thermodynamic assessment of state-of-the-art engine technologies and Reactivity Controlled Compression Ignition (RCCI) combustion to identify and characterize mechanisms leading to improved efficiency (June 30, 2012).**

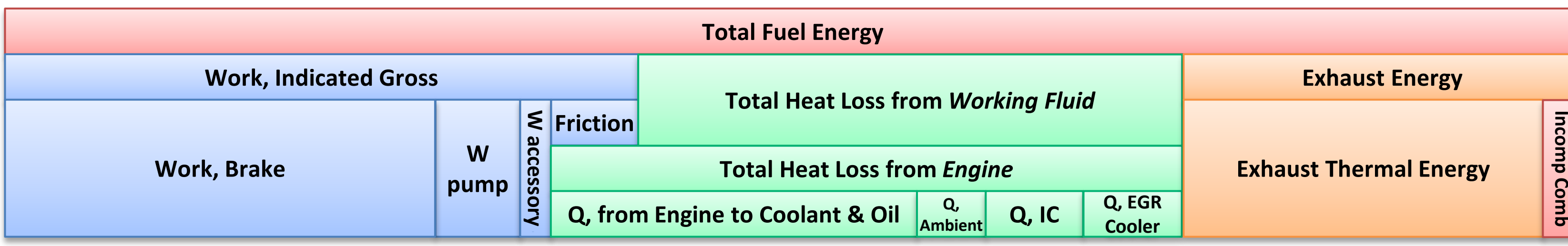
Status

- **Methods have been developed to assess potential efficiency gains in ICEs based on experimental engine data**
- **Preliminary analysis has been performed using light-duty diesel and SI engine data**
- **More detailed analysis of additional engine and/or model data is planned**
- **Assessment of RCCI data has begun and is on track for completion**

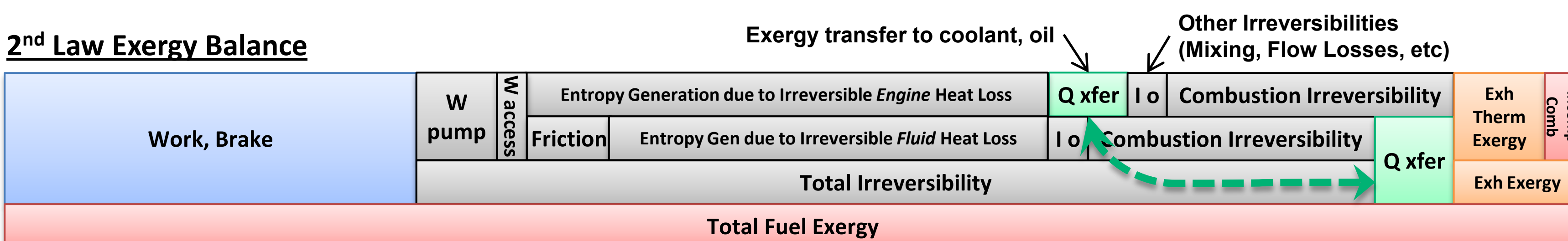
Technical Approach

- **Thermodynamic analysis provides insight to energy usage and barriers to efficiency improvement**
  - » **Gain better understanding of loss mechanisms and assess trade-offs of loss reduction**
  - » **Compare potential efficiency benefits of new technologies and approaches to engine design and operation**
  - » **Understand potential efficiency benefits of advanced combustion modes**
  - » **Develop strategies to concentrate energy/exergy where it can provide the most benefit**
- **Effort relies on experimental engine data and models supplied by industry partners or leveraged from ongoing projects**

1st Law Energy Balance



2nd Law Exergy Balance



Collaborations

- **Providing direction on engine efficiency and emissions controls**
  - » **Development of new roadmap with USCAR and US DRIVE ACEC Tech Team on engine efficiency and emissions**
  - » **Provided supporting analysis and direction in establishing next round of light-duty engine efficiency goals for US DRIVE ACEC Tech Team**
- **Recent efficiency related publications and presentations**
  - » **2011 DEER Conference**
  - » **AEC/HCCI Working Group Meeting, August 2011**
  - » **GAMC 2011 Global Powertrain Congress**
  - » **Multiple presentations at ACEC Tech Team meetings**

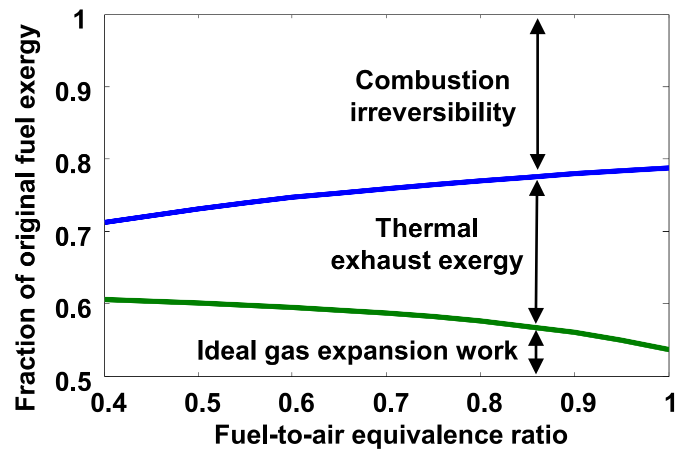
Summary of Technical Accomplishments

- **Efforts have focused on developing greater understanding of efficiency losses and potential strategies for maximizing engine efficiency in support of future goal setting**
- **Created a working document that consolidates state-of-the-art thinking regarding efficiency potential of ICEs (presented at 2011 DEER Conference)**
- **Identified focus areas for future efficiency improvement efforts**
- **Developed approach to use experimental engine data to assess potential for maximizing engine efficiency**
  - » **Preliminary analysis performed on light-duty diesel and SI engine data**
- **Ongoing investigation of potential efficiency benefits of advanced combustion regimes**

Maximizing ICE efficiency requires a comprehensive, system-wide approach

- **Energy pathways in the engine are highly inter-dependent**
  - » **Reduction of a loss term seldom results in an equivalent increase in efficiency**
    - Exceptions: friction, pumping work, and accessory loads
  - » **Need to gain a better understanding of these dependencies**
  - » **How much can each loss mechanism be reduced or recovered? …**
  - » ***And*, how will that energy be redistributed either as work or to the other loss mechanisms?**
- **Prioritize efforts which concentrate fuel energy where it is most beneficial**
  - » **Increase work extraction by the piston**
  - » **Increase recoverable exhaust energy (bottoming cycle, turbo-compounding, thermo-electrics, etc)**
- **Manage trade-offs based on your priorities**
  - » **Dilute operation**
    - Increases combustion irreversibility *but* increases work-extraction efficiency of the piston (higher gamma)
  - » **Low-conductivity materials to reduce in-cylinder heat loss**
    - Increases work potential *but* reduces work-extraction efficiency resulting in hotter exhaust, not more work
- **Priorities and trade-offs may vary with speed and load**

Lean operation increases brake efficiency at the expense of exhaust energy and increased combustion irreversibility… an acceptable trade-off.



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Important concepts and strategies for maximizing engine efficiency

- Reduce friction, pumping work, and accessory loads
  - Parasitic losses may consume 10-20% of fuel energy at typical light-duty road-load operation
  - Direct 1:1 efficiency benefit
- Maximize in-cylinder pressure to increase work potential from piston
  - Increased compression ratio (diesel, ethanol)
  - Increased boost
  - Rapid combustion with high pressure rise rate
  - *Limited by material strength and durability*
- Increase specific heat ratio (gamma) to increase work-extraction efficiency of piston
  - Dilute (lean or high-EGR), low-temperature operation
- Fully-expanded cycles
- Avoid high in-cylinder temperatures to limit heat loss and NOx aftertreatment fuel penalty
  - Advanced dilute, low-temperature combustion strategies
- Reduce environmental heat loss to increase exhaust energy
  - But not at expense of piston work
- Efficient recovery of waste heat
  - Bottoming cycles, turbo-compounding
- Operate closer to the peak efficiency point of the engine throughout the drive cycle
  - Downsizing, cylinder deactivation, series hybrid

Several technological advances will be required to maximize efficiency

- **Advanced lubricants and low-conductivity materials with high mechanical and thermal tolerance and durability**
- **Advanced, low-temperature combustion techniques**
- **Improved understanding and modeling of heat loss mechanisms**
- **Electrification and intelligent control of accessory loads**
- **Possible redesign of mechanical systems (*e.g.*, variable stroke for fully expanded cycles)**
- **High-efficiency turbo-machinery to extract exhaust energy and provide boost**

Assessing potential efficiency goals for light-duty applications

- **We developed a simple approach to analyze experimental data from state-of-the-art engines to assess potential strategies for maximizing efficiency of IC engines**
- **Our approach involves:**
  - » **Thermodynamic analysis of experimental engine data – *does not require detailed models***
  - » **Assessment of recovery potential from various energy streams**
  - » **Assessment of how recovered energy is redistributed to other energy streams**
- **Recovery and redistribution factors are based on experience and best engineering judgment**
  - » **Parametric sweeps provide sensitivity analysis of each strategy**
  - » **Input from industry and detailed engine modeling will be important in refining values**
- **This approach has been applied to light-duty diesel and SI applications**

Example analysis for light-duty diesel

- **The following example describes one scenario applied to ORNL data from a GM 1.9-L diesel**
  - » **Typical road load: 2000 RPM, 2-bar BMEP**
  - » **Peak BTE: 2250 RPM, 18.5-bar BMEP**
- **Assumptions and limits of study**
  - » **Conventional operation and engine architecture**
  - » **Waste heat recovery from exhaust and EGR cooler**
  - » **Same reduction factor values applied at all engine conditions**
    - Identifies maximum-benefit design point for each approach
  - » **Air and fuel rates are not altered to maintain initial load**
    - Thus efficiency improvements provide additional brake work output

GM 1.9-L light-duty diesel installed at ORNL

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Example stretch goals for energy recovery and redistribution for light-duty diesel

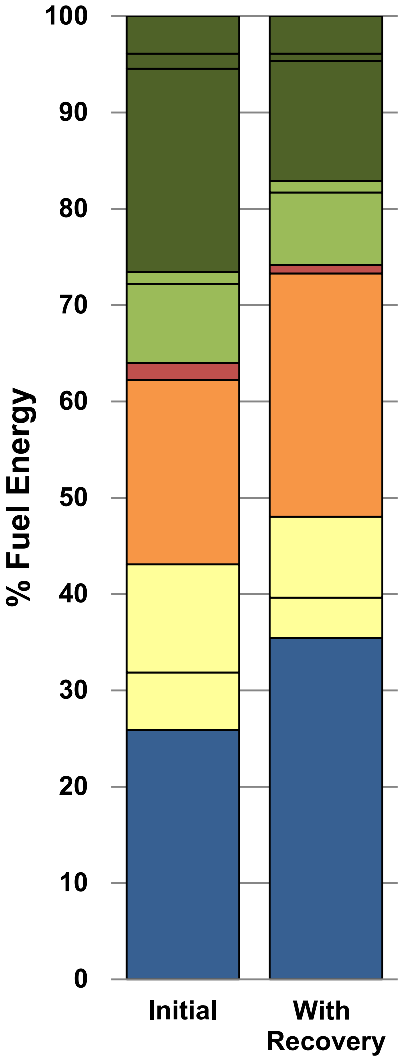
- **These values represent one possible scenario, shown here only as an example**

Loss Category	Reduction Factor	Redistribution Factors: Brake Work	Redistribution Factors: Heat Loss	Redistribution Factors: Exhaust	Redistribution Factors: Combustion Irreversibility	Notes
Friction and Accessories	25%	100%				Friction reduction, downsizing, electrification and intelligent control of accessory loads
Pumping Losses	30%	100%				Variable valve timing, reduced blow-down losses Includes 2nd Law valve losses
Incomplete Combustion	50%	Based on original energy/exergy distributions				Improved combustion efficiency for dilute operation
Turbocharger Losses	50%	20%*		80%*		Improved turbomachinery efficiency providing additional boost & consuming less exhaust energy
Intercooler	0					Reducing intercooler losses lowers charge density Exergy too low for effective waste heat recovery
Engine Heat Loss	30%	10%*		90%*		Low-temperature combustion and low-conductivity materials Advanced combustion strategies could provide further work recovery by increasing gamma of exhaust gases Friction reduction also reduces engine heat loss
WHR from Exhaust and EGR Cooler	20%	100%				Recovery of available energy through bottoming cycle, turbo-compounding, thermo-electrics, etc

* Value represents a 1st Law recovery. 2nd Law factors calculated based on available energy (exergy).

Energy distributions resulting from the example scenario
Light-duty diesel @ Road Load (2000 RPM, 2-bar BMEP)

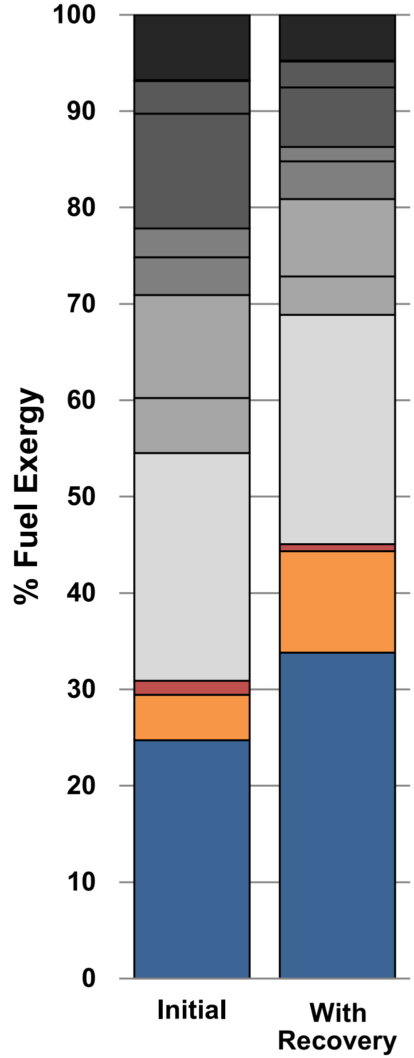
1st Law Energy Balance



% Fuel Energy	Initial	With Recovery
Qo - Piping	3.9 %	3.9 %
Qo - Turbocharger	1.6 %	0.8 %
Qo - Engine	21.1 % *	12.4 %
Q - Intercooler	1.2 %	1.2 %
Q - EGR Cooler	8.2 %	7.5 %
Q - Oil	0 % *	0 % *
Q - Engine Coolant	0 % *	0 % *
Incomplete Combustion	1.8 %	0.9 %
Exhaust	19.2 %	25.3 %
Friction Work	11.2 %	8.4 %
Pumping Work	6.0 %	4.2 %
Brake Work	25.9 %	35.4 %
Total Fuel (kW)	25.2 kW	25.2 kW

* Insufficient oil and coolant data to separate ambient heat losses from block

2nd Law Exergy Balance

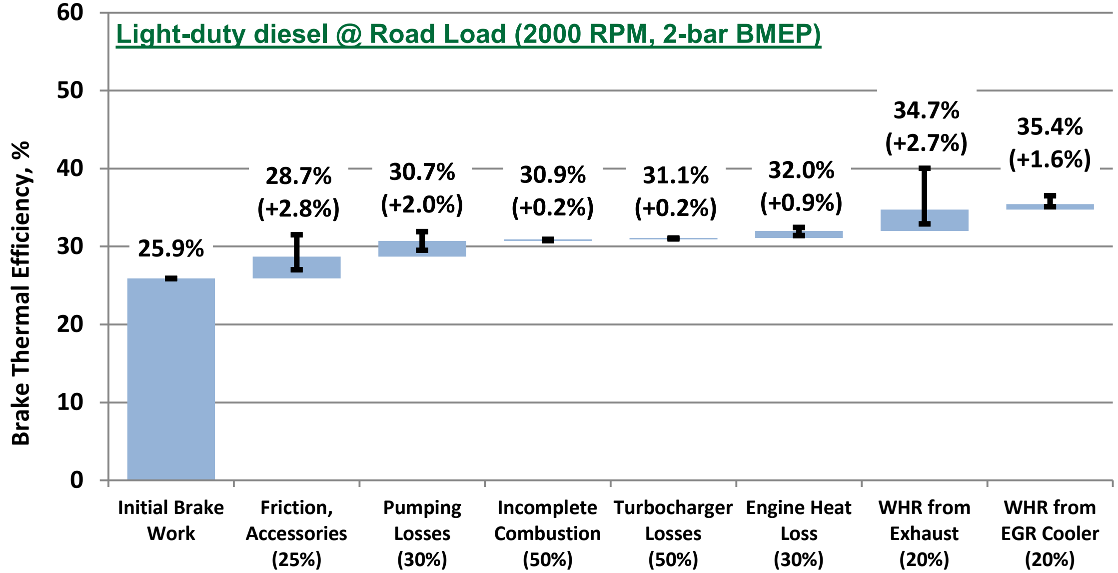


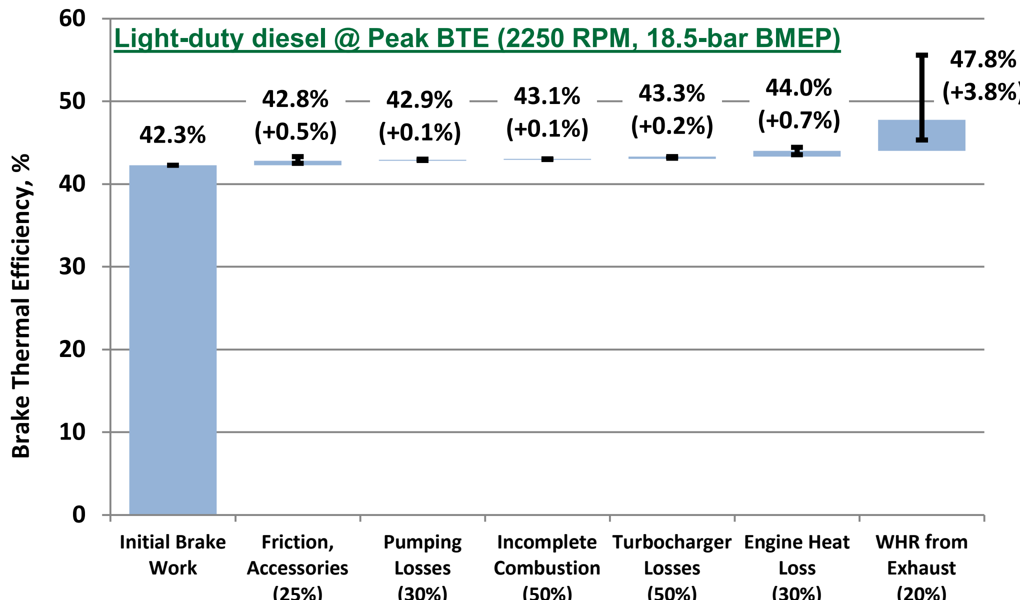
% Fuel Exergy	Initial	With Recovery
I – Mixing & valve loss	6.8 %	4.8 %
I - ΔP - Intercooler	0 %	0 %
I - ΔP - EGR Cooler	0 %	0 %
I - Q - Intercooler	0.1 %	0.1 %
I - Q - EGR Cooler	3.4 %	2.7 %
I - Q - Engine	11.9 %	6.2 %
I - Qo - Turbocharger	3.0 %	1.5 %
I - Qo - Piping	3.9 %	3.9 %
I - Friction Work	10.7 %	8.0 %
I - Pumping Work	5.7 %	4.0 %
I – Combustion Irreversibility	23.6 %	23.8 %
Qx – Coolant, Oil	0 % *	0 % *
Incomplete Combustion	1.5 %	0.7 %
Exhaust	4.7 %	10.5 %
Brake Work	24.7 %	33.8 %
Total Fuel (kW)	26.4 kW	26.4 kW

* Insufficient oil and coolant data to determine exergy transferred to these streams that could be recoverable

Breakdown of contributions to efficiency increase for the example scenario

- Distribution bars indicate sensitivity of BTE improvement using reduction factors of 10-50% for each loss term
- Reduction of parasitic losses provides large direct efficiency benefit, especially at part load
- Reducing heat loss provides limited direct efficiency gain but significantly increases exhaust exergy available for WHR
  - » Advanced low-temperature combustion strategies may provide additional direct efficiency benefit
- WHR on exhaust (and EGR cooler at part load) provides significant efficiency benefit – especially when combined with reduced heat loss
- Even with stretch recovery goals, other changes only provide incremental efficiency gains





Future Work

- **Continued analysis of efficiency improvement strategies for goal setting activities**
- **Continued analysis of efficiency benefits of advanced combustion regimes**

- **Project will continue to evolve as needed to support DOE and industry in efficiency-related concerns**
- **Spin-off project will support DOE and industry in modeling efforts which leverage ORNL's leadership in high-performance computing**
  - » **Detailed examination of fundamental issues affecting engine efficiency including combustion stability**

Summary

- **Relevance**
  - » **Directly addresses barriers to achieving improved engine efficiency and understanding of advanced combustion regimes**
- **Approach**
  - » **Thermodynamic analysis of engine data provides insight to energy usage and potential efficiency improvements**
- **Technical Accomplishments**
  - » **Developed approach to use experimental engine data to assess potential for maximizing engine efficiency**
  - » **Preliminary analysis performed on light-duty diesel and SI engine data**
  - » **Ongoing investigation of potential efficiency benefits of advanced combustion regimes**
- **Collaborations**
  - » **Extensive interaction with industry, university, and National Laboratory partners including ACEC Tech Team**
- **Future Work**
  - » **Analysis of additional engine and/or model data is planned**
  - » **Continue analysis of efficiency benefits of advanced combustion regimes**

Contact Information

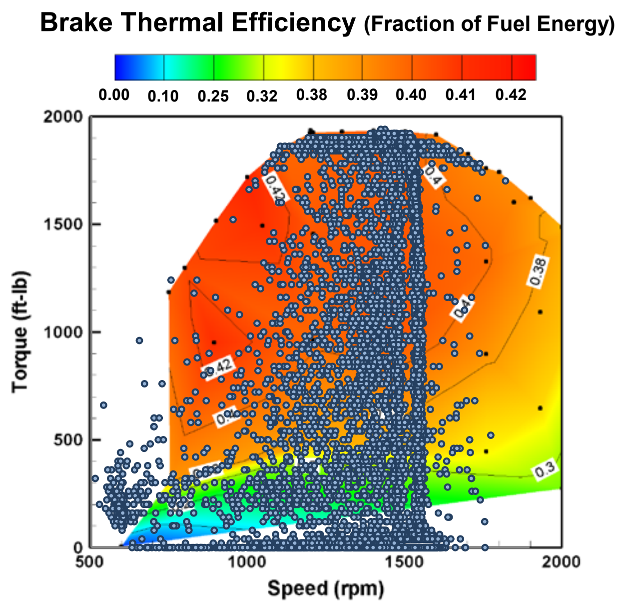
- **K. Dean Edwards**
  - » **edwardskd@ornl.gov, 865-946-1213**
- **Robert M. Wagner,** Director, Fuels, Engines, and Emissions Research Center
  - » **wagnerrm@ornl.gov, 865-946-1239**

Technical back-up slides

Engine design and operation should be tailored to application

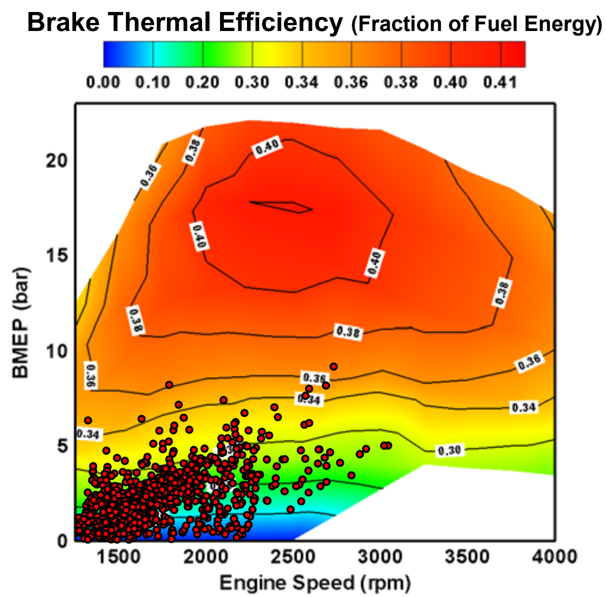
- **Typical engine operation should occur where efficiency is highest**
  - » **For stationary power and heavy-duty transportation applications, this is usually the case**
  - » **For light-duty transportation applications, the engine is usually geared for on-demand power and normal operation typically falls well below peak efficiency**
    - Some options for improving part-load efficiency include cylinder deactivation and using a downsized engine with turbocharger

Heavy-duty Transportation



*** Data from Cummins ISX 15-L diesel**
*** Blue markers are from a real-world drive cycle by a Class 8 Volvo tractor during a regional delivery route**

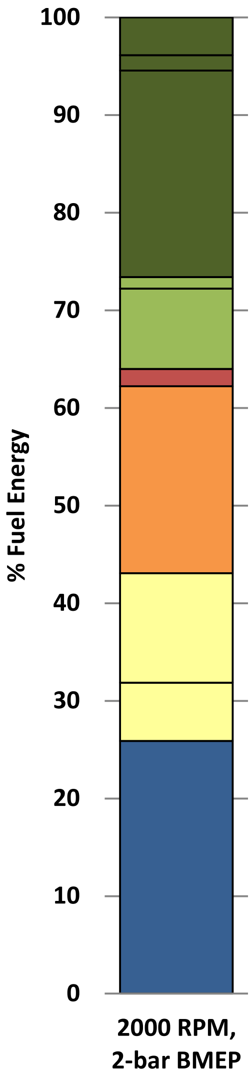
Light-duty Transportation



*** Data from GM 1.9-L diesel**
*** Red markers are points visited during light-duty federal drive cycle simulation**

Explanation of “slices” in energy/exergy balances

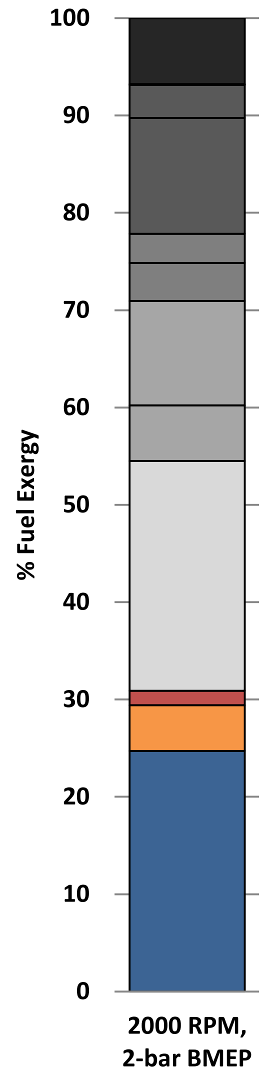
1st Law Energy Balance



Slice	Explanation
Qo - Piping	Any measured ambient heat loss from intake, EGR, and exhaust piping
Qo - Turbo.	1st Law losses from turbocharger
Qo - Engine	Ambient heat loss from engine block. Includes losses to coolant and oil if that information is unknown. NOTE: Add friction for total heat loss.
Q - Intercooler	Heat loss from air side (or heat gain to coolant side if known)
Q - EGR Cooler	Heat loss from EGR side (or heat gain to coolant side if known)
Q - Oil *	Heat gain to oil if known. Requires oil T (in and out) and flow rate.
Q - Engine Coolant *	Heat gain to coolant if known. Requires coolant T (in and out) and flow rate.
Incomp Comb	Based on HC and CO in exhaust
Exhaust	Leaving tailpipe
Friction Work	Based on Pcyl and brake torque. Friction includes accessory loads. Friction eventually leaves as heat.
Pumping Work	
Brake Work	From shaft torque
Total Fuel Energy (kW)	Calculated for complete combustion at measured air-fuel ratio (not just = LHV which assumes a stoichiometric mixture).

* Not shown

2nd Law Exergy Balance



Slice	Explanation
I - Mixing & valve loss	Mixing: Entropy generation due to mixing (air+EGR, air+fuel, etc) Valves: flow losses, blow-down, etc
I - ΔP - Intercooler	Due to air-side pressure drop
I - ΔP - EGR Cooler	Due to EGR-side pressure drop
I - Q - Intercooler	Unrecoverable portion of heat transfer from engine, EGR cooler, and intercooler. Includes heat loss to ambient and entropy generation term.
I - Q - EGR Cooler	
I - Q - Engine	
I - Qo -Turbo.	2nd Law losses from turbocharger
I - Qo - Piping	Ambient heat loss from manifolds, etc
I - Friction Work	Leaves engine as heat
I - Pumping Work	Put back into system
I - Combustion Irreversibility	Fuel exergy destroyed during chemical reaction. Usually around 20-25%. Requires radical change in combustion to reduce.
Qx - Coolant, Oil *	Recoverable portion of heat transferred to coolant (from engine, IC, and EGR cooler) and oil (if known).
Incomp Comb	Based on HC and CO in exhaust
Exhaust	Recoverable portion of exhaust energy
Brake Work	From shaft torque
Total Fuel Exergy (kW)	Based on chemical exergy. May be > or < fuel energy depending on fuel.

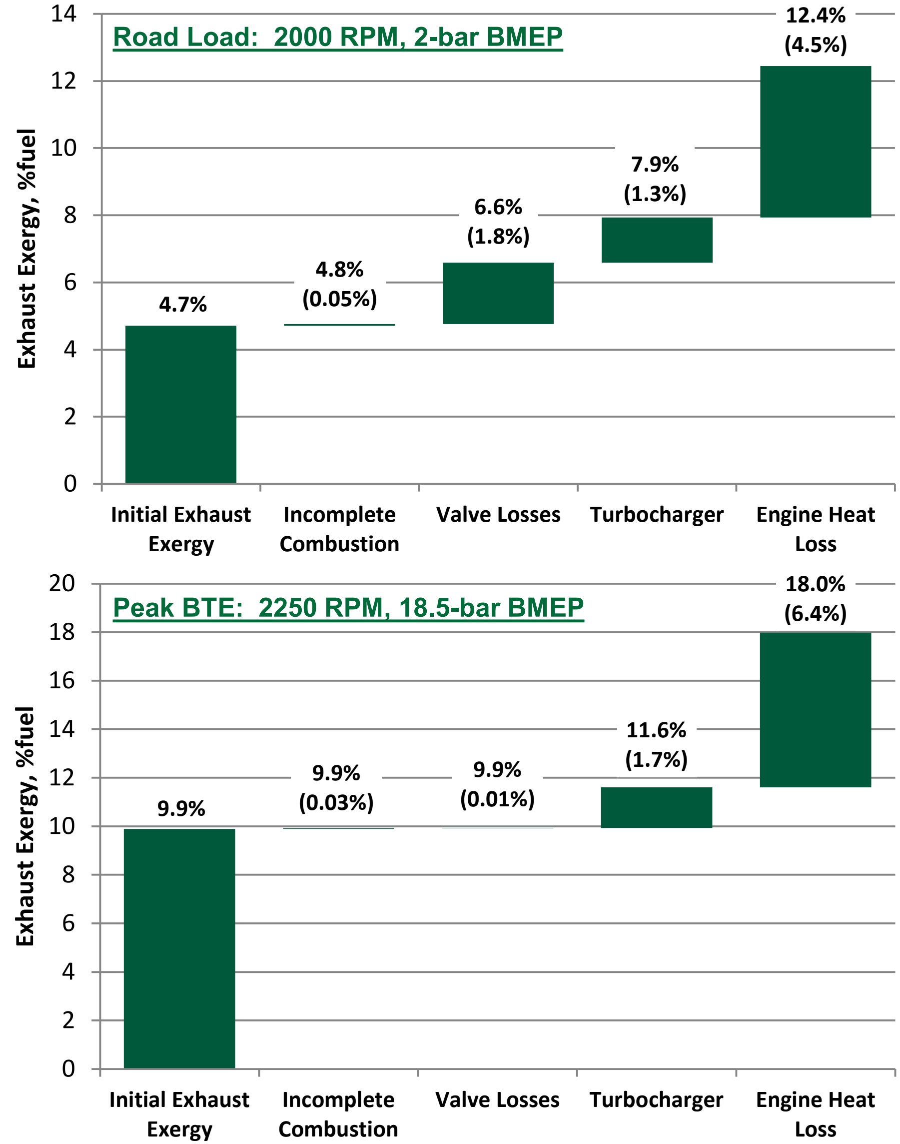
* Not shown

Selection of reduction factors for light-duty diesel

Loss Category	Stretch Reduction Goal	Discussion
Friction and accessory losses	25%	Any friction reduction should provide a 1:1 gain in brake power. Since friction losses ultimately leave the engine as heat, there will be net reductions in oil and engine coolant losses. Frictional losses represent a larger fraction of the fuel energy at typical road loads, making this reduction highly significant. Electrification and intelligent control of accessories.
Pumping losses	30%	Diesel engines have relatively low pumping losses, but improved volumetric efficiency through optimized ports, manifolds, and ducting and reduction of blow-down losses could permit a further reduction in these losses. Reducing these losses will also reduce additional exergy destruction associated with pumping work.
Heat loss to coolant	30%	A combination of low temperature combustion and port insulation will permit a significant reduction in the heat loss from the combustion chamber and exhaust ports to the engine coolant. Some of this will be directed into higher indicated work on the piston, while the remainder will go into the exhaust for use by the turbo, aftertreatment, and bottoming cycle. Running the coolant at a higher temperature will also impact cooling losses through reducing the exergy destruction during heat transfer and through increasing the exergy in the coolant stream.
Exhaust loss	20%	A bottoming cycle can recover roughly 20% of the post-aftertreatment exhaust energy and produce extra shaft or electrical power. This category will leverage all other loss reductions that direct more energy into the exhaust relative to the baseline case.
Combustion losses	50%	At lower loads, incomplete combustion represents approximately a 2% loss. Leveraging the aftertreatment system and optimizing combustion should permit halving this loss.
Turbo losses	50%	Turbo losses are 2-2.5% of the fuel exergy. Working with suppliers to improve turbo efficiencies could cut this loss in half.
Intercooler losses	0%	Low-quality heat loss represents less than 1% of fuel work potential (exergy). Reduction would reduce charge density and negatively impact BTE.

Breakdown of contributions to increase in exhaust exergy for the example scenario

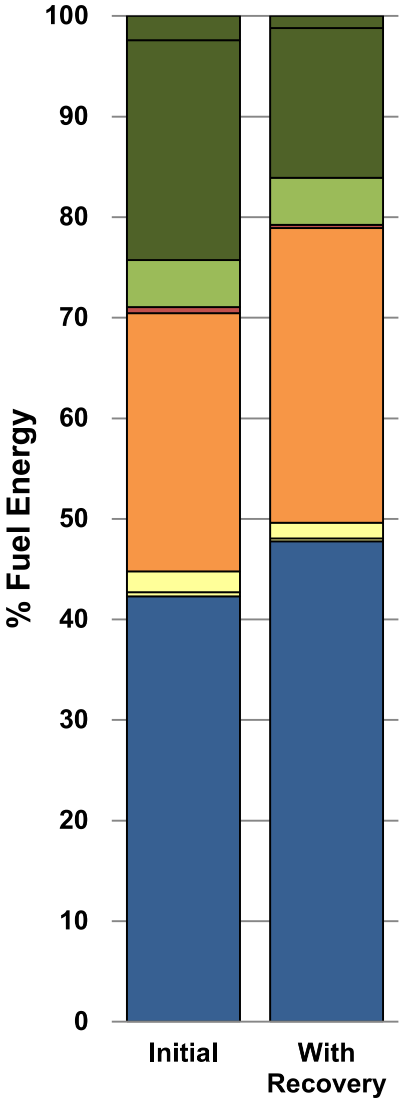
- **Reducing heat loss from the engine significantly increases exhaust exergy (almost double at part load)**
- **Provides benefits for both WHR and diesel aftertreatment systems**



Energy distributions resulting from the example scenario

Light-duty diesel @ Peak BTE (2250 RPM, 18.5-bar BMEP)

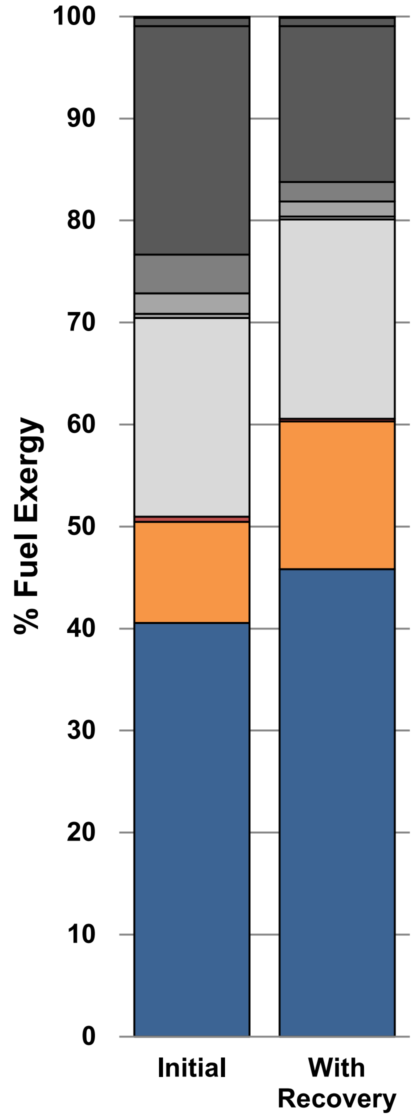
1st Law Energy Balance



% Fuel Energy	Initial	With Recovery
Qo - Piping	0 %	0 %
Qo - Turbocharger	2.4 %	1.2 %
Qo - Engine	21.8 % *	14.9 %
Q - Intercooler	4.7 %	4.7 %
Q - EGR Cooler	0 %	0 %
Q - Oil	0 % *	0 % *
Q - Engine Coolant	0 % *	0 % *
Incomplete Combustion	0.6 %	0.3 %
Exhaust	25.7 %	29.3 %
Friction Work	2.1 %	1.5 %
Pumping Work	0.4 %	0.3 %
Brake Work	42.3 %	47.8 %
Total Fuel (kW)	156.9 kW	156.9 kW

* Insufficient oil and coolant data to separate ambient heat losses from block

2nd Law Exergy Balance



% Fuel Exergy	Initial	With Recovery
I – Mixing & valve loss	0 %	0 %
I - ΔP - Intercooler	0.1 %	0.1 %
I - ΔP - EGR Cooler	0 %	0 %
I - Q - Intercooler	0.8 %	0.8 %
I - Q - EGR Cooler	0 %	0 %
I - Q - Engine	22.4 %	15.3 %
I - Qo - Turbocharger	3.8 %	1.9 %
I - Qo - Piping	0 %	0 %
I - Friction Work	2.0 %	1.5 %
I - Pumping Work	0.4 %	0.3 %
I – Combustion Irreversibility	19.5 %	19.5 %
Qx – Coolant, Oil	0 % *	0 % *
Incomplete Combustion	0.5 %	0.3 %
Exhaust	9.9 %	14.5 %
Brake Work	40.6 %	45.8 %
Total Fuel (kW)	163.5 kW	163.5 kW

* Insufficient oil and coolant data to determine exergy transferred to these streams that could be recoverable