

Modeling Analysis of Waste Heat Recovery via Thermo Electric Generators for Fuel Economy Improvement and CO₂ Reduction in Small Diesel Engines

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ABSTRACT

This paper deals with modeling and analysis of the integration of ThermoElectric generators (TEG) into a conventional vehicle, specifically aimed at recovering waste heat from exhaust gases. The model is based on existing and commercial thermoelectric materials, specifically Bi₂Te₃, having ZTs not exceeding 1 and efficiency below 5%, but a trade-off between cost and performance that would be acceptable for automotive applications. TEGs operate on the principle of thermoelectric energy conversion via Seebeck effect, utilizing thermal gradients to generate electric current, with exhaust gases at the hot side and coolant at the cold side. In the simulated configuration the TEG converters are interfaced with the battery/alternator supporting the operation of the vehicle, reducing the energy consumption due to electrical accessories and HVAC.

Heat exchanger models for steady-state solutions have been simulated to estimate the actual temperature of hot and cold sides, as a function of vehicle operation and TEG configuration. The TEG module model has been validated with respect to existing literature, showing agreement with published results.

The overall model - integrated into a backward longitudinal model of a FIAT Punto 1.3 Diesel - outputs recovered electric energy as function of hot side (exhaust gas) and cold side (coolant) temperature and mass flow (provided by the vehicle model). Several simulations have been carried out to explore different driving conditions and TEG configurations. Results show that for the analyzed vehicle model, TEGs can displace up to 15-20% of the alternator energy with average CO₂ savings above 1g/km on standard driving cycles.

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INTRODUCTION

CO₂ emissions from road transportation in Europe increased by nearly 23% between 1990 and 2010, currently contributing about 20% of total EU CO₂ emissions. Transportation is the only major sector in the EU where greenhouse gas emissions are still rising. Besides energy and environmental concerns, a crucial role is played by emission standards and regulations.

In 2009, the European Union legislation adopted mandatory emission reduction targets for new vehicles, stating that the fleet average to be achieved by all new cars is CO₂ 130 g/km by 2015 (target phased in from 2012) and 95g/km by 2020 [1].

On the energy side, it is worth noting that in current vehicles, approximately 60% of the chemical energy of fuel is lost in the form of waste heat, dissipated by the exhaust and cooling systems. The former offers high-grade heat that approaches temperatures of 900 K while the latter is a considerably more modest heat source at approximately 370 K. There is clearly an opportunity to recover waste heat through after-market solutions, improving current vehicle technologies without the recourse to expensive alternative powertrain technologies. Thus, research efforts are moving towards technologies that can extract mechanical energy/electricity from the energy lost to engine exhaust and/or from the coolant loop. Furthermore, the growing demand for electric energy in vehicles is currently being met with inefficient mechanical generators that are driven off of the vehicle engine. Although improvements in generator

These interfaces must accommodate the massive fluctuations in thermomechanical strain between heat exchangers and the thermoelectric converters while providing excellent thermal and electrical contact.

Traditionally, thermoelectric waste heat recovery has been considered impractical for standard passenger vehicles because of the extremely low thermal efficiencies of thermoelectric devices [18]. Power generation thermal efficiencies for conventional bismuth-telluride (Bi_2Te_3) TEGs have been in the range of 1 to 3% depending on hot and cold side temperatures. These low efficiencies combined with the relatively high costs of the thermoelectric semiconductor materials have typically kept TEs from being considered as viable technology for automotive applications. A system approach can help making TE technology more feasible; radiator and exhaust gas waste can both be used for TE generation, as suggested in references. It should be noted that, while TE efficiencies are quite low, even 3% recovery of the waste heat from a radiator expelling 60 kW might be adequate for displacing an alternator assembly in a passenger vehicle. Systems have been proposed which act between ambient air and exhaust gases or engine coolant, as well as between the exhaust and coolant. For example, Crane *et al.* developed extensive computer models of thermoelectric modules recovering waste heat in the radiator, including both transient and steady state cases. In [10, 19, 20], the authors attempt to optimize the actual heat recovery and thermoelectric design in accordance with automotive constraints.

One of the critical challenges for implementing thermoelectric devices into automotive applications (where cost and volume limitations are critical) involves achieving adequate waste heat recovery to merit the added expense of the TEG device. The challenge then becomes the design of such a thermoelectric device such that it does not provide significant system weight penalties or impair the performance of other systems such as the engine coolant loop. This involves optimizing TEG performance within the constraints of the automotive power plant requirements.

Currently, major automotive OEMs, including BMW, FIAT, Ford, General Motors, Volkswagen, and Volvo are investing in R&D activities on thermoelectric waste heat recovery systems, with promising results [16, 21]. In particular, the TEG prototype system developed by Amerigon for BMW, Ford, and General Motors has shown power output peaks of up to 608 W in testing activities with hot side and cold side of 890K and 290K, respectively [16], expecting fuel economy improvement of 2-3%. Most of the issues, due to the high temperature tolerances necessary for waste heat recovery systems, are *i)* the development and choice of the correct type of material systems, interconnects, *ii)* the critical safety characteristics, and *iii)* need for low cost solutions. The crucial challenge is making good electrical and thermal contacts. The large temperature gradient across the device puts mechanical stress

on the contact-thermoelectric interface. Plus, joining the different materials introduces resistance that heats up the contact, degrading the device.

Furthermore, the integration of TEGs, heat exchangers and related power electronics comes at an additional weight, which eventually reduces the benefits in terms of fuel economy. Considering that the prototypes developed so far by the automotive OEMs represent only a rough estimate of what one could expect in terms of final product, [22] aims at evaluating the weight penalty of incorporating a TEG, calculating an additional weight of about 80 grams per generated Watt (12 W/kg).

Finally, cost needs be properly assessed for a complete technical/commercial feasibility analysis. Being the technology at the prototype stage, with the focus on integration issues rather than the TEG equipment itself, it is difficult to estimate the expected production cost for commercial application. Today's commercial TEGs with ZT around 1 cost about \$30/W [23], but a target incremental cost less than US \$1000/unit will likely be required (and is expected) for commercial application of the technology, making 5% the required gain in fuel economy to offset the equipment cost [24]. However, a cost/benefits analysis is not that trivial and should also *i)* include monetary and non-monetary benefits for the automotive industry itself (and not a simple payback estimate for customers), energy harvesting potential, future emissions regulations and related penalty costs, and *ii)* explore opportunities of innovative materials both for TEG modules and automotive components.

In fact, recent advances in thermoelectric materials and in materials processing are increasing the ability of TEG devices such that much higher operating temperatures and higher efficiencies may be obtainable for power generation from TEG waste heat recovery. New TEG materials such as Zn_4Sb_3 -based semiconductors offer improved performance with a broader temperature range than the conventional Bi_2Te_3 -based TEG devices. Along with these new materials, advances in materials processing have increased the performance and of Bi_2Te_3 , thus making the TEG technology more feasible.

VEHICLE MODELING

The baseline vehicle has been simulated through a partially validated [14] backward model, including the driveline and the internal combustion submodels with the standard equipment of turbocharger, in addition to the electrical components (e.g. the alternator), auxiliaries and accessories.