Identification and evaluation of near-term opportunities for efficiency improvement

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Introduction

Identify and prioritize opportunities for efficiency gains in internal-combustion engines through complete thermodynamic analysis of experimental engine data and model simulations.

Near-term Pathways

- Waste-heat recovery
  - Bottoming cycles
  - Turbo-compounding
  - Thermo-electrics
- Reduce heat loss
  - Advanced combustion modes
  - Advanced materials
- Reduce friction losses
  - Advanced lubricants
  - Electrification of accessories

Long-term Pathways

- Reduction of combustion irreversibilities with unconventional combustion
  - Counter-flow Preheating with near-Equilibrium Reaction and Thermo-Chemical Recuperation (CPER-TCR)
  - Staged Combustion with Oxygen Transfer (SCOT)

Perform thermodynamic analysis to evaluate potential success of the recovery techniques.

Light-duty diesel platforms at ORNL

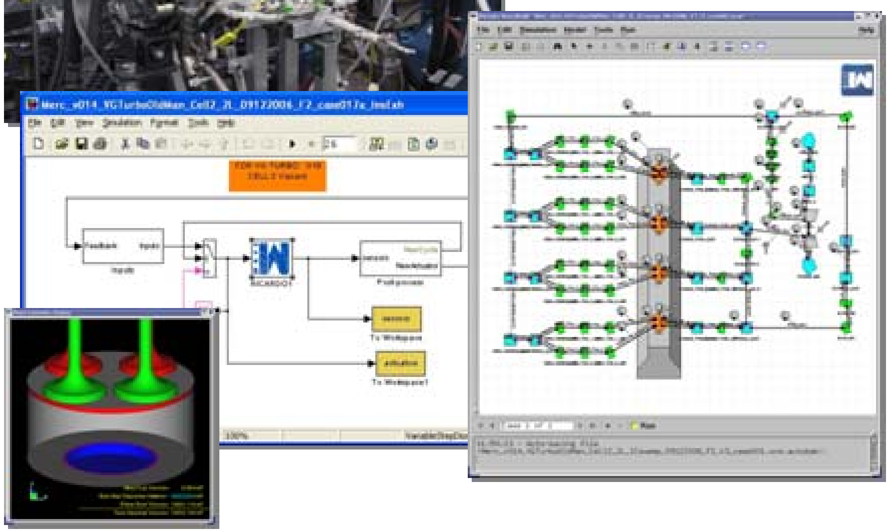
MB 1.7-L 4-cylinder common-rail

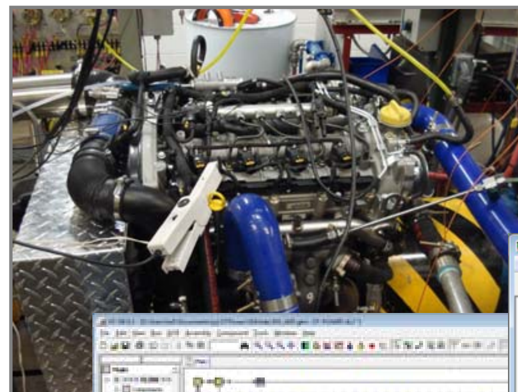
- 1999 version
- WAVE model
- Modifications include VGT, electronic EGR, EGR cooler, throttle
- High- and low-pressure EGR circuits
- Full-pass engine control
- Variable CR version available

GM 1.9-L 4-cylinder common-rail

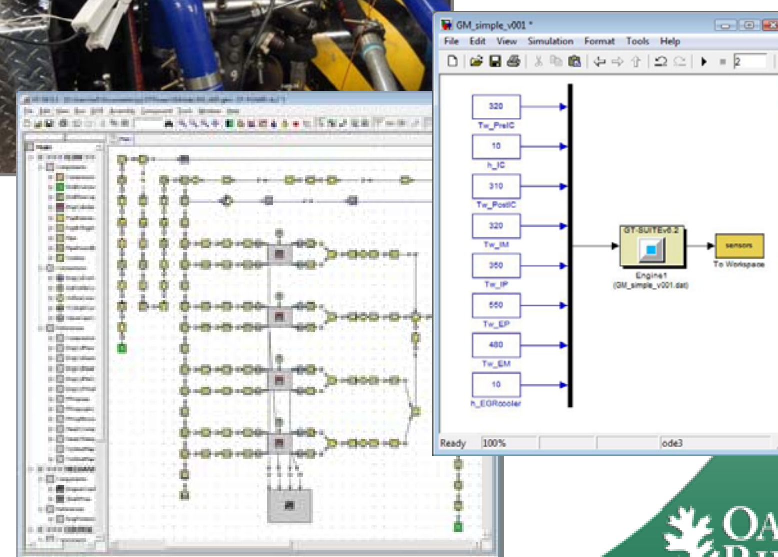
- 2005 and 2007 versions
- GT-Power model
- OEM hardware includes VGT, electronic EGR, EGR cooler, throttle
- “Open” ECU and full-pass engine control unit
- Common platform: ORNL (multi-cyl), SNL (1-cyl optical), UWisc (1-cyl optical and metal)

Number of Cylinders	4
Bore, mm	80.0
Stroke, mm	84.0
Compression Ratio	19.0
Rated Power, kW	66
Rated Torque, Nm	180



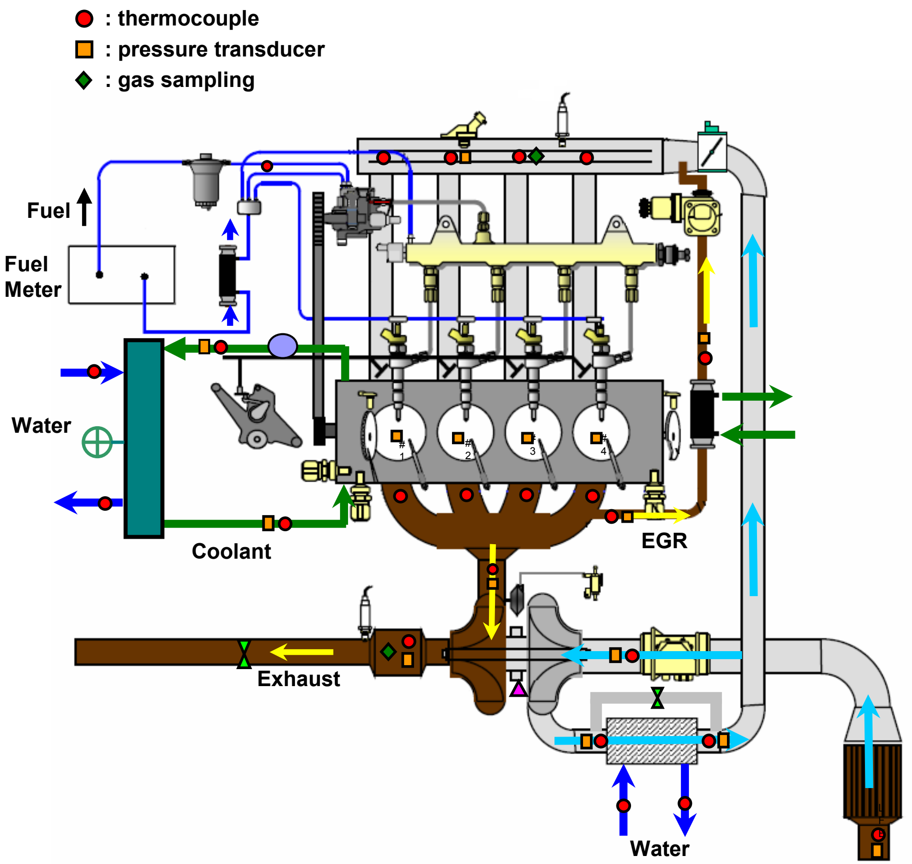


Number of Cylinders	4
Bore, mm	82.0
Stroke, mm	90.4
Compression Ratio	17.5
Rated Power, kW	110
Rated Torque, Nm	315



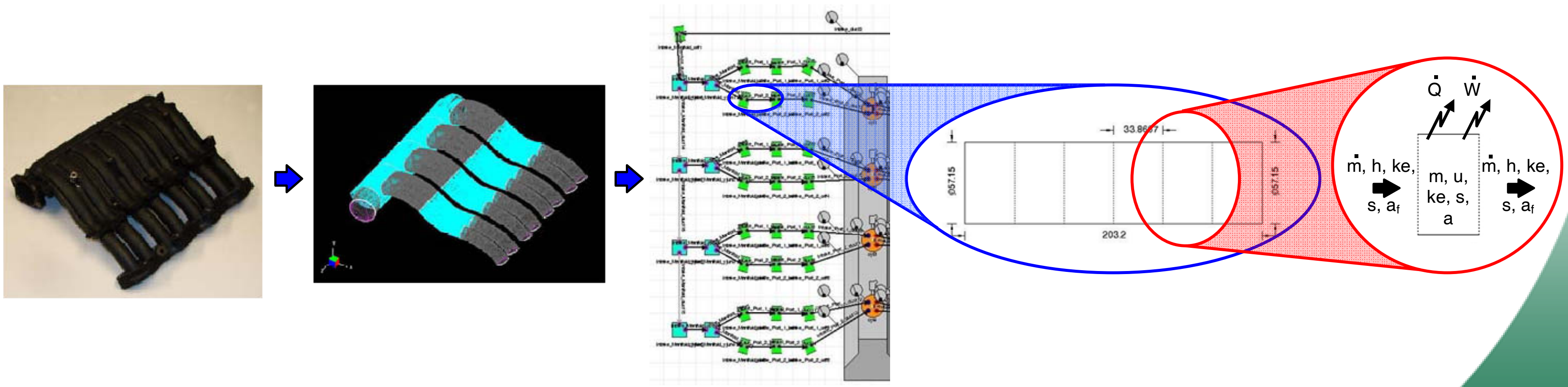
Overview of thermodynamic analysis of experimental data

- Analysis based on experimental measurements of
  - Mass flow rates of fuel, air, and coolant
  - Brake work and indicated work (from cylinder pressure)
  - Exhaust composition
  - EGR mass fraction
  - Temperatures: exhaust, EGR, block, & coolant
- Fraction of fuel energy/availability apportioned to
  - Brake work
  - Exhaust
  - Friction losses
  - EGR and charge-air cooler losses (gas-side)
  - Losses to coolant losses (from block)
  - "Other": combustion irreversibility, convective and radiant heat loss, mixing, flow losses, etc.



Overview of thermodynamic analysis for model results

- **Thermodynamic analysis is performed on the engine system as a whole and on individual components (turbocharger, intercooler, individual cylinders, etc.).**
- **Our analysis requires evaluation of property balances for mass, energy, entropy, and availability (a.k.a. exergy) for all elements in the engine model at all timesteps in the cycle simulation.**
- **WAVE provides all information necessary to perform the analysis except for entropy and availability which must be calculated from the working-fluid composition and thermodynamic properties.**
- **GT-Power provides entropy and (as of Version 6.2, Build 9) physical availability flux. The addition of chemical availability, control-volume availability (including in-cylinder), and user-defined dead-state is planned for a future release.**



Governing equations (neglecting potential energy)

Mass Balance

$$\left.\frac{dm}{dt}\right|_{CV} = \sum_{in} \dot{m} - \sum_{out} \dot{m} + \dot{\varepsilon}_{mass}$$

Error terms, $\dot{\varepsilon}$, in the numerical solutions for mass and energy are on the order of the convergence criteria for the solver.

Energy Balance

$$\left.\frac{d[m(u+ke)]}{dt}\right|_{CV} = \sum_{in} \dot{m}(h+ke) - \sum_{out} \dot{m}(h+ke) + \dot{Q} - \dot{W} + \dot{\varepsilon}_{energy}$$

Entropy Balance

$$\left.\frac{dS}{dt}\right|_{CV} = \frac{\dot{Q}}{T_w} + \sum_{in} \dot{m}s - \sum_{out} \dot{m}s + \frac{\dot{I}}{T_o}$$

Irreversibility is a measure of the useful work that could have been done, but was not.

$$\dot{I} = T_o \dot{S}_{gen}$$

Availability (Exergy) Balance

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

Availability is the potential to do useful work due to physical and chemical differences between the working fluid and the surroundings.

where,

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

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

- Subscript $_o$ denotes dead-state (*i.e.*, ambient) properties.
- T_w = wall temperature

Edwards, *et al.*, SAE 2008-01-0293

Evaluation of thermodynamic properties

Properties not provided by GT-Power and WAVE are determined from the NIST-JANAF tables for each gaseous component and known fuel properties.

- **Dead state defined as air at ambient (not Standard) conditions**
  - Working fluid composition frozen
  - Properties of working fluid at ambient conditions evaluated using NIST-JANAF tables
  - Chemical availability accounts for differences between chemical composition of the working fluid and ambient environment (air)
- **Chemical availability only dependent upon chemical composition**
  - Sum of chemical availability of each gaseous species and fuel
    - Bejan, Tsatsaronis, Moran (1996) *Thermal Design and Optimation*
  - Chemical availability of each gaseous species
    - Ahrendts (1977) "Die Exergie Chemisch Reaktionsfähiger Systeme", see Bejan, Tsatsaronis, Moran (1996)
  - Chemical availability of fuel based on lower heating value and fuel composition (H/C, O/C, S/C)
    - Rodríguez (1980) "Calculation of Available-Energy Quantities" Thermodynamics – Second Law Analysis, American Chemical Society Symposium, Series No. 122.
- **Total internal energy:** $(u+ke)=(h+ke)-PV$
- **Wall temperature of each element used as boundary temperature at which heat transfer from that element occurs**

Edwards, *et al.*, SAE 2008-01-0293

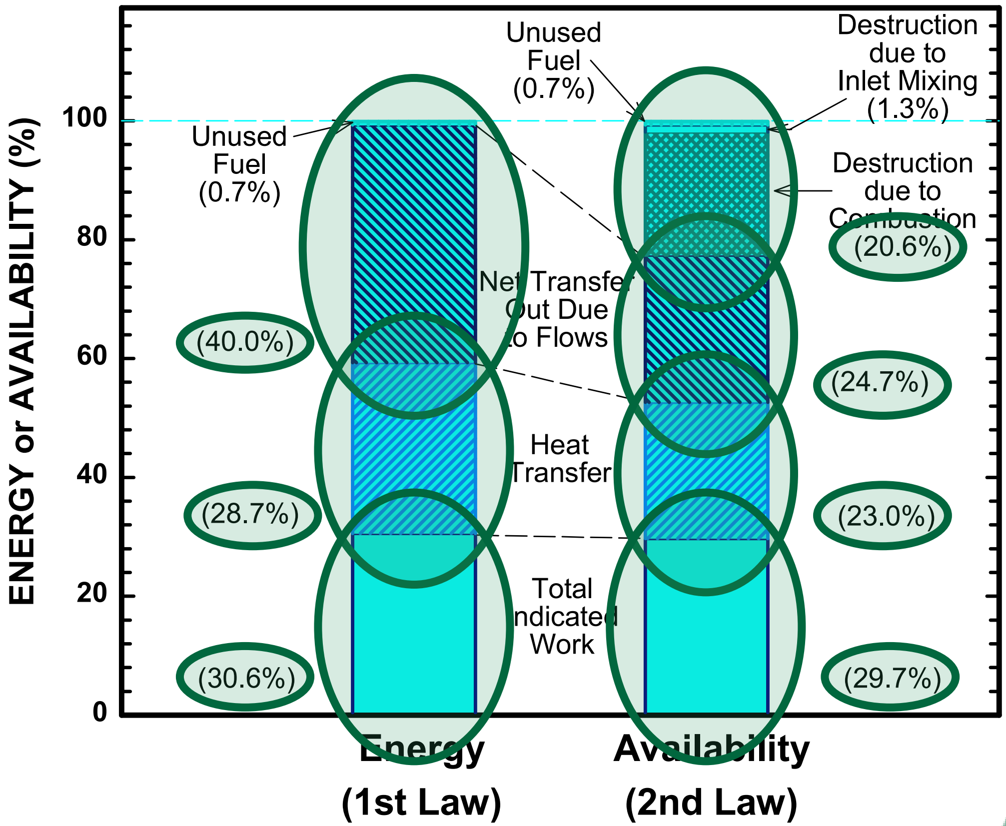
Assessment of opportunities to recover and reduce losses

Largest thermodynamic losses in IC engines are typically due to wall heat transfer, unrecovered exhaust energy, and combustion irreversibility

- **Recovering exhaust availability requires cycle compounding.**
- **Reducing heat transfer depends upon the materials and combustion details and results in increased exhaust availability.**
- **Recovering wall heat transfer requires cycle compounding on coolant (*e.g.*, refrigerant in vapor power cycle).**
- **Reducing the combustion irreversibility requires a fundamental change to the combustion process.**

Octane-fueled spark-ignition engine

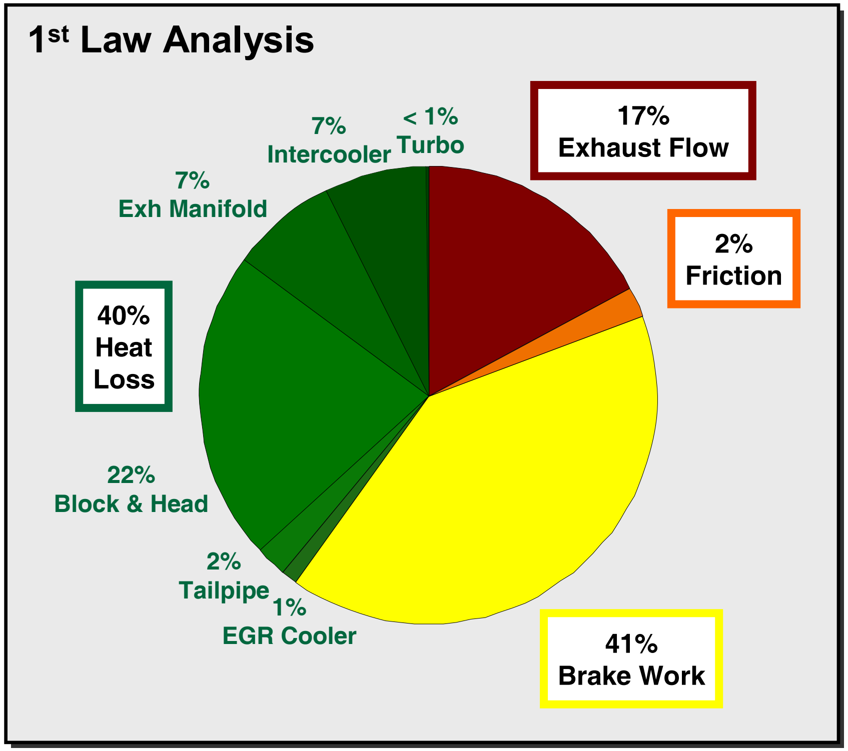
Caton, SAE 2000-01-1081

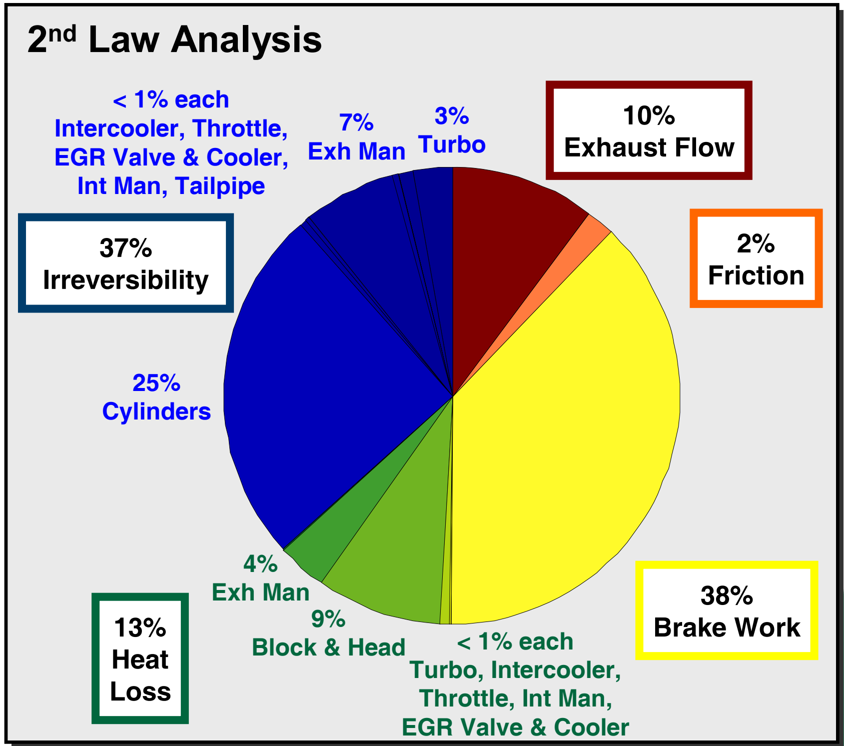


Prioritizing waste-heat recovery efforts

- 1st Law analysis shows that 14% of the fuel energy is lost by heat transfer through the exhaust manifold and intercooler (7% each) suggesting equal priority.
- 2nd Law analysis shows that 4% of fuel availability is lost by radiant and convective heat loss through the exhaust manifold. Less than 1% of fuel availability is lost through the intercooler.
- Unlike the charge air, the hot exhaust gases in the exhaust system have significant availability which should not be squandered through unrecoverable heat loss to the environment.

T_{intake} = 22°C, Un-insulated exhaust manifold, peak efficiency, WAVE MB model





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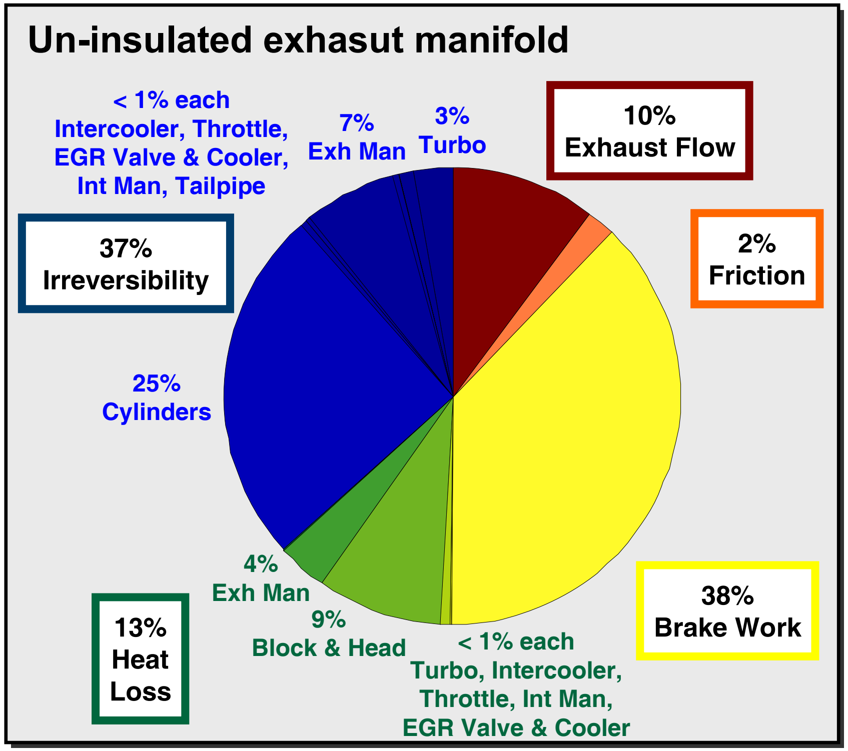
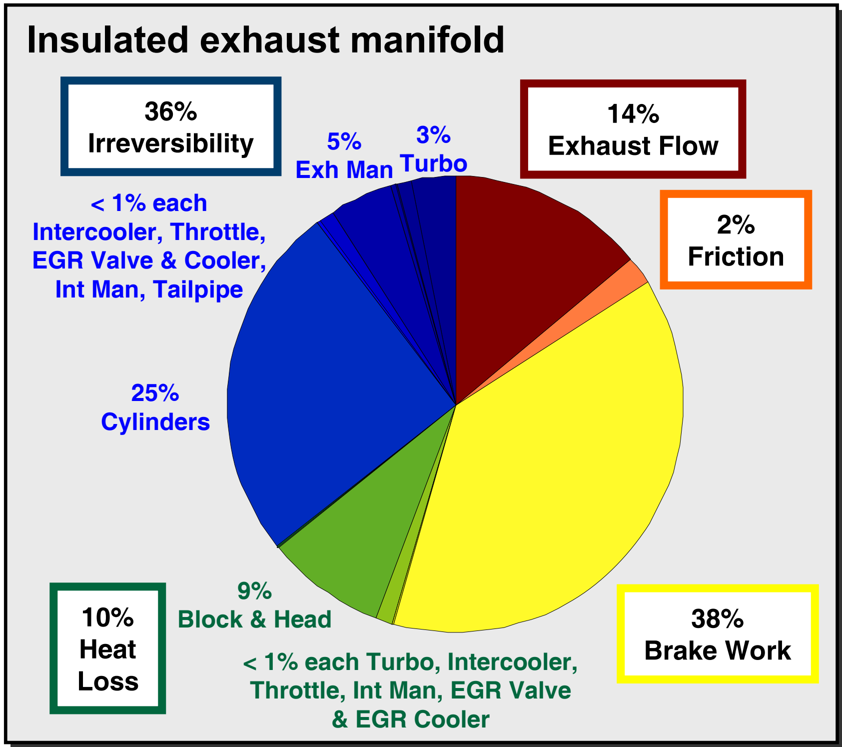
Managing exhaust energy for WHR and aftertreatment

- Insulating the exhaust manifold to reduce heat loss produces an exhaust stream with more energy and higher availability to maximize potential gains from a waste heat recovery system or to increase exhaust gas temperarture for downstream aftertreatment devices.
- Note that in this example, the VGT rack position was increased to maintain equivalent boost and mass flow.

T_{intake} = 22°C, peak efficiency, WAVE MB model





Edwards, *et al.*, SAE 2008-01-0293

Experiments make use of modal conditions representative of light-duty diesel drive cycle

- Considered representative speed-load points for light-duty diesel engines.
- Does not include cold-start or other transient phenomena.
- Represents method for estimating magnitude of drive-cycle emissions.

Point	Speed / Load	Weight Factor	Description
1	1500 rpm / 1.0 bar	400	Catalyst transition temperature
2	1500 rpm / 2.6 bar	600	Low speed cruise
3	2000 rpm / 2.0 bar	200	Low speed cruise with slight acceleration
4	2300 rpm / 4.2 bar	200	Moderate acceleration
5	2600 rpm / 8.8 bar	75	Hard acceleration

For more information:

SAE 1999-01-3475
SAE 2001-01-0151
SAE 2002-01-2884
SAE 2006-01-3311 (ORNL)

ORNL is working with the ACEC Tech Team to propose a new set of operating conditions for use in characterizing efficiency & emissions improvements from advanced engine technologies.

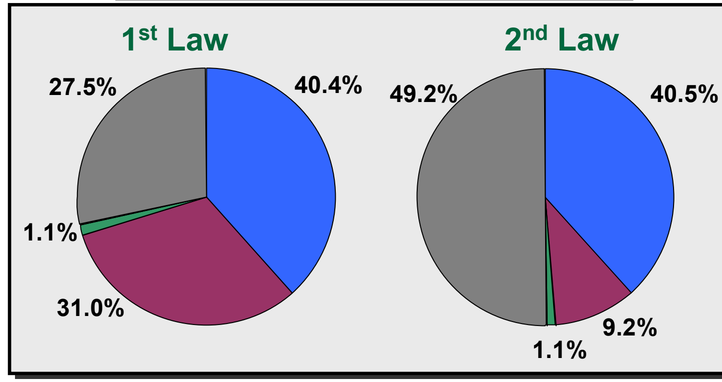
Analysis of representative speed/load modal points

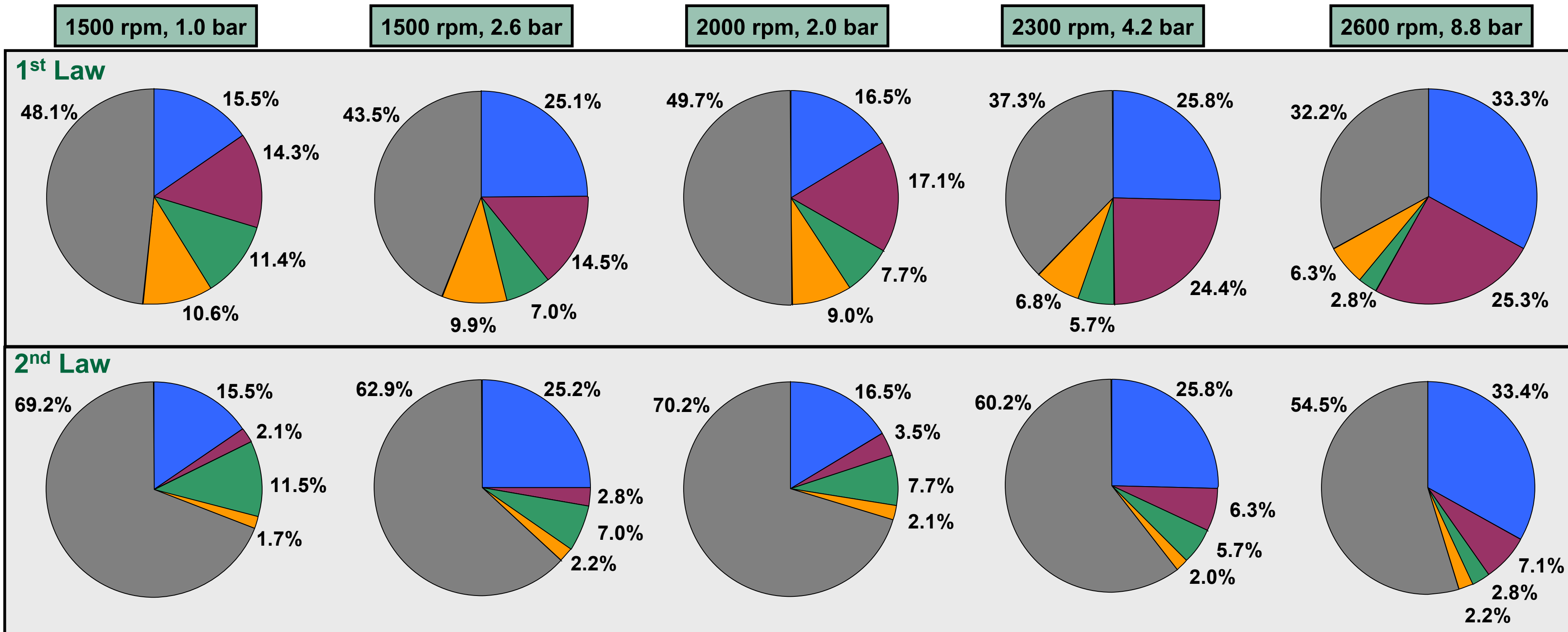
Multiple strategies for waste-heat recovery may be needed to improve efficiency over the whole speed/load range due to variations in quality of availability streams.

Fraction of Fuel Energy/Availability

- Brake Work
- Friction
- Exhaust
- EGR Cooler
- Other (Heat Loss, Combustion Irreversibility, etc.)

Peak Efficiency, 2250 rpm, 18 bar



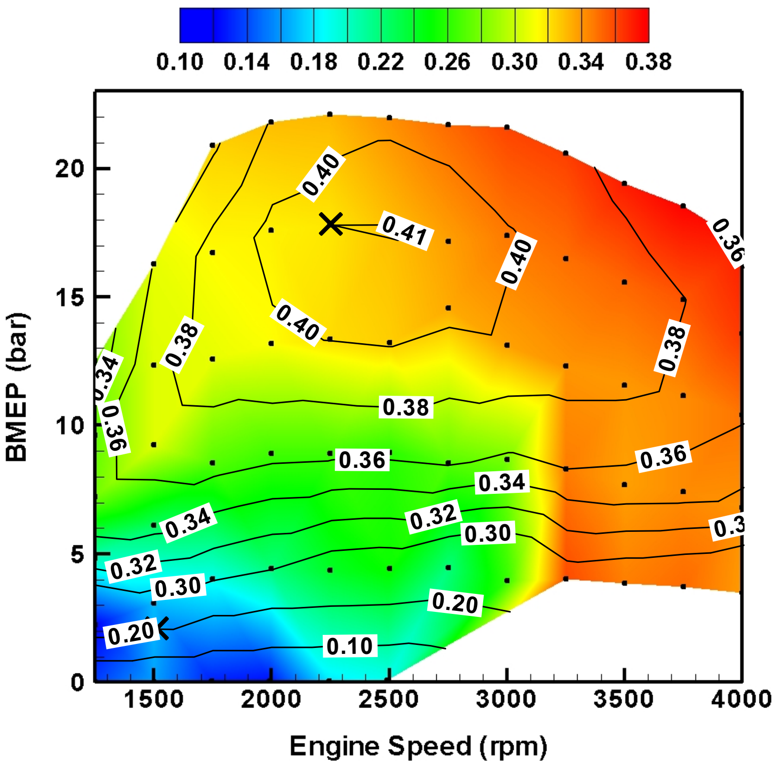


1.9-L GM engine, experimental data

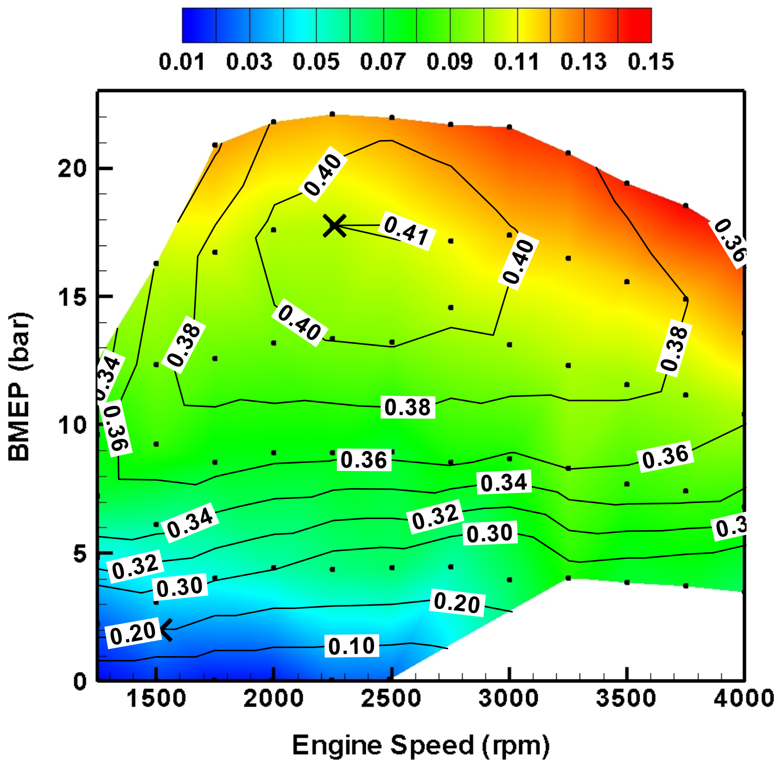
Energy and availability maps

- Energy and availability maps show how fuel energy and availability are apportioned across the speed/load range.
- Similar maps can be made for each energy/availabilty stream.

Exhaust Energy
(Fraction of Fuel Input)



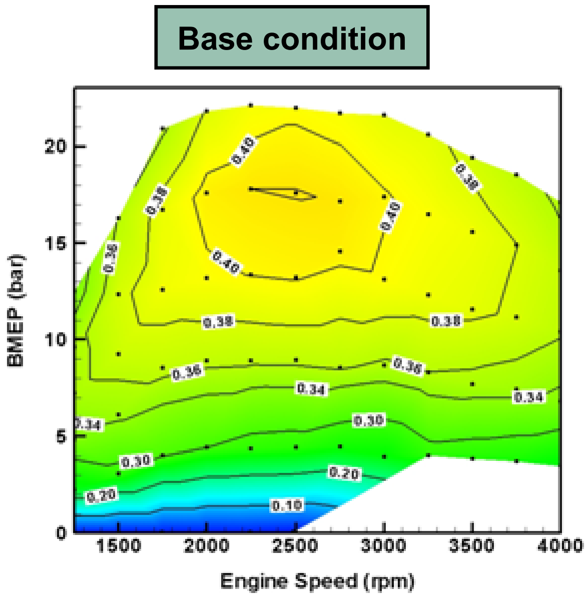
Exhaust Availability
(Fraction of Fuel Availability)

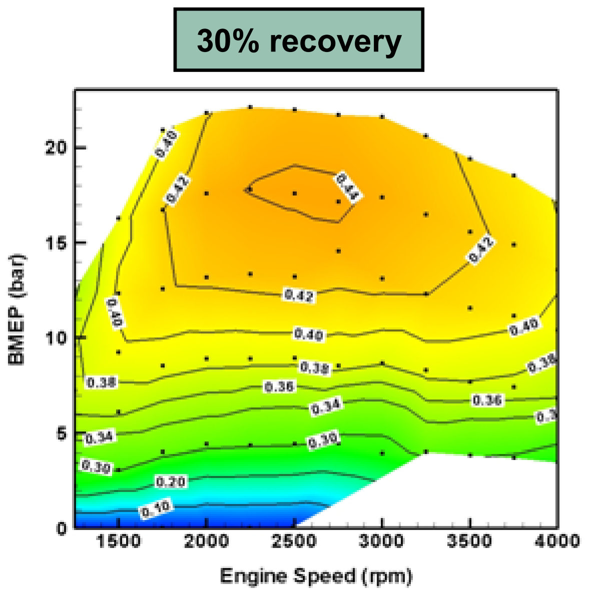


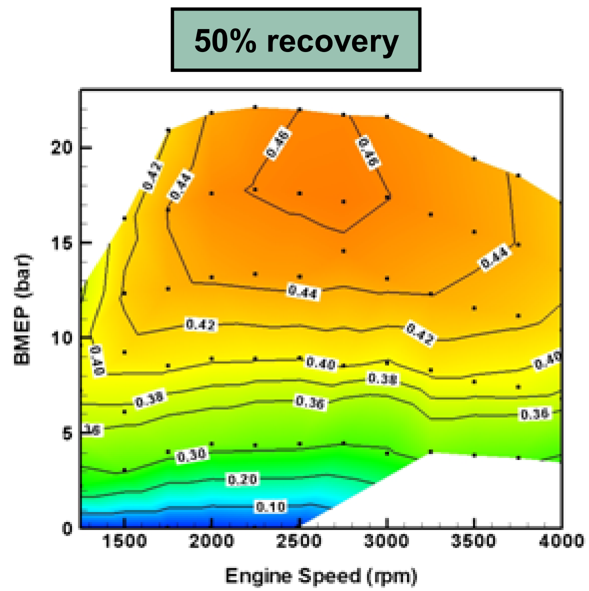
Solid contour lines correspond to BTE, GM 1.9-L engine data

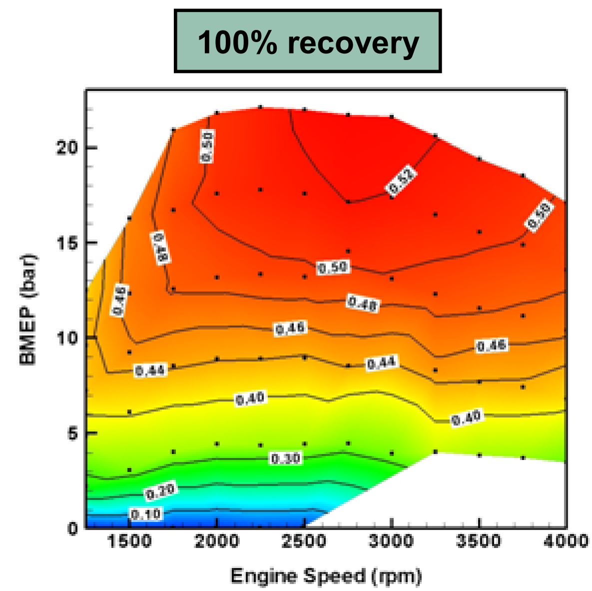
Potential improvements in BTE estimated with partial recovery of exhaust availability

- Maps of brake thermal efficiency (BTE). All on same scale.
- Estimated BTE of combined engine/WHR system using exhaust availability estimations from across the speed/load range.
- WHR efficiency is assumed fixed across the speed/load range for simplification of the estimates.
- Note that WHR may change the BTE/speed/load relationship.



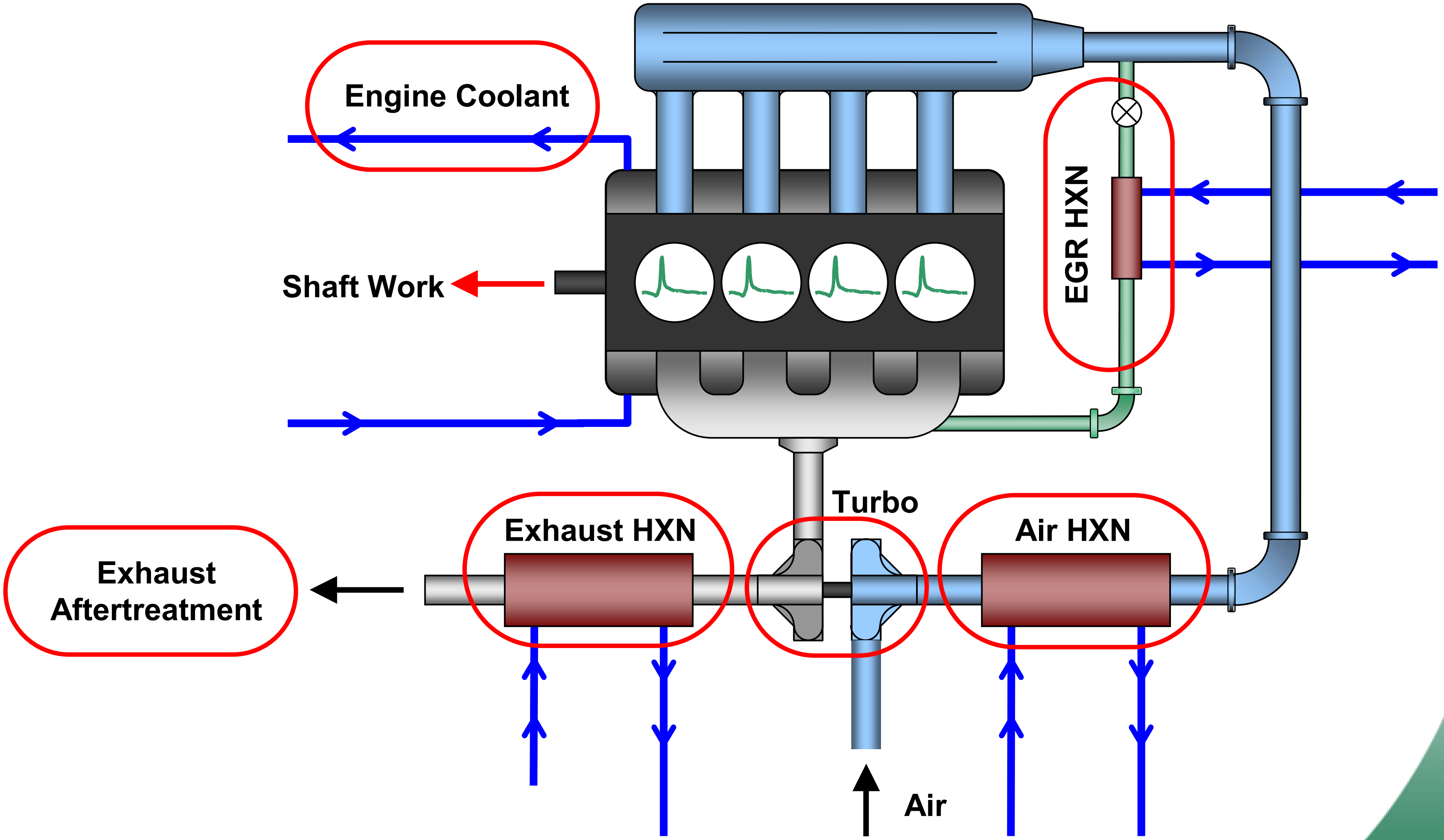






Contours correspond to BTE, GM 1.9-L engine data

Must balance energy use and recovery over speed/load range



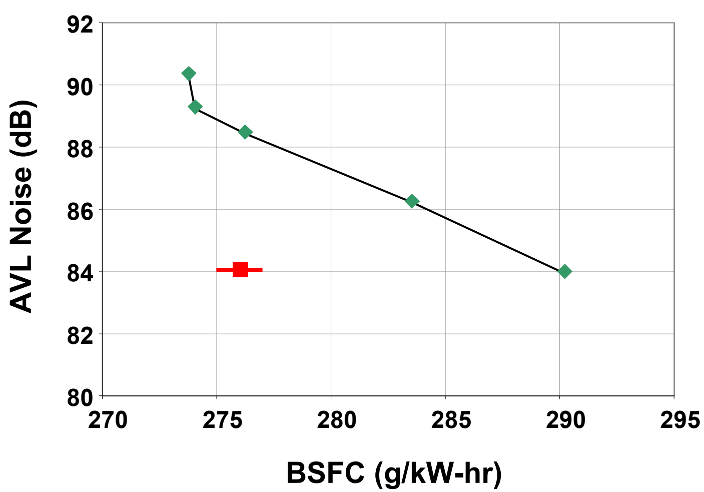
PCCI combustion approach

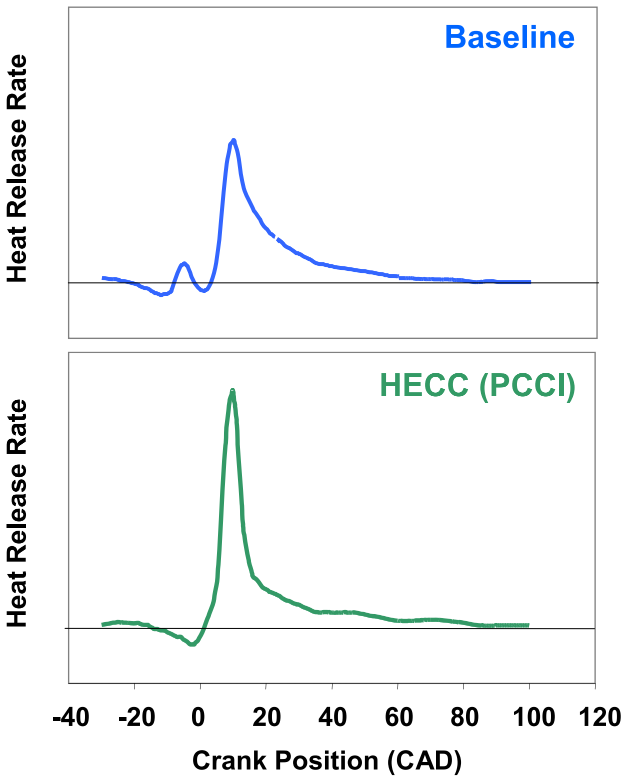
- Baseline conditions approximated with OEM calibration parameters.
- HECC modes achieved with

  Higher dilution, higher fuel injection pressure, & proper combustion phasing (single event, timing before but near TDC).

Example from MB 1.7-L engine
(1500 rpm, 2.6 bar BMEP)

BSFC similar for OEM & HECC calibrations.

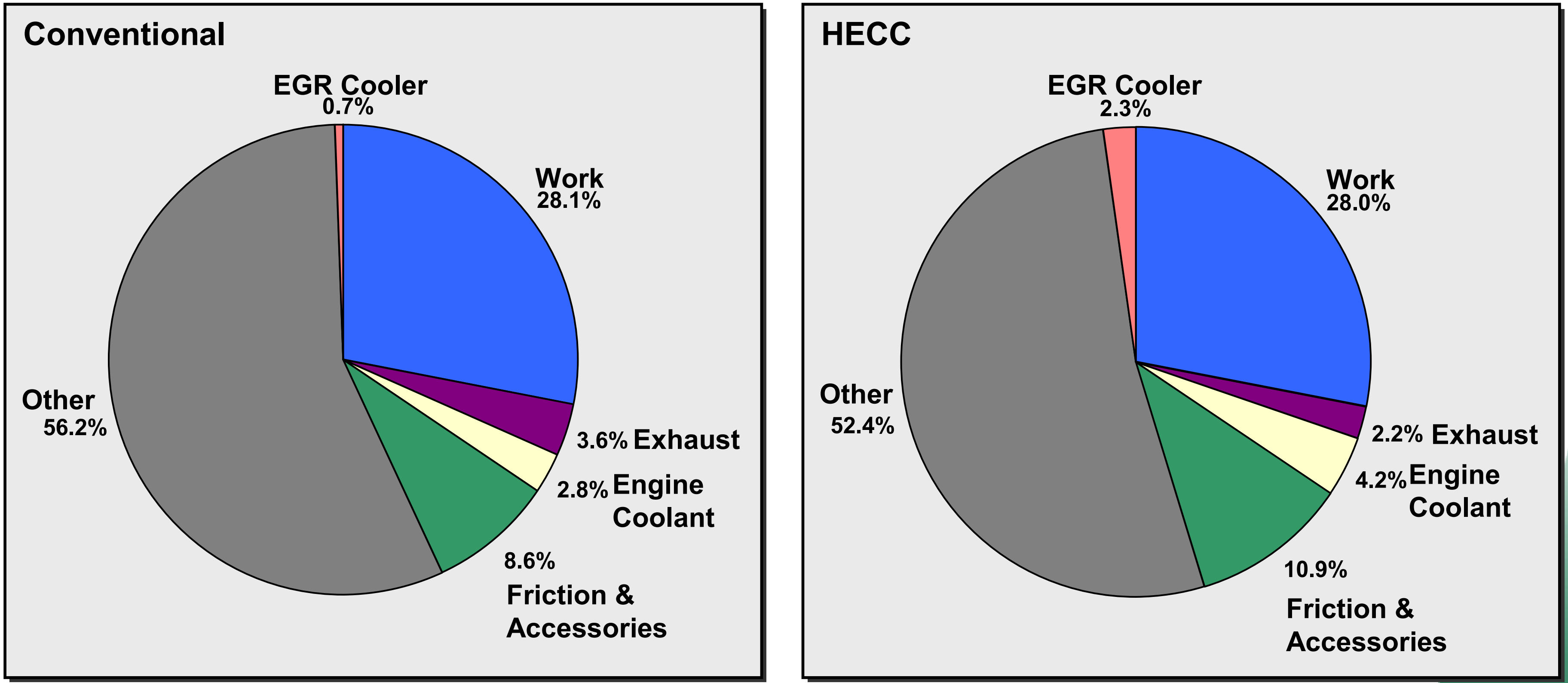




Comparison of combustion modes

- **Availability recovered in one component tends to show up as losses elsewhere in the system.**
- **In this example, transitioning to High-Efficiency Clean Combustion (HECC) mode reduces losses through the exhaust but increases losses through the EGR cooler and to the coolant.**

1500 rpm, 2.6 bar BMEP – 2nd Law Analysis of Experimental Data from MB 1.7-L

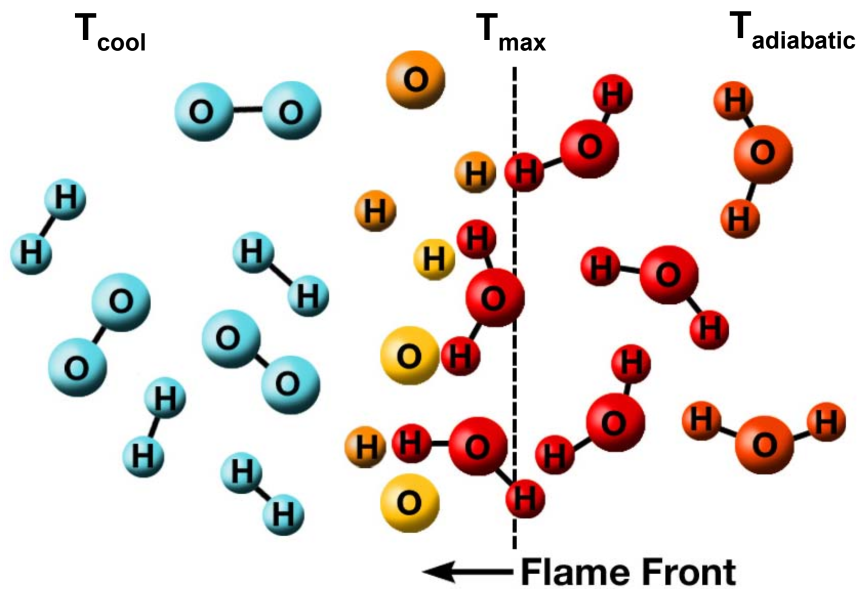


***Other* includes combustion irreversibilities, heat transfer, mixing, etc.**

Combustion irreversibility is the least understood of the major losses

- **Irreversibility is caused by combustion reactions occurring far from chemical & thermal equilibrium (unrestrained chemical reactions)**
- **Molecular-scale gradients result in entropy generation,* reducing availability**
  - **Internal heat transfer**
  - **Molecular rearrangements**
  - **Gradients in chemical potential**
- **Lost availability can never be recovered (2nd Law)**

$$\underbrace{\left.\frac{dS}{dt}\right|_{CV} = \sum_{in} \dot{m}s - \sum_{out} \dot{m}s}_{\text{Path Independent}} + \underbrace{\int \frac{\partial \dot{Q}}{T_w} + \frac{\dot{I}}{T_o}}_{\text{Path Dependent}}$$

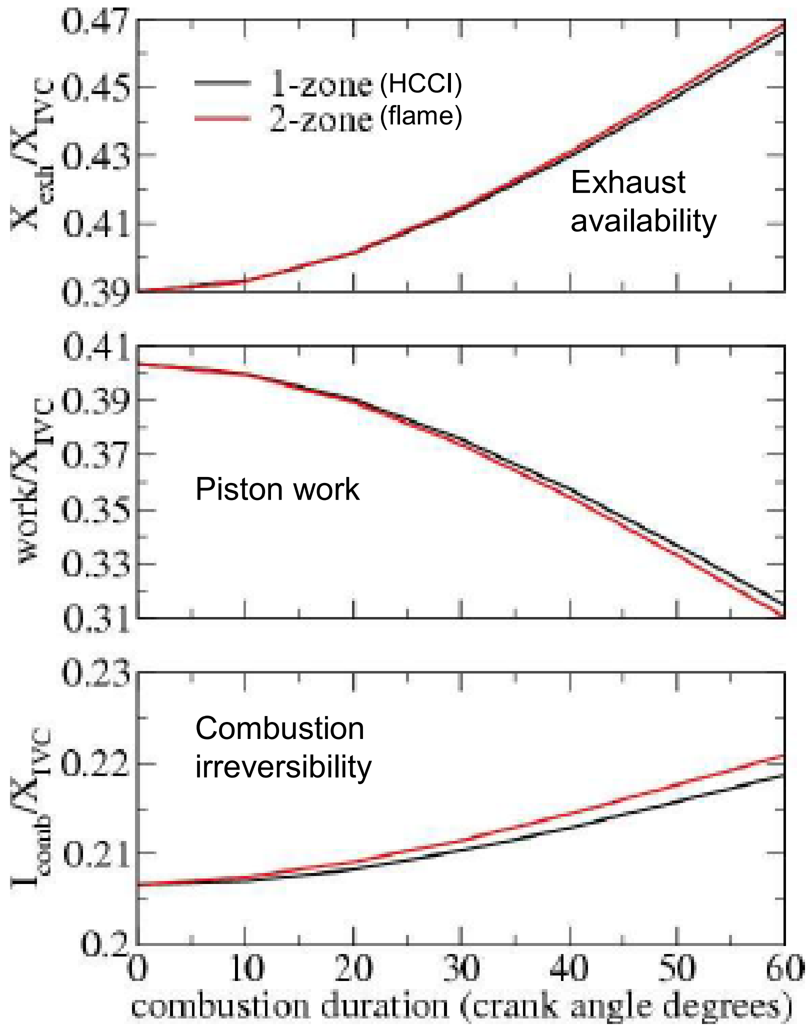


Daw, *et al.* (2006) *International Journal of Hydrogen Energy*, 31

* Dunbar & Lior, (1994) Combustion Science and Technology, 103.

Combustion irreversibility is essentially unchanged for HCCI and HCCI-like modes

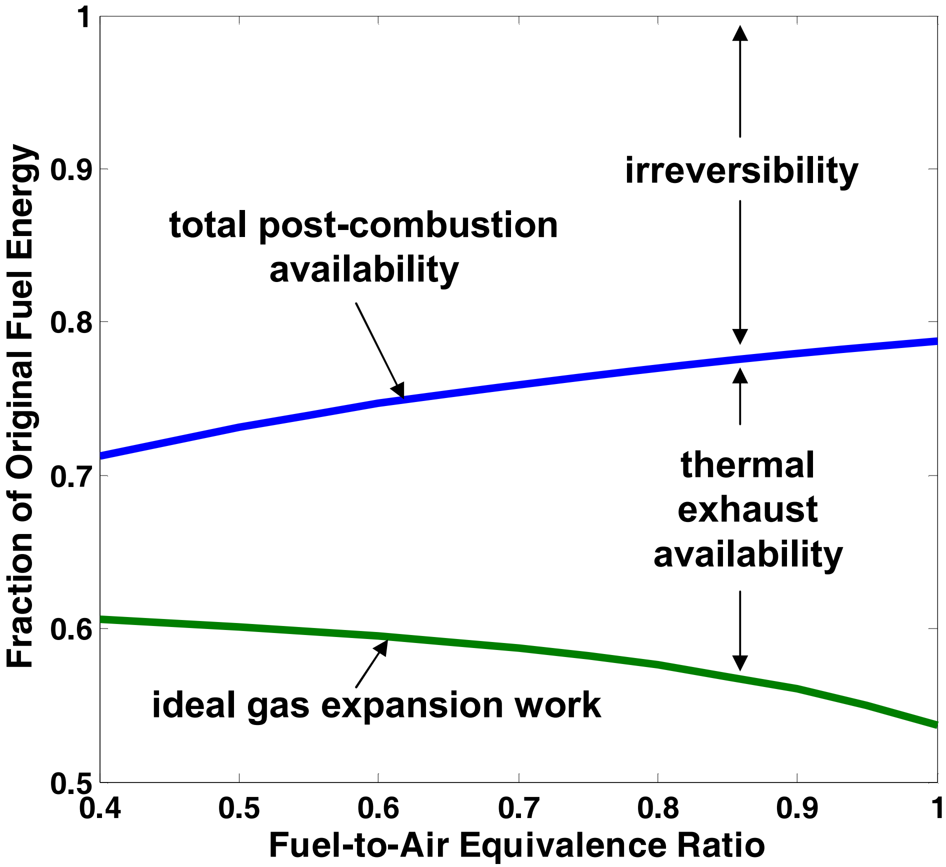
- **Comparison of conventional and HCCI H_2 combustion in adiabatic engine**
- **Even with homogeneous combustion (no macroscopic spatial gradients), irreversibility substantial**
- **Reactions still occurring far from chemical and thermal equilibrium (unrestrained)**
- **Entropy generation and availability loss effectively unchanged**



Chakravarthy, *et al.* (2006) "Second Law Comparison of Volumetric and Flame Combustion in an Ideal Engine with Exhaust Heat Recovery," The Combustion Institute 2006 Central States Meeting.

Combustion irreversibility minimized by stoichiometric fueling, but at expense of reduced expansion work

- Combustion irreversibility is reduced for stoichiometric equivalance ratio.
  - Reactions still unrestrained but with fewer molecules
  - Less dilution of reaction products
  - Lower entropy generation
- Effect is masked in traditional ICEs by reduced expansion work extraction for stoichiometric mixture.
- Recovering higher availability from stoichiometric combustion will require cycle compounding.



Plot details:

- Ideal adiabatic combustion of iso-octane and air
- Fully expanded Otto cycle with initial compression ratio = 10

Summary

- Operation across the speed-load range produces sizable variations in the availability of the different waste energy streams.
- Management strategies will be needed to recover energy from multiple waste streams and to balance the different thermal requirements of aftertreatment, turbochargers, advanced combustion modes, and waste-heat recovery efforts.

Higher-impact paths:

- Waste heat recovery
  - From multiple streams (exhaust, EGR, coolant)
  - Turbocompounding
  - Bottoming cycles
  - Over-expanded cycles
- Stoichiometric combustion (with exhaust heat recovery)
- Reduced wall heat transfer (with exhaust heat recovery)
- Staged combustion, with near-equilibrium reactions (reduction of combustion irreversibility)

Lower-impact paths:

- HCCI, HECC, PCCI, etc.
  - Unless resulting in reduced heat losses or aftertreatment fuel penalties
- Lean-burn
- Matching reaction rates to work extraction
- CR>10

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