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Feasibility of Thermoelectrics for Waste Heat Recovery in Hybrid Vehicles

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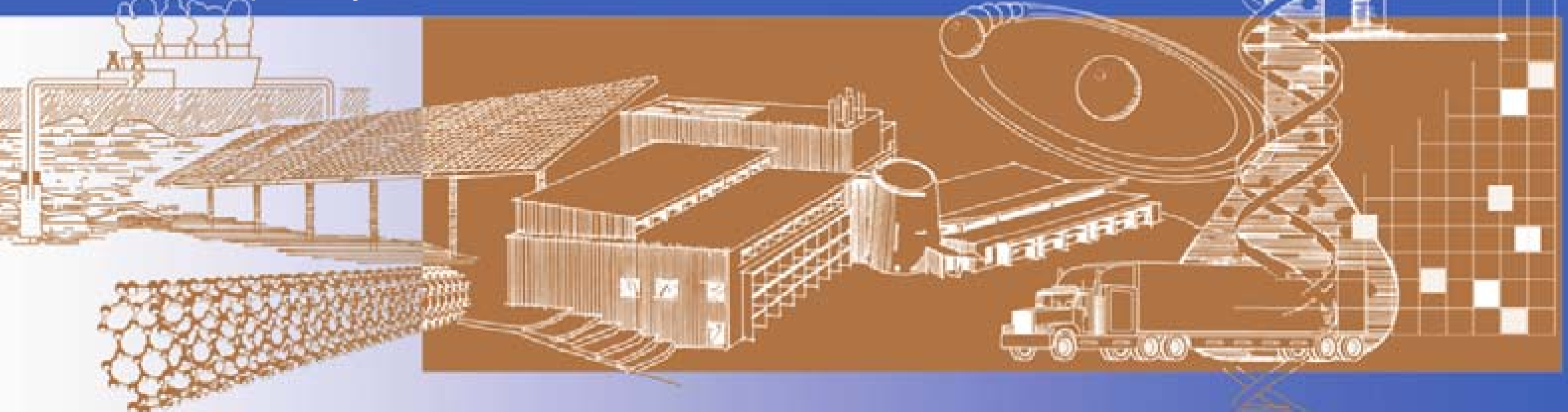

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FEASIBILITY OF THERMOELECTRICS FOR WASTE HEAT RECOVERY IN HYBRID VEHICLES

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Abstract

Thermoelectric generators are devices that convert heat directly into electricity utilizing the Seebeck effect. Using advanced materials, thermoelectric conversion efficiencies on the order of 20% may be possible in the near future. Such devices offer potential to increase vehicle fuel economy by recapturing a portion of the waste heat from the engine exhaust and generating electricity to power vehicle accessory or traction loads. The feasibility of such devices is assessed in the context of hybrid electric vehicles. The transient effects of engine start/stop cycles on the availability of exhaust heat, and hence thermoelectric power, are quantified. Taking necessary ancillary devices such as heat exchangers and pumps into account, requirements are given for system efficiency, specific power, and cost of future thermoelectric systems.

Keywords: Thermoelectric, Waste Heat, Hybrid Electric Vehicle

1. Introduction

Thermoelectric (TE) generators offer the potential to increase vehicle fuel economy by converting a portion of engine waste heat to electricity [1, 2]. Conventional vehicles may derive a fuel economy benefit by using the extra electrical power to reduce alternator loads and/or electrically drive accessories such as power steering [3]. Integrated into a hybrid electric vehicle (HEV), TE generators may also assist with vehicle propulsion—a scenario explored in this paper. As an initial look at device feasibility, this work neglects thermal transients due to cold starts and repeated engine starts for HEVs.

In a typical engine with 30% efficiency, 70% of the fuel combustion energy will be wasted as heat. Some waste heat is transferred to the coolant system and/or carried from the engine block by convection and radiation. This paper assumes that the TE generator recovers heat from the engine exhaust, the highest temperature and, consequently, the most thermodynamically available waste heat. In vehicle applications, a TE device typically must employ heat exchangers to carry heat from the exhaust system to the hot side of the device (and isolate the device from peak exhaust system temperatures), and to remove heat from the cold side of the device. The cold side commonly uses ethylene glycol as a working fluid, either shared with the engine cooling loop or using its own dedicated radiator.

2.0 Model

2.1 Thermoelectric System

First discovered by Thomas Johann Seebeck in 1821, a thermoelectric device generates electricity when a temperature gradient is applied across junctions of two dissimilar metals. The performance of the device, determined by properties of the junction materials, is typically quoted using a figure of merit, *ZT*. Yang [4] gives a timeline of advances in thermoelectric materials and their figures of merit. Bulk materials, such as bismuth telluride and lead telluride, identified in the 1960s and 1970s have *ZT* in the range of 0.5 to 1.0. These materials are most common in present-day applications, including demonstration vehicle waste heat recovery programs. More recently discovered thin film materials silicon carbon and boron carbon, operating on a quantum well principle, have demonstrated ZT of 4 to 5 in the laboratory, but have yet to be scaled up to practical systems. In addition to higher efficiency, these thin film designs offer the potential for much lower cost compared to bulk designs because less junction material is required.

The efficiency of a TE device, that is the amount of electrical power generated for a given amount of heat input, $\eta_{TE} = P_{elec} / P_{h,\,in}$, can be calculated as a function of the hot side temperature T_h, cold side temperature T_c and *ZT* as [5]:

$$\eta_{TE} = \frac{T_h - T_c}{T_h} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + T_c / T_h} .$$

Figure 1 gives TE device efficiency for a system with T_c = 95ºC and various T_h. For near-term applications, a *ZT* in the range of 0.85 to 1.25 gives device efficiencies from 5% to 12%. In the future, thin film devices could approach 25% efficient.

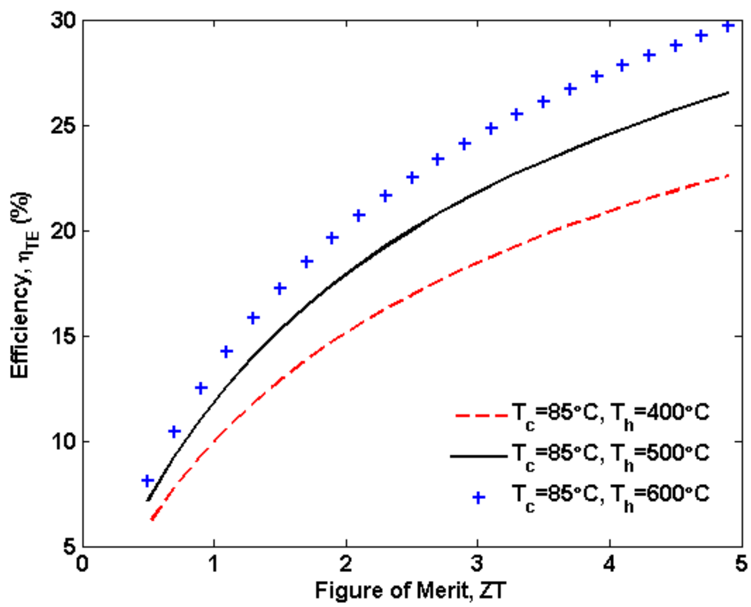

Figure 1: Conversion efficiency of a thermoelectric device versus figure of merit, *ZT*

In vehicle applications, thermoelectric system efficiencies, $\eta_{TE\ sys} = P_{elec} / P_{exh}$ where P_{exh} is the engine exhaust heat, will be much less than the device efficiencies due to factors such as cold and hot side heat exchanger effectiveness ε_c and $\varepsilon_h < 1$, and temperature drops along the exhaust line between the engine and the hot side heat exchanger input, $\Delta T_{eng\text{-}TE}$, as examples. With heat exchanger effectiveness in the range of 50% to 80% and approximately 15% of heat lost for each 50ºC temperature drop, the electrical output will be reduced:

$$P_{elec} = \eta_{TE} \varepsilon_c \varepsilon_h \left(P_{exh} - \dot{m}_{exh} c_{p\,exh} \Delta T_{eng-TE} \right).$$

Therefore, it is reasonable to expect the efficiency of a complete system, $\eta_{TE\ sys}$, to be roughly half that of the actual thermoelectric device, η_{TE}.

To complete a large design space search across multiple vehicle platforms, this study did not attempt to size heat exchangers or predict temperature drops. Instead, a simple "black box" TE system model was used to predict the TE system electrical power output P_{elec} as a function of the engine's rate of exhaust heat output P_{exh} as

$$P_{elec} = \min\left(\eta_{TE\ sys} P_{exh} \,,\, P_{\max,\,TE\ sys} \right).$$

The TE system efficiency, $\eta_{TE\ sys}$, and TE system maximum power output rating, $P_{max,\ TE\ sys}$, were both treated as constant parameters for a given design.

2.2 Steady-State Vehicle Model

The vehicle model consists of simple road load, engine waste heat, and HEV drivetrain sub-models. A block diagram of the model, including the TE system, is given in Figure 2.

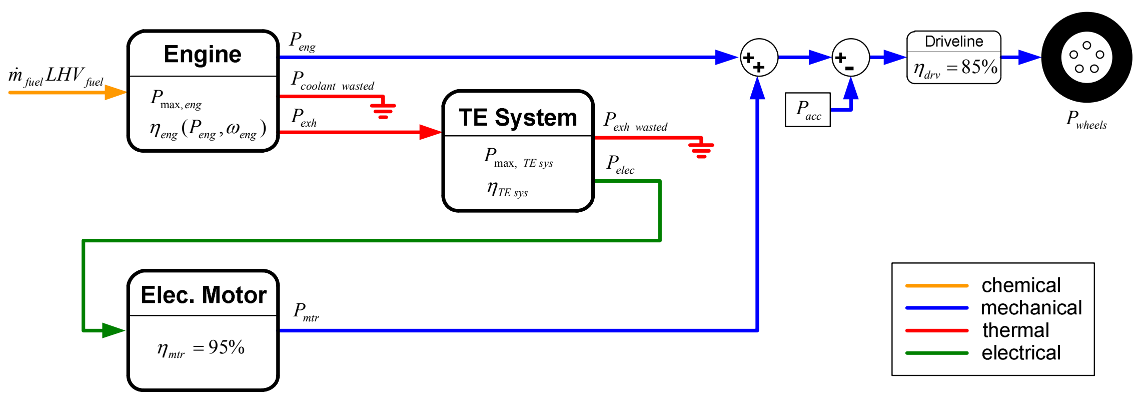

Figure 2: Block diagram of steady-state system model.

The power required at the wheels to drive the vehicle at constant speed, v, is

$$P_{wheels} = \left(F_{aero} + F_{roll} \right) v \,,$$

where the aerodynamic drag and rolling resistance forces are, respectively,

$$F_{areo} = \tfrac{1}{2} \rho_{air} C_d A_f v^2 \,,$$

$$F_{roll} = mg\cos(\theta)\ a\ .$$

The power at the wheels is met by a combination of electric motor and engine power, P_{mtr} and P_{eng}, respectively, with driveline efficiency, η_{drv}:

$$P_{wheels} = \left(P_{mtr} + P_{eng} - P_{acc}\right)\eta_{drv}\ .$$

In addition to meeting road loads, the motor and engine must also drive accessories consuming power P_{acc}. Electric motor power and engine power are calculated, respectively, as

$$P_{mtr} = \eta_{mtr} P_{elec}\ ,$$

$$P_{eng} = \eta_{eng}\dot{m}_{fuel} LHV_{fuel}\ ,$$

where electric motor efficiency is assumed constant and engine efficiency and fuel flow rate are interpolated from empirical engine maps as a function of engine torque and speed. Engine exhaust waste heat power output is calculated as

$$P_{exh} = P_{eng}(1-\eta_{eng})\,r\ ,$$

where r is the fraction of engine waste heat exiting through the engine exhaust. Shown in Figure 3, we fit r to engine exhaust temperature and flowrate data for a diesel engine and obtained an adequate fit with $r = 0.30$ at low torque and 0.46 at peak torque. Values of r are interpolated for intermediate torques. The model suggests that 54% to 70% of total engine waste heat is dissipated by the coolant system, and convection and radiation from the engine block.

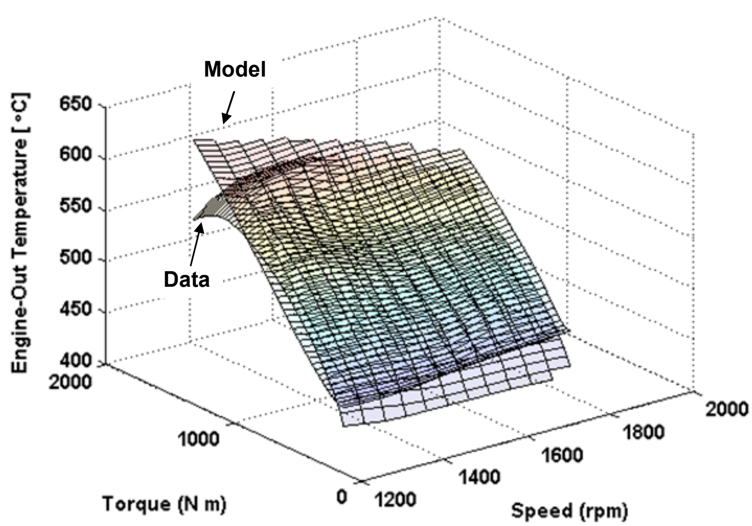

Figure 3: Comparison of exhaust waste heat model with data from a Caterpillar C12 engine

3.0 Results

3.1 Steady-State

Three HEV platforms were considered as candidates for integration of a TE system to recover waste heat. In this section, the steady-state model is used to predict fuel savings attributable to a TE system under the assumption that the system adds no mass to the vehicle. Mass compounding effects on fuel consumption are later considered using a transient model. The steady-state model predicts the availability of waste heat for various vehicle speeds and duty cycles and thus provides guidelines for system sizing for a given driving cycle. Model parameters for the three platforms: (1) midsize sedan, (2) midsize SUV, and (3) Class 4 truck HEVs are given in Table 1.

Table 1: Parameters for three classes of hybrid electric vehicles considered in this study

	Midsize Sedan	**Midsize SUV**	**Class 4 Truck**
Test mass, m_{veh} (kg)	1565	2151	7700
Frontal area, A_f (m^2)	2.27	2.88	6.89
Drag coefficient, C_d	0.30	0.41	0.7
Rolling resistance coeff., a	0.009	0.009	0.009
Engine type	Gasoline	Gasoline	Diesel
Engine power, $P_{max,\ eng.}$ (kW)	83	135	149
Accessory load, no AC (kW)	0.82	0.82	2
Accessory load, with AC (kW)	2.47	2.86	N/A
Accessory load, 50% AC duty cycle, $P_{acc.}$ (kW)	1.65	1.84	2

Figure 4 shows potential fuel savings for the three different vehicles employing TE systems with efficiencies $\eta_{TE\ sys}$ = 5%, 10%, and 15%. The fuel consumption of the three vehicles is presented relative to three baseline HEVs with no TE system. In general, the percentage fuel savings offered by a TE system does not significantly vary with vehicle speed and is roughly 3%, 5.5% and, 8% for the three respective values of $\eta_{TE\ sys}$. These fuel savings projections are somewhat of a best case scenario as Figure 4 includes no additional mass in the model to account for the TE system and assumes that the system has no maximum power limit.

In Figure 4, the midsize SUV platform captures a slightly larger fuel savings benefit than the midsize sedan because its design is less aerodynamic. Unlike the midsize sedan or SUV, the Class 4 truck is equipped with a diesel engine and captures less of a benefit than the other two vehicles due to higher engine efficiency and less waste heat. (As a general rule, the present waste heat model predicts P_{exh} roughly equal to P_{eng} for gasoline engines but slightly less, ~2/3 P_{eng}, for diesel engines given their higher efficiency.)

Available exhaust heat is heavily dependent upon vehicle speed; providing much electric power generation potential at high speed, but little at low speed. Figure 5 presents this dependency for the midsize SUV platform for various values of $\eta_{TE\ sys}$. To recover all waste heat available at a given speed, a TE system must be sized such that its maximum power rating is as follows:

$$P_{max,\ TE\ sys} \geq P_{elec}(v).$$

At 40 mph (64 km/hr) with $\eta_{TE\ sys}$ = 10%, for example, the SUV system requires $P_{max,\ TE\ sys}$ = 0.75 kW power to achieve the fuel savings shown in Figure 4. At speeds greater than 40 mph, this 0.75 kW system would achieve less fuel savings than that shown in Figure 4. The drawbacks of oversizing a system are high cost and heavy weight, potentially negating any fuel savings and economic benefit.

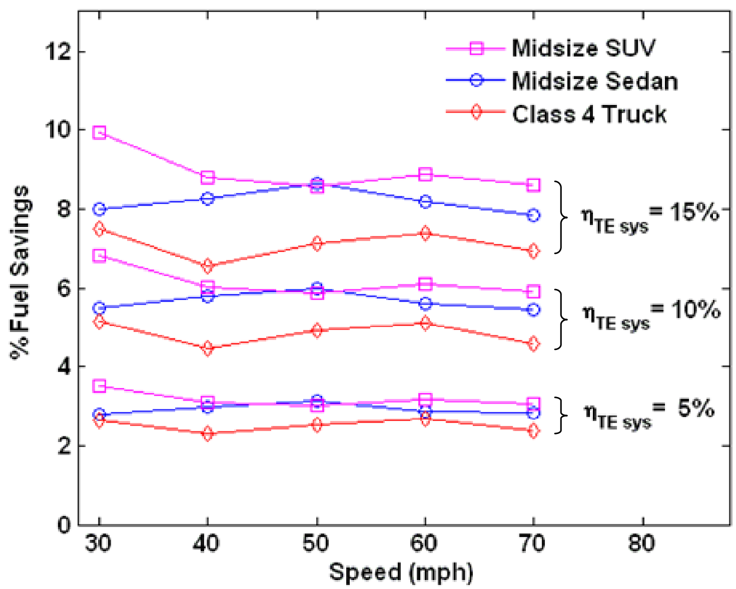

Figure 4: Best-case fuel savings of HEVs with TE systems relative to baseline HEVs with no TE system, assuming no engine-off cycling, no maximum power recovery limitation $P_{max,\ TE\ sys}$, and no mass introduced by the TE system.

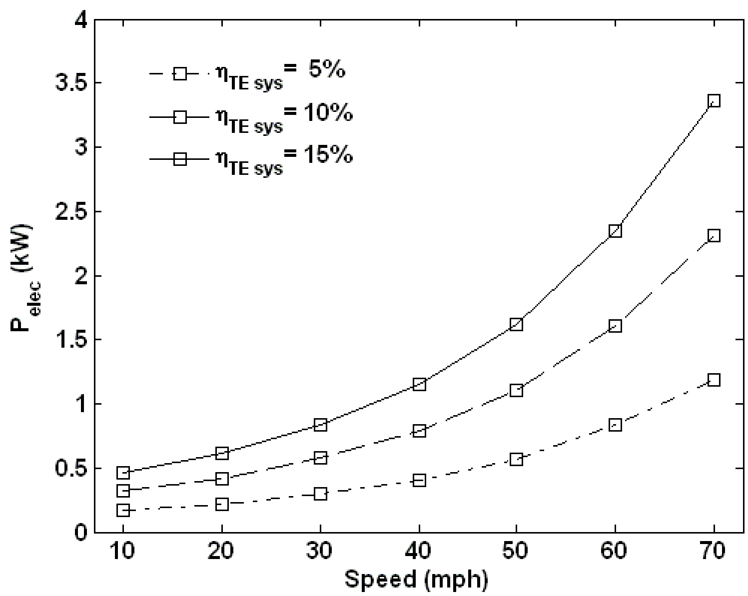

Figure 5: Amount of electrical power that must be generated by TE system for midsize SUV to achieve fuel savings shown in Figure 4.

Figure 6 shows the percentage of time spent above various speed thresholds for three driving cycles. The UDDS cycle, representative of moderate city driving, spends most of it time at slow speeds and contains numerous start-stop acceleration events. Less than 10% of UDDS cycle driving is above 40 mph (64 km/hr). The HWFET cycle, representative of moderate highway driving, contains just one start-stop acceleration event and spends nearly 90% of the time above 40 mph. The US06 cycle, representative of aggressive, high speed, mixed city/highway driving, contains multiple start-stop acceleration events and spends 50% of the time above 60 mph (97 km/hr).

By definition, the steady-state HEV model presented in Figures 4 and 5 assumes the engine to always be running. In actual (transient) operation of an HEV, the engine will commonly be turned off at low speeds, during decelerations, and at stops. This engine on/off cycling further reduces waste heat available to the TE system. To quantify this effect, Figure 6 also plots the UDDS, HWFET, and US06 time-above-speed multiplied by the fraction of time the engine is on at a given speed for a 2006 Toyota Prius, recorded by NREL on a chassis dynamometer at 75ºF. Engine on/off cycling is shown to reduce waste heat availability as much as 30% in low speed city driving (UDDS). The effect is less substantial for highway driving (HWFET and US06) where the engine remains on the majority of the time.

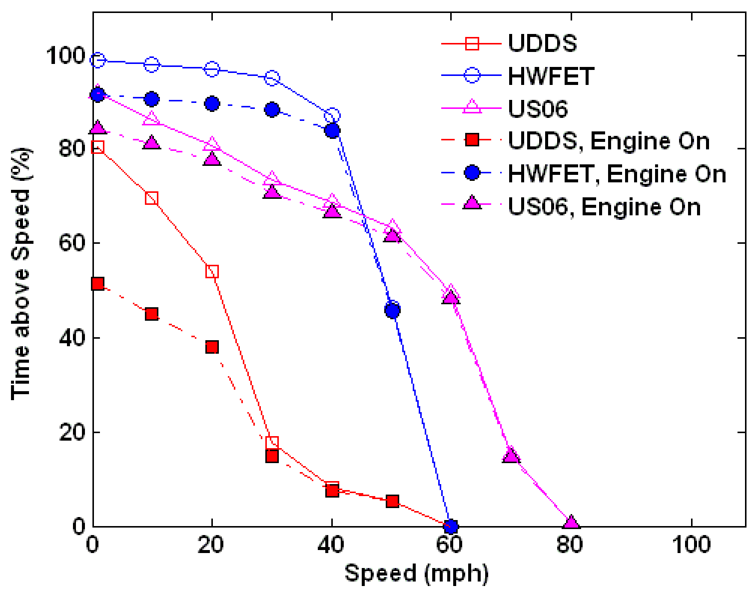

Figure 6: Fraction of time spent above a speed threshold for three different driving cycles. "Engine on" data points give fraction of time that the engine is on above a speed threshold measured from dynamometer testing of a 2006 Toyota Prius HEV.

To gain an idea of what system size might be most advantageous under different driving scenarios, Figure 7 presents the average electrical power output, $P_{elec,\,avg}$ (contour lines) expected for various system sizes, vehicle speeds, and duty cycles for the SUV with $\eta_{TE\,sys.}$ = 10%. Smaller systems, where the contour lines are nearly horizontal, hold the advantage of being less sensitive to duty cycle. The left axis of Figure 7 is the TE system's maximum rated power $P_{max,\,TE\,sys}$. The right axis gives limits of how much electrical power is available at various constant speeds. Electrical power output may be limited by either axis. As an example, the SUV with TE system efficiency $\eta_{TE\,sys}$ = 10% and size $P_{max,\,TE\,sys}$ = 0.75 kW will generate $P_{elec,\,avg}$ = 0.75 kW when driving a constant 40 mph (64 km/hr), i.e. 100% duty cycle. This same system will only generate 0.375 kW when driving 40 mph with 50% duty cycle (the engine is assumed to be off the other 50% of the time). Driving higher speeds, such as 50 mph (80 km/hr) with 50% duty cycle, the system will still generate only 0.375 kW because it is undersized to capture the peak exhaust power available at 50 mph. Figure 8 depicts this example in a schematic.

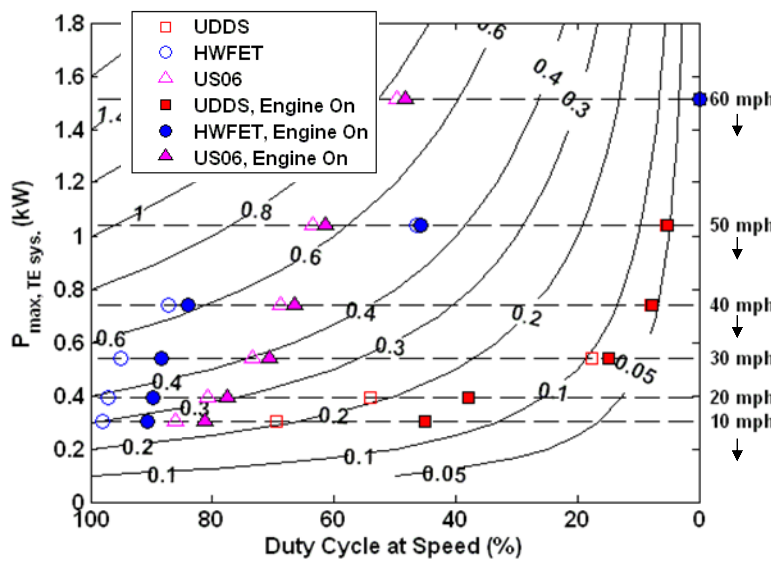

Figure 7: Contour lines showing average power, $P_{elec. avg.}$ in kW, generated by a TE system with efficiency $\eta_{TE sys.}$ = 10% for the midsize SUV platform. Duty cycle (x-axis) is fraction of time spent driving constant speed (100%) versus engine-off (0%). Left y-axis gives limits on $P_{elec. avg}$ due to the maximum power rating of the TE system, $P_{max, TE sys}$. Right y-axis gives limits on $P_{elec. avg}$ due to waste heat availability at various constant speeds.

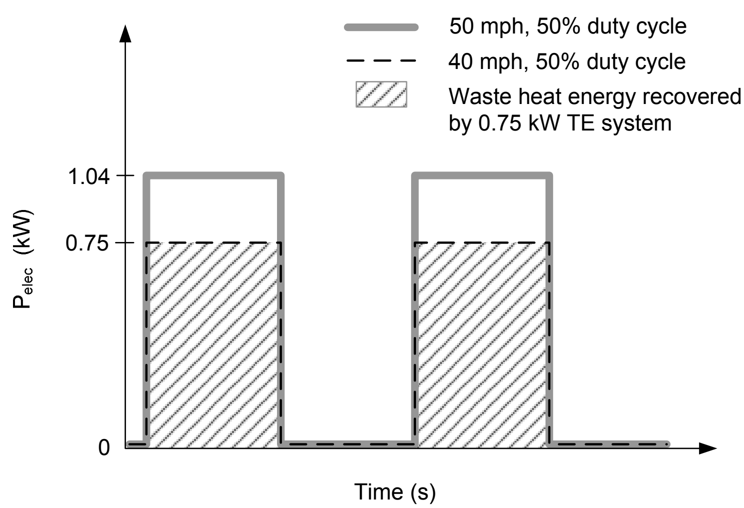

Figure 8: Schematic showing potential thermoelectric power recovery for a midsize SUV with TE system efficiency $\eta_{TE sys.}$ = 10% and rated power $P_{max, TE sys}$ = 0.75 kW. The system recovers the same energy for both the 50 mph (80 km/hr) and 40 mph (64 km/hr) 50% duty cycle cases because it is undersized to capture 50 mph peak waste heat.

Overlaying Figure 7 with duty cycle statistics from Figure 6 presents a general idea of how much electrical power might be generated on average for the three driving cycles. Taking the HWFET cycle as an example, a system sized for the midsize SUV to capture 40 mph peak power will generate approximately 0.63 kW. Sizing the system any larger provides little advantage as the higher speeds are visited less frequently. For example, there is no advantage in sizing the system to capture HWFET 60 mph (97 km/hr) peak waste heat as that speed is visited with near 0% duty cycle. Thus, system sizing is something of a compromise. On the US06 cycle, the 0.63 kW TE system is limited by $P_{max,\ TE\ sys}$ (left y-axis of Figure 7) and might produce 0.50 kW of electricity on average. On the UDDS cycle, the 0.63 kW TE system is limited by the small amount of waste heat generated by the engine at low speeds (right y-axis of Figure 7) and might produce approximately 0.15 kW. Table 2 lists characteristics of TE systems sized in this manner to capture 40 mph peak power, along with the average electrical power output expected when operating these systems and vehicles over the three driving cycles. The midsize SUV example with $P_{max,\ TE\ sys} = 0.75$ kW, described above, appears in Table 2 for system efficiency $\eta_{TE\ sys} = 10\%$.

Table 2: Thermoelectric system designs (maximum power ratings, $P_{max,\ TE\ sys}$, chosen for various system efficiencies, $\eta_{TE\ sys}$) sized to capture peak waste heat at 40 mph (64 km/hr); average electrical power output predicted by steady-state duty cycle model.

	TE System Characteristics		**Average Electrical Output, $P_{elec.\ avg.}$ (kW)**		
	$\eta_{TE\ sys}$	$P_{max,\ TE\ sys}$ (kW)	HWFET	US06	UDDS
Midsize Car	5%	0.25	0.21	0.17	0.06
	10%	0.49	0.41	0.32	0.11
	15%	0.71	0.60	0.47	0.16
Midsize SUV	5%	0.39	0.32	0.26	0.08
	10%	0.75	0.63	0.50	0.15
	15%	1.10	0.92	0.74	0.22
Class 4 Truck	5%	0.88	0.75	0.57	0.12
	10%	1.72	1.45	1.15	0.23
	15%	2.53	2.1	1.7	0.35

3.2 Transient

With TE systems sized based on the steady-state waste heat model according to Table 2, the PSAT vehicle simulator [6] was used to consider mass compounding effects for a midsize SUV with power-split hybrid drivetrain (135 kW engine, 106 kW and 43 kW motor/generators, 43 kW battery). Three cases were simulated: (1) a baseline vehicle with no TE system, (2) a vehicle with a TE system but no mass increase, and (3) a vehicle with a TE system and an incremental mass increase of 100 kg.

The baseline SUV with no TE system consumes gasoline at a rate of 9.29 L/100km (25.32 mpg) on the HWFET cycle. Holding the vehicle mass constant, a TE system with $\eta_{TE\ sys.} = 5\%$ (and $P_{max,\ TE\ sys} = 0.390$ kW) reduces fuel consumption by 1.6% over the base SUV. A TE system with $\eta_{TE\ sys.} = 10\%$ (and $P_{max,\ TE\ sys} = 0.750$ kW) reduces fuel consumption by 3.3% over the baseline SUV. Fuel savings are roughly half of what was predicted in Figure 4. In both cases the TE system is slightly undersized to capture peak exhaust powers during acceleration events. Additional fuel savings might be expected from a larger TE system with the drawbacks of additional cost and mass.

Extrapolating from simulation results with incremental mass, the upper weight limit at which there would be no fuel savings is 385 kg/kW for $\eta_{TE\ sys.}$ = 5% and 413 kg/kW for $\eta_{TE\ sys}$ = 10%. In practice, it would be preferred if the system weighed a tenth of this ~40 kg/kW to retain the majority (~90%) of the potential fuel savings. Assuming 12,000 miles traveled per year and using the 2006 average gasoline price of $2.58/gallon, the 40 kg/kW TE system would pay for itself in 3 years provided the initial cost was no more than $169/kW for $\eta_{TE\ sys.}$ = 5% and $153/kW for $\eta_{TE\ sys.}$ = 10%. (Recall that to achieve system efficiencies of $\eta_{TE\ sys.}$ = 5% and 10% requires TE device efficiencies roughly twice that, respectively, η_{TE} = 10% and 20%.)

4.0 Conclusions

This study considered three HEV platforms (midsize sedan, midsize SUV, and Class 4 truck) for integration of a thermoelectric (TE) generation system to recapture engine waste heat and power electric drive systems. A steady-state model showed the SUV platform to derive slightly more fuel savings benefit than the car (due to the SUV's less efficient aerodynamic profile resulting in a higher engine power requirement and an increase in exhaust waste heat) and the Class 4 truck (due to the SUV's less efficient gasoline engine compared with the diesel engine of the Class 4 truck). The steady state model predicted vehicle fuel savings on the order of 3% and 5.5% using TE systems which recapture 5% and 10% of the engine's waste heat, respectively. Due to heat exchangers, temperature drops, and the like, these respective scenarios would require thermoelectric device efficiencies on the order of 10% (near term, bulk material devices) and 20% (future, thin film devices).

Identifying an optimal system size is challenging. Sufficient waste heat is available at highway speeds, but little is available in city driving where the effect of engine start-stop cycles is expected to reduce waste heat by 30%. As a compromise, this study sized TE generators based on the amount of waste heat available at 40 mph (64 km/hr) constant speed driving. In transient simulations, these systems were slightly undersized to capture peak waste heat during accelerations. Mass and cost constraints for TE systems simulated were on the order of 50 kg/kW and $150/kW to capture ~1.5% fuel savings in the near-term and ~2.9% fuel savings in the future. Cold starts, repeated engine starts, and cold temperature operation, none of which were explored in the present study, can be expected to negate some of this benefit.

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Thermoelectric; waste heat; hybrid electric vehicle; HEV; engine exhaust; vehicle accessories

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