Opportunities & Challenges of Thermoelectric Waste Heat Recovery in the Automotive Industry

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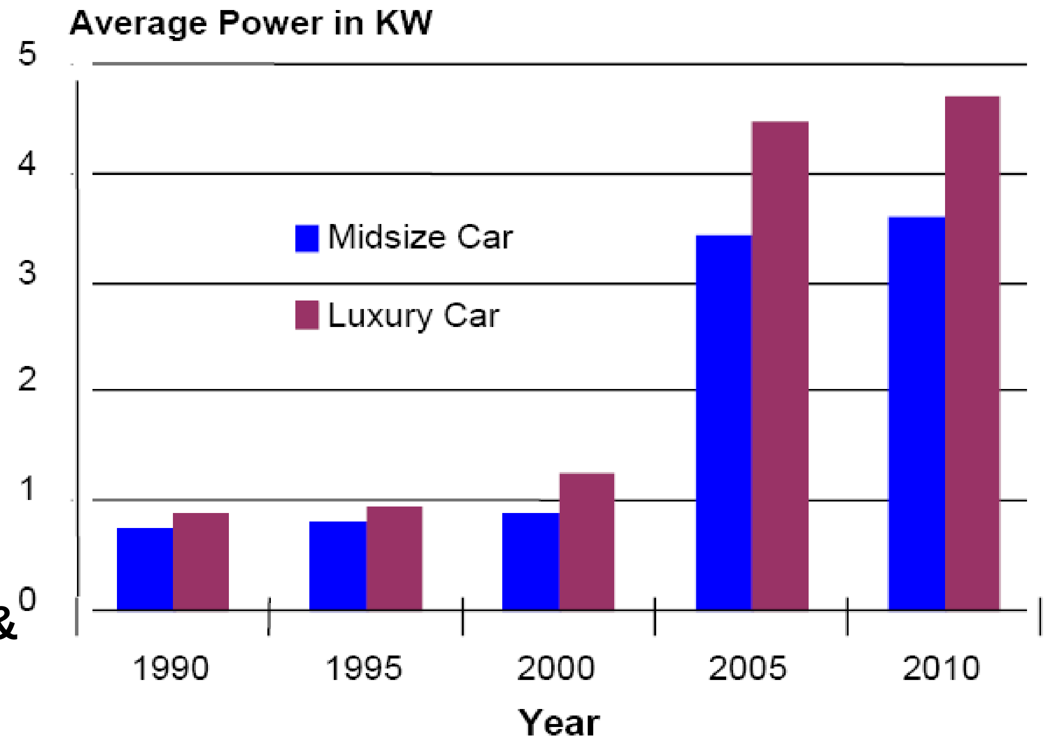
Outline

- Introduction
- Locations of TE waste heat recovery units on automobiles
- Efficiencies of TE waste heat recovery units
- Fuel economy improvement methods
- Weight and cost targets
- Energy benefits
- Additional applications of TE waste heat recovery

Automotive Market Need for APU

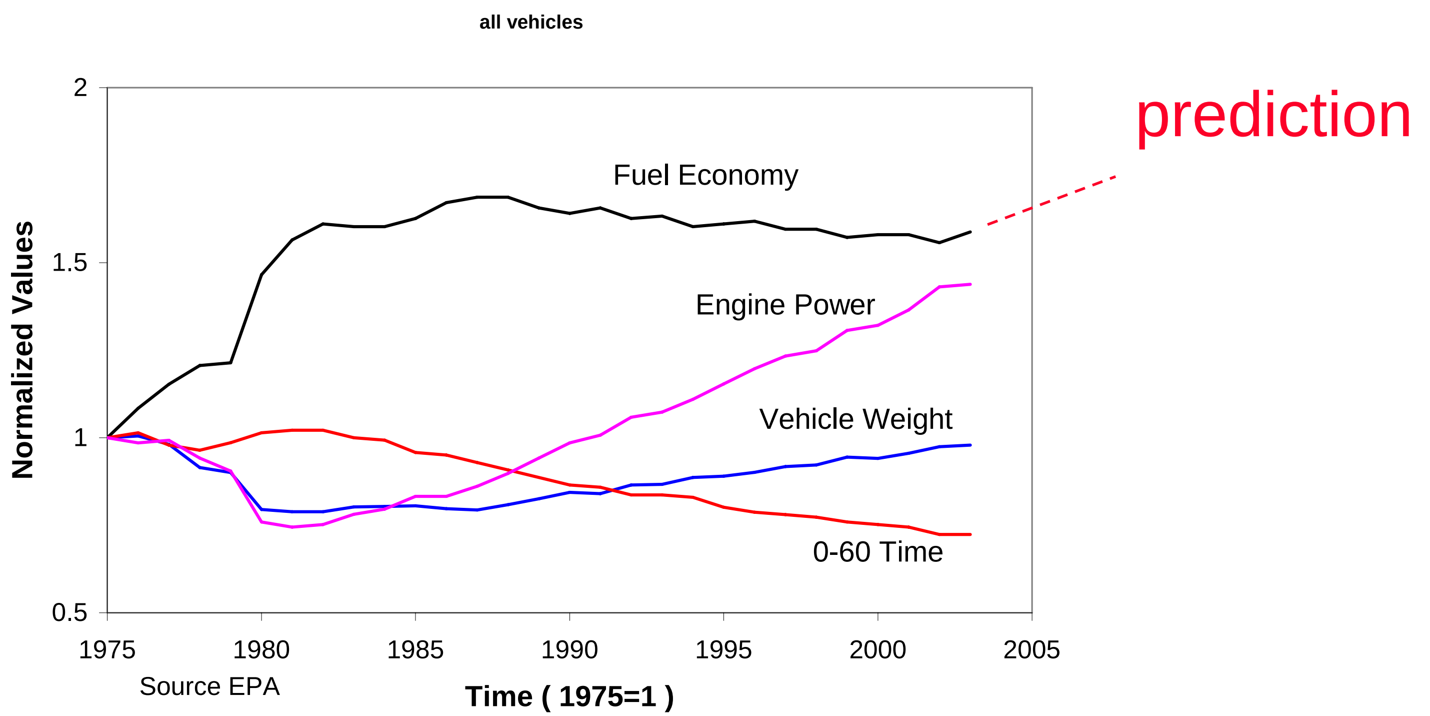
- Increased electrical power needs are being driven by increasing safety requirements, advanced IC Engines for enhanced performance, emission controls, and creature comforts

  - **Stability controls**
  - **Telematics**
  - **Collision avoidance systems**
  - **Onstar Communication systems**
  - **Navigation systems**
  - **Steer by-wire**
  - **Electronic braking**
  - **Powertrain/body controllers & Sensors**



- These requirements are beyond the capabilities of the current generators and require supplemental electrical generation, such as from a TE waste heat recovery unit – ***technology enabler***

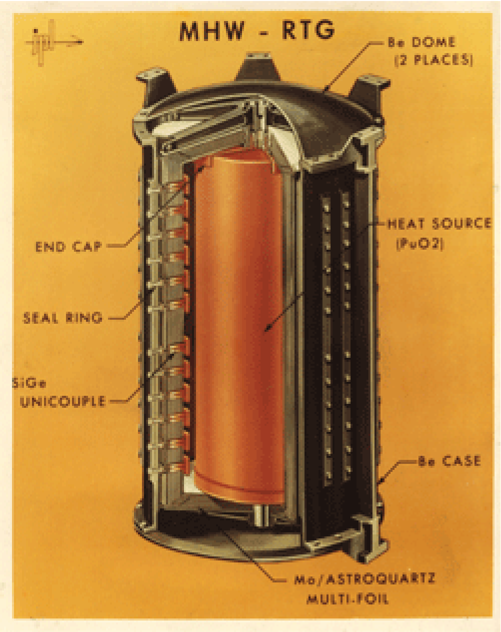
CAFE Demands

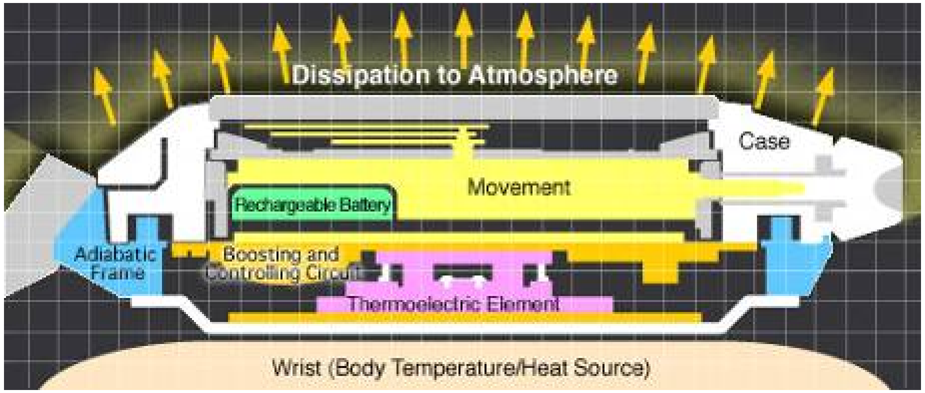


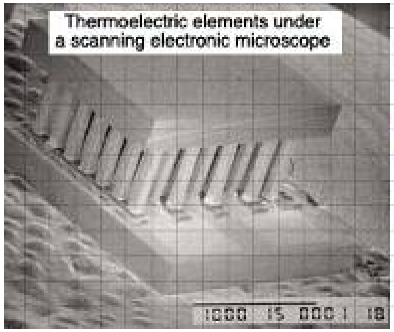
- Note that vehicles are, on average, continually getting heavier and faster, making it impossible to meet the CAFE standard without continued improvements in energy efficiency.
- Slight FE decrease in recent years does not mean we have less efficient vehic but rather due to the change of vehicle mix.
- CAFE does not take into account the changing customer demand for larger vehicles with improved performance.

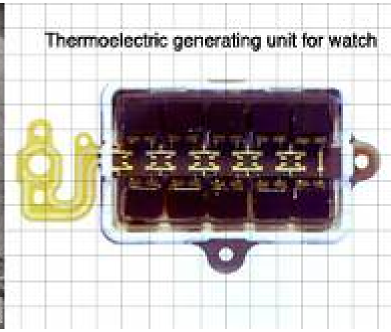
Current Applications

- Power generation for NASA's interplanetary spacecrafts: Voyager, Galileo, and Ulysses
- Power generation for remote areas
- Cooling solid state lasers and IR detectors
- Cooling small refrigerators, picnic baskets and electronic equipment enclosures
- Climate Control Seating
- Wrist watch power generators









TE Power Generators & Coolers (Solid State Heat Pumps)

- **Attributes:**
  - All solid state operation
  - Easily controllable electronically
  - Complete reversible for heating and cooling
  - No noise and vibration, extremely reliable
  - No harmful refrigerants

- **Challenges:**
  - Low energy conversion efficiency
  - Low COP

TE Figure of Merit ZT

Power Generation Equation:

$$\varepsilon = \frac{T_H - T_C}{T_H} \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_C}{T_H}}$$

$$Z = \frac{S^2}{\kappa_T \rho} = \frac{S^2}{(\kappa_L + \kappa_e)\rho}$$

Cooling Equation:

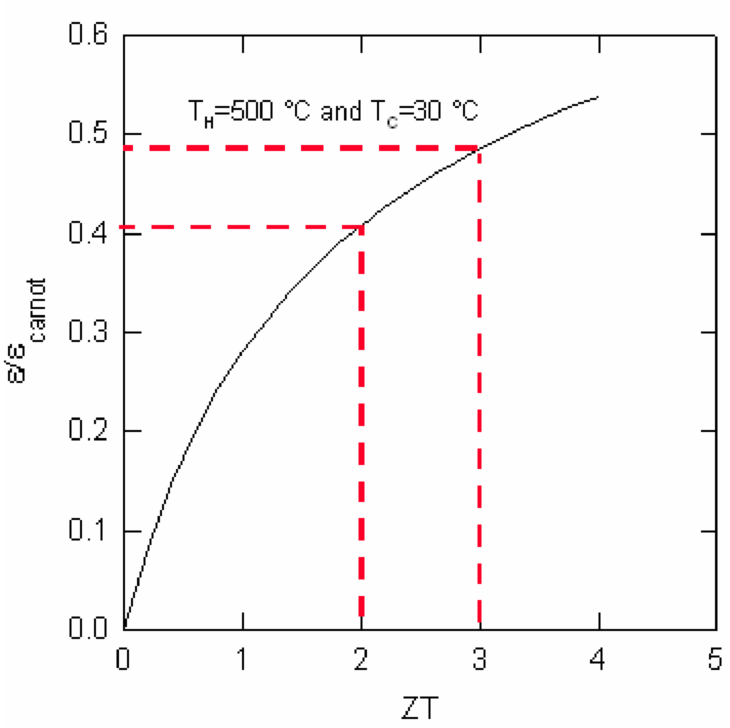
$$COP = \frac{T_c}{T_H - T_C} \frac{\sqrt{1 + ZT} - \frac{T_H}{T_C}}{\sqrt{1 + ZT} + 1}$$

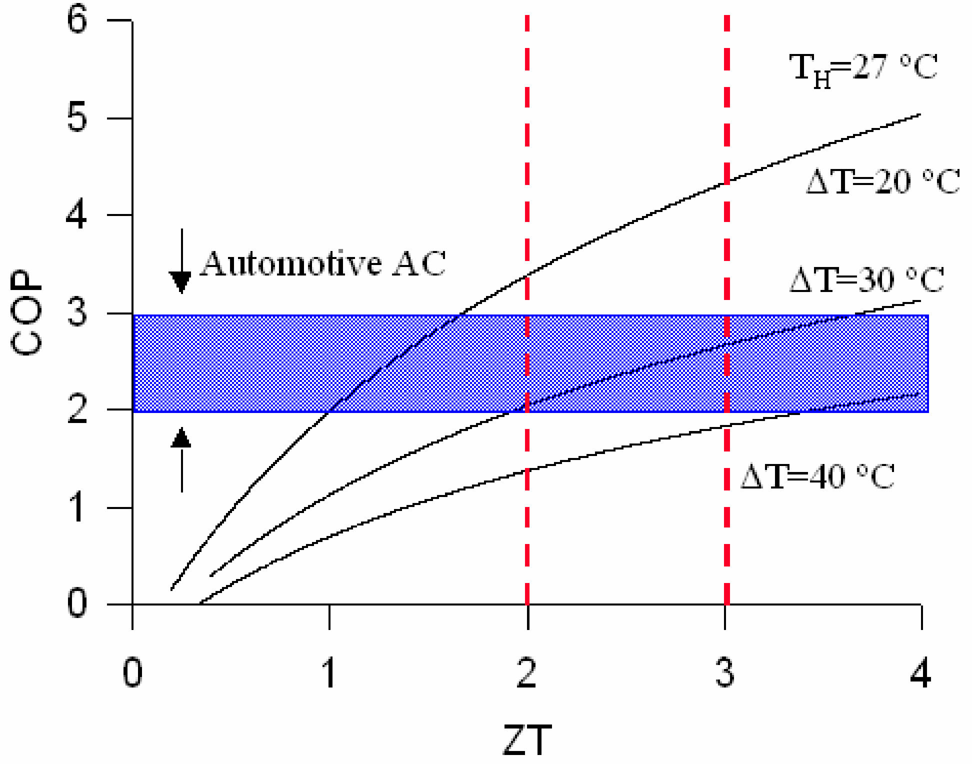
S - Thermopower
κ_T - Total thermal conductivity
κ_L - Lattice thermal conductivity
κ_e - Electronic thermal conductivity
ρ - Electrical resistivity

Z has the dimension of T^{-1}. ZT is usually called dimensionless Figure of Merit

The performance of a TE based system is determined by the intrinsic materials FOM

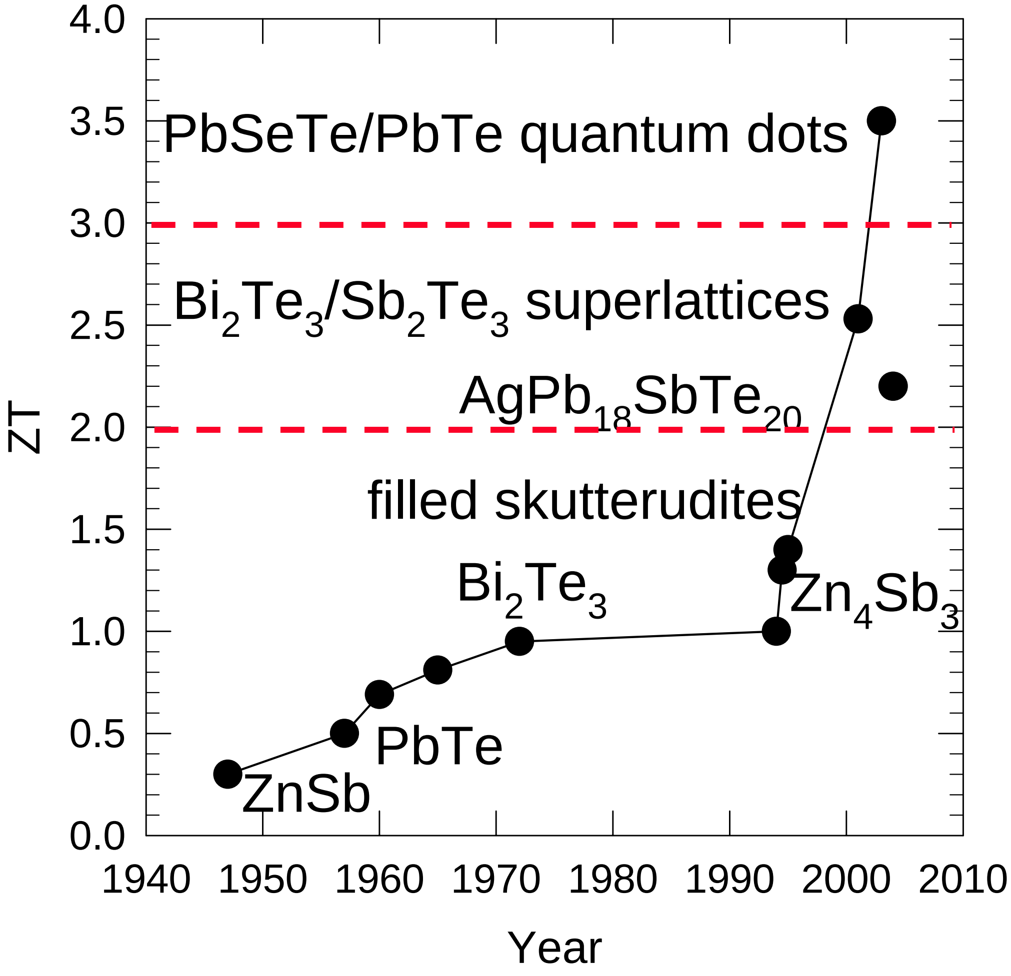
TE Power Generation & Refrigeration



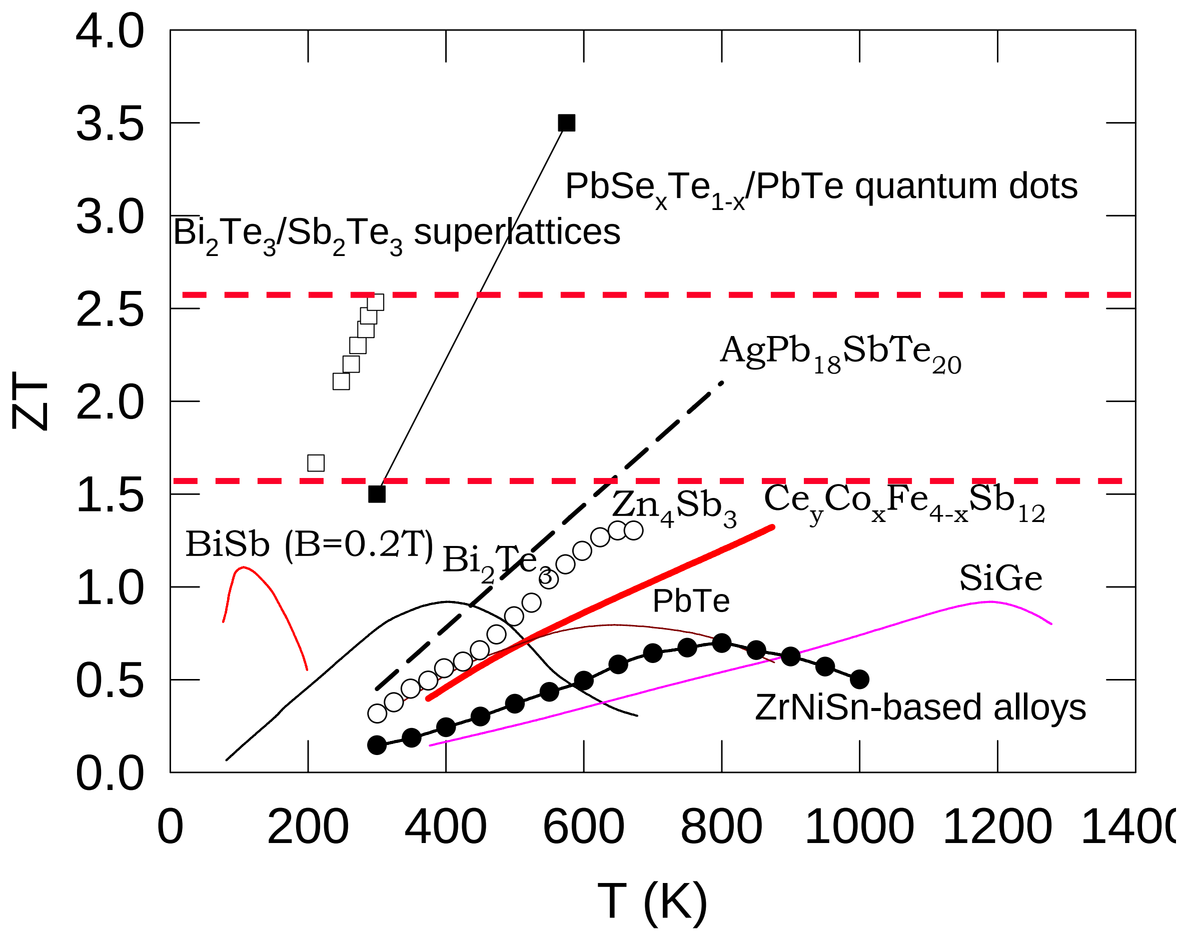


ZT ~ 2 to 3 would warrant us to explore TE technology development for large scale applications

Timeline of ZT

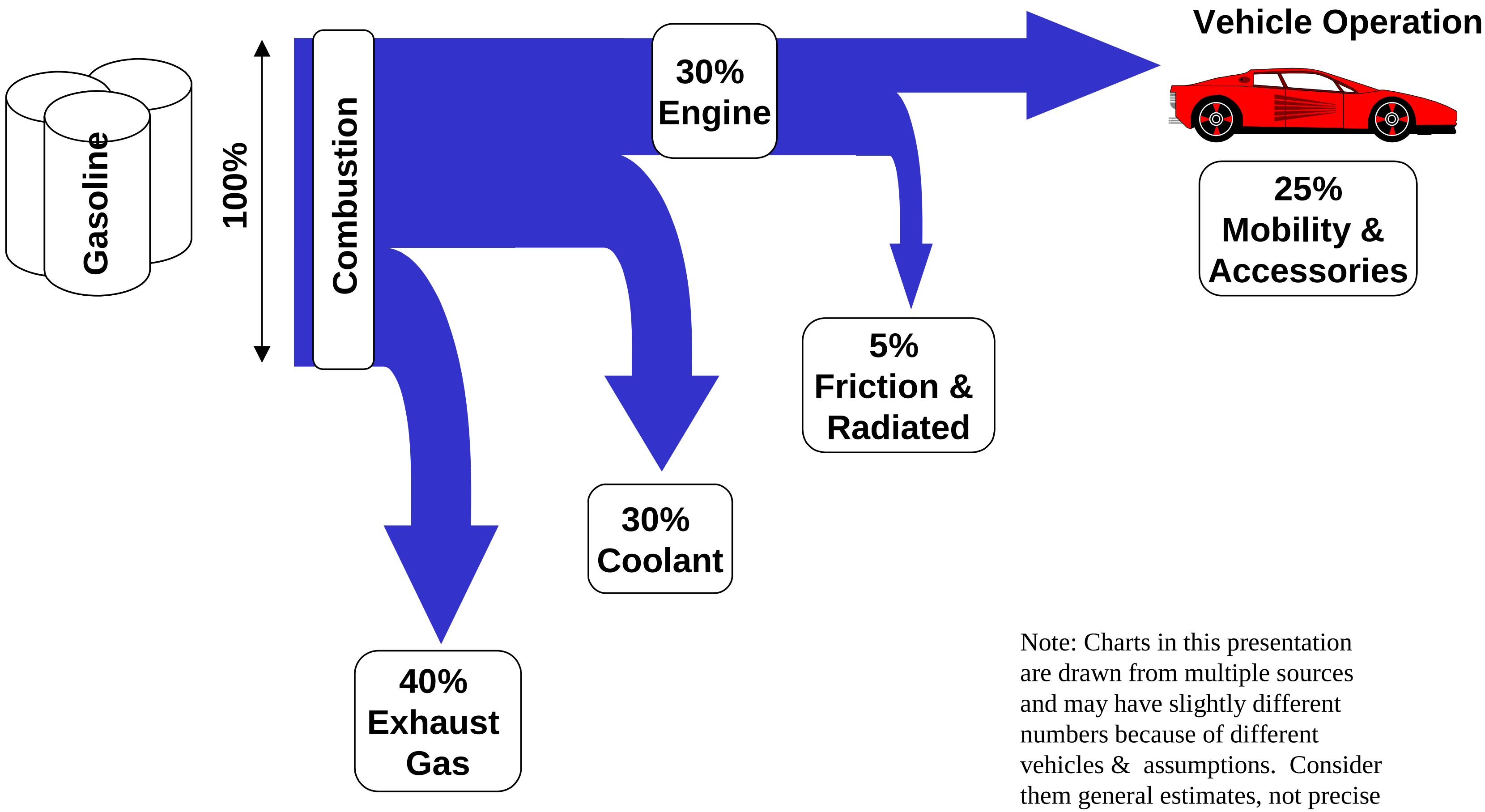


Temperature Dependence of ZT



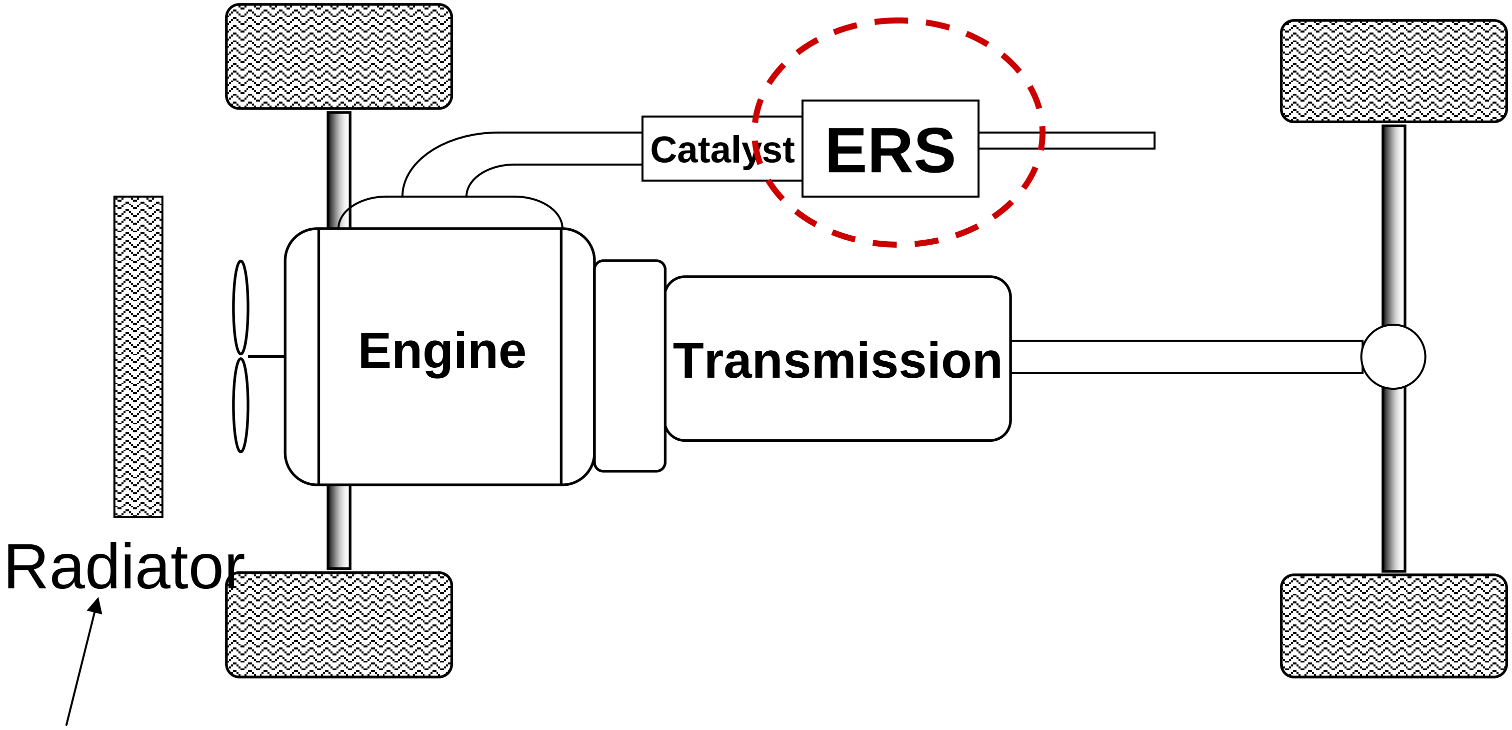
Challenge: we need materials with higher ZT

Typical Energy Path In Gasoline Fueled Internal Combustion Engine Vehicle



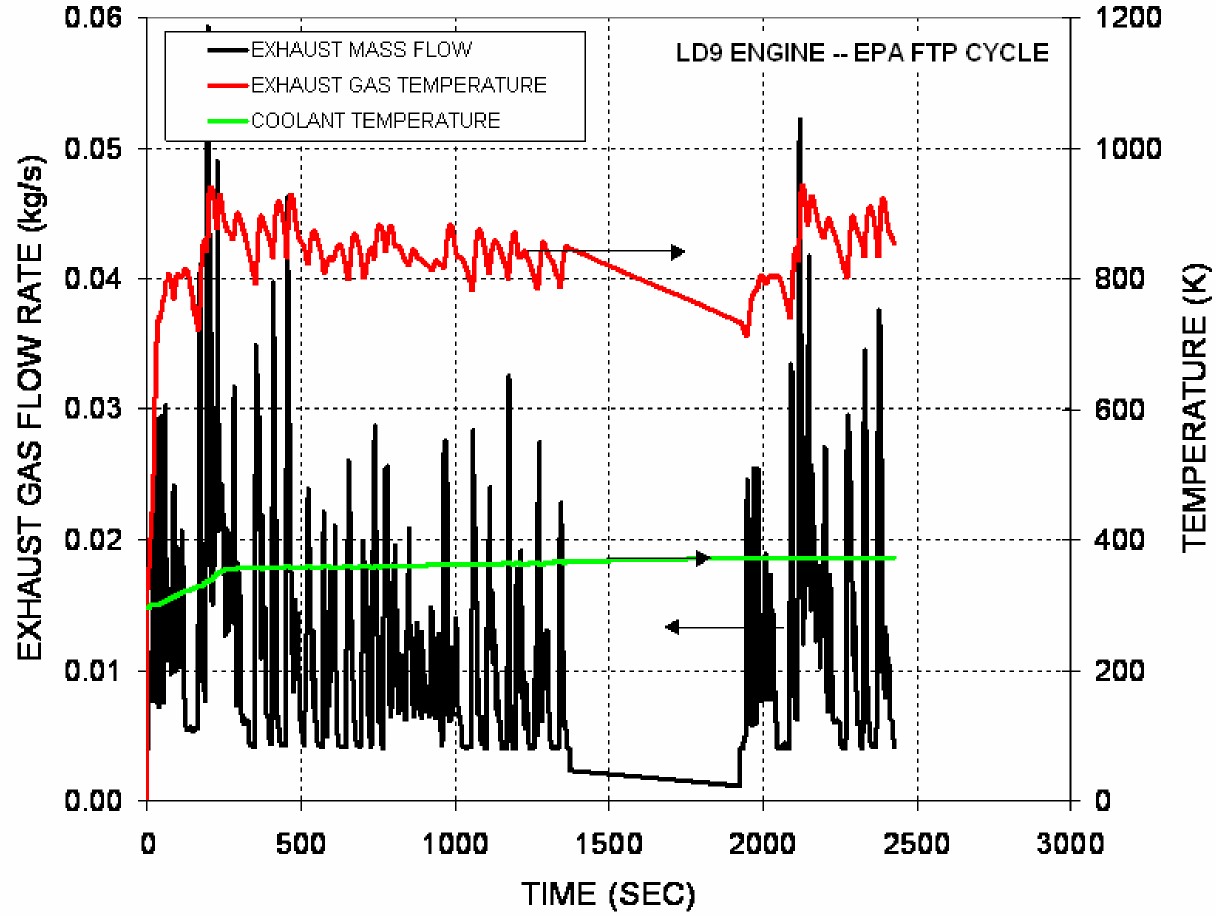
Note: Charts in this presentation are drawn from multiple sources and may have slightly different numbers because of different vehicles & assumptions. Consider them general estimates, not precise analysis.

Example of an Energy Recovery System



Alternate: make the radiator into an energy recovery device. (small delta T)

Exhaust Flow and Temperatures for a 4- Cylinder Engine



There are tens of kW heat energy per unit time in the exhaust & coolant

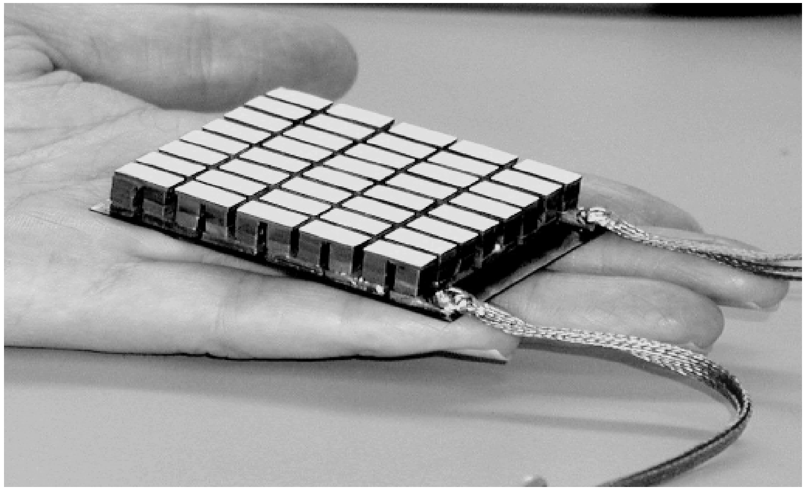
Efficiencies of Waste Heat Recovery Units

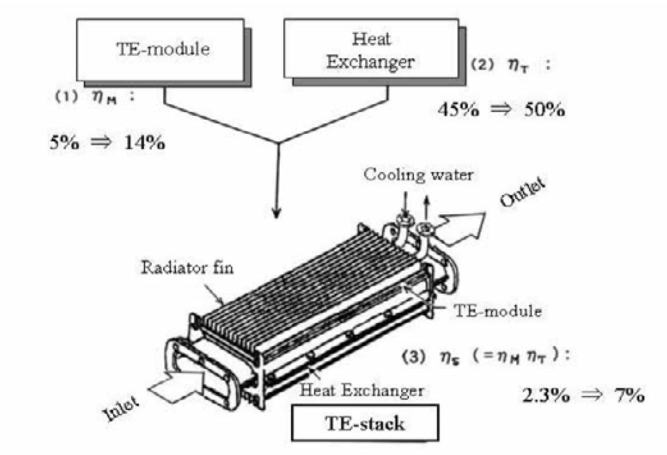
$$\varepsilon = \frac{\dfrac{T_H - T_C}{T_H} \displaystyle\int_{T_c}^{T_H} \frac{\sqrt{ZT+1}-1}{\sqrt{ZT+1}+\dfrac{T_C}{T_H}}\, dT}{T_H - T_C}$$

- **Exhaust:** T_H = 400 °C & T_C = 100 °C
  - skutterudites: $\varepsilon \approx$ 6.7 %
  - segmented couples: $\varepsilon \approx$ 7.5 % [1]
- **Radiator:** T_H = 100 °C & T_C = 27 °C
  - Bi_2Te_3/Sb_2Te_3 superlattices: $\varepsilon \approx$ 6.9 % [2]

1. T. Caillat, *et al.*, Proceedings of the 21st ICT, (2001) p. 282.
2. R. Venkatasubramanian, *et al.*, Nature **413**, 597 (2001).

Exhaust TE Generators



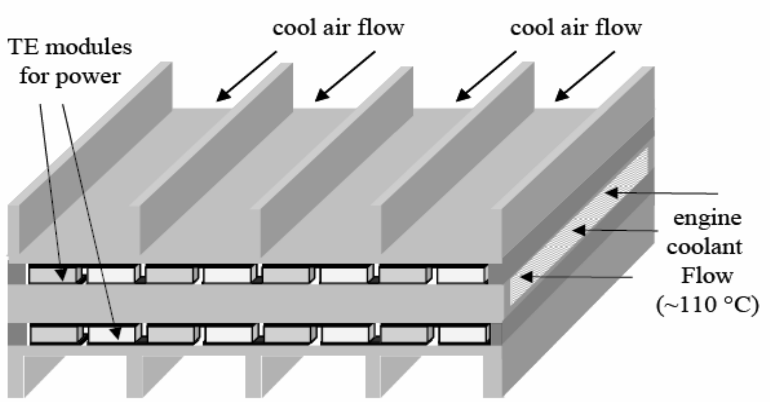


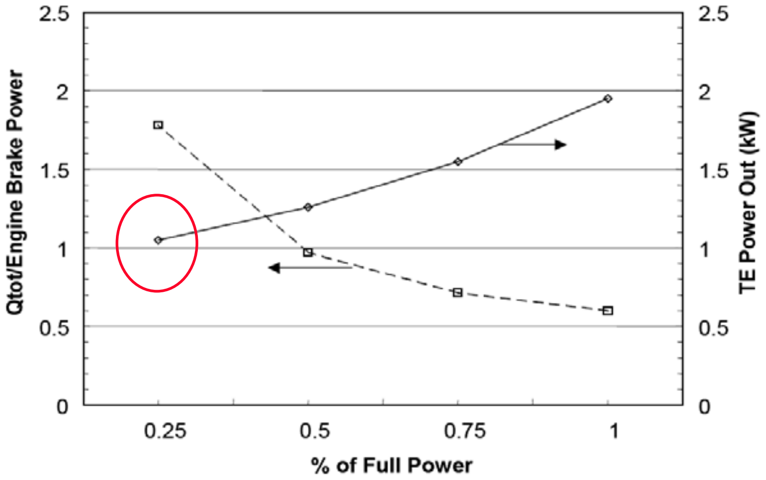
- Segmented TE Module – 6-8% with ΔT = 560 °C
- Max. Output – 160 W
- 700 W expected assuming 10 kW heat power in exhaust

Challenge: design and optimization of exhaust heat exchanger without increasing backpressure

1. A. B. Neild, Jr., SAE-645A (1963).
2. U. Birkholz, *et al.*, Proceedings of the 7th ICT, (1988), p. 124.
3. E. Takanose, *et al.*, Proceedings of the 12th ICT (1994), p. 467.
4. G. L. Eesley, *et al.*, , unpublished (1996).
5. K. Matsubara, MRS Symp. Proc. **691**, G9.1, 2002

Radiator TE Generator - Model





- Bi_2Te_3-based
- 1 kW at 25% engine load – potential to replace the generator
- experimental validation needed

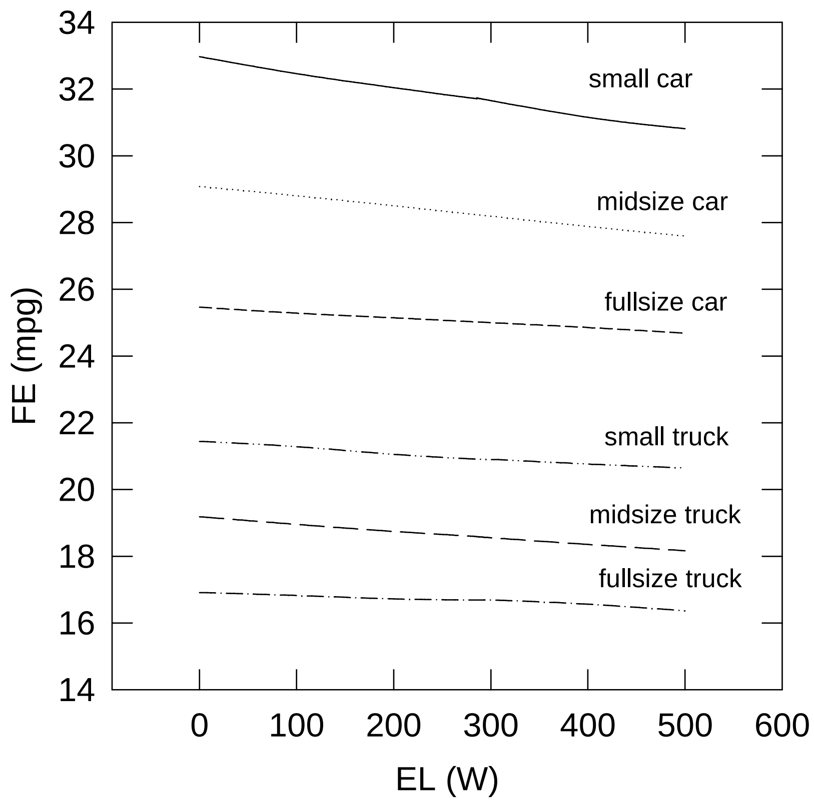
D. Crane, *et al.*, SAE 2001-01-1021

Objective – Recent DOE Programs

Demonstrate a 10% fuel economy improvement using thermoelectric waste heat recovery technology, without increased emissions and at a cost-effective way.

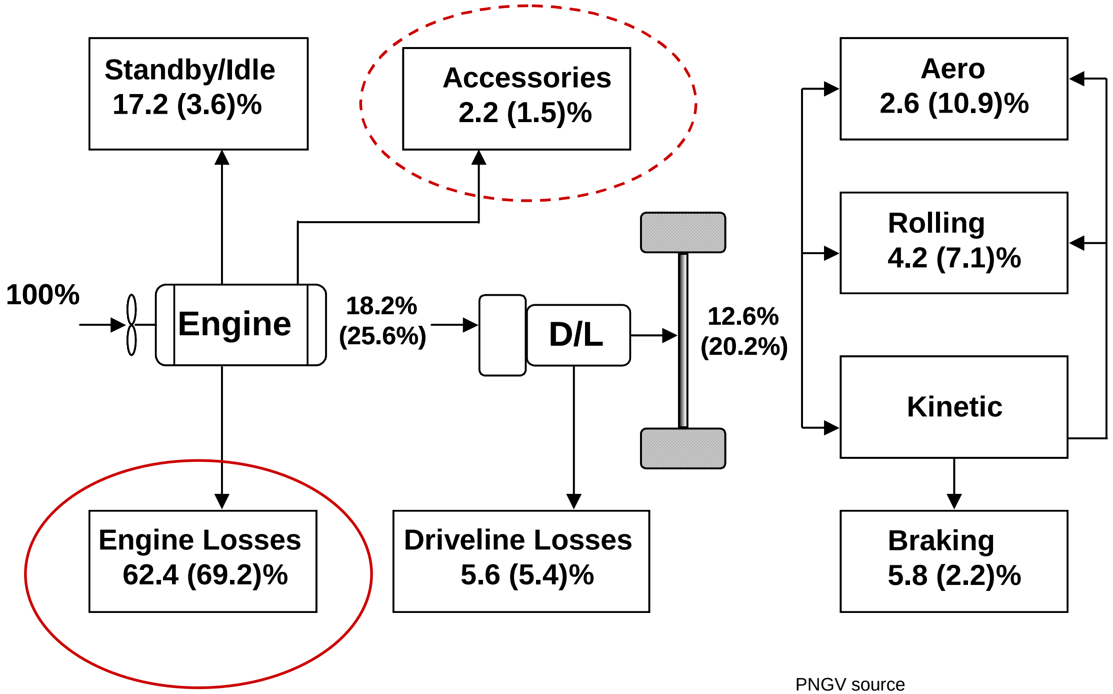
How do we improve FE?

FE vs. Generator load



- **A typical vehicle electrical load is only about 300 W (EPA FTP).**
- **If the 10% FE goal is achieved, then more electrical power will be produced than is consumed by the vehicle electrical system under most driving scenarios, including EPA FTP.**

Methods of Improving Fuel Economy

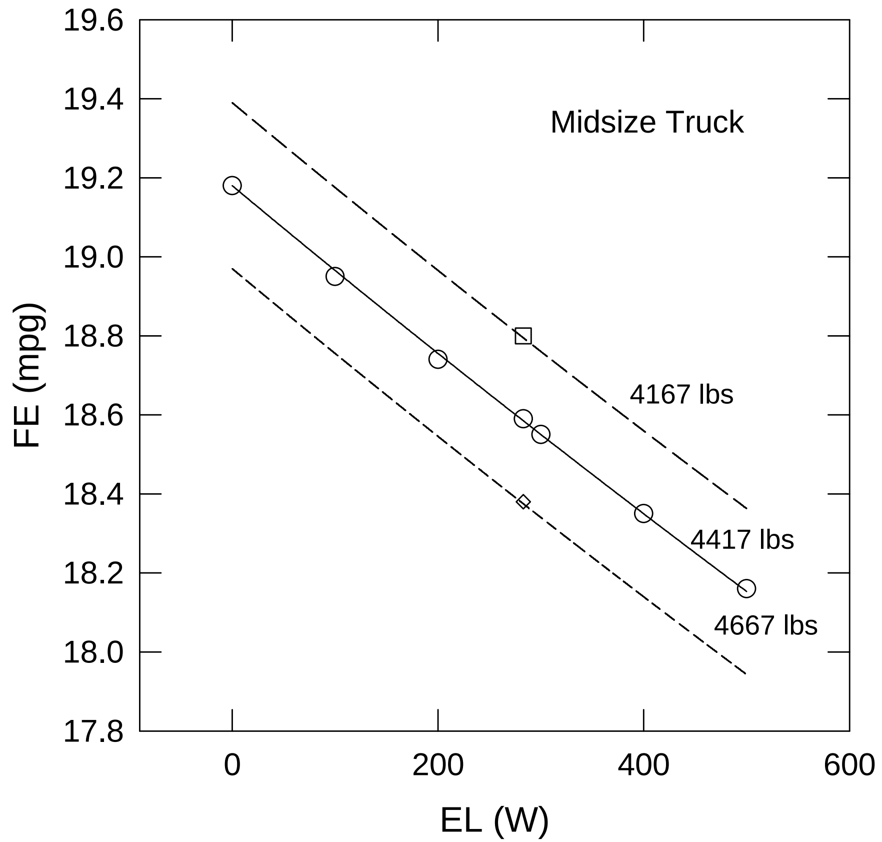


Energy Distribution - Typical Mid-Size Vehicle on Federal Test Procedure (FTP)-Urban (Highway) % energy use

- reduce electric accessory loads on the alternator using TE generated power
- shift some of the engine-driven accessories to electric drive to raise the electric accessory load consumption,
- use the excess electrical power for the vehicle propulsion - hybrid.

A combination of choices above should be used to achieve the goal

Weight Target for TE Generators



- FE = 18.6 mpg at 300 W
- Mass penalty ~ 1190 lbs/Δmpg
- Mass penalty should not exceed 5% of FE gain

Mass target ~ 111 lbs

Cost Target for TE Generators - consumer prospective

10 % FE improvement means the consumer fuel savings over a 3-year period is (assuming 23.5 mpg, 15,000 miles/yr., and $2/gallon):

~ $400

Energy Benefits

10 % FE means:

- **100 million gallons of fuel saving per year for conventional vehicles**
  -- using GM's 2003 NA model year volumes (2.0 million cars & 2.8 million trucks) and CAFE standards, assuming 15000 miles per vehicle per year

- **1.5 million gallons of fuel saving per year at 2010 for hybrids**
  -- 50,000 hybrids per year

Even if all of the energy of a TE generator cannot be used, or if a reasonably sized TE generator produces less power than is implied for in the program, a significant savings in national fuel consumption can be achieved by applying this technology across the board to the conventional vehicles.

Additional applications of thermoelectric waste energy recovery

While these DOE programs are directed toward developing advanced thermoelectric materials for waste heat recovery on light duty passenger vehicles, there are many other transportation-related & other applications for the technology, i.e., waste heat energy from:

- **locomotive diesel engines**
- **diesel-electric hybrid buses**
- **heavy-duty trucks**
- **fuel cells**
- **aircraft engines**
- **power plants**
- **industrial infrastructures**

Major challenges for TE Technology Development

- **Materials: higher conversion efficiency desired**
- **Processes: modules & subsystems**
- **Integrations: optimization at a vehicle level**

Acknowledgements

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Thank You !