Potential Applications of Thermoelectric Waste Heat Recovery in the Automotive Industry

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Abstract

Several proposed applications of thermoelectric (TE) waste heat recovery devices in the automotive industry are reviewed. To assess the feasibility of these applications at a vehicle level, the effect of electrical load and weight on fuel economy for a series of cars and trucks was investigated. These results will help us to identify the appropriate vehicle platforms for TE waste heat recovery, and to establish a set of requirements for an automotive TE waste heat recovery subsystem. The key to the realization of this technology is still the continued development of new materials with increased TE efficiency.

Introduction

An increasing awareness of energy and the environment has rekindled prospects for automotive and other applications of thermoelectrics. The number of motor vehicles on US roads and the number of miles driven by those vehicles continue to grow, resulting in increased air pollution, increased petroleum consumption, and increased reliance on foreign sources of that petroleum, despite improvements in vehicle emissions control and fuel efficiency. To counter these trends, new vehicle technologies must be introduced that can achieve better fuel economy without increasing harmful emissions. For a typical gasoline fueled internal combustion engine (ICE) vehicle, only about 25% of the fuel energy is utilized for vehicle mobility and accessories; the remainder is lost in the form of waste heat in the exhaust and coolant, as well as friction and parasitic losses (Fig. 1) [1]. Furthermore, in order to meet increasing safety requirements, improve engine performance, and reduce exhaust emissions, automotive original equipment manufacturers (OEMs) are incorporating increased electronic content, such as stability controls, telematics, collision avoidance systems, Onstar communications systems, navigation systems, steer by-wire, electronic braking, additional powertrain/body controllers, and sensors that can automatically optimize performance, improve fuel economy, and enhance vehicle safety. All these additional electronic devices require more energy from the engine, or utilize enhanced energy management schemes. Unfortunately, current engine designs may not meet all our future needs. In order to meet the ever increasing requirements of electrical power the OEMs are considering several alternatives like 42 volt systems, hybrid vehicles, fuel cell vehicles, and so on. One such alternative is the use of thermoelectric (TE) technology.

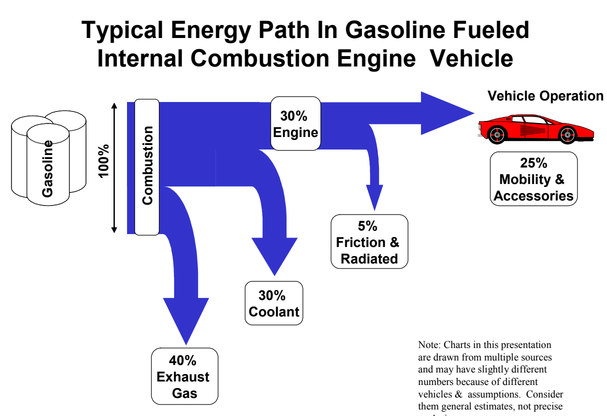

Figure 1: Typical energy path in gasoline fueled internal combustion engine vehicles [1].

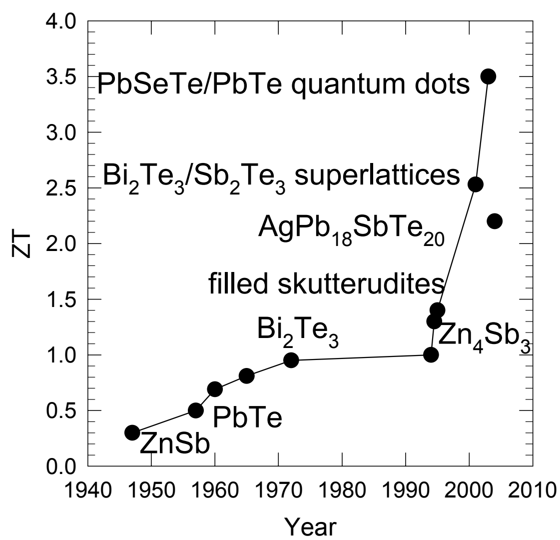

Figure 2: Timeline of the highest thermoelectric figure of merit, *ZT*.

TE devices can transform heat directly into electrical energy and can also act as solid state coolers. Advances in TE technology can have a significant impact on the US automotive industry in terms of both fuel economy improvements by generating electricity from waste heat and high-efficiency air conditioning. First, TE technology has the ability to utilize the tens of kilowatts of heat losses in vehicles [1] to generate electricity without added engine load. Second, TE technology could lead to an all solid-state, extremely reliable, reversible automotive air conditioning system that does not use refrigerants with greenhouse gas concerns and can be simpler, easier to package, and more efficient to operate. TE coolers will almost certainly require more electrical power than current mechanical systems and this should be considered. The increased reliability of batteries and selected components is generally due to being able to use TE devices to control the temperature of the battery or other device.

TE power generators could help to increase the ability of ICEs to convert fuel into useful power. By converting the waste heat into electricity, engine performance, efficiency, reliability, and design flexibility could be improved significantly. TE generators could also be used to eliminate secondary loads from the engine drive train, thus reducing torque and horsepower losses from the engine. This would help to reduce engine weight and direct the full power to the drive shaft, which would in turn help to improve the performance and fuel economy. Furthermore, TE power generators could help to improve fuel efficiency (through waste energy recovery) by supporting engine off operation with minimum battery needs, and could increase electric power for new features. TE power generators can function for only a short period of time after the engine is turned off using available exhaust or coolant heat. A fuel burner added to the TE subsystem will use fuel, but at a much lower rate than a fully operating engine; thereby improving fuel economy without a large battery pack. One recent study suggests that automotive fuel economy could be increased by up to 20% (for FTP tests, and real world fuel economy gain may be somewhat less) simply by capturing the waste heat and converting ~ 10% of it to electricity, an efficiency gain comparable to what would be obtained by converting the US car and light truck fleet to diesel engines, but without the penalty in NO_x or particulate emissions [2].

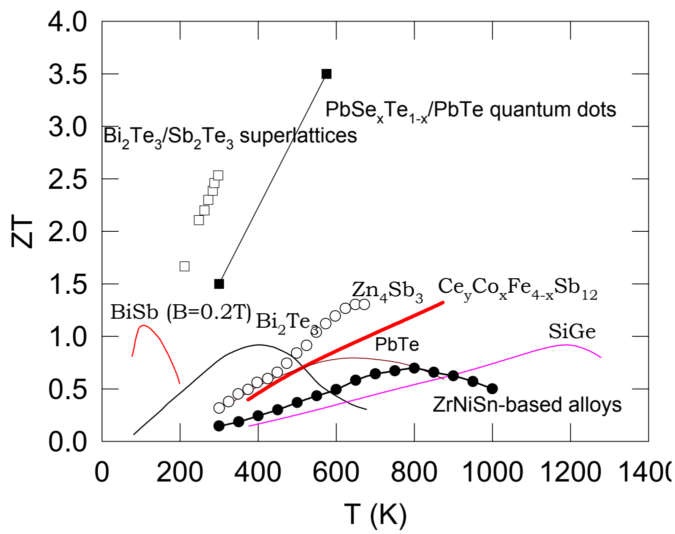

Figure 3: Temperature dependence of ZT for state-of-the-art materials: BiSb, Bi_2Te_3, PbTe, and SiGe; and for the newly discovered materials: Bi_2Te_3/Sb_2Te_3 superlattices, $PbSe_{1-x}Te_x/PbTe$ quantum dots, $Ce_yCo_xFe_{4-x}Sb_{12}$ (Ce-filled skutterudites), ZrNiSn-based half-Heusler alloys.

Historically, due to low cooling coefficient of performance (*COP* ~ 1) and energy conversion efficiency (~ 5%), TE technology has only occupied niche areas, such as the radioisotope TE generators for NASA spacecraft, where low *COP* and efficiency are outweighed by the application requirements. The *COP* and energy conversion efficiency of a TE device are determined by the TE materials' figure of merit,

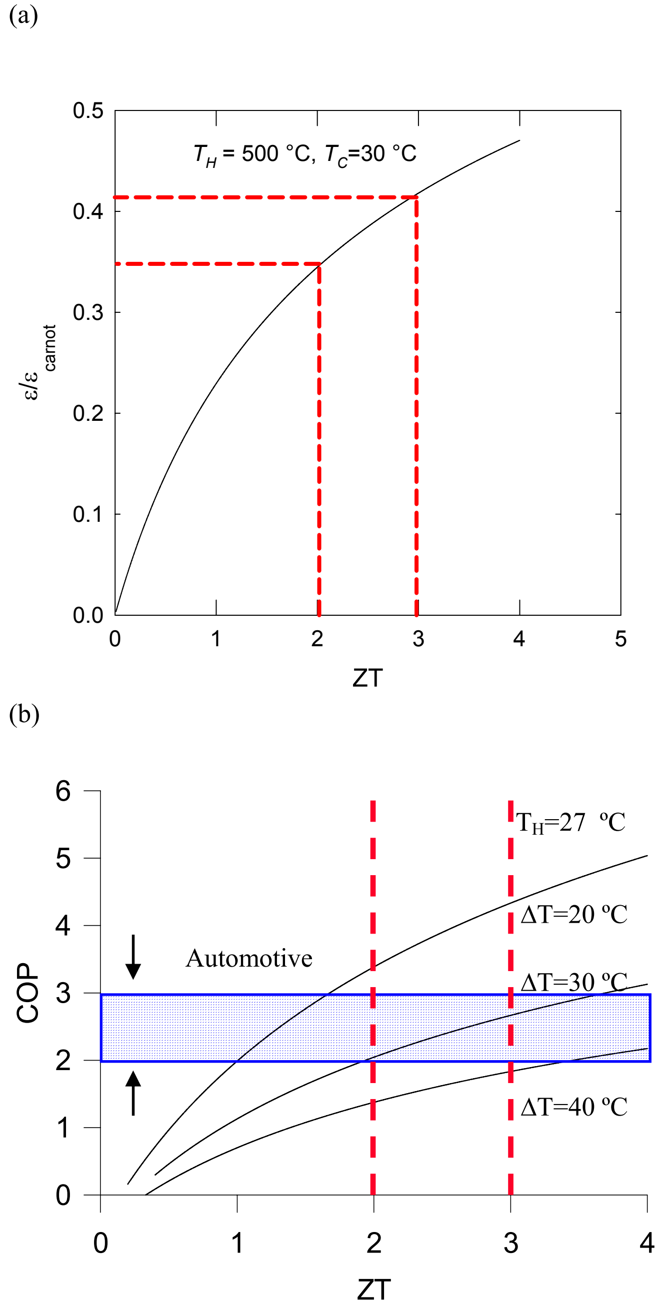

Figure 4: (a) The ratio of TE power generation efficiency ε vs. the Carnot efficiency ε_{carnot} vs *ZT* for a TE power generator operating between 30 °C and 500 °C, and (b) *COP* at room temperature as a function of *ZT* and temperature gradient, *COP* of mechanical systems over similar temperature gradient is also shown.

$ZT = {S^2T}/{\kappa\rho}$, where S is the thermopower, T the absolute temperature, κ the total thermal conductivity, and ρ the electrical resistance. For almost a half century between the 1940s and the early 1990s, the highest *ZT* values of all materials remained below 1 (Fig. 2) [3]. Substantial federal funding since the early 1990s as well as private enterprise R&D have led to significant increases in *ZT* in recent years (Fig. 2) [4-8], reinvigorating interest in TE technology. In particular, the rate of ZT increase has grown by a factor of 20 according to the data in Fig. 2. Not only have the highest ZT values increased substantially, a large variety of new high efficiency materials that cover a wide temperature range between 200 K (-73 °C) and 900 K (627 °C) (Fig. 3) has emerged.

Figure 4 shows that $ZT \sim 3$ would lead to the efficiency of a TE generator approaching 50% of the Carnot efficiency (a thermodynamic limit) and COP of TE coolers that outperform those of mechanical air conditioning units [9]. Recent materials research breakthroughs that provide $ZT > 1$, and some as high as 3.6 (Fig.3), motivate significant interest for automotive applications of TE technology.

Despite many new material discoveries in the past decade, the development of large scale automotive TE waste heat recovery technologies remains extremely challenging because fewer efforts have been directed at evaluating thermal stability of new materials, assessing TE performance at a module level using the advanced TE materials, designing optimum automotive heat exchangers, integrating TE subsystems into vehicle electrical power management, or examining fuel economy impact at a vehicle level. The great uncertainty in materials, module, and subsystem cost and OEM market size is also a major factor inhibiting this technology development. Bulk materials with $ZT > 1$ have not been evaluated sufficiently to define high volume production costs. Integrated-circuit-type devices (quantum dot, superlattices, quantum wells, etc.) have only been demonstrated on the laboratory scale with major uncertainty as to production efficiency and cost. Until both performance and cost are better understood, the ability to select the best TE materials for automotive waste heat recovery remains difficult.

In this report, we discuss the potential of achieving fuel economy improvements, present several specific possible applications, and estimate weight and cost targets for automotive TE waste heat recovery units.

Efficiencies of TE Waste Heat Recovery Units

Because of the strong temperature dependence of ZT for most materials plotted in Fig. 3, we estimate the energy conversion efficiency ε of a TE waste heat recovery unit by

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

where T_H and T_C are the temperatures of the hot-side and cold-side of a TE generator, respectively. A typical vehicle exhaust gas temperature is approximately 500 °C. T_H of a TE generator at vehicle exhaust is generally lower than 500 °C, because it is difficult to extract heat energy from flowing gas to the solid surface of the heat changer. Optimistically, we assume T_H = 400 °C and T_C = 100 °C, such that the cold side of the generator is cooled by radiator coolant. According to Fig. 3, the best materials for such a temperature range would be the n- and p-type filled skutterudites. Using their reported ZT values and Eq. [1], ε is approximately 6.7%. Based on recently developed models and test data for TE unicouples, a TE generator made of segmented unicouples with the same values of T_H and T_C and two to three different materials on each leg would have ε = 7.5% [10], which provides an additional increase in the thermal to electrical energy conversion efficiency.

For a radiator TE generator, one should have $T_H \approx 100$ °C and $T_C \approx 27$ °C. The materials choices in this case are the thin film-based Bi_2Te_3/Sb_2Te_3 superlattices and $PbSe_{1-x}Te_x/PbTe$ quantum dots (Fig. 3). Even though these materials have the highest ZT values ever reported, a small temperature gradient for the radiator TE generator limits the Carnot efficiency (thermodynamic limit) to only 19.6%. Assuming that the ZT values for n- and p-type Bi_2Te_3/Sb_2Te_3 superlattices are identical and can be extrapolated (according to data in Fig. 3) into the temperature range under consideration, $\varepsilon \approx 6.9$ % is estimated using Eq. [1].

The estimates above are not meant to be absolute, but to show that TE waste heat recovery technology is attractive for mitigating electrical load on a vehicle generator and could also potentially be used for vehicle propulsion, both leading to fuel economy improvement.

Potential Applications for TE Waste Heat Recovery in Automobiles

The first exhaust TE generator was constructed in 1963 [11]. Several prototype exhaust TE generators were built for passenger vehicles in the past 17 years, none of which delivered electrical power exceeding 200 W [12-15]. TE modules based on $FeSi_2$ [12], PbTe [13], Bi_2Te_3 [14], and skutterudites and segmented unicouples [15] were used for the exhaust generators. A 6-8% conversion efficiency was estimated for the segmented TE modules with a ΔT = 560 °C [15]. If we assume the average heat energy per unit time in the vehicle exhaust tested is approximately 10 kW under steady driving conditions [15], a 700 W electrical power output is expected. This number is more than 4 times higher than the measured values. The difficulty here lies in the design and optimization of the heat exchanger. Evidently the heat transfer from the exhaust gas stream to the hot side of a TE generator is not enough if one allows the exhaust to run freely down the pipe [12,13]. One has to come up with some innovative design to keep the exhaust gas inside the heat exchanger as long as possible. It is important to keep in mind that the backpressure produced by the addition of a heat exchanger at the exhaust pipe should not exceed the maximum allowable, otherwise, any fuel economy gains due to TE waste heat recovery are going to be offset by the reduced engine efficiency.

Preliminary modeling of a TE radiator generator [16] showed that over 1 kW electrical power can be generated by an integrated generator even with Bi_2Te_3-based modules and low engine load (25%). The values of electrical power suggested here are approaching those sufficient for replacing vehicle alternators, which would lead to significant fuel economy improvements. These encouraging results, however, have yet to be experimentally validated. Radiator power generation can be efficient even with low ΔT because of the potential of much better heat exchangers than in exhaust systems – liquid to metal heat transfer better than gas to metal, longer flow paths and longer dwell times for the heated fluid without 'back pressure' issues found in the exhaust, and potentially lower system weight because half the heat exchanger (the radiator) is already in the vehicle.

Methods of Improving Fuel Economy

Recently the US Department of Energy initiated several programs on automotive TE waste heat recovery technologies [17]. The overall objective is to achieve a 10% improvement in fuel economy. This means that at any given engine steady-state operating point (speed, torque), an additional 10% power is obtained from the TE generator. A typical vehicle electrical load according to the EPA Federal Test Procedures is about 300 W. Fig. 5 shows the dependence of fuel economy (FE) on electrical load (EL) at the alternator for a group of representative cars and trucks in the 0 to 600 W load range. These results were generated by the Overdrive simulation tool internally developed by GM [18]. Overdrive solves systems of ordinary differential equations that approximate the rigid body dynamics of the vehicle. The output from the simulation is a set of parameters that reflect vehicle performance, fuel economy, drive quality, and energy management [18]. These data illustrate that if the 10% fuel economy goal is achieved, then more electrical power will be produced than is consumed by the vehicle electrical system under most driving scenarios, including EPA fuel economy and emissions test procedures.

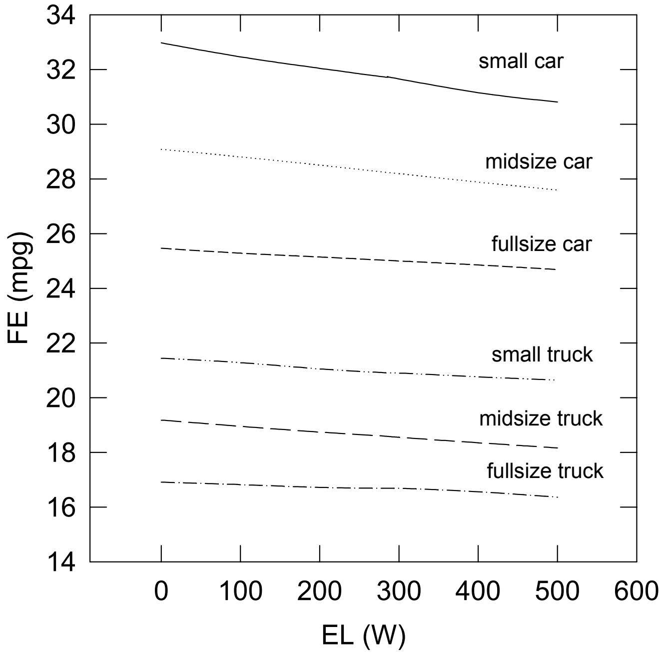

Figure 5: Dependence of fuel economy (FE) on electrical load (EL) at the alternator for representative cars and trucks.

This leads to several choices: 1) reducing electrical accessory load on the alternator using thermoelectrically generated power, 2) shifting some of the engine-driven accessories to electrical drive to raise the electrical accessory load consumption, or 3) attempting to use the excess electrical power for something other than the vehicle electrical load such as propulsion. Examples of choice 2) include electric power steering, electric coolant pump, electric cooling fan, oil pump assist, electric valve actuation & timing, electric heating for catalytic converters, etc. The use of electric power steering or coolant pump alone, for example, could result in 2-3% or 3-5% fuel economy improvements, respectively [19]. Choice 3) is easily adaptable for hybrid vehicles. It is difficult to estimate the fuel economy gains for a TE augmented hybrid before detailed information on packaging, electrical interface, mechanical interface, control interface, powertrain, etc, are available. Because the excess electrical power is used directly for vehicle propulsion, this choice potentially has the largest fuel economy gains amongst the three. In order to achieve the 10% fuel economy improvement goal, a combination of choices mentioned above should be used. It should be pointed out that the fuel economy improvement technologies are not necessary additive.

It is also important to keep in mind that the addition of a TE waste heat recovery unit would increase the overall vehicle weight and, therefore, reduce fuel economy. Fig. 6 shows the dependence of fuel economy on electrical load at the alternator for a midsize truck at various weights. The truck weighs 4417 lbs with 18.6 mpg EPA composite rating; a 10% fuel economy improvement means 1.88 mpg improvement. The mass penalty should generally not exceed 5% of the 1.86 mpg gain. Data in Fig. 6 indicate an 1190 lbs/Δmpg mass penalty, the total mass of a TE generator for this truck should be below ~ 111 lbs.

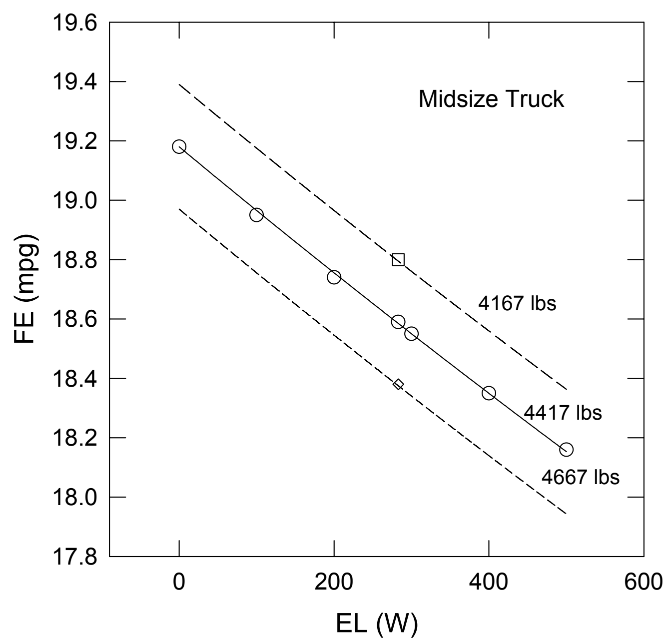

Figure 6: Dependence of fuel economy (FE) on electrical load (EL) at the alternator for a midsize truck at various weights. The symbols are data simulated by Overdrive, and the lines are guides for the eye.

Cost Considerations

There can only be an economic benefit if the savings a consumer realizes by purchasing a technology outweighs the cost. The consumer fuel savings for a 23.5 mpg vehicle over a three-year period is slightly under \$400, assuming \$2/gallon, 15000 miles/yr, and a 10% fuel economy improvement. From a systems engineering point of view, $\$/\Delta$mpg values should be used to balance various fuel saving technologies.

Conclusions

In conclusion, it is clear that TE waste heat recovery technology could potentially offer significant fuel economy improvements. If this is demonstrated feasibly on large scale applications such as automotive, a significant savings in national fuel consumption can be achieved by applying it across the board to conventional and/or hybrid vehicles. In this report, we have analyzed the efficiencies of various TE generators based on appropriate materials properties, described potential automotive applications, discussed several methods of utilizing the recovered electrical power for vehicle fuel economy improvements, and estimated cost and weight limits of a TE generator. There remain, however, many challenges for large scale development: discovery of new materials with higher thermoelectric figure of merit, design and engineering of TE modules with advanced TE materials, design and engineering of optimum heat transfer mechanisms for various subsystems, and integration of TE subsystems into the vehicle electrical power management systems. The key to the realization of this technology is still the continued development of new materials with increased TE efficiency.

Acknowledgments

The author would like to thank F. Stabler for many fruitful discussions, K. Deer for assistance with the Overdrive simulation, and Drs. J. F. Herbst and M. W. Verbrugge for continuous support and encouragement. The work is also in part supported by DOE under corporate agreement DE-FC26-04NT42278.

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