Fuel Displacement Potential of a Thermoelectric Generator in a Conventional Vehicle

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Abstract

This paper evaluates the fuel displacement potential of a Thermoelectric Generator (TEG) device in a conventional gasoline vehicle using vehicle simulation and engine in the loop. A TEG device was modelled in Simulink, to exhibit the thermal and electrical characteristics of such a device. This TEG model was integrated into the vehicle simulation software, Autonomie and evaluated in a real engine − virtual vehicle scenario using Engine in the loop (EIL) technique. The EIL approach was used to evaluate the fuel consumption benefit of TEG under cold and hot conditions. The complete vehicle model was then validated and used to evaluate the impact of the current TEG system on additional drive cycles as well as future TEG systems (i.e. no device temperature limits). EIL evaluation shows a fuel economy gain within the current device of 1% on the US06 cycle. The simulation study will quantify the impact of driving cycles and TEG design on fuel displacement potential.

Keywords: simulation, hardware-in-the-loop (HIL), energy consumption

1 Introduction

The TEG device used for this study is an early prototype developed by General Motors (GM), which consists of 42 Bismuth Telluride modules (6 parallel strings with 7 modules in series). Figure 1 shows its integration into a vehicle. This TEG is designed to utilize the exhaust line and engine coolant loop as the high temperature heat source and low temperature heat sink respectively. The TEG model was developed and validated by GM. Integration of the model to a conventional gasoline vehicle model in Autonomie [1] enabled its use for Engine in the loop study as well as simulation studies.
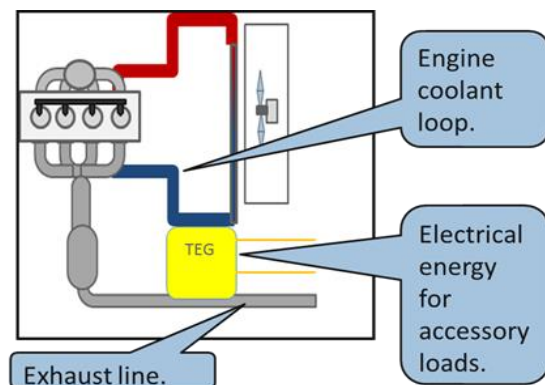

Figure 1. Integration of a TEG in a conventional vehicle

This paper investigates the benefit of a current TEG device on the US06 drive cycle during both cold and hot conditions using Engine-in-the-Loop. As a second stage, pure vehicle simulation is used to assess the benefit of the existing TEG technology on a large number of drive cycles. Finally, the fuel consumption benefit will be simulated using different TEG electrical outputs to estimate the potential of future technologies.

2 Engine in the loop testing

The vehicle specifications used for this study are shown in Table 1. The setup allowed us to consider both the TEG benefits (i.e. waste heat recovery) and drawbacks (i.e., higher cooling fan load).

Table 1 EIL Test Assumption

Drive Cycle	US06
Vehicle platform	Conventional , compact (Ford Focus)
Engine	2.2 L SIDI ECOTEC GM Opel Vectra
Test conditions	Cold start - @ 20°C Hot start – after 10 min soak
# test cases	6 cold start tests 6 hot start tests

The experiments were performed with a Simulink model of the TEG device, embedded in a virtual vehicle model as shown in Figure 2. The TEG model is described in detail in [2]. While studies have been conducted for designing and developing TEG devices for similar purposes [3-5], the approach of using EIL and simulation to estimate the potential of TEGs in a vehicle is unique. For the engine in the loop tests, the TEG model, in the virtual vehicle, has real time feedback from the engine on the dynamometer.
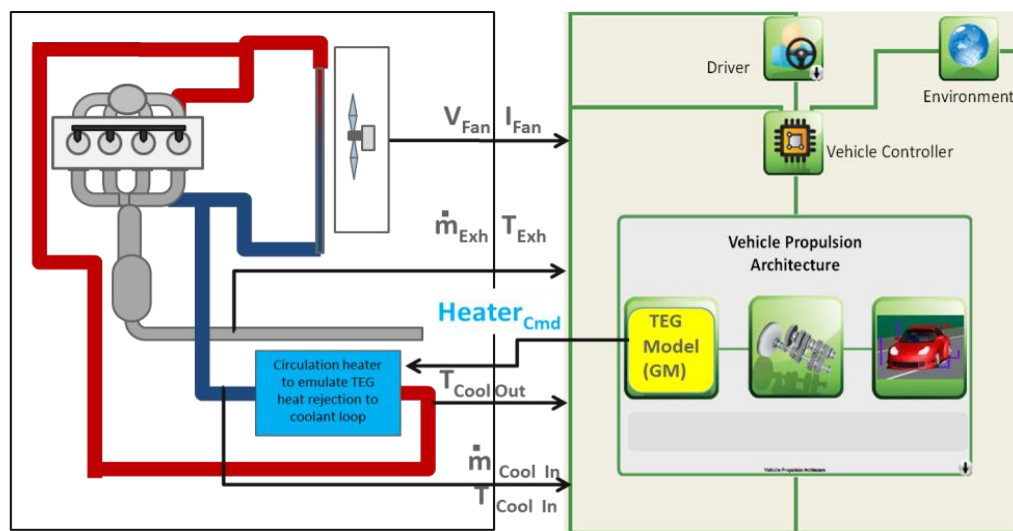
Figure 2. Integration of the real Engine (left) on the bench with the virtual vehicle (right)

2.1 EIL Results

During the EIL study, we assumed an electrical load of 200W, which is representative of the vehicle base load on the standard drive cycles. The TEG will be used to meet all or part of this load. The additional heat generated by TEG flows into the cooling loop of the engine which could help the engine to warm up faster. The results are summarized in table 2.

Table 2. EIL test results on the US06 Drive Cycle

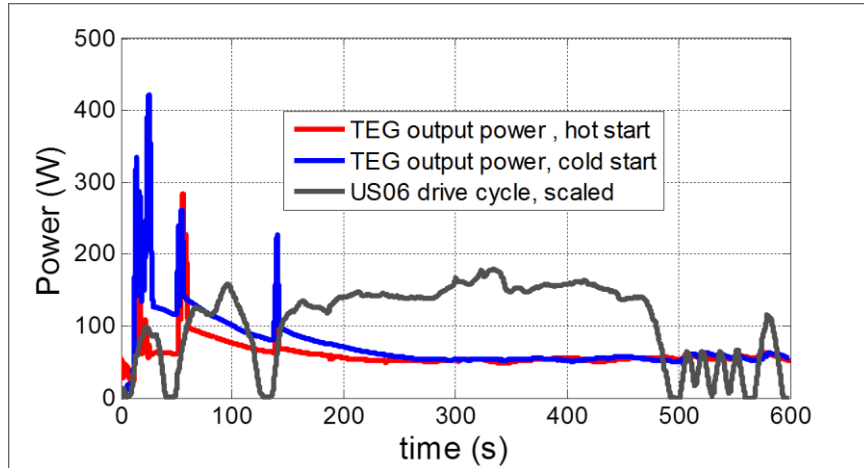| FUEL CONSUMPTION	Without TEG device	With TEG device	Percentage improvement over baseline, as a 90% CI **
Cold start	28.5 mpg	28.8 mpg	[0.5 % to 1.6%]
Hot start	30.07 mpg	30.35 mpg	[-0.3% to 1.4%]

Figure 3. Power output from TEG during EIL study

Cold start shows a more consistent reduction in fuel consumption. This is attributable to the lower coolant initial temperature. The TEG device produces less than 100W on average, even though it is capable of power outputs as high as 400W as shown in the plot below.

Closer examination of the performance reveals that there are two limitations for this particular TEG system

1. The temperature limits imposed on TEGs (decided by the material properties)
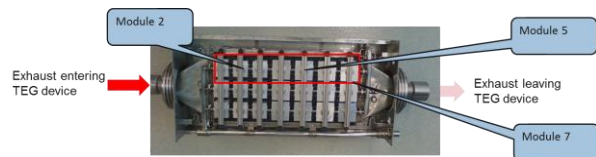2. The physical design of the TEG which underutilize the downstream modules.

Figure 4. TEG system, using 7 series modules and 6 such parallel strings

In the TEG device, several modules are connected electrically to generate the required voltage to match the system bus voltage of the vehicle. Due to packaging constraints, some TEG modules may be 'downstream' of other modules and be exposed to a lower exhaust temperature.

The modules are numbered from 1-7 from left to right. Module 2 is upstream of the exhaust flow and is subjected to high exhaust temperature. By the time the same exhaust gas reaches module 7, it cools down to a point barely above the coolant temperature, and results in no significant thermal potential. This can be viewed in Figure 5
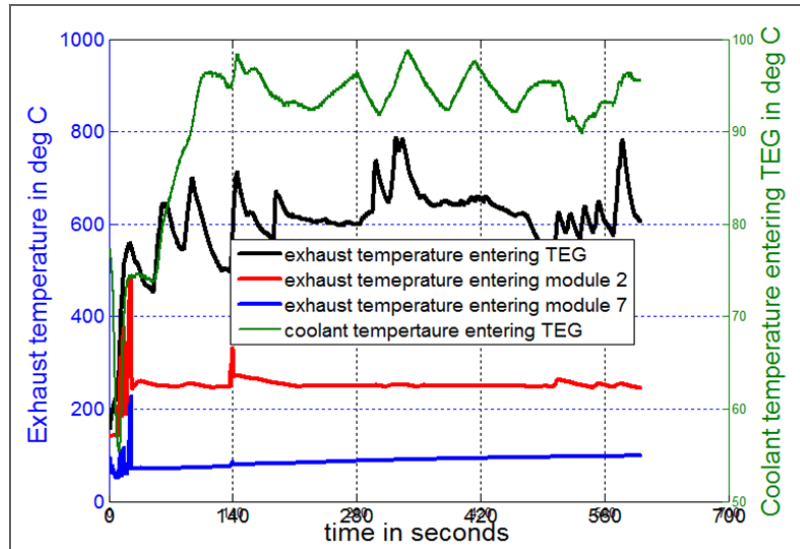
Figure 5. Exhaust & Coolant temperatures available across different modules

Faster engine warmup also contributes to the fuel savings obtained from TEGs. However, it should be noted that the additional heat dumped in to the engine cooling circuit increases the load on the cooling fan, but this additional load is only 11% of the energy recovered by the TEG. The additional fan load measurement in shown in Table 3.

Table 3. Additional cooling fan load due to TEG

Energy Consumed by Cooling Fan	
Fan load No TEG (kJ)	90.2
Fan load with TEG (kJ)	94.6
Extra fan load due to TEG (kJ)	4.2
TEG energy produced (kJ)	38.7
% TEG output consumed by additional fan load	< 11 %

3   Simulation Analysis

System simulations are performed to analyse the TEG potential over a wide range of drive cycles. A baseline vehicle with 1kW electrical power was assumed. To increase the simulation accuracy, HIL test data was used as inputs to the TEG model.

For that phase of the study, we assumed that the TEG was not constrained by the design limitations enumerated earlier. As a result, we assumed an average electric power of 500W since the TEG can utilize all the modules and work at higher temperature ranges. This power will be used to offset the auxiliary load demand on the engine. The variation on the engine load will then translate to lower fuel consumption. Hence the effect of having a TEG that produces 'x' kW of average power is similar to the effect produced by a reduction of electric load on the vehicle by 'x' kW. The figure 6 is a plot of % improvement in fuel economy due to a reduction in average engine load (in Watt) caused by improved TEG power output (with increasing operating temperature limits).

The simulations assume a warmed-up engine, so the effects of TEG in aiding a quicker warm up are not considered.
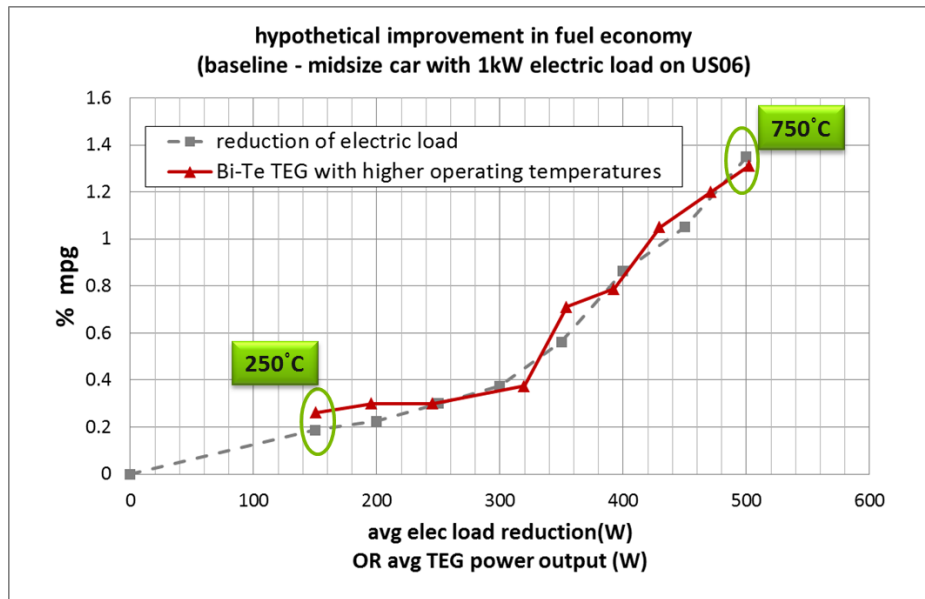
Figure 6. Hypothetical effect of increased temperature limit on TEG and fuel economy improvements
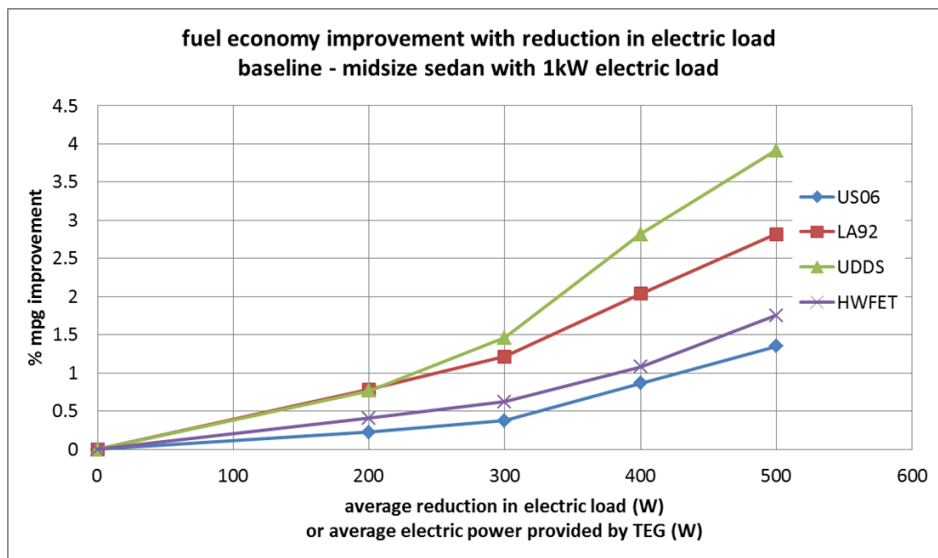

Figure 7. Fuel economy improvement potential of TEG for a conventional vehicle, assuming the generated electric power can be fully utilized.

An interesting outcome of this study is shown in figure 7. While the benefits observed for the US06 cycle match closely with the EIL tests, it also shows that this cycle is not the one delivering the higher benefits.

If a conventional vehicle can utilize the electric power generated by a TEG, then with a TEG capable of producing 500W of power, we are likely to see about 4% improvement in fuel economy in a UDDS cycle and about 1.7% improvement in Highway cycle.

4   Conclusions

The benefits of a TEG which consists of 42 Bismuth Telluride modules (6 parallel strings with 7 modules in series) were assessed using two complimentary approaches: engine-in-the-loop and vehicle simulation.

EIL results showed a fuel economy gain between 0.5 % to 1.6 % for cold starts on the US06 drive cycle. These fuel economy improvements are due to lower initial coolant temperature results in higher TEG electrical power output as well as quicker engine warm-up due to heat rejected to the coolant loop.

The fuel consumption benefits on the US06 drive cycle during hot conditions showed a gain ranging from 0.3 to 1.4% with an average of 0.55%. Based on the number of tests performed, the results are however not statistically significant and additional tests should be performed.

EIL testing demonstrated that the contribution of 'downstream' modules is greatly reduced due to lower exhaust temperatures, and slow temperature rise, and higher coolant temperature of downstream modules. As a result, full vehicle simulation was used to assess the benefits of future TEG devices under different driving cycles. The results demonstrated that with a TEG capable of producing 500W of power, 4% improvement on the UDDS cycle and about 1.7% improvement in Highway cycle could be achieved, in case of a conventional midsize vehicle.

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