

Design of a Thermoelectric Generator for Waste Heat Recovery Application on a Drivable Heavy Duty Vehicle

Arash E. Risseh and Hans-Peter Nee
KTH, Royal Institute of Technology

Olof Erlandsson
TitanX

Klas Brinkfeldt
Swerea IVF

Arnaud Contet
TitanX Engine Cooling Holding AB

Fabian Frobenius Ing and Gerd Gaiser
Eberspacher GmbH & Co

Ali Saramat
Scania CV AB

Thomas Skare
TitanX

Simon Nee
KTH, Royal Institute of Technology

Jan Dellrud
Scania CV AB

ABSTRACT

The European Union's 2020 target aims to be producing 20 % of its energy from renewable sources by 2020, to achieve a 20 % reduction in greenhouse gas emissions and a 20 % improvement in energy efficiency compared to 1990 levels. To reach these goals, the energy consumption has to decrease which results in reduction of the emissions. The transport sector is the second largest energy consumer in the EU, responsible for 25 % of the emissions of greenhouse gases caused by the low efficiency (<40 %) of combustion engines. Much work has been done to improve that efficiency but there is still a large amount of fuel energy that converts to heat and escapes to the ambient atmosphere through the exhaust system. Taking advantage of thermoelectricity, the heat can be recovered, improving the fuel economy. A thermoelectric generator (TEG) consists of a number of thermoelectric elements, which advantageously can be built into modules, arranged thermally and electrically, in a way such that the highest possible thermal power can be converted into electrical power. In a unique waste heat recovery (WHR) project, five international companies and research institutes cooperated and equipped a fully drivable Scania prototype truck with two TEGs. The entire system, from the heat transfer in the exchangers to the electrical power system, was simulated, built and evaluated. The primary experimental results showed that approximately 1 kW electrical power could be generated from the heat energy. In this paper the entire system from design to experimental results is presented.

KEYWORDS: Thermoelectric generator, thermoelectricity, waste heat recovery, heavy duty vehicle, heat exchanger, power converter, internal combustion engine, power conditioning, vehicle exhaust, fuel economy

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INTRODUCTION

In a report published in 2014, the Emissions Database for Global Atmospheric Research (EDGAR) mentions that the European Union (EU) is responsible for 10.5 % of the total CO₂ emissions in the world [1]. Due to greenhouse issues and climate changes in the world, governments and different organizations have proposed new policies and rules to decrease the consumption of fossil fuels and thereby the emission of greenhouse gases. One example is the EU's 20-20-20 target which has the goal to produce 20 % renewable energy, to achieve a 20 % reduction in greenhouse gas emissions, and to improve energy efficiency by 20 % compared to 1990 levels [2]. Another example is the European Automobile Manufacturers Association (ACEA) that, with oil and fuel guidelines, is promoting to have environment friendly and sustainable transports [3]. To reach these goals and fulfill the rules and policies active steps must be taken.

After the energy sector, the transport sector is the second largest source of greenhouse gas emissions. This is the only sector in Europe where the emissions are still increasing with 25 % of the total emission. Road transport is a sub-sector of the transport sector and it is responsible for 20 % of the total CO₂ emissions in the whole EU [4]. The main reason of the large amount of CO₂ emissions from the transport sector is the use of inefficient internal combustion engines (ICE) in vehicles. As seen in Table 1, approximately one third up to a half of the fuel energy is converted into waste heat and escapes to the ambient through the exhaust system. If the waste heat is converted into useful energy, the overall efficiency of the vehicle will increase and the emission of greenhouse gases and the fuel economy improve.

Much work has been done to improve the efficiency of combustion engines internally by improving the mechanical and electrical components of the vehicles. As examples, the six-stroke engines, turbocharging, turbo-compounding, exhaust gas recirculation (EGR), and waste heat recovery (WHR), can be mentioned [5], [6], [7], [8], [9]. However, in average the efficiency of internal combustion engines may still be as low as 15 % [10]. Due to the large amount of waste heat energy the opportunity of WHR drives the scientific communities and companies around the world to improve the fuel economy by recovering heat. Today, the focus of research has been on two types of WHR systems; the organic rankine cycle (ORC) and the thermoelectric generator (TEG). In an ORC, a fluid extracts the heat from the exhaust gases and through a steam turbine, connected to the power shaft, partly unloads the ICE, improving the overall efficiency. F. Liming et al. report a maximum heat recovery of 20 % efficiency from an ORC [11] and M. Wei et al. report 16 % ORC-efficiency in a Heavy Duty Vehicle (HDV) [12]. The amount of recovered power is a function of engine load, pressure, temperature, and the type of working fluid. Simulation results on a 2006MY Cummins ISM 10.8 L diesel engine showed an output power between 1 and 9 kW from an ORC [13]. However, the ORC is a complex system which requires large volume and operates with a high-temperature and pressure steam, and includes moving parts. Furthermore, due to the relatively large time constant in an ORC, the demand of power in the system may be low when the amount of

recovered power is high. This issue causes a mismatch in the demand and generation of power which is challenging to handle. Another concern for the ORC is the number of components, which creates a relatively large mass. Therefore, the ORC is a less attractive option for automotive applications but may be more suitable for marine or stationary power generators where the demand of power is comparably constant over time, and space and weight are not as critical as in a vehicle.

Table 1. Fuel energy distribution in combustion engines in percent [14].

Engine Type	Shaft Power	Cooling	Exhaust	Other
Petrol	25-28 %	17-26 %	34-45 %	5-15 %
Diesel	34-38 %	16-35 %	22-35 %	3-8 %

By taking advantage of thermoelectricity, heat can be directly converted to electricity or vice versa where cooling or heating is needed. Thermoelectric conversion is based on the Seebeck effect, which causes electrical energy to be generated when a temperature gradient is applied to thermoelectric elements. Currently, the total output power of existing TEGs is lower than those of ORCs. However, a TEG has other advantages that should be considered. Unlike the ORC, a TEG has no need for maintenance or complicated control systems. It is a compact and non-moving energy conversion system with a stable and fast response. Thermoelectric generators have been used in military applications such as fighting vehicles, nuclear-powered TEGs, and in medical applications, e.g. in pacemakers. Due to their reliability and simplicity, TEGs have even been used in space to provide the satellite electronic components with power [15], [16]. For instance, TEGs have been utilized for power generation in NASAs deep space explorations for over 40 years [17]. The mentioned advantages make the TEG a good candidate for WHR in vehicles, improving the overall efficiency and fuel consumption.

In an analysis made by M. Srinivasan et al. TEGs have the potential to generate 2-3.5 kW in light and heavy duty vehicles [18]. In two different studies, J.C. Bass et al. reported about a 1 kW prototype TEG which was designed for an exhaust system in a Cummins NTC 350 diesel engine, using modules (HZ-13 and HZ-14) from Hi-Z technology INC. [19], [20]. It was found that the total output power from the TEG is heavily dependent on the total engine load and less on the engine speed, which is an important design factor. In another study S. Kumar et al. used software tools to simulate a complete TEG containing 50 modules [21]. The main focus in the study was to investigate the impact of various geometries of heat exchangers on the output power, in automotive WHR-systems. Furthermore, the effect of a hybrid configuration with different modules in the same TEG, based on the temperature drop, was investigated. It was found that a transverse heat exchanger in combination with a hybrid configuration gives the highest power which was approximately 800 W. In another successful study at Science University of Tokyo, a TEG was designed for an exhaust system in a Toyota ESTIMA with a 2000 cc gasoline engine. The obtained electrical power at 60 km/h was 141 W and after some system modifications, it increased to 266 W [22].

In a wide study Q.E. Hussain et al. [23] present the most important design parameters to consider in a TEG in hybrid vehicle applications. It was found that the time constant and the weight of the TEG as well as the backpressure have a significant impact on the generated TEG power and fuel economy. The suggested TEG system was designed for a 2.5 L gas-electric hybrid vehicle and was able to recover 300-400 W under an EPA-based highway driving cycle. According to another study made by Arsie et al. [24] the recovered TEG power in a personal car equipped with a 70 kW diesel engine could reach a peak power of 449 W and the mean power was estimated to 91 W which corresponds to a 1.5 g/km reduction of CO₂ emissions. The amount of fuel saving caused by the TEGs is due to the reduction in the mechanical load of the shaft and explained more in detail in [25].

Designing TEGs for automotive applications is a challenging task for several reasons. The most important issue is the large temperature variation of the exhaust gases which is highly dependent on the engine load. Handling of this temperature variation and optimizing the system is critical in order to increase the extraction of heat power from the exhaust gases. The main component influencing the power extraction is the heat exchanger (HX). With a suitable HX the highest amount of heat energy can be generated while the maximum temperature on the thermoelectric modules (TEM) does not exceed the thermal limits.

In this paper, the complete design of a TEG system for HDVs is addressed. To the best knowledge of the authors, this is the first time the losses due to the backpressure, the impact of the charge air cooler (CAC) temperature, and the efficiency of the power converter are considered when evaluating the total system efficiency. Never before, a complete TEG including all auxiliaries and actuators has been designed, integrated and evaluated on a real and drivable HDV. During this project, two TEGs and the related components for WHR on a real class 8 truck (440 kW) from Scania were designed, built, installed, and tested. The TEGs were placed downstream of the after treatment system (ATS) and upstream EGR, and were communicating with the main electronic control unit (ECU) of the truck. In order to evaluate such a system, it is important to consider the average TEG-power and the losses when figures of merits such as *Watt per weight* and *price per Watt* are estimated. The main targets in this study was to high-light the potential of TEGs in commercial vehicles as well as present, not only the recovered gross power but also the TEG's net- and average power affecting the actual fuel reduction. In the first part, a summary of the physics of thermoelectricity and some important parameters of the thermoelectric material are given. Later, an overview of the design procedure of the TEGs and the related parameters are given. In the last section the experimental results from the complete system in a real environment created in a dyno-cell, are presented.

THERMOELECTRICITY

When two different conductive materials are connected and exposed to a temperature gradient, charge carriers within the conductors will move in the same direction as the thermal energy. The movement of charge carriers, due to the temperature gradient, creates an

electromotive force (emf), which is a function of the temperature gradient and the material properties. This phenomenon is known as the Seebeck effect [26], see Figure 1.

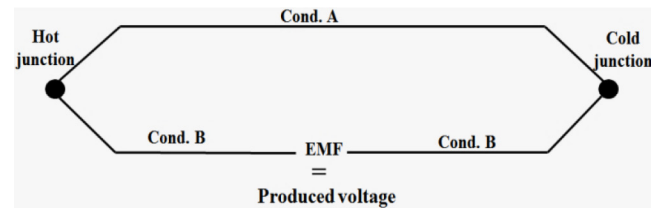


Figure 1. The Seebeck effect on two dissimilar conductors with applied temperature gradient at the junctions creates an emf.

The produced voltage in a thermoelectric circuit is given by

$$V = \int_{T_1}^{T_2} (\alpha_A - \alpha_B) dT, \quad (1)$$

which can be written as

$$V = (\alpha_A - \alpha_B)(T_1 - T_2) = \alpha_{AB} \Delta T, \quad (2)$$

where the V is the produced open voltage, T is the temperature at the junctions, α_A and α_B are the absolute Seebeck coefficient of each conductor, and α_{AB} is the *Relative Seebeck Coefficient* [26]. The most of metals have a Seebeck coefficient of 10 $\mu\text{V/K}$ which makes a TEM inefficient and uneconomical. In the middle of the 20th century during the period of the semiconductors invention, thermoelements based on semiconductors with Seebeck coefficients of higher than that of 100 $\mu\text{V/K}$ were developed. Today's TEMs usually consists of pairs of heavily doped n- and p-type legs that are connected electrically in series to generate a reasonable voltage and thermally in parallel, see Figure 2. The temperature difference causes accumulation of electrons and holes on one side of the conducting legs resulting in a built-in electric field [27].

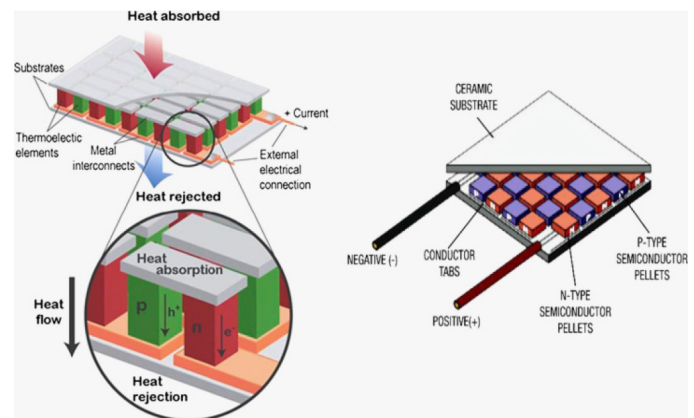


Figure 2. A typical TEM is made by a large number of n- and p-type semiconductors legs sandwiched between two ceramic plates. The figure is used with permission from the authors [28].

Additional thermoelectric effects that can be mentioned are the Peltier and the Thomson effects. The Peltier effect is a thermoelectric phenomenon where an electric current applied to two dissimilar

conductors actively pump the heat from one junction to another. The Thomson effect refers to reversible heating or cooling in a homogeneous single conductor when it is exposed to a temperature gradient and electrical current simultaneously. This effect causes temperature changes on the conductor.

The energy balance in a thermoelectric pair in power generation mode according to Figure 3, can be described by

$$Q_{IN} = \alpha T_H I - \frac{1}{2} R I^2 + \kappa (T_H - T_C), \quad (3)$$

$$Q_{OUT} = \alpha T_C I + \frac{1}{2} R I^2 + \kappa (T_H - T_C), \quad (4)$$

$$P_E = Q_{IN} - Q_{OUT} = \alpha I (T_H - T_C) - R I^2, \quad (5)$$

Where Q_{IN} and Q_{OUT} are the input and output thermal power, R is the electrical resistivity, I indicates the current in the circuit, P_E is the electrical power, and κ is the thermal conductivity of the material [29].

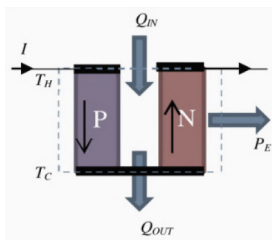


Figure 3. Energy balance in thermoelectric elements shows the input and output heat power as well as the electrical current and power.

From eq. (4) and (5) it is clear that an optimal TE material exhibits a high Seebeck coefficient α , high electrical conductivity $\sigma (=1/R)$ and low thermal conductivity κ , which is characterized by the figure-of-merit ZT [26],

$$ZT = \frac{\alpha^2 \sigma}{\kappa} \cdot T, \quad (6)$$

where T is the mean operating temperature of the module. In addition, ZT is related to the maximum working efficiency, by

$$\eta = \left(\frac{T_h - T_c}{T_h} \right) \cdot \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_c}{T_h}}, \quad (7)$$

where T_h and T_c are the hot side and cold side temperatures of the module. Nonetheless, the challenge of optimizing ZT arises from the dependence of α , σ and κ on one another through physical properties of materials, such as Fermi level, effective mass, carrier concentration, lattice thermal conductivity (κ_l), and thermal conductivity caused by electrical current (κ_e). As illustrated in Figure 4, maximizing ZT involves a compromise between large α and σ

(shown as $\alpha^2 \sigma$) with low κ . This behavior is observed at concentrations between 10^{19} and 10^{20} carriers per cm^3 , which corresponds to metals and heavily doped semiconductors.

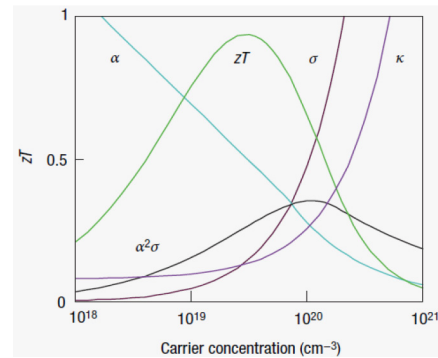


Figure 4. Optimizing ZT through carrier concentration tuning. As seen, thermal and electrical conductivities increase with carrier concentration while Seebeck coefficient decreases. The figure is used with permission from the authors [28].

Bi-Te Alloys

A thermoelectric material exhibits maximum ZT at a certain temperature, which can be optimized to peak at different temperatures by adjusting the carrier concentration through doping [28]. This means that different TE materials are suitable for various operating temperature ranges. Bi_2Te_3 alloys with Sb, Se ($\text{Bi}_{2-x}\text{Sb}_x\text{Te}_{3-y}\text{Se}_y$) have been the primary TE material since the 1950s and are today the most efficient material for low-temperature applications ($<200^\circ\text{C}$) [30], [31]. For moderate temperature ($400\text{--}700^\circ\text{C}$), half-Heuslers skutterudites, and lead chalcogenides are mainly utilized [32], [33], [34]. For high-temperature operation ($>700^\circ\text{C}$) silicon-germanium alloys are the most suitable alloy [35], [36].

Bi_2Te_3 alloys are obtained through a slight change of its stoichiometric composition, n-type or p-type Bi_2Te_3 . This can be achieved by applying various methods such as doping composition optimization [37], [38], [39], or device engineering [40]. The modules investigated in this study were made of “hot-pressed” Bi-Te based semiconductors, Figure 5.

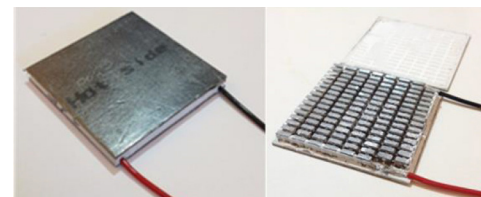


Figure 5. Thermoelectric module, produced by Thermoamic Electronics used in the prototype Scania truck.

Design of the Thermoelectric Generators

Generally, a TEG system makes use of two HXs for the hot and cold sides respectively, and the TEMs are electrically and thermally connected such that the highest possible power is generated.

Furthermore, an electrical power management and control system of hot- and cold media have to be employed to ensure the correct operation of the TEG. This is a multi-disciplinary research project

where mechanical, electrical, and thermodynamic sub-systems have to, individually and collectively, work in an optimal way. For that reason the design of a TEG for vehicles is a complicated process, because all components in the system are interdependent, and the final result relies on interaction between different parts. For example, various modules are optimized for different temperatures while the hot and cold side temperature on the other hand are dependent on the design of the HXs which in turn gives rise to a design-dependent amount of losses and, therefore affects the recovered net power. Due to the large variation in exhaust gas temperatures, the greatest challenge becomes designing a system optimized for a wide range of temperatures and power. The only realistic way to overcome these design problems is optimizing the system iteratively. The main parts were studied first and added together into a model of a complete TEG system to be simulated later on. The results of the simulations were used to change and improve the properties and boundary conditions. With the new parameters a more optimized TEG model was built and simulated again. Figure 6 shows the workflow diagram of the design process which was repeated a few times to satisfy the basic requirements. Furthermore, a TEG for WHR in a drivable vehicle has to fulfill other important criteria and standards which are dictated by the automotive industry. For instance, it is important that the TEG is designed in a way that its disturbance on the main and existing systems on-board is minimal. Extremely small, long channels or aggressive surface enhancement in HXs results in very high pressure drop in the exhaust system. Placing the TEG upstream ATS causes high temperature drop and obstructs the ATS function and needs to be avoided. Limited volume, the allowed weight, the reliability, and the cost of the TEG are the other restrictions when it comes to the design and manufacturing process. Furthermore, the design of the TEG should be performed such that the highest possible power can be extracted and stored. The type of TEMs, the design of the HXs, the attachment of the TEMs, the thermal end electrical arrangement of the TEMs, and the power converter and the related control system have a significant impact on the final power extraction of the system.

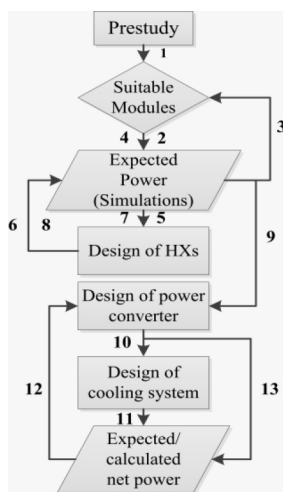


Figure 6. The iterative workflow-diagram to design and optimize the TEG system.

Heat Sources and Placement

There are four heat sources that may be used for TEGs in a diesel vehicle; Exhaust gas, Exhaust gas recycling, Charge air, and Engine coolant. However, there are several aspects to consider when

choosing heat source and positioning of the TEG. By placing the TEG close to the hot media streams, unnecessary tubing can be avoided and thereby the pressure and heat losses to the ambient can be minimized. On the other hand, to capture a large part of the heat power from the exhaust system a relatively large TEG should be designed and consequently it cannot be placed anywhere in the vehicle due to space constraints. Also, a larger TEG is heavier and the weight issues have to be considered.

For the key function of transforming a temperature difference between two fluid streams into electrical power it is beneficial if the streams have high mass flows, with high temperature for the hot side and low temperature for the cold side. Fluids with high specific heat capacity are desirable since the temperature will not change rapidly when the heat is transferred. This means that cold sinks will still keep cold and hot sources still keep hot, despite the heat transfer. Furthermore, the fluids should have a high thermal conductivity, which enables that heat is easily pulled, or released, to and from the media. There are four significant fluid streams that are possible to use as heat sources in a modern heavy vehicle:

Exhaust Gas

This source has the highest mass flow on the vehicle, but the temperature varies significantly with engine load. There are a number of possible locations. However, due to other prioritized emission control systems such as particulate filters and catalysts, the only suitable location is downstream the ATS. Here, temperature can still be quite high (200-400 °C), and the engine-out temperatures swings are damped due to the high mass of the ATS system which is an advantageous property. The pressure level is closer to ambient and the temperature levels and flows make this source the first choice. A disadvantage is that any additional backpressure in the form of a TEG on the exhaust side means that the engine has to pump the gas through it, which increases the engine load and causes losses.

Exhaust Gas Recycling (EGR)

Exhaust gas recirculation is used to limit NOx and particulate emissions. Typically, the exhaust gas is extracted upstream of the turbine at significantly elevated pressures (1-3 bars abs at operation, 5-6 bars abs during exhaust braking). The temperatures are higher than in the ATS (300-600 °C) but the mass flow is low and varies with both engine speed and load. The mass flow is controlled by the engine ECU with an EGR-valve. The ratio of EGR gas to combustion air gas is in the 0-30 % range, i.e. the mass flow is less than 30 % of the air flow in to the combustion. However, the temperatures are close to the highest achievable outside of the cylinders. One important aspect is that the mass flow of the EGR is very dependent on the overall emission control strategy of the engine. Engines can be EGR intensive, have low EGR-rate or even exclude the EGR. The temperature level makes this source the second choice. Placing a TEG in the EGR stream can bring additional benefit; the EGR gases have to be cooled down to 85-95 °C, i.e. additional cooling may be required. With an EGR-TEG, the original EGR cooler can be reduced in size since the TEG does some of this work and hence part of the allowed pressure loss can be transferred to the TEG. To drive the EGR mass flow the engine operates with a negative pressure drop, i.e.

the inlet pressure is lower than the exhaust manifold pressure. This means that the engine operates as a pump, and the higher the pressure loss over the EGR line, the higher the pumping loss becomes in order to achieve the same EGR mass flow. Therefore, a requirement is that the pressure drop over the TEG has to be as low as possible.

Charge Air - Air Downstream the Compressor Stage

charge air temperatures are limited (max 200-300 °C) and highly engine-load dependent. The temperature variation has a very fast response to engine load since there is very little thermal inertia in the compressor, and the tubing downstream the compressor is usually limited. The mass flow is quite high compared to others on the vehicle and follows engine speed and load. The pressure varies between 1-3 bars abs. The operation medium is air which is poor in terms of heat transfer and requires a lot of surface enhancement to support the heat transfer. Compared to the exhaust the potential is lower simply due to the lower temperatures. Placing a TEG in the charge air has similar benefits as in the EGR stream because the charge air still needs to be cooled down to close to ambient. The pressure drop over the TEG in charge air should also be as low as possible. The engine requires a certain amount of air flow and hence inlet pressure. Any pressure drop results either in lower inlet pressure of the engine, which leads to lower performance, and/or that the engine must run at a higher exhaust backpressure, i.e. the pump work increases.

Engine Coolant

The operating temperature of the engine coolant is in the range of 95-100 °C, and the pressures are 1-2 bars abs. The media are typically water-glycol mixtures with very good heat transfer characteristics. However, the temperature level is too low to be interesting for this type of waste heat recovery, at least at the time of writing.

This study focuses on the first two options i.e. using the heat from the exhaust (ATS) and EGR streams. Due to the reasons mentioned earlier in this section, the TEGs have to be placed downstream of the ATS and upstream of the EGR. For the cold streams, the only possible source is the ambient air that the truck moves through, or that the engine cooling fan or an additional one is pulling into the cooling module. Due to the nature of air, large surface areas are required to transfer the heat. Also combining heat exchanger surfaces for gaseous media, for both the heat source and cold sink, would create a very large design due to the large heat transfer surfaces on both sides. Instead, an indirect cooling system of the TEG is appropriated with a heat transfer medium (coolant) on the cold side and the gaseous heat source on the hot side. This way, the cold side heat transfer area can be reduced. In addition, the indirect system makes it possible to have a significant distance between the heat source and heat sink. The coolant can be pumped at low cost and typical engine coolants are good energy carriers due to their high density and specific heat capacity.

The data needed to design the TEGs was provided by Scania and contains the engine speed, the gas mass flow, and temperatures in EGR and ATS. All calculations and experimental results were based

on the data with 9-steady-state-points that together, create the Long Haulage Cycle (LHC) which emulates real driving conditions for a long haulage, see [Table 2](#).

Table 2. The 9-steady-state-points (LHC) showing the load of the ICE and conditions in exhaust system. The data is provided by Scania.

LHC	Engine Speed (RPM)	Relative load (%)	Exhaust mass flow [kg/h]	Exhaust temp [°C]	EGR mass flow [kg/h]	EGR temp [°C]
1	1000	25	420	248	127	318
2	1000	50	556	347	143	452
3	1000	100	1017	386	167	551
4	1150	25	423	259	197	335
5	1150	75	949	352	194	489
6	1300	25	532	251	215	325
7	1300	50	803	313	247	425
8	1300	75	1079	346	276	481
9	1300	100	1393	396	213	560

Modules

The thermoelectric module is the main component in a TEG. There are a number of suppliers that manufacture TEMs with different properties. As mentioned before, the performance of a TEM is determined by the figure of merit, ZT , and also is dependent on the applied temperatures. Hence, based on TEM supplier's data, parametric sweeps were made early to find an overall design guide and to identify the most suitable TEM. Off-the-shelf TEMs were a project requirement, and therefore only modules where TEMs and supplier data was accessible were considered. Studying the manufacturer's data, there is one key trade-off between heat transfer and electrical power. Combining these properties, it is possible to find a conversion efficiency which is the produced power over heat transfer in to the TEM. Three modules were considered and simulations based on rough data from manufacturers were performed. The modules were used the same thermoelectric material but had different area and height. The results showed that two of the three simulated modules had an efficiency of 3 % at 300 °C while the efficiency of the third module reached only 2.5 % at the same temperatures. It should be noticed that the first simulations were established with constant hot and cold side temperatures which implies an infinite heat source and an infinite heat sink. However, this is not the case in a real TEG where the gas is cooled down and the coolant is heated along the flow. This issue results in a temperature reduction along the flow, especially on the gas side, and hence the conversion efficiency of the module drops. This shifts the advantage to modules with proportionally less heat transfer, despite having lower conversion efficiency. In order to identify the most suitable TEM, all possible TEMs have to be evaluated in a conceptual TEG design with realistic operating conditions and constraints according to [Figure 7](#).

When a clear picture of the basic operation of a TEM was obtained, a more detailed study on a test bench was performed. A number of possible TEMs were chosen and exposed to temperature gradients based on available heat power and resembling to the 9-point LHC as given in [Table 2](#). The basic performances and the size of the selected