Defining engine efficiency limits

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Defining pathways to maximize engine efficiency for future goal setting

- **Goals:**
  - Investigate the practical and thermodynamic efficiency limits of IC engines
  - Define the barriers to approaching these limits
  - Develop pathways to overcome those barriers
- **Scope:**
  - Focus on engine efficiency, not vehicle fuel economy
  - Engine applications include LD and HD transportation and stationary NG engines for power generation and CHP
  - No radical changes to conventional engine architecture (no free-pistons, staged combustion, etc)
  - Economic feasibility recognized as important but not used to invalidate any approach
- **Approach:**
  - Thermodynamic analysis of engine data and simulation results
    - Identify and assess opportunities for efficiency gains
    - Gain better understanding of loss mechanisms (heat loss, combustion irreversibility, etc) and how they interact and compete with one another
  - Estimate potential for recovery/reduction for each loss mechanism
  - Assess how recovered/reduced losses contribute to work output or increase in other losses
  - Interaction with industry, academia, and other labs will be crucial to success throughout the process

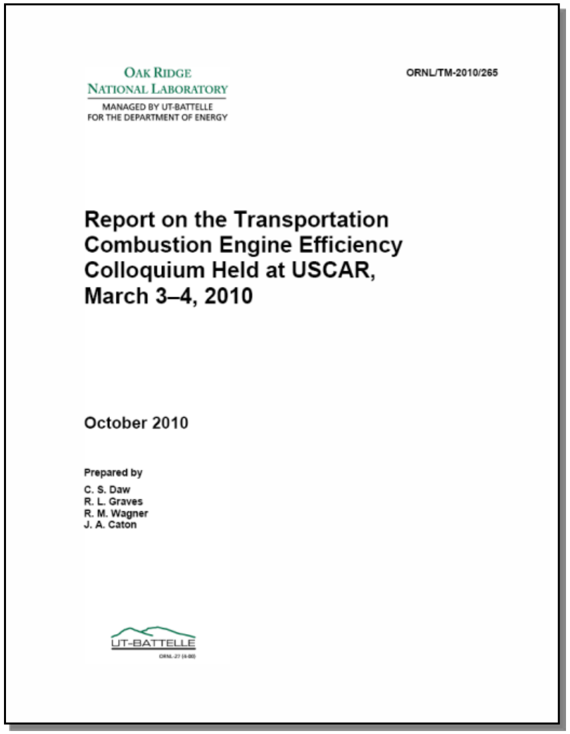
Effort builds upon recent engine efficiency forums

- **Recent engine efficiency forums organized by ORNL have provided a foundation for this effort**
  - » Transportation Combustion Engine Efficiency Colloquium held 3-4 March 2010 in Southfield, MI, USA
  - » SAE High-Efficiency IC Engine Symposium held 10-11 April 2011 in Detroit, MI, USA
- **While these forums focused primarily on transportation engines, the general conclusions reached are applicable to all IC engines**

Participants in the 2010 *Engine Efficiency Colloquium*

Oak Ridge National Laboratory (managed by UT-Battelle for the Department of Energy), Ford, GM, Sandia National Laboratories, Chrysler, Lawrence Livermore National Laboratory, Caterpillar, Cummins, Argonne National Laboratory, Pacific Northwest National Laboratory, Volvo, Delphi, GE, United States Department of Energy, U.S. Army, ExxonMobil, SwRI, AVL, Texas A&M University, The University of Wisconsin–Madison, Penn (University of Pennsylvania), Lund University, Stanford University

2010 *Engine Efficiency Colloquium*
Final Report edited by Daw, et al.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Report on the Transportation Combustion Engine Efficiency Colloquium Held at USCAR, March 3–4, 2010

October 2010

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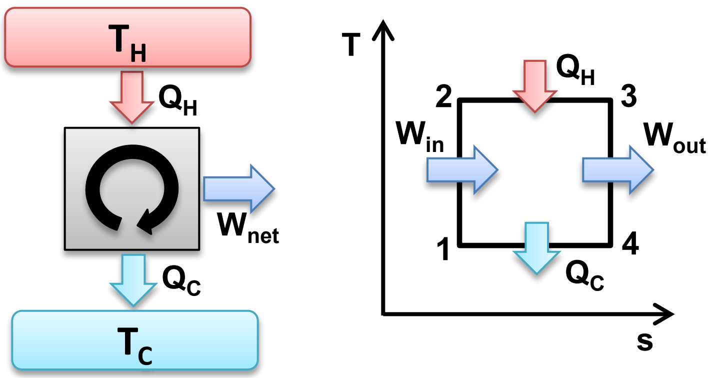
Carnot efficiency: a common misconception

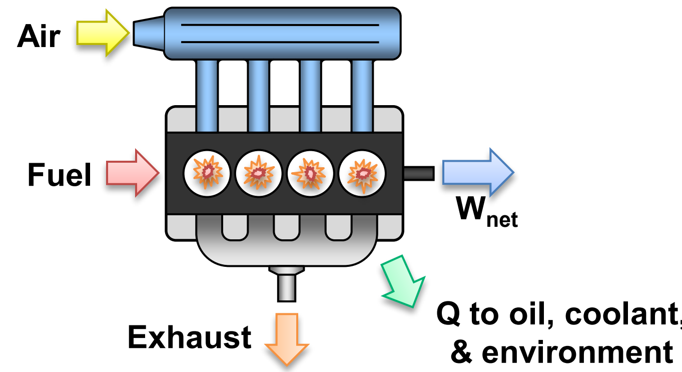
- **IC engines are *not* Carnot heat engines and therefore are *not* limited by Carnot efficiency**

Carnot heat engine



- **Operates on reversible, *closed* cycle**
- **Must reject heat to return working fluid (entropy) to its original condition and 'close' the cycle (2nd Law of Thermodynamics)**
- $\eta_{max} = 1 - \frac{T_C}{T_H}$

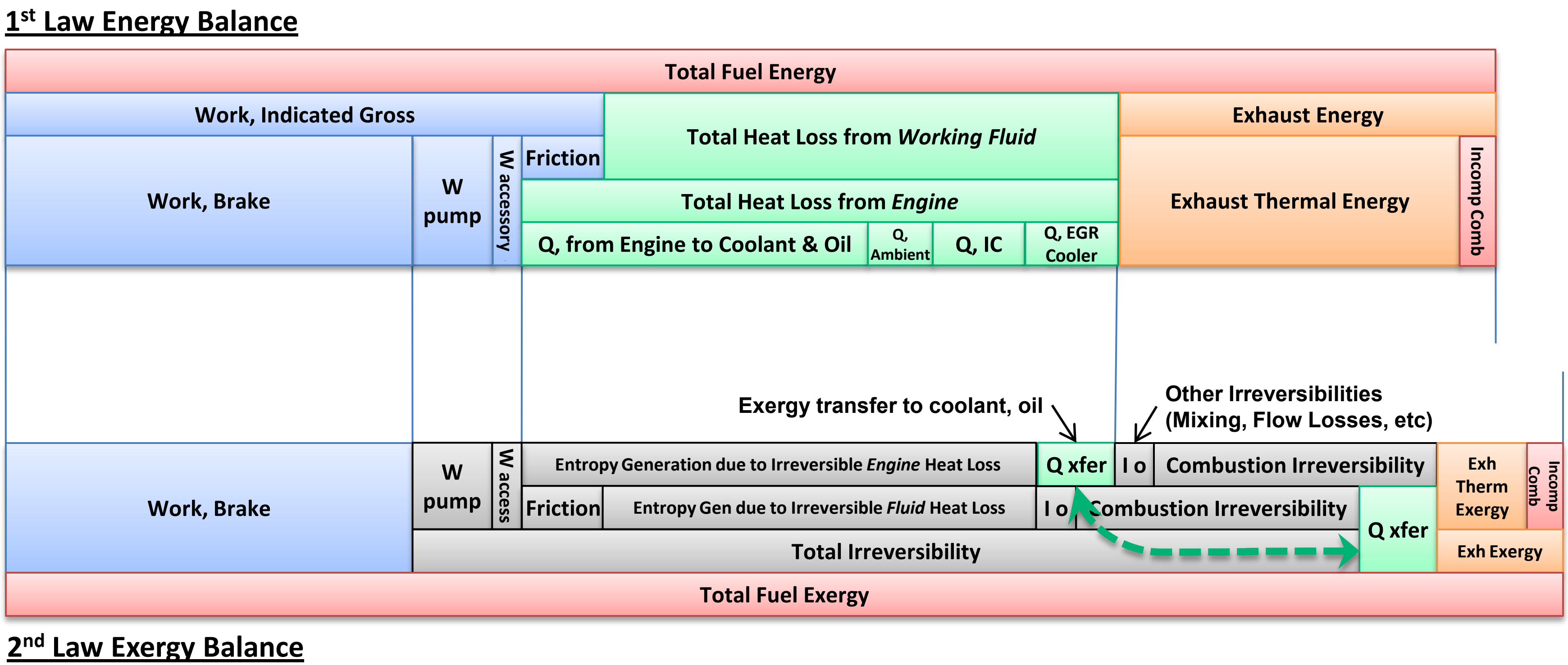
Internal combustion engine



- **Operates on *open* cycle involving a chemical reaction and gas exchange (not *ideal, closed* Otto or Diesel cycle)**
- **No *thermodynamic* requirement for heat rejection to thermal reservoir for open cycle**
  - » **Fresh working fluid is introduced (exhaust not changed back to air and fuel)**
  - » **Coolant heat loss only required to prevent material and component failures and lubricant breakdown**
- **In theory,** $\eta_{max} \cong 100\,\%$
- **However, practical efficiency limits are defined by**
  - » **Irreversible losses (friction, combustion irreversibility, etc)**
  - » **Work extraction efficiency**
  - » **Material limits**
  - » **Cost**

Thermodynamic analysis provides insight on potential for efficiency gains

- **1st and 2nd Laws of Thermodynamics can be used to provide detailed analysis of how fuel energy and exergy are used to produce work or lost due to inefficient processes**
- **Actual distribution varies with engine, operating point, etc**
- **'Pie' can be 'sliced' differently depending on choice of control volume**
  - » For example, *combustion products* do *work* to overcome friction, but friction generates *heat* which is transferred out of the *engine*



Exergy balance derives from additive combination of 1st Law energy balance and 2nd Law entropy balance…

Working Definition: ***Exergy*** *(a.k.a. availability) is a measure of a system's potential to do useful work due to physical (P, T, etc.) and chemical differences between the system and the ambient environment.*

Neglecting changes in kinetic and potential energy:

$$\left.\frac{dU}{dt}\right|_{CV} = \sum_{in} \dot{m}h - \sum_{out} \dot{m}h + \dot{Q} - \dot{W}$$

1st Law Energy Balance

$$- \quad T_o \times \left[\left.\frac{dS}{dt}\right|_{CV} = \sum_{in} \dot{m}s - \sum_{out} \dot{m}s + \frac{\dot{Q}}{T_x} + \dot{S}_{gen} \right]$$

Entropy Balance

$$\left.\frac{dA}{dt}\right|_{CV} = \sum_{in} \dot{m}a_f - \sum_{out} \dot{m}a_f + \left(1 - \frac{T_o}{T_x}\right)\dot{Q} - \dot{W} - \dot{I}$$

2nd Law Exergy Balance

where

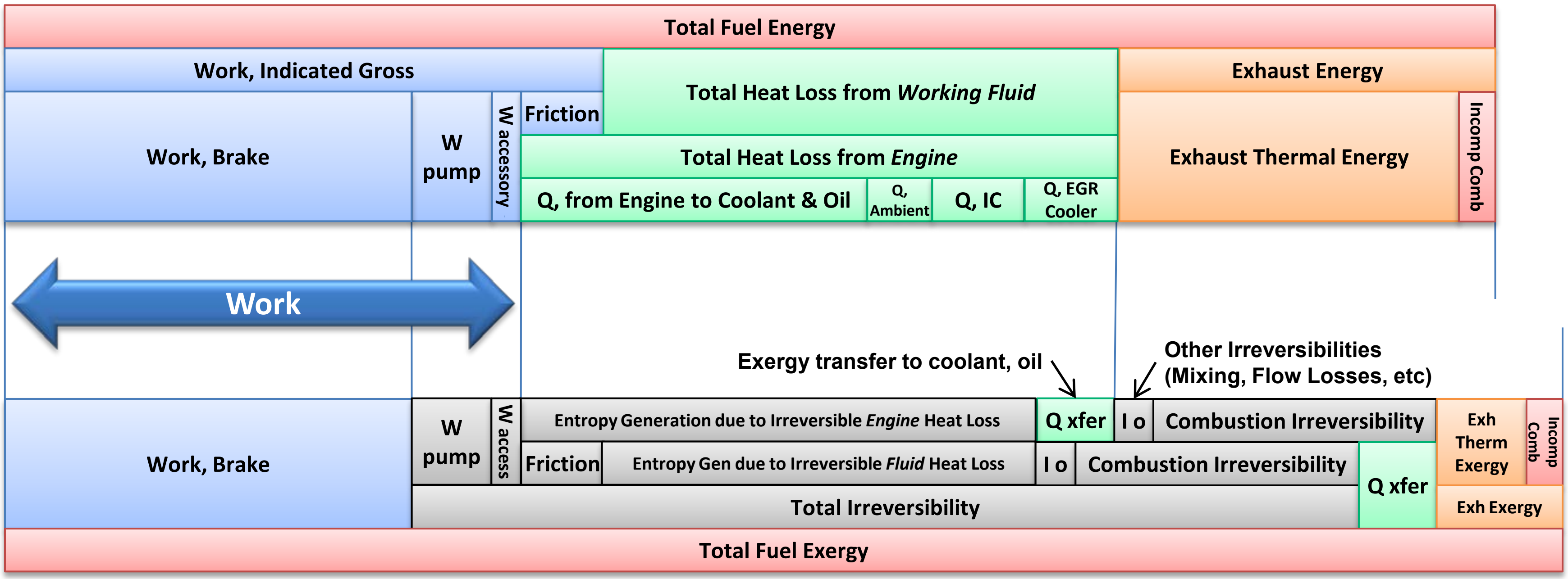
$$A_{CV} = m\left[a_{chem} + \left(u - u_o\right) - T_o\left(s - s_o\right)\right] + P_o\left(V - V_o\right)$$

$$a_f = a_{chem} + \left(h - h_o\right) - T_o\left(s - s_o\right)$$

… as a result, work terms are equivalent in 1st and 2nd Law analyses

1st Law Energy Balance

$$\left.\frac{dU}{dt}\right|_{CV} = \sum_{in} \dot{m}h - \sum_{out} \dot{m}h + \dot{Q} - \boxed{\dot{W}}$$



2nd Law Exergy Balance

$$\left.\frac{dA}{dt}\right|_{CV} = \sum_{in} \dot{m}a_f - \sum_{out} \dot{m}a_f + \left(1 - \frac{T_o}{T_x}\right)\dot{Q} - \boxed{\dot{W}} - i$$

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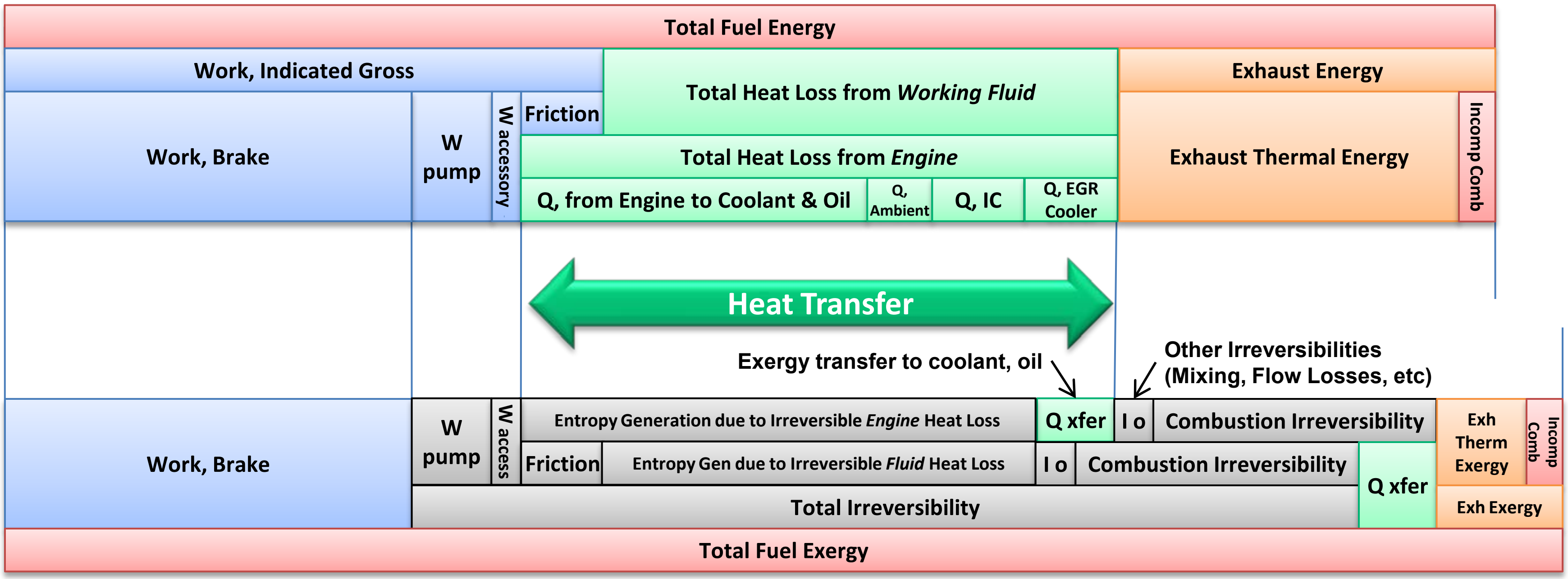
Heat loss also shows up equivalently in 1st and 2nd Law analyses…

1st Law Energy Balance

$$\left.\frac{dU}{dt}\right|_{CV} = \sum_{in} \dot{m}h - \sum_{out} \dot{m}h + \dot{Q} - \dot{W}$$



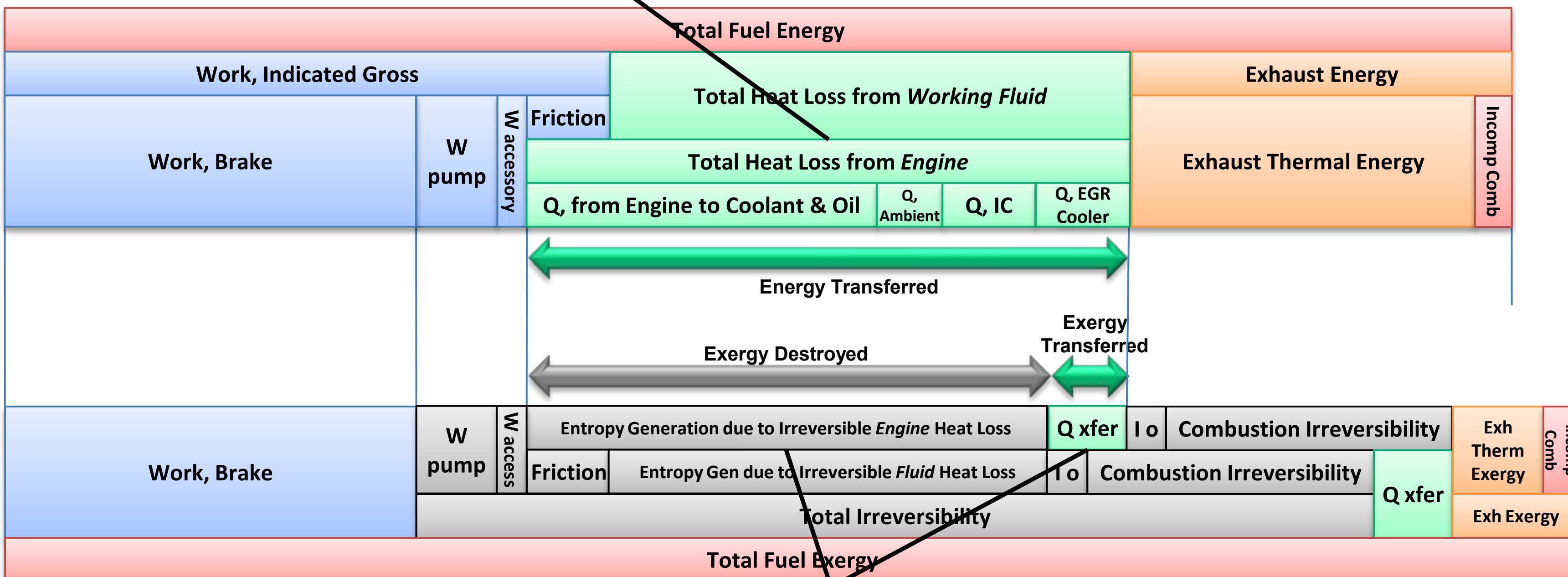
2nd Law Exergy Balance

$$\left.\frac{dA}{dt}\right|_{CV} = \sum_{in} \dot{m}a_f - \sum_{out} \dot{m}a_f + \left(1 - \frac{T_o}{T_x}\right)\dot{Q} - \dot{W} - \dot{i}$$

… but not all of the energy transferred is available for recovery

1st Law Energy Balance

$$\left.\frac{dU}{dt}\right|_{CV} = \sum_{in} \dot{m}h - \sum_{out} \dot{m}h + \boxed{\dot{Q}} - \dot{W}$$



2nd Law Exergy Balance

$$\left.\frac{dA}{dt}\right|_{CV} = \sum_{in} \dot{m}a_f - \sum_{out} \dot{m}a_f + \boxed{\left(1 - \frac{T_o}{T_x}\right)\dot{Q}} - \dot{W} - \boxed{\dot{I}}$$

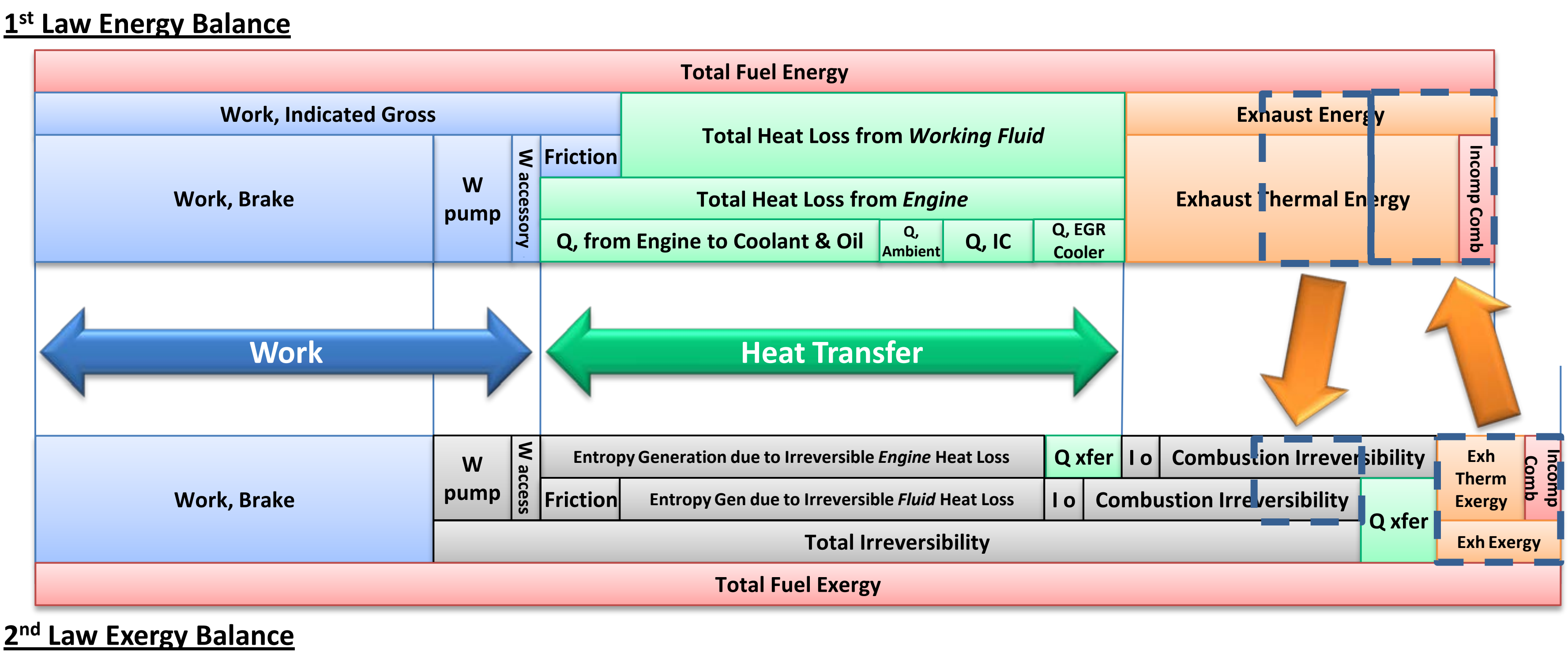
Irreversibility:

- Can not be directly *recovered* but can be *reduced* with 'saved' energy/exergy showing up elsewhere.
- Includes the 'unrecoverable' portion of heat transferred to coolant and oil and ***all*** heat transferred to the environment

- 'Recoverable' portion of heat loss that is transferred to another fluid at temperature Tx.
- Increasing Tx increases recoverable portion.
- If Tx = To, all of Q is 'unrecoverable'.

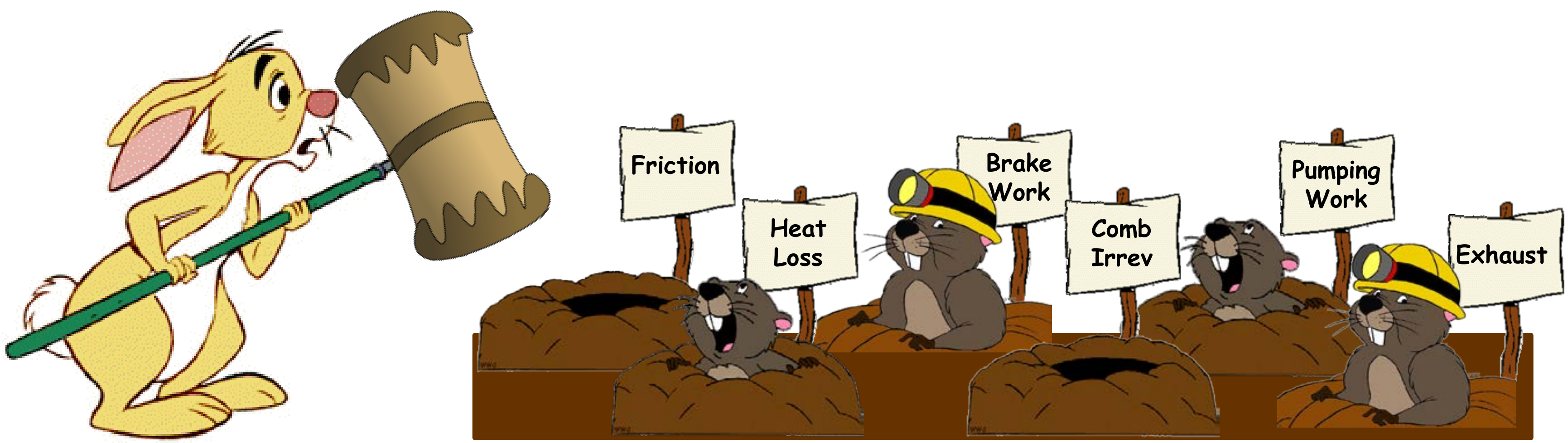
2nd Law limits waste heat recovery from exhaust

- **Exhaust exergy determines the amount of exhaust energy that is recoverable**
- **Recovery of additional work would require an equivalent increases in exhaust exergy through…**
  - » Reduced combustion irreversibility
  - » Reduced heat loss



Increasing engine efficiency involves a Whack-a-mole (or Gopher) approach

- **Reduction of one loss term tends to result in an increase of another, for example,…**
  - Reducing in-cylinder heat loss tends to increase exhaust energy rather than piston work
  - Lean operation increases piston work *but* increases combustion irreversibility and decreases exhaust energy
- **Maximizing efficiency will require a combination of strategies which…**
  - Increase work extraction by the piston (top priority)
  - Concentrate remaining energy/exergy in the exhaust where it can be recovered (bottoming cycle, thermo-electrics, etc)
- **Must consider how much each loss mechanism can be reduced or recovered *and* how that energy will be redistributed either as work or to the other loss mechanisms**
- **When trade-offs are required, give preference to options which increase work extraction with the piston**



Fuel selection impacts on efficiency

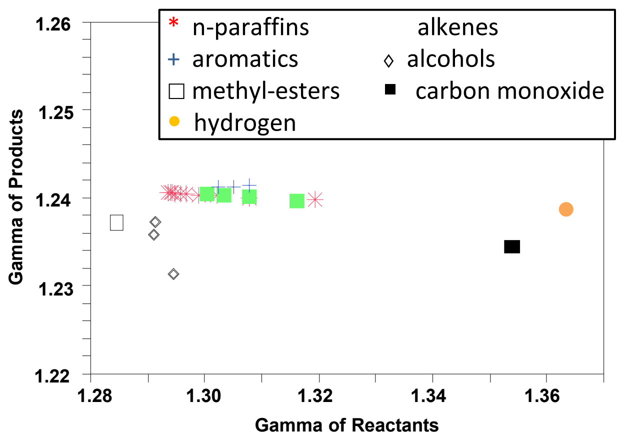
Total Fuel Exergy

- **In general, higher fuel energy provides a higher potential work output**
  - » Energy/exergy ratio indicates how well available fuel energy (exergy) is converted to thermal energy during combustion
- **Fuels with simpler molecular formulas typically produce lower combustion irreversibility**
- **Additional factors may also contribute, for example…**
  - » In SI applications, high-octane fuels (such as ethanol) can be used at higher compression ratios without knock
  - » Higher ratio of $\gamma_{products}/\gamma_{reactants}$ provide higher work-extraction efficiency (γ = specific heat ratio)

Fuel	Fuel Energy (kJ/kg)	Fuel Exergy (kJ/kg)	Energy/Exergy	Combustion Irreversibility (% Fuel Exergy)
Hydrogen	119,951	111,635	1.074	12.58
Natural Gas	48,839	48,767	1.001	18.28
ULS Diesel	43,544	45,393	0.959	20.73
UTG-96 Gasoline	43,370	44,304	0.979	19.54
E10	42,564	43,528	0.978	19.62
E85	31,395	32,837	0.956	21.18
Ethanol	26,806	28,462	0.942	22.19

*** stoich, $T_{iN,OUT}$ = 298K, all water leaves as vapor**

Szybist (2011)



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Maximizing work extraction with conventional piston-cylinder architecture

Brake Work	Remaining Fuel Exergy

- **Assuming polytropic compression and expansion, the work done on/by the piston is given by…**

$$W = \int P_{cyl}\,dV = \int cV^{-\gamma}dV = \frac{\Delta(PV)}{1-\gamma} \qquad \text{where } \gamma = \text{specific heat ratio of cylinder gases}$$

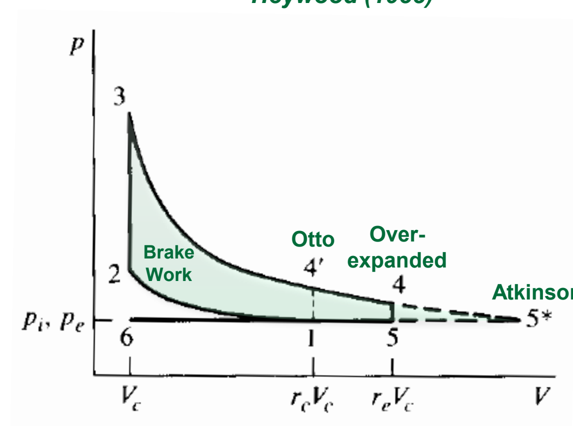
  » Increases with gamma and change in volume and pressure

Some strategies for increasing cylinder pressure and volume change…

- **Increase physical compression ratio**
- **Over-expanded cycle with variable valve actuation or variable stroke (*e.g.*, Atkinson cycle)**
- **Turbocharging with charge-air cooler to boost cylinder charge density**
- **Advanced combustion strategies with rapid pressure rise rates (*e.g.*, HCCI)**
- ***Drawbacks:***
  - » Resultant thermal and physical stresses from increased cylinder pressure can exceed material limits
  - » Increasing compression ratio may eventually become friction limited
  - » In SI applications, higher in-cylinder temperatures increase risk of knock and production of NOx

P-V diagram and engine efficiency for over-expanded and Atkinson cycles

Heywood (1988)

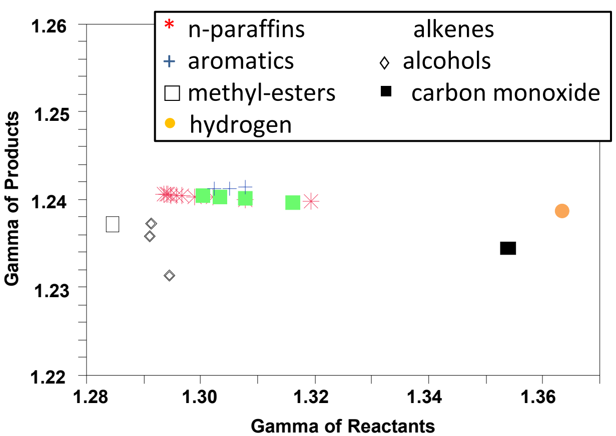


Some strategies for increasing work extraction by increasing exhaust gamma…

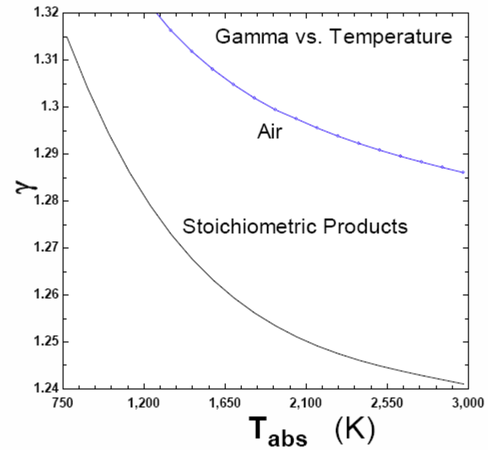
Brake Work	Remaining Fuel Exergy

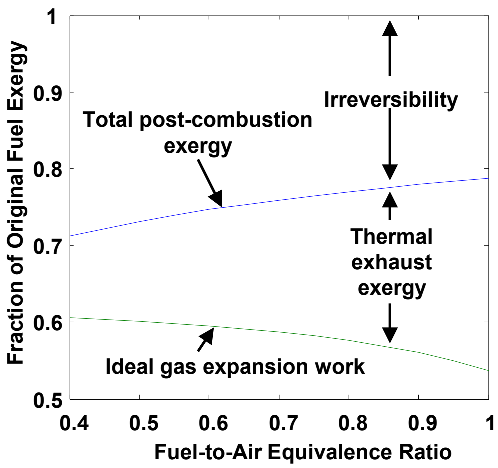
- **Fuel selection**
  - Desire a fuel which provides a high gamma ratio for products to reactants
- **Decreased exhaust temperature**
  - Advanced, low-temperature combustion strategies
  - Reducing cylinder heat losses increases cylinder pressure and temperature which provides more work potential <u>*but*</u> decrease in gamma reduces work extraction efficiency (∴ little net gain)
- **Dilute operation**
  - Lean operation increases gamma <u>*but*</u> also increases combustion irreversibility and decreases exhaust energy

Szybist (2011)



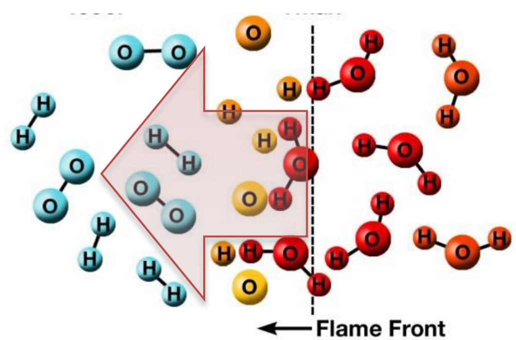
Provided by Dave Foster of U Wisconsin



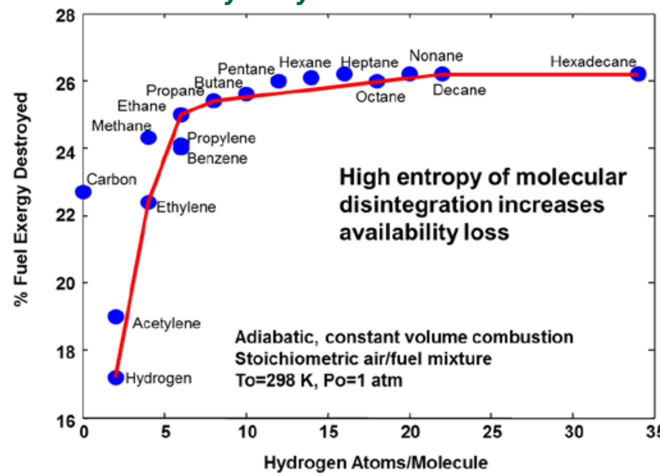


Combustion irreversibility… and learning to live with it

- **Modern IC engines rely on unrestrained combustion reactions which occur far from chemical and thermal equilibrium, go to completion (or extinction), and are inherently irreversible**
- **Some energy released in reaction is consumed to heat reactants, break chemical bonds, and drive non-equilibrium reactions**



Provided by Jerry Caton of Texas A&M

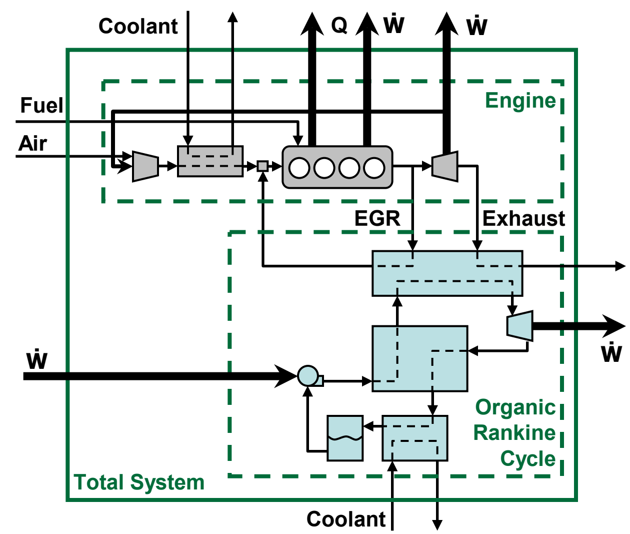


- **Fuel selection has some impact**
  - » Fuels with simpler molecular structures tend to produce lower combustion irreversibility
- **Higher for dilute combustion (*e.g.*, lean or high EGR)**
- **Reduced by pre-heating reactants using excess exhaust energy (but this reduces charge density)**
- **Significant reductions will require radical changes in how combustion occurs in engines**
  - » Thermochemical recuperation, staged reactions (chemical looping), etc

Reducing environmental heat loss is a key strategy

- **For open cycles, there is no thermodynamic requirement to reject heat to satisfy the 2nd Law**
  - » Heat loss is only required to prevent material and component failure and lubricant breakdown
- **Reducing in-cylinder heat loss increases cylinder pressure and temperature**
  - » Provides more work *potential* **but** decreases gamma and reduces work-extraction *efficiency*
  - » Result is hotter exhaust with little net gain in piston work
- **Real benefit of reducing heat loss is concentrating waste energy in the exhaust where it may be recovered through a bottoming cycle, turbo-compounding, thermo-electrics, etc**
- **Options for reducing engine heat loss include…**
  - » Advanced low-temperature combustion strategies
  - » Decreased cylinder surface area / volume ratio (engines with fewer, but larger cylinders)
  - » Advanced materials with low thermal conductivity and high thermal tolerance and durability
  - » Operating at higher engine coolant temperatures (also increases potential for waste heat recovery from coolant)
- ***Drawbacks:***
  - » Higher in-cylinder temperatures increase risk of knock (SI) and production of NOx

Energy flow diagram with turbo-compounding and an organic Rankine cycle for waste heat recovery from exhaust and EGR cooler

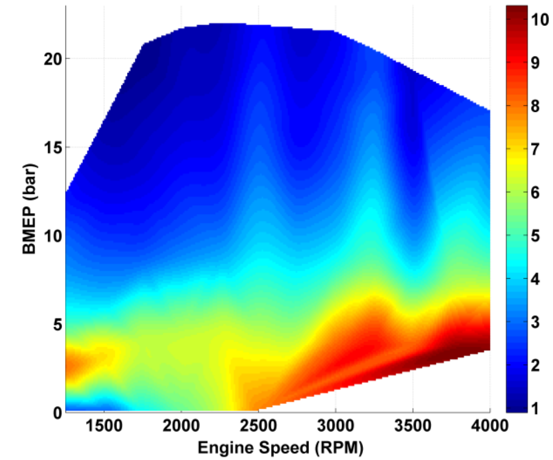


Reducing friction, pumping losses, and accessory loads has a direct benefit

Brake Work	Combustion Irreversibility	Q_o	W_f	Remaining Fuel Exergy

- **Reduction of these losses directly increases brake work output**
- **Friction**
  - » Losses eventually leave the engine as heat loss
  - » Tends to increase with speed and load <u>*but*</u> consumes a higher percentage of fuel energy at <u>*low*</u> speed and load
  - » Advanced lubricants and modest redesign of engine architecture
- **Pumping Losses**
  - » Variable valve actuation can reduce pumping and throttling losses at part load in some applications
  - » Some advanced combustion techniques can lead to increased pumping losses
    - *e.g.*, negative valve overlap to retain excess residual gases and promote HCCI combustion may offset some gains in reduction of throttling losses
- **Accessory Loads**
  - » High-pressure fuel rails require substantial accessory loads
  - » Electrification of accessory loads with intelligent controls

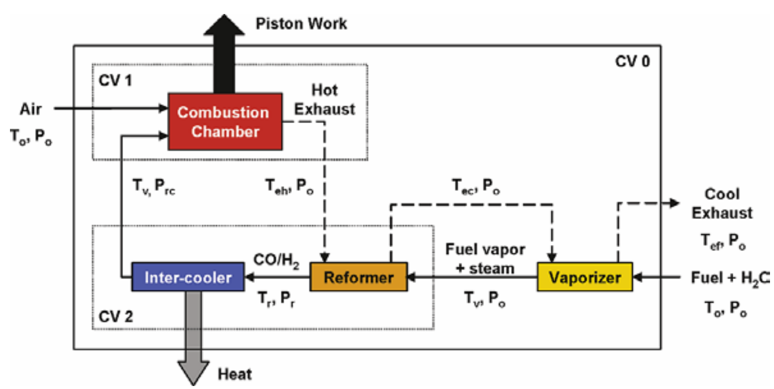
Friction Losses **(Fraction of Fuel Energy)**
Data from GM 1.9-L diesel



Maximize exhaust energy for WHR… but not at expense of piston work

- **Waste heat recovery from high-energy exhaust will likely play an important role in achieving significant increases in engine efficiency**
- **Exhaust energy can also be used to reduce combustion irreversibility**
  - » Preheating of reactants (but this may reduce charge/power density)
  - » Fuel reformation to H_2 and CO (lower combustion irreversibility than complex hydrocarbon fuels)
- ***<u>However</u>*, higher priority should be given to strategies which increase piston work, even at the expense of higher exhaust energy**
  - » Fully expanded cycles (*e.g.*, Atkinson cycle)
  - » Highly efficient turbo-machinery for higher boost (especially at part load)
  - » Lean or dilute operation (improved work-extraction efficiency)
  - » Advanced, low-temperature combustion techniques

<u>Conceptual thermochemical recuperation strategy</u>



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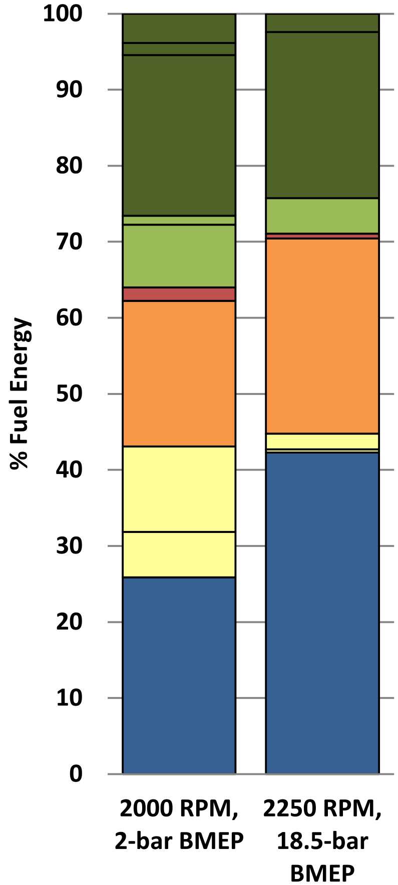
Assessing potential improvements for light-duty applications

- **Our approach involves:**
  - » Thermodynamic analysis of engine data
  - » 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**
  - » Input from industry will be important in refining values
- **Applied to ORNL data from GM 1.9-L diesel at two operating conditions**
  - » 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
    - Conventional diesel combustion
    - Non-hybrid
    - No free pistons, cross-head cylinders, thermochemical recuperation, etc
  - » Waste heat recovery from exhaust and EGR cooler is considered
  - » 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
  - » Recovery factors are applied on a 1^{st} Law basis with 2^{nd} Law used to insure that proposed recoveries are feasible
  - » Effects of higher compression ratio and increased boost were not directly considered in this initial study
- **Future plans include assessing data from SI engines and advanced combustion strategies**

Initial energy distributions for GM 1.9-L diesel at road load and peak efficiency

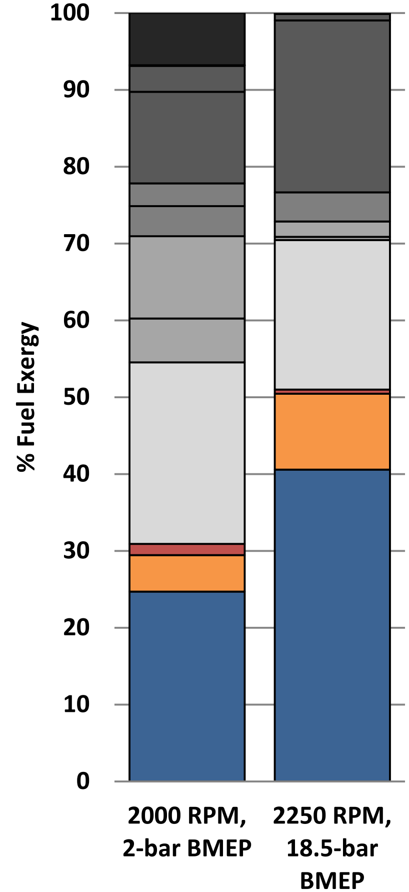
1st Law Energy Balance



% Fuel Energy	2000 RPM, 2 bar	Peak BTE
Qo - Piping	3.9 %	0 %
Qo - Turbocharger	1.6 %	2.4 %
Qo - Engine	21.1 % *	21.8 % *
Q - Intercooler	1.2 %	4.7 %
Q - EGR Cooler	8.2 %	0 %
Q - Oil	0 % *	0 % *
Q - Engine Coolant	0 % *	0 % *
Incomplete Combustion	1.8 %	0.6 %
Exhaust	19.2 %	25.7 %
Friction Work	11.2 %	2.1 %
Pumping Work	6.0 %	0.4 %
Brake Work	25.9 %	42.3 %
Total Fuel (kW)	25.2 kW	156.9 kW

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

2nd Law Exergy Balance



% Fuel Exergy	2000 RPM, 2 bar	Peak BTE
I – Mixing & valve loss	6.8 %	0 %
I - ΔP - Intercooler	0 %	0.1 %
I - ΔP - EGR Cooler	0 %	0 %
I - Q - Intercooler	0.1 %	0.8 %
I - Q - EGR Cooler	3.4 %	0 %
I - Q - Engine	11.9 %	22.4 %
I - Qo - Turbocharger	3.0 %	3.8 %
I - Qo - Piping	3.9 %	0 %
I - Friction Work	10.7 %	2.0 %
I - Pumping Work	5.7 %	0.4 %
I – Combustion Irreversibility	23.6 %	19.5 %
Qx – Coolant, Oil	0 % *	0 % *
Incomplete Combustion	1.5 %	0.5 %
Exhaust	4.7 %	9.9 %
Brake Work	24.7 %	40.6 %
Total Fuel (kW)	26.4 kW	163.5 kW

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

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Selection of reduction factors for light-duty diesel

Loss Category	Stretch Reduction Goal	Discussion
Friction and accessory losses	50%	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.

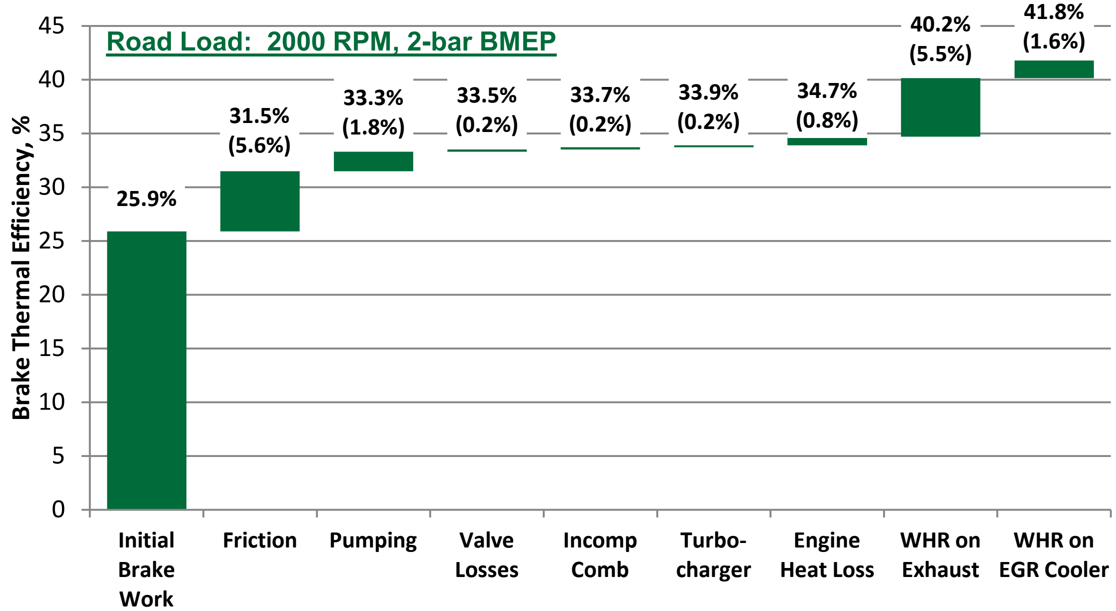
Redistribution of recovered energy for light-duty diesel

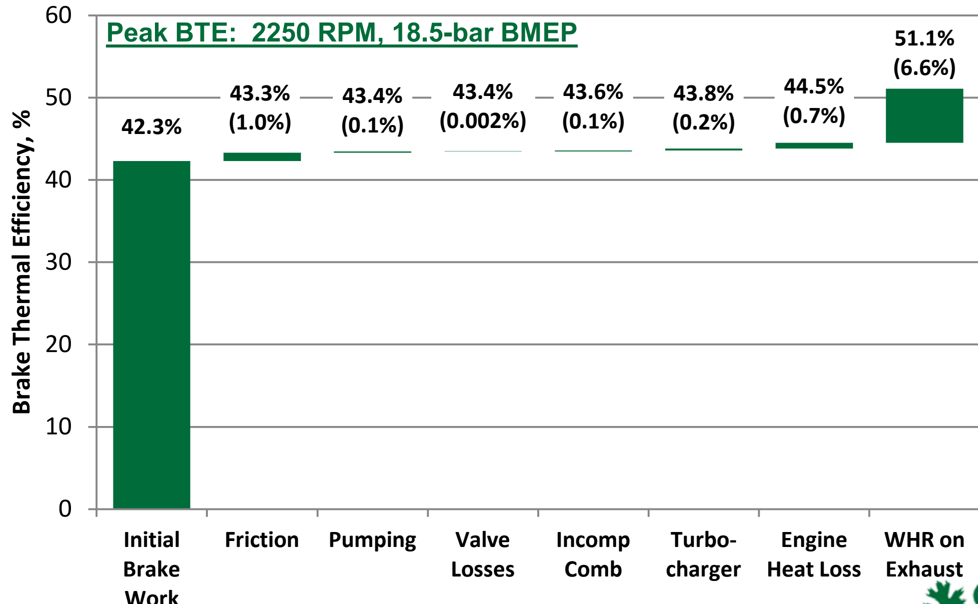
Loss Category	Reduction Factor	Redistribution Factors				Notes
		Brake Work	Heat Loss	Exhaust	Combustion Irreversibility	
Friction and Accessories	0.5	1				
Pumping	0.3	1				Includes 2nd Law valve losses
Incomplete Combustion	0.5	Based on original energy/exergy distributions				
Turbocharger	0.5	0.2*		0.8*		Improved boost
Intercooler	0					Reducing intercooler losses lowers charge density. Exergy too low for effective waste heat recovery.
Engine Heat Loss	0.3	0.1*		0.9*		Includes friction losses. Advanced combustion strategies could provide higher work recovery by increasing gamma of exhaust gases and work-extraction efficiency of piston.
Exhaust and EGR Cooler	0.2*	1				Using WHR system with 1st law efficiency equal to reduction factor

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

BTE increase with recovery for GM 1.9-L diesel

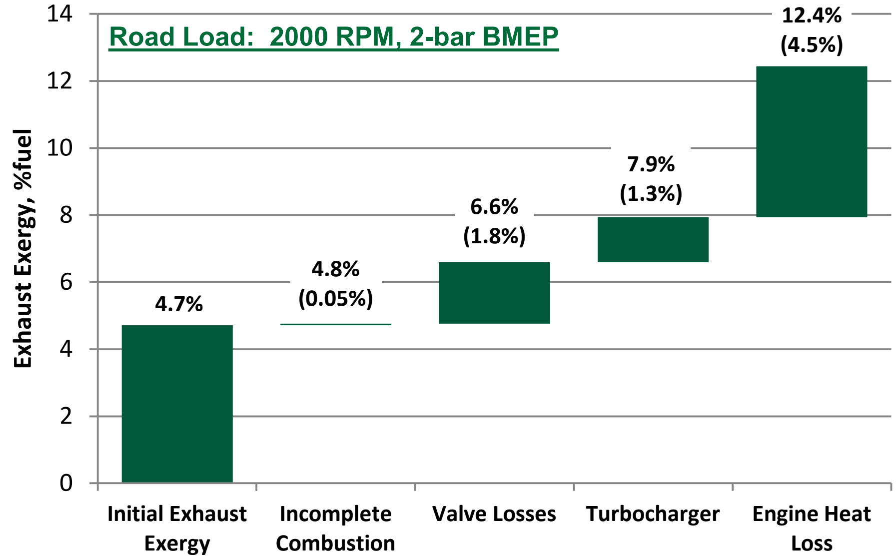
- **Reduction of friction and accessory loads provides largest direct benefit to BTE, especially at part load**
- **Reducing engine heat loss provides little direct BTE gain but significantly increases exhaust exergy for WHR**
- **Even with stretch recovery goals, other changes only provide incremental BTE gains**
- **WHR on exhaust (and EGR cooler at part load) can provide substantial improvements in system efficiency (especially when combined with reduced heat loss)**
- **Low thermal quality of conventional engine coolants limits its potential for WHR**
  - » Architecture changes for use of 2-phase engine coolants could provide additional WHR benefits

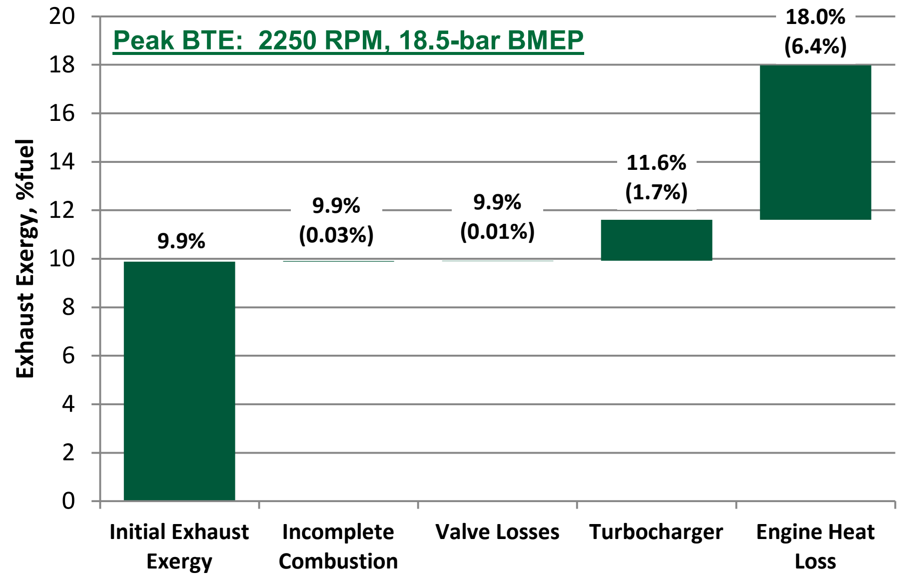




Impact of recovery efforts on available energy (exergy) in exhaust for GM 1.9-L diesel

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





So what is the maximum practical peak BTE for an IC engine?

- **This is a difficult question to answer and few are likely to agree on a single answer**
- **The participants at the *Transportation Combustion Engine Efficiency Colloquium* concluded:**
  - » *"The maximum BTE expected for slider-crank engines is about 60%, assuming that cost is not a constraint."*
  - » *"Achieving BTEs > 60% will require radical changes to present engines, including cycle compounding, new engine architectures, and more constrained combustion reactions."*
- **This would be a very aggressive, stretch goal**
- **Significant advances in engine efficiency will require balancing multiple approaches to…**
  - » Improve work extraction with the piston
  - » Reduce heat loss to coolant and ambient environment
  - » Concentrate remaining waste energy in the exhaust where some of it may be recovered
- **Significant technological advances will be required in a number of areas**
  - » Advanced materials and lubricants with high thermal tolerance and durability
  - » Advanced, low-temperature combustion techniques
  - » 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
- **Larger engines are likely to approach higher limits than smaller engines**
- **Similarly, single-cylinder research engines are more likely to approach higher limits than multi-cylinder production engines which have additional durability and reliability constraints**
- **Final constraint on efficiency of production engines will be *<u>cost</u>* and *<u>economic feasibility</u>***

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- JP Szybist, K Chakravarthy, CS Daw (2011). Molar Expansion Ratio, Enthalpy and Exergy: Modeling Fuel-Specific Efficiency Differences of an Almost-Ideal Otto Cycle. AEC/HCCI Working Group Meeting. Sandia National Laboratory; 22 February 2011.
- JB Heywood (1988). *Internal Combustion Engine Fundamentals*. McGraw-Hill, Inc. ISBN: 007028637X

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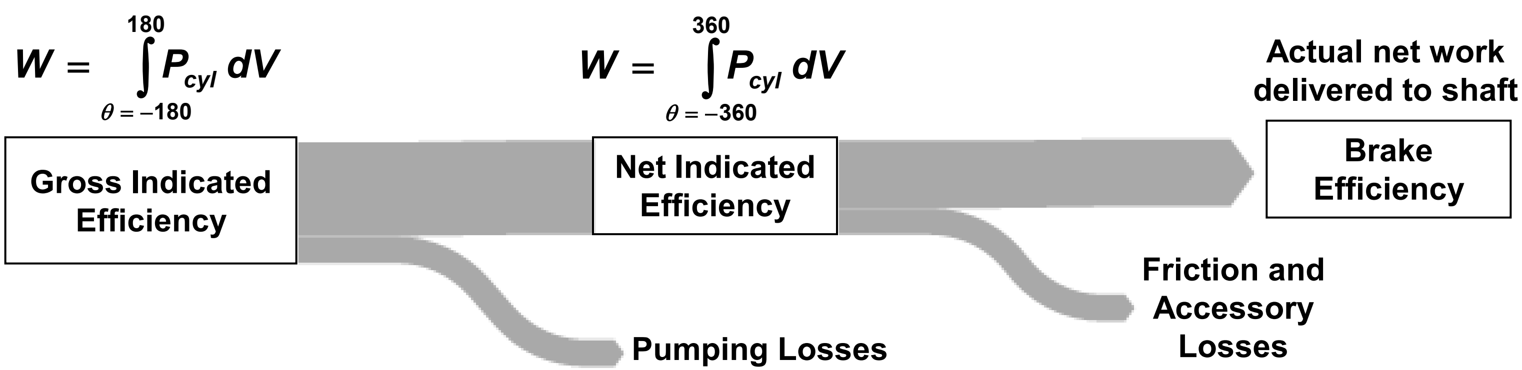
Bonus Slides

Defining engine efficiency

- **Engine efficiency = work output / fuel energy input**
  - 1st Law efficiency: uses lower heating value (LHV) of fuel (thermal energy released during combustion)
  - 2nd Law efficiency: uses fuel exergy (energy available for doing useful work)
- **Gross indicated efficiency**
  - Based on net work done on the piston during compression and expansion strokes
  - Includes work used to overcome pumping losses during intake and exhaust strokes
  - Value often cited for single-cylinder research engines
- **Net indicated efficiency**
  - Based on net work done on the piston over full engine cycle
  - Includes work used to overcome friction and accessory loads
- ***<u>Brake thermal efficiency (BTE)</u>***
  - Based on net work delivered to shaft

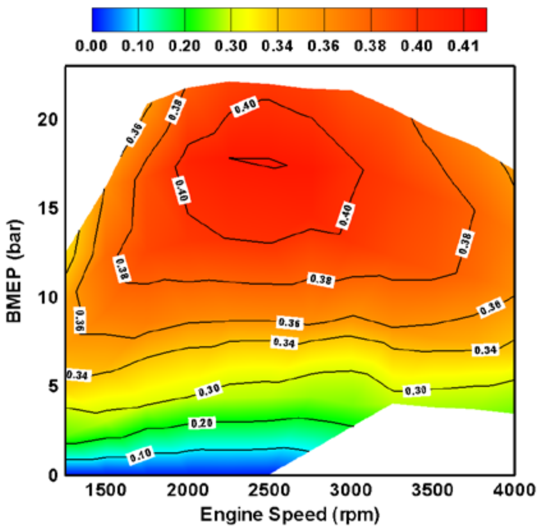


Energy distribution varies across the operating range

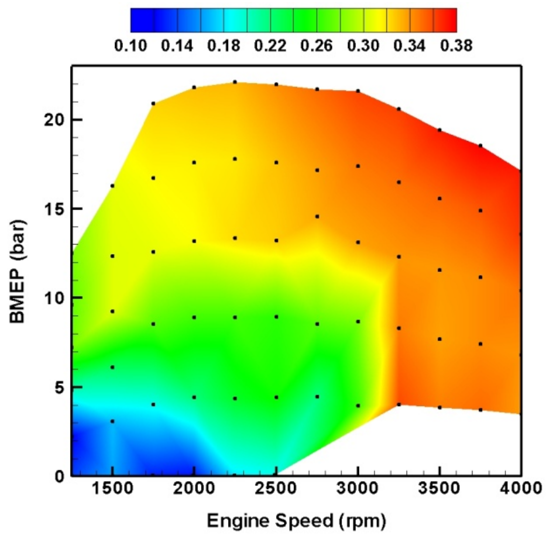
- **Apportioning of the fuel energy varies with engine speed and load and operating strategy**
  - » Exhaust energy is highest at high load and speed
  - » Friction losses account for a higher fraction of fuel energy at low load and speed
- **EGR cooler losses can be significant when using advanced combustion techniques with high dilution for in-cylinder NOx and PM reduction**

<u>Data from GM 1.9-L diesel</u>

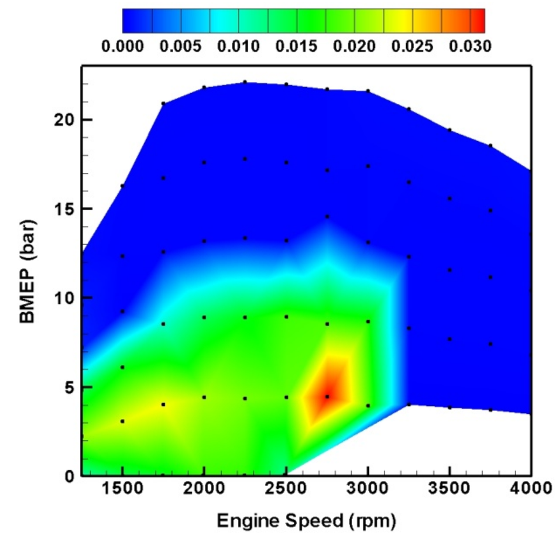
Brake Work (Fraction of Fuel Energy)



Exhaust Energy (Fraction of Fuel Energy)



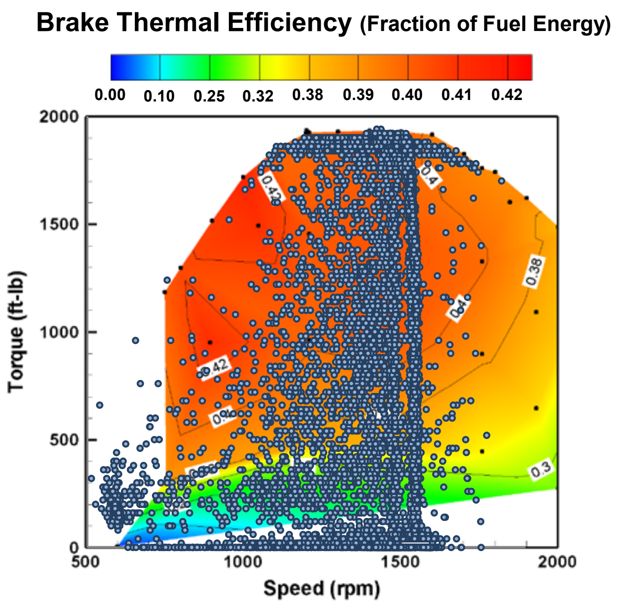
EGR Cooler Losses (Fraction of Fuel Energy)



Engine design and operation should be tailored to application

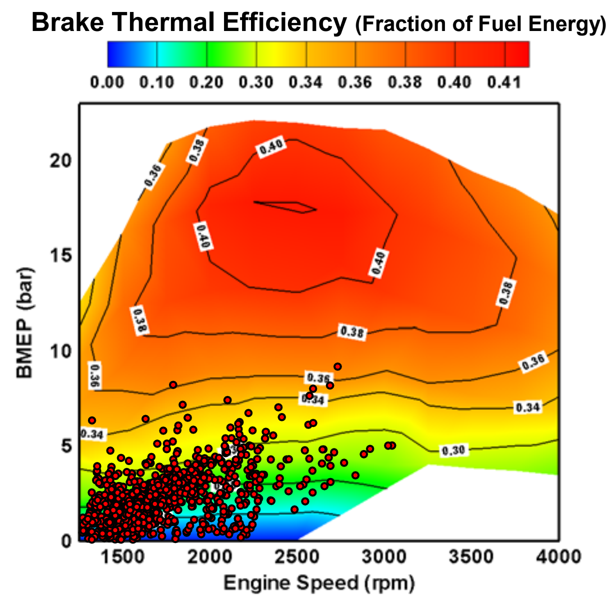
- **Typical engine operation should occur where efficiency is highest**
  - » For stationary power and heavy-duty transportation applications, this is usually the case
  - » For light-duty transportation applications, the engine is usually geared for on-demand power and normal operation typically falls 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**

Efficiency varies with engine size and application

- **Small engine cylinders typically provide lower efficiency**
  - Higher heat transfer losses (large surface area/volume ratio)
  - Higher blow-by losses and lower combustion efficiency (crevice volume larger relative to cylinder volume)
  - Usually not cost effective to apply advanced technologies
- **Large engine cylinders typically provide higher efficiency**
  - Often operate at lower speeds resulting in lower friction losses
  - Easier to absorb cost of advanced technologies
- **Cross-head design of large marine diesels provides increased efficiency**
  - Slow engine speed for low friction
  - Long stroke for efficient work extraction
  - Low surface area / volume ratio for low heat transfer losses

Brake efficiencies of some modern IC engines

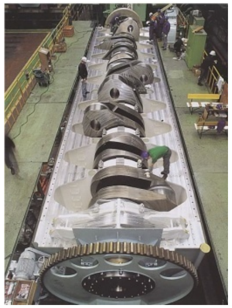
UAV, RC hobby
<5%

Small genset
~15-20%

LD transportation
~30-35% gasoline
~40-42% diesel

HD transportation
~42-47%

Large genset
~45-50%



Marine diesel
~55%

Equations used in thermodynamic analysis and applied to each component (e.g., cylinder, turbocharger, intercooler, etc)

1st Law Energy Balance

$$\left.\frac{dU}{dt}\right|_{CV} = \underbrace{\sum_{in}\dot{m}h - \sum_{out}\dot{m}h}_{} + \dot{Q} - \dot{W}$$

Heat Transfer

Energy/exergy change in component. Usually = 0 (steady state) except for the engine cylinders.

Energy/exergy of mass entering and leaving the component

Net work output: Equivalent in 1st and 2nd Law analyses

Irreversibility:
Losses due to entropy generation.
Can not be directly *recovered* but can be *reduced* with 'saved' energy/exergy showing up elsewhere.
Includes the portion of heat loss not transferred to coolant, oil, etc. (see below).

2nd Law Exergy Balance

$$\left.\frac{dA}{dt}\right|_{CV} = \overbrace{\sum_{in}\dot{m}a_f - \sum_{out}\dot{m}a_f}^{} + \underbrace{\left(1 - \frac{T_o}{T_x}\right)}_{}\dot{Q} - \dot{W} - \dot{I}$$

'Recoverable' portion of heat loss that is transferred to another fluid at temperature Tx. Remainder is included in irreversibility (entropy generation due to heat transfer across finite temperature difference).
Bigger ΔT = more entropy generation, so increasing Tx increases recoverable portion.
If other fluid is coolant or oil at Tx ≠ To, some of this portion may be recoverable.
If other fluid is ambient air at Tx = To, this portion = 0, and all heat transfer is irreversible.

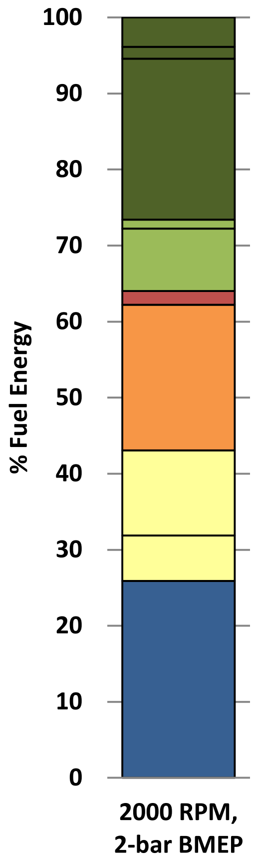
where

$$A_{CV} = m\left[a_{chem} + (u - u_o) - T_o(s - s_o)\right] + P_o(V - V_o)$$

$$a_f = a_{chem} + (h - h_o) - T_o(s - s_o)$$

Explanation of “slices” in energy/exergy balances

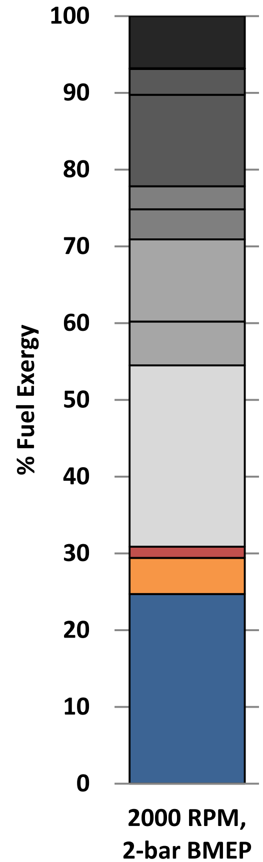
1st Law Energy Balance



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

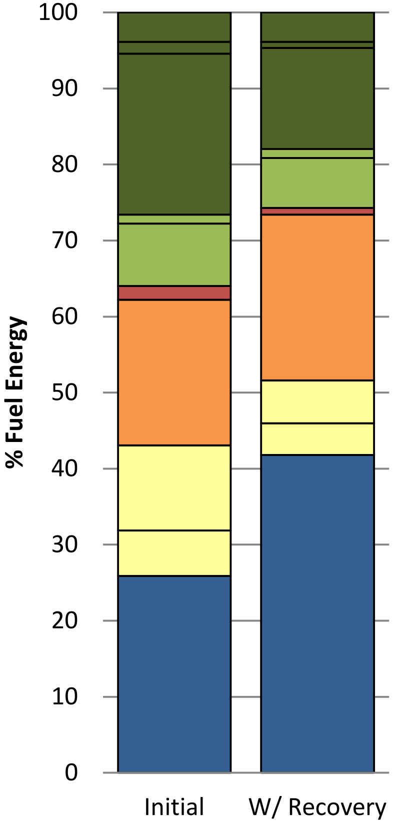


Slice	Explanation
I - Mixing & valve loss	Mixing: Entropy generation due to mixing (air+EGR, air+fuel, etc) Valves: flow losses, blow-down, etc
I - ΔP - Intercooler	Due to air-side pressure drop
I - ΔP - EGR Cooler	Due to EGR-side pressure drop
I - Q - Intercooler	Unrecoverable portion of heat transfer 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

Revised energy distributions for GM 1.9-L diesel in recovery assessment analysis @ Road Load (2000 RPM, 2-bar BMEP)

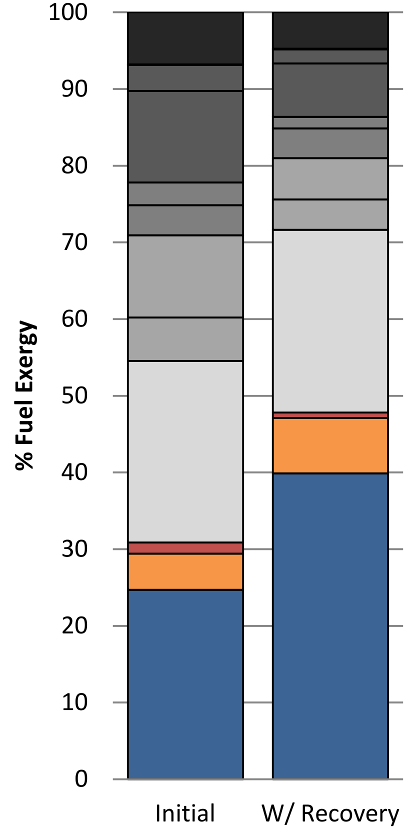
1st Law Energy Balance



% Fuel Energy	Initial	With Recovery
Qo - Piping	3.9 %	3.9 %
Qo - Turbocharger	1.6 %	0.8 %
Qo - Engine	21.1 % *	13.3 %
Q - Intercooler	1.2 %	1.2 %
Q - EGR Cooler	8.2 %	6.6 %
Q - Oil	0 % *	0 % *
Q - Engine Coolant	0 % *	0 % *
Incomplete Combustion	1.8 %	0.9 %
Exhaust	19.2 %	21.8 %
Friction Work	11.2 %	5.6 %
Pumping Work	6.0 %	4.2 %
Brake Work	25.9 %	41.8 %
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

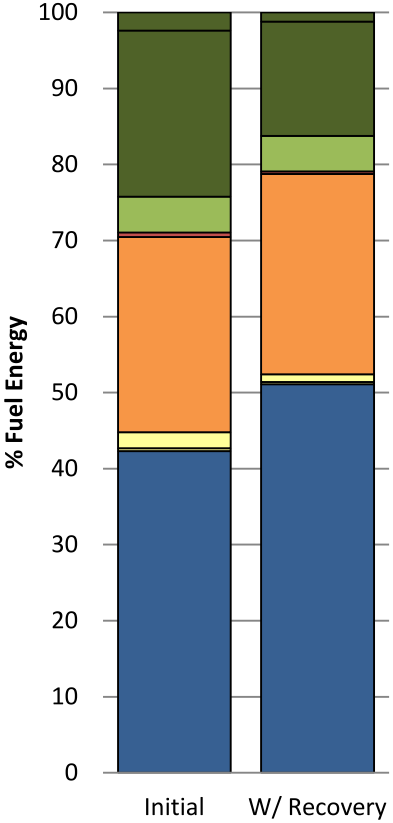


% Fuel Exergy	Initial	With Recovery
I – Mixing & valve loss	6.8 %	4.8 %
I - ΔP - Intercooler	0 %	0 %
I - ΔP - EGR Cooler	0 %	0 %
I - Q - Intercooler	0.1 %	0.1 %
I - Q - EGR Cooler	3.4 %	1.8 %
I - Q - Engine	11.9 %	7.0 %
I - Qo - Turbocharger	3.0 %	1.5 %
I - Qo - Piping	3.9 %	3.9 %
I - Friction Work	10.7 %	5.4 %
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 %	7.2 %
Brake Work	24.7 %	39.9 %
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

Revised energy distributions for GM 1.9-L diesel in recovery assessment analysis @ Peak BTE (2250 RPM, 18.5-bar BMEP)

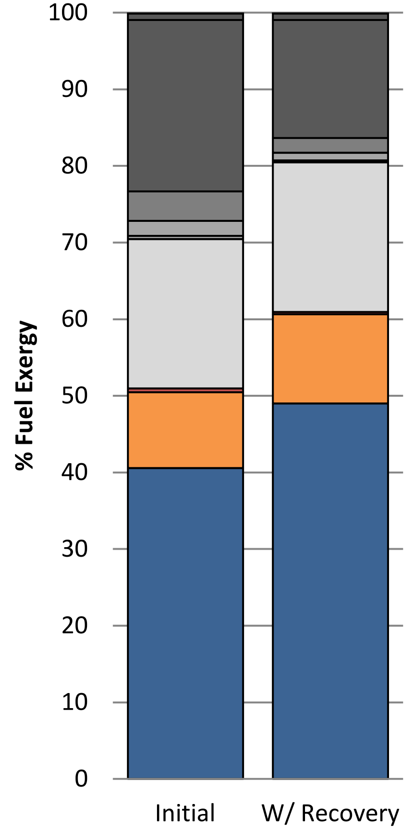
1st Law Energy Balance



% Fuel Energy	Initial	With Recovery
Qo - Piping	0 %	0 %
Qo - Turbocharger	2.4 %	1.2 %
Qo - Engine	21.8 % *	15.0 %
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 %	26.3 %
Friction Work	2.1 %	1.0 %
Pumping Work	0.4 %	0.3 %
Brake Work	42.3 %	51.1 %
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 %	15.4 %
I - Qo - Turbocharger	3.8 %	1.9 %
I - Qo - Piping	0 %	0 %
I - Friction Work	2.0 %	1.0 %
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 %	11.6 %
Brake Work	40.6 %	49.0 %
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

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