Thermoelectric Generators for Wasted Heat Energy Recovery

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Government regulations stemming from environmental concerns and worldwide oil consumption are forcing the automotive industry to make improvements in tailpipe emissions and vehicle fuel economy. In contrast, consumers' expectations in vehicle performance and capabilities are driving the energy consumption rate to ever-increasing levels. Recent studies show electronic content in vehicles is estimated to increase at an accelerated rate as depicted in Figure 1. Automotive Original Equipment Manufacturers (OEMs) are now planning to incorporate telematics, collision avoidance systems, vehicle stability controls, navigation, steer-by-wire, electronic braking, additional powertrain/body controllers, sensors and other electronic subsystems into the vehicle. Current electrical systems for mid- and large-sized vehicles currently have average electrical power loads of 0.8 to 1.5 kW and peak power loads of less than 2 kW. In five years, the average power load is projected to be 3 to 5 kW with peak power loads of over 7 kW. Future automobiles, therefore, must generate more energy and/or utilize enhance energy management scheme to support safety features and accessory electronics while reducing fuel consumption and emission.

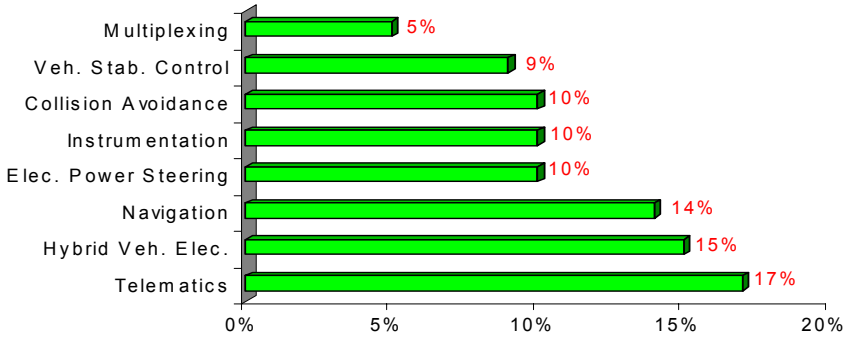

Figure 1. Estimated annual growth through 2005.

Unfortunately, today's vehicle can not meet tomorrow's needs. The internal combustion engine efficiency is, at most, 40% efficient and much of this net mechanical energy not only provides power to the wheels, but also supports peripheral systems such as pumps, condensers, generators and peripheral electronics. In order to increase vehicle efficiency and reduce energy

constraints, OEMs are looking into alternatives like 42-Volt power systems, fuel cells and hybridized vehicle architectures. Fuel cells, which are based on catalytic chemical reactions, show great potential as extremely efficient and 'clean' power generators when compared to the combustion engine. However, many technical issues, such as the incorporation of fuel reformers or lowering of operational temperature, are not fully developed for mass production. Given that the technology for mass production of hybrid vehicles is now relatively well developed, it appears evident that electric and hybrid vehicle architectures will likely provide the solution in the next 5 to 10 years. Honda and Toyota have production hybrid vehicles, the *Insight* and the *Prius*, which yield an average fuel economy of approximately 60 mpg in city drive cycles and 50 mpg on the highway. These vehicles also meet Ultra-Low Emission Vehicle standards (ULEV). Ford and General Motors are also working on their concept hybrid vehicles, the *Prodigy* and the *Precept*, and DaimlerChrysler has successfully introduced and demonstrated the *ESX3* hybrid concept vehicle. However, even in five years these hybrid vehicles may not meet the high fuel economy and low emission standards when electrical loads are increased to 3 ~ 5 kW.

An estimate of the 'real' fuel savings (taking into account the cooling pump effort required, and the added weight of the generator/alternator and pump systems) is summarized in Figure 2 below. This data is based upon the fact that power generation of 1 kW (1.3 hp) from a mechanically driven generator requires around 1.5 liters (0.4 gal.) of fuel per 100 km (62 mi.). As an example, when a 2 kW electrical load is applied to a 70-mpg vehicle, the average fuel economy will drop to approximately 36 mpg. Hence, reclamation of the wasted energy, approximately 60% of the consumed fuel, must be considered for next generation vehicles

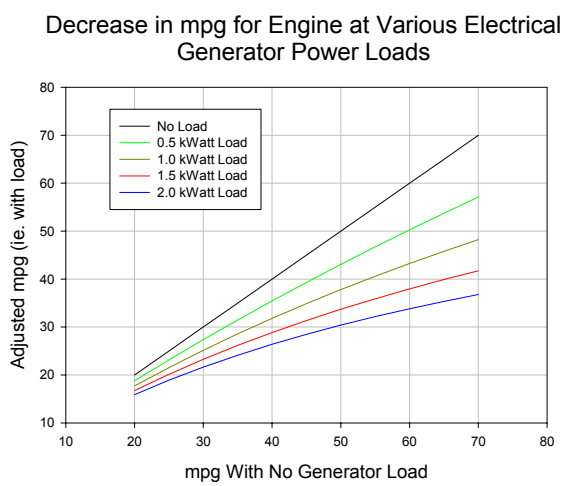

Figure 2. Adjusted fuel economy based on additional electrical load.

One way of accomplishing this energy recovery in commercial vehicles would be to incorporate thermoelectric devices into the exhaust system. In a typical vehicle, the exhaust gas contains one of the largest portions of wasted energy, approximately 34% of available energy from the fuel. When the thermoelectric generator is mounted between a heat source and a cooling channel, electrical power on the order of several watts to several kilowatts can be produced depending on the design and thermoelectric materials used in the system. To date, thermoelectric power generators have been primarily employed in space and military

applications. Overall efficiency of 5% has made these devices somewhat impractical and expensive for automotive mass-production application. Porsche, General Motors, Nissan, and others have previously investigated thermoelectric power generation, and have concluded similarly. Most systems were based upon bulk Bismuth Telluride (Bi_2Te_3), Lead Telluride (PbTe), and Bismuth Antimony (BiSb).

Current devices have improved only slightly over the years and the cost is about $ 4 to $ 5 per watt. Therefore, applications have been limited to radioisotope thermoelectric generation (RTG), communications and surveillance satellites, space probes such as the Voyager missions, and remote, unattended terrestrial control and monitoring stations. Also, Peltier cooling has been used for detectors such as photomultipliers and military infrared focal plane arrays.

Recent developments by JPL, Research Triangle Institute, and others, however, have changed the landscape, enabling new applications to be considered. But, use of thermoelectric devices in automobile application remains to be cost ineffective. For a viable production application, the system should generate at least 1 kW of net energy in a packaging volume similar to a catalytic converter, and the cost of the system should be less than $0.10 per watt. Continued research in development of efficient thermoelectric materials is very important if thermoelectric is to be applied in the automotive industry. Furthermore, manufacturing and application studies must be carried out in conjunction with material researches to identify and evaluate necessary concepts that will allow efficient and cost effective application of thermoelectrics in the automobile industry.

Application of thermoelectics is not limited to exhaust waste heat recovery. The thermoelectric devices have the potential to be applied in waste heat recovery from fuel cell vehicles, especially from high temperature fuel cell systems like Solid Oxide Fuel Cells, Molten Carbonate, and Phosphoric Acid. In addition, thermoelectrics could be directly integrated into the combustion engine for a power generation system, and heating, ventilation, and air conditioning (HVAC) could benefit by replacing the refrigerant cycle with thermoelectric, if efficiency improves dramatically. The current refrigerant R-134a, tetrafluoroethane, is a known green house gas. It has approximately 1000 times the global-warming potential of carbon dioxide.

An efficient thermoelectric device will make significant impact on the automobile industry. It will help reduce transportation sector's dependence on foreign oil, and allow efficient transition of transportation systems from petroleum to hydrogen base. Moreover, replacement of refrigerant used in air conditioning units would make automobiles much more environmentally friendly.