Publication metadata

Title: Potential of Fuel Consumption Saving of Brayton Waste Heat Recovery Systems on Series Hybrid Electric Vehicles

Author(s): Wissam Bou Nader, Charbel Mansour, Clément Dumand and Maroun Nemer

Conference title: Proceedings of the 31st International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2018)

Handle: http://hdl.handle.net/10725/12258

How to cite this post-print from LAUR:

Bou Nader, W., Mansour, C., Dumand, C., & Nemer, M. (2018). Potential of fuel consumption saving of Brayton waste heat recovery systems on series hybrid electric vehicles. In Proceeding of the 31st International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, http://hdl.handle.net/10725/12258

Potential of Fuel Consumption Saving of Brayton Waste Heat Recovery Systems on Series Hybrid Electric Vehicles

Wissam Bou Nader[a,c], Charbel Mansour[b], Clément Dumand[c] and Maroun Nemer[d]

[a] Ecole des Mines de Paris, Centre Efficacité Energétique des Systèmes CES, Palaiseau, France,
wissam.bou_nader@mines-paristech.fr
[b] Lebanese American University, Industrial and Mechanical Engineering department, New York, United-States, charbel.mansour@lau.edu.lb
[c] Groupe PSA, Centre technique de Vélizy, Vélizy, France,
wissam.bounader@mpsa.com, clement.dumand@mpsa.com
[d] Ecole des Mines de Paris, Centre Efficacité Energétique des Systèmes CES, Palaiseau, France,
maroun.nemer@mines-paristech.fr

Abstract:

In the global attempt to increase the powertrain overall efficiency of hybrid vehicles while reducing the battery size, engine waste heat recovery (WHR) systems are nowadays promising technologies. This is in particular interesting for series hybrid electric vehicles (SHEV), as the engine operates at a relative high load and under steady conditions. Therefore, the resulting high exhaust gas temperature presents the advantage of increased WHR efficiency. Brayton cycle offers a relative reduced weight compared to other WHR systems and present low complexity for integration in vehicles since it relies on open system architecture with air as working fluid, which consequently avoid the need for a condenser compared to Rankine systems. This paper investigates the potential of fuel consumption savings of a SHEV using Brayton cycle as WHR system from the internal combustion engine (ICE) exhaust gas. An exergy analysis is conducted on simple Brayton cycle and several Brayton waste heat recovery (BWHR) systems were identified. A SHEV with the ICE-BWHR systems are modelled, where the engine waste heat recovered is converted into electricity using an electric generator, and stored in the vehicle battery. Energy consumption simulations are performed on the worldwide-harmonized light vehicles test cycle (WLTC), considering the additional weight of the BWHR systems. The intercooled Brayton cycle (IBC) architecture is identified as the most promising for automotive application as it offers the most convenient compromise between high efficiency and low integration complexity. Results show 5.5% and 7.0% improved fuel economy on plug-in and self-sustaining SHEV configurations respectively, as compared to similar vehicle configurations with ICE auxiliary power unit. In addition to the fuel economy improvements, IBC-WHR system offers other intrinsic advantages such as low noise, low vibration, high durability which makes it a potential heat recovery system for integration in SHEV.

Keywords:

Waste heat recovery, thermodynamic machines, Brayton cycle, exergy analysis, series hybrid electric vehicles, global optimization.

1. Introduction

Engine waste heat recovery (WHR) systems are promising way to increase power train effiency and to reduce vehicle fuel consumption in order to comply with GHG and pollutant emissions regulations. Many WHR machines have been explored as WHR systems for automotive applications by automotive constructers and OEM's [1-12]. Some of these WHR systems are compatible with low temperature waste heat sources, such as engine coolant. Others are more appropriate for medium and high temperature waste heat sources such engine exhaust gases [13].

The Brayton waste heat recovery (BWHR) system, a high temperature WHR suited technology [14], is the main focus of this study. It is based on a turbomachinery system operating according to a modified open loop Brayton thermodynamic cycle, where the air working fluid is heated in a heat exchanger as illustrated in Figures 1. The thermal heat source considered in this study, the engine exhaust gases, is partially recovered downstream the catalytic converter through a heat exchanger (HEX) that heat the Brayton air working fluid. The choice of exhaust gases as hot source, offers high potential of recovered work, since exhaust gases are at high temperature when comparing to other engine wasted thermal sources. The turbine provides the mechanical work required to drive the air compressor and a generator to produce electricity.

This technology, based on gas turbine system components, offers many automotive advantages compared to the other WHR systems, namely a reduced number of moving parts, vibration-free operation and high durability [15]. The high-speed turbomachinery, coupled to the electric generator, offers reduced weight, and is congruent with today vehicle power train components electrification strategy. Adding to that, BWHR machines present low integration complexity because using of ambient air as working fluid instead of water, ethanol or organic Rankine fluid (ORF) in Rankine systems, or helium, hydrogen and other gases in Stirling and thermoacoustic machines.

However, BWHR system presents low system efficiency in automotive applications preventing their use as WHR systems in conventional vehicles. This main drawback is caused by:

- Low turbine inlet temperature (TIT) due to low exhaust gas temperature during significant portion of engine operation.
- Low net power because of compressor high mechanical work consumption.
- Low amount of thermal power recovered from exhaust gases, because of high Brayton compressor outlet temperature.

Moreover, the HEX adds a thermal inertia on the upstream of the turbine, which further worsens the heat recovery during transitory operations, and makes the Brayton system non-compatible for fast response power delivery to follow the variable load applied in conventional powertrains.

Nonetheless, a review of recent research and development programs revealed interests in simple and stationary WHR systems for automotive application, where the machine operates steadily at constant speed and drives an electric generator [16]. For instance, Erias et al [17], shows by studying a spark ignition engine that the constant load conditions in the hybrid vehicle are a potential advantage for the implementation of a heat recovery system. A study at Chalmers university [18] confirms that WHR systems are more favorable in highway driving style where the vehicle runs at constant speed and for a longer time.

Therefore, based on the aforementioned findings, BWHR systems present a forthcoming potential for improving fuel economy and emissions of passenger vehicles, with the benefit of reliable low complex open loop systems; particularly, in series hybrid electric vehicles (SHEV). SHEV combines a thermal and an electric powertrain in a series energy-flow arrangement [19]. The thermal powertrain is constituted of an ICE-BWHR-system and an electric generator, and is referred to as the Auxiliary Power Unit (APU). It is mainly used to recharge the battery once depleted. The electric powertrain provides the necessary traction power to overcome the driving load, and serves to recover the braking energy. It is important to note that the APU operating speed is cinematically decoupled from the vehicle velocity; therefore, the APU operation is controlled to meet its best efficiency, mainly when highly loaded, which enable high exhaust gas temperature beneficial for BWHR. Figure 1 below illustrates the powertrain configuration of the modeled SHEV and an ICE with simple BWHR system.

On another hand, several BWHR-system options could be considered for integration in SHEV, combining a simple Brayton, to intercooled Brayton and water injection Brayton systems. The survey of published studies in the academic literature treating BWHR-system configurations and performance analysis, confirms that most BWHR-systems are designed based on efficiency and or power density optimizations [20-23]. Likewise, there are no recent studies on the most BWHR-system configuration suitable for automotive applications, due to the lack of competitiveness of simple BWHR compared to other WHR systems in conventional powertrains.

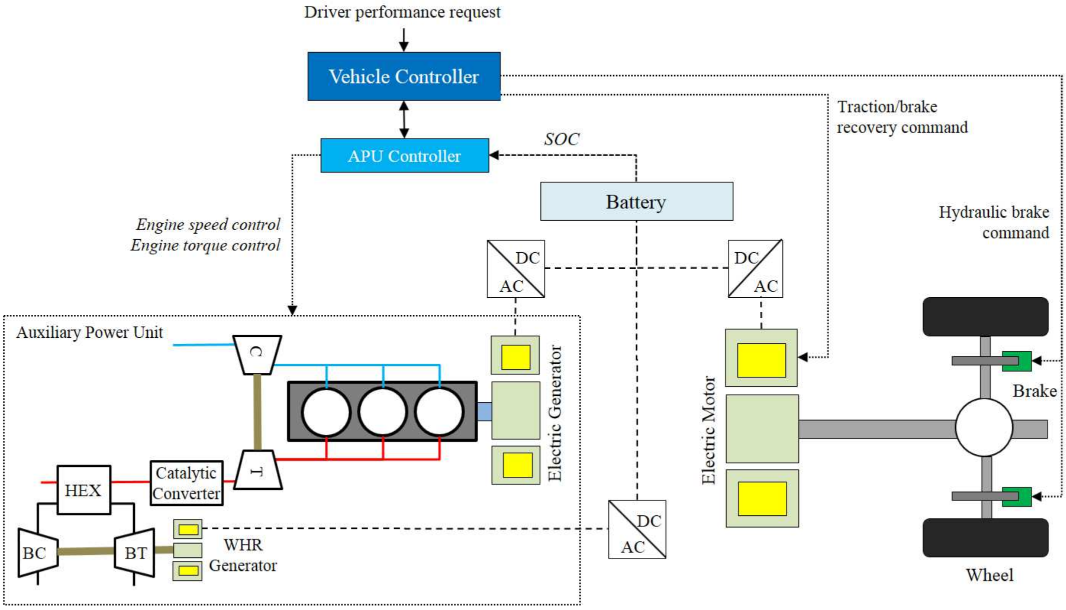


Fig. 1. Configuration of a simple open loop Brayton WHR system on ICE-SHEV powertrain

Hence, the following main gaps and limitations in the recent literature are underlined:

- There are no studies assessing different BWHR-systems performance based on a Brayton thermodynamic cycle for automotive applications on SHEV.
- No specific methodology on selecting the best-suited BWHR-system for any type of application is adopted. The studies in the literature focus on the performance investigations without taking into consideration any configuration optimization requirements or technological constraints.

Therefore, based on the above synthesis of the insights and gaps in the literature for adopting BWHR systems in automotive applications, this study proposes a comprehensive methodology to identify the potential BWHR-system options and select the optimal system configuration for SHEV application. A methodology for the identification and assessment of the different BWHR-system options applicable to SHEV is carried out in section 2, based on exergy analysis and automotive technological constraints. Observed results are then used for the selection of the BWHR-system configurations. Thereafter, the weight of the identified BWHR-systems in accounted and the systems are integrated in an SHEV model. A comparison between SHEV models with different ICE-BWHR APU technologies is presented: (1) a simple Brayton cycle, (2) an intercooled Brayton cycle, (3) a high pressure intercooled Brayton cycle, (4) a water injection simple Brayton cycle, (5) a water injection intercooled Brayton cycle and (6) a water injection high pressure Brayton cycle. Energy consumption simulations of these powertrains are compared on the WLTC, and the Dynamic Programing (DP) is adopted as Energy Management Strategy (EMS) in order to provide the global optimal strategy to power ON and OFF the APU and control the engine operation on the powertrain maximal efficiency.

2. Methodology

This section presents the methodology adopted to select the potential BWHR systems on SHEV powertrain. This methodology consists of three steps assessment plan.

In the first assessment step, a thermal balance is performed on a gasoline ICE. This thermal balance consists of an energetic analysis in which engine net mechanical work and thermal heat losses maps are identified. Then, exergy calculations are performed on engine thermal heat losses in order to identify the exergy or potential work which can be recovered from each thermal source. The result highlights the choice of the waste heat sources for the rest of the study.

In the second assessment step, the basic configuration of BWHR, the simple open loop Brayton cycle (SBC) is selected. Exergetic analysis are carried out to identify the exergetic losses and to adapt explicitly the basic WHR system. Based on the resulting exergy destructions in the system, modifications of the basic Brayton system are proposed, by considering several measures such as intercooled compression and water injection downstream compressors in order to reduce exergy losses. Accordingly, the list of potential Brayton WHR configurations is identified. Then, thermodynamic calculations are then carried out on all identified configurations. Components technological constraints and automotive design constraints are considered. The optimal overall system efficiencies are computed function on system variable parameters and on each engine operating point. The net electric power recovered is then calculated.

Finally, in the third assessment step, a SHEV model is developed, and components are sized according to vehicle specification. Two vehicle configurations, a self-sustaining SHEV and a plug-in SHEV are considered. Battery capacity and the additional weight of each BWHR-system are considered. DP is used as energy management strategy and fuel consumption simulation are performed on WLTC.

2.1 ICE analysis

This section presents the energetic and exergetic analysis of the ICE selected for the rest of the study. From the thermal balance analysis, the chemical energy contained in the fuel is distributed mainly in three parts: net mechanical power recovered on the engine crankshaft, thermal losses to engine coolant and thermal losses in the exhaust gases [24]. Note that the data presented below, are retrieved from a 1.2 liters gasoline turbocharged internal combustion engine (ICE) where the maximum thermal efficiency of 36% is reached in the map zone near 2500 RPM and around 65% of load.

2.1.1 Energy analysis of the ICE

The ICE thermal powers rejected from the engine coolant and exhaust gases are presented in figure 2 (a) and (b) below. Note from the figures that thermal heat losses from both sources are comparable at low and medium engine power operation. However, exhaust gases thermal power are higher at high power operating points, which correspond to high rotation speed and high load [25].

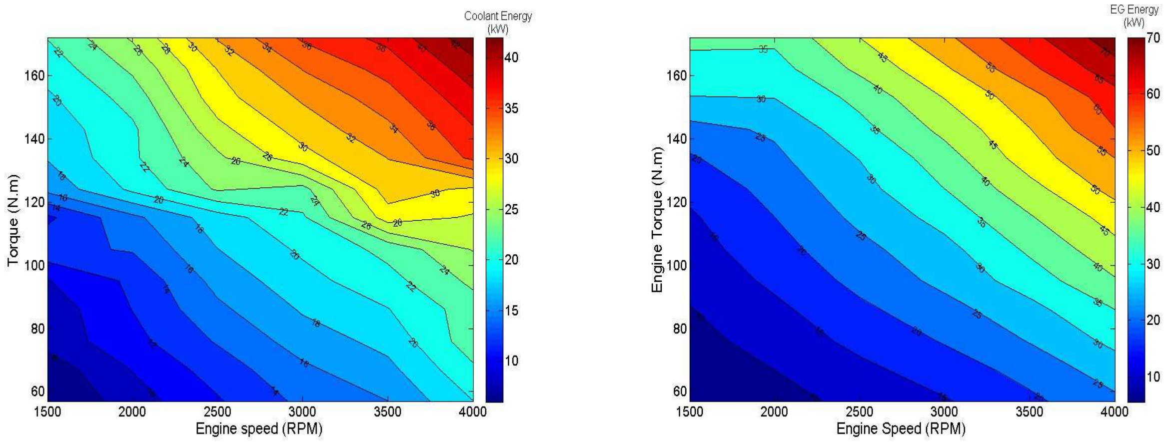
2.1.2 Exergy analysis of the ICE waste heat

Exergetic analysis is carried out on thermal heat sources as expressed in equation (1) in order to trace the potential work losses from the engine coolant and the exhaust gases. Energy and exergy model equations are available in thermodynamic fundamentals books such as [26-27].

$$E = \int \left(1 - \frac{T0}{Tmax}\right) . Q \tag{1}$$

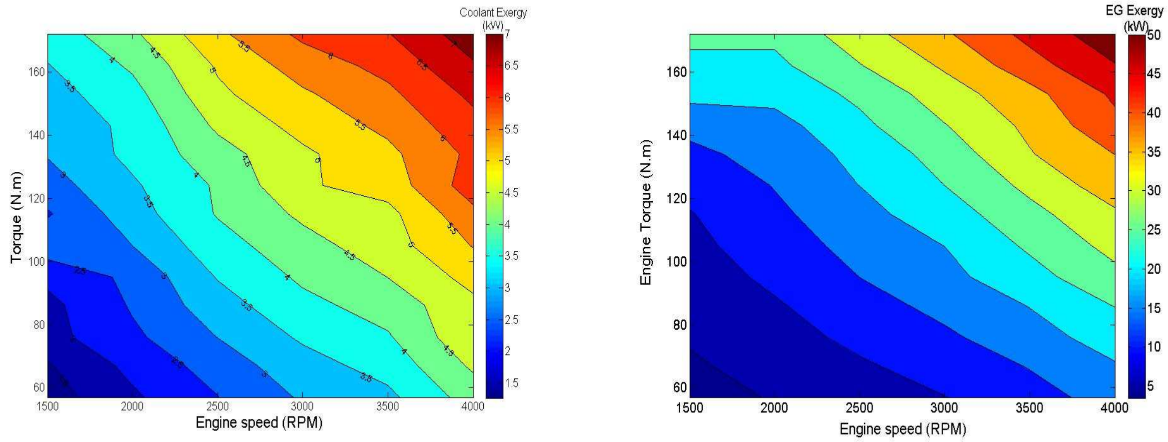
With E : Exergy recovered (kW)
Q : Energy available (kW)
$T0$: Reference temperature (K) supposed to be 293K
$Tmax$: Max hot source temperature

Exergy power recovered from the coolant circuit and form the exhaust gases are presented in the figures 3(a) and 3(b) below. While energetic analysis show comparable amount of heat lost in these sources, exergetic analysis informs us better on the potential of mechanical work that can be recovered. For example, in reference to figures 2(a) and 2(b), when engine operates at 2500 RPM, 120 N.m, a comparable thermal heat power is available in the coolant and the exhaust gases (20 to 26 kW respectively). However, around 4kW of maximum mechanical power can be recovered from thermodynamic machine operating with engine coolant as hot source temperature, compared to 18kW with the same machine operating with exhaust gases as hot source. Also, at maximum operating power, 7kW of exergy are available in the coolant circuit where around 50kW are available in the exhaust gases. As result, the exhaust gases with higher temperature have higher potential of work and therefore, from thermodynamic point of view, a waste heat recovery machine will perform better when engine exhaust gases is the hot thermal source. Also, the Brayton machines are more suitable for high temperature sources, the exhaust gases are selected as hot source in the following work.



(a) (b)

Fig.2. Thermal power rejected in the a) coolant circuit b) exhaust gases



(a) (b)

Fig.3. Exergy lost in the a) coolant circuit b) exhaust gases

2.2 Brayton Waste Heat Recovery

This section presents the modelling of the simple BWHR system recovering heat from engine exhaust gases. In the first section of this paragraph, thermodynamic equations are applied to account for efficiencies and exergy losses in the system. Based on the resulting exergy destructions in the system, modifications of the basic simple BWHR cycle are presented, by considering several measures such as intercooling compression, water injection, multi-stage compressions among others, in order to reduce exergy losses. Accordingly, the list of potential BWHR-system configurations is identified.

The energy and exergy calculations are then carried out in the second assessment step on all identified configurations. Components technological constraints and automotive design constraints are considered, and the net electrical power recovered from each configuration is then accounted.

2.2.1 Energy and exergy analysis of the Brayton WHR

The Brayton system is an external heat addition thermodynamic cycle and presents two loops: (1) exhaust gas loop which consists of the engine exhaust line and a HEX and (2) Brayton machine loop, which consists of a compressor, a turbine and the HEX. Both loops exchange heat in the common HEX. It is important to note that air is considered as the working fluid in both loops for simplification.

Energy analysis is carried out on the simple Brayton cycle (SBC) in order to account for the system overall efficiency as expressed in equation (2) [26-27].

$$\eta_{Brayton} = \frac{W_{turbine} - W_{compressor}}{Q_{max}} = \frac{W_{net}}{Q_{HEX}} * \frac{Q_{HEX}}{Q_{max}} = \eta_{cycle} * \eta_{Heat\ extraction} \tag{2}$$

With $W_{turbine}$: Turbine work (kJ/kg)
$W_{compressor}$: Compressor work (kJ/kg)
Q_{max} : Heat available in the exhaust gases (kW)
Q_{HEX} : Heat recovered from the exhaust gases in the HEX (kW)
η_{cycle} : Thermal thermodynamic cycle efficiency
$\eta_{Heat\ extraction}$: Heat extraction efficiency

Then, exergy analysis is carried out as expressed in equation (3) in order to trace the work losses in the system, to better inform on the possible options to reduce the inefficiencies [26-28].

$$E_{in} = [W_{CV}]_{in}^{out} + \left(E_{out}^{Q} - E_{in}^{Q}\right) + E_d + E_{out} \tag{3}$$

With E_{in} : Exergy of the entering flow
E_{out} : Exergy of the leaving flow
$[W_{CV}]_{in}^{out}$: Net Work output
E_{out}^{Q} : Exergy of the heat rejected
E_{in}^{Q} : Exergy of the heat added
E_d : Exergy destruction in the system

Exergy destruction results of the investigated simple BWHR-system are illustrated in figure 4. The figure points out the three highest shares of exergy losses, occurring in the hot air released from the Brayton turbine outlet (61%), in the exhaust gas at the outlet of the HEX (17%) and in the HEX (9%).

Exergy destruction in the air released from the turbine outlet can be decreased in two ways: (1) recovering heat through a bottom cycle, and (2) increasing the cycle pressure which induces higher expansion and therefore lower outlet temperature. The first option relies on the adoption of a bottoming WHR cycles, and presents higher complexity since another thermodynamic machine is required. This option has been disregarded in this study targeting automotive applications, where the complexity and the weight added are primordial aspects. As for the second option, high maximum cycle pressure requiring multi compression and expansion stages machine is investigated.

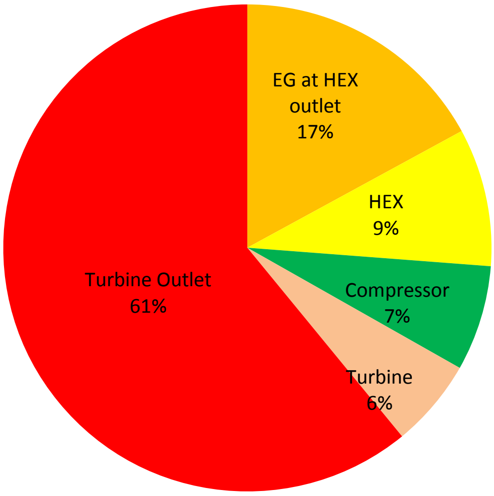


Fig. 4. Distribution of exergy destruction in the simple Brayton WHR system with maximum TIT=672°C, maximum cycle pressure of 3 Mpa, η_compressor = 78% and η_turbine = 82%

Exergy lost in the exhaust gases can be reduced by recovering more heat at the HEX outlet. This can be achieved by reducing compressed air temperature in three ways: (1) Increasing compressor efficiency in order to approach isentropic adiabatic compression. (2) Performing isothermal compression. (3) A more realistic technical option, consists of using an intercooler between the compression stages [26-28]. This allows to reach the required pressure at lower temperature compared to non-intercooled configurations. Note that this option has also the advantage of reducing the total compression work enabling higher efficiency and an increase in the net specific work. Another way to reduce the HEX inlet temperature is through water injection downstream the second compressor. This option is investigated in this study and the air-water mixture temperature can be accounted by calculating the enthalpy according to the adiabatic mixing formula presented in the literature [26, 27].

$$(\dot{m}_{air} + \dot{m}_{water}) * H_{mix} = \dot{m}_{air} * H_{air} + \dot{m}_{water} * H_{water} \tag{4}$$

With H_{air} : Air enthalpy at a given temperature and pressure (kJ/kg)
H_{water} : water enthalpy at a given temperature and pressure (kJ/kg)
H_{mix} : Air-water mixture enthalpy (kJ/kg)
$\dot{m}_{air}$: Air mass flow rate (kg/s)
$\dot{m}_{water}$: Water mass flow rate (kg/s)

As for the HEX exergy destruction, it can be reduced by reducing the HEX pinches between hot and cold fluids. However larger exchange surfaces would be required. Also, the exergy destruction shares of the compressor and turbine can be further reduced by improving their efficiency.

Based on these findings, the list of the different BWHR-system options considered in this study is presented below, based on the combination of the suggested techniques for exergy losses reduction and the two main thermodynamic configurations, the IBC and the HPIBC are shown in figure A.1. Note that the list is not exhaustive and other systems issued from this explicit method can be proposed in other later studies.

1. Simple Brayton Cycle (SBC)
2. Intercooled Brayton Cycle (IBC)
3. High Pressure Intercooled Brayton Cycle (HPIBC)
4. Water Injection Simple Brayton Cycle (WI-SBC)
5. Water Injection Intercooled Brayton Cycle (WI-IBC)
6. Water Injection High Pressure Intercooled Brayton Cycle (WI-HPIBC)

2.2.2 Energy and Exergy analysis of identified potential BWHR systems

The identified BWHR-system options are assessed here in order to prioritize these options based on their respective efficiency. Thermodynamic calculations are performed first with the Refprop software, knowing the map of ICE exhaust gas temperature downstream catalytic converter and using the set of physical parameters such as the heat exchanger pinch, the intercooler outlet temperature, the water injection temperature, the maximum cycle pressure, the components efficiencies, among others; as summarized in table 1. These parameters correspond to the state-of-the-art specifications and limitations of BWHR component technologies and to automotive design constraints.

The energy and exergy calculations are made as function of the compression ratio (π_i) parametric design criteria, with *i* referring to the number of compressor stages. Therefore, the second calculation step uses a dichotomy optimization method, to determine the optimal efficiency solution for the optimal (π_i). The maximum electric power recovered is then accounted for, knowing the exhaust gases mass flow rate maps and by fixing the electric generator efficiency.

Table 1. Simulation parameters based on state-of-the-art component specifications and automotive design constraints.

Parameter	Unit	Value	Parameter	Unit	Value
Compressor technology	-	Radial	Turbine technology	-	Radial
Max number of compression stages	-	2	Max number of expansion stages	-	2
LP Compressor max pressure ratio	-	2.5	Turbines isentropic efficiency	%	82
HP Compressor max pressure ratio	-	2.5	Turbine max expansion ratio	-	3
Compressors efficiency	%	78	Electric Generator efficiency	%	90
Compressor inlet pressure drop	%	0.5	HEX pinch	°C	75
Maximum cycle pressure	MPa	0.8	HEX pressure drop cold side	mbars	100
Intercooler pressure drop	mbars	50	HEX pressure drop hot side	mbars	50
Intercooler outlet temperature	°C	50	Water temperature	°C	25°C
Water pump efficiency	%	60	Water injection pressure	MPa	1

2.3 Vehicle model and powertrain management strategy

In order to evaluate the benefits of the different BWHR systems in terms of fuel savings, a medium-class series hybrid electric vehicle (SHEV), consisting of an ICE-BWHR-APU and an electric traction system (as illustrated in figure 1) is modelled and presented in this section. SHEV powertrain configuration presents the advantage of tackling the poor-efficiency main deficiency of BWHR systems in automotive applications as discussed in the literature. On one hand, the ICE-BWHR operates in an SHEV quasi-steadily in a high efficiency zone, where the engine is highly loaded, with high exhaust gas temperature, and on the other hand, the quasi-stable operation of the power train offers lower complexity control BWHR system. Note that the vehicle is propelled by an electric motor, powered by a battery and/or the APU, and properly sized to ensure the vehicle performance.

The vehicle parameters considered in this study are summarized in table 2. Powertrain backward model equations are presented in the reference [19]. Note that the additional mass of the BWHR-system, are accounted and presented in table 3. Turbomachinery weight data are retrieved from literature [29]. The HEX weight are calculating using internal code developed on Dymola software and validated through experimentation. It is also noteworthy to mention that two different battery capacities of 2kWh and 10kWh, emulating self-sustaining hybrid and plug-in hybrid SHEV configurations are considered. The plug-in hybrid offers the advantage of long electric drive range without the need of turning ON the APU. Also, the additional battery mass with the increased capacity is taken into account and values were retrieved from commercialized battery specifications [19].

The vehicle controller and the APU controller are the two distinct controllers in the SHEV model as illustrated in figure 1. The vehicle controller is responsible for delivering the driver's performance request, by controlling the electric motor power in order to meet the traction and brake energy recovery demand. The APU controller monitors the battery state of charge (SOC) by controlling the APU operations in order to maintain the SOC in the desired range. Hence, when the APU is turned ON, the APU controller manages the engine speed control and the engine torque control in order to operate the APU (ICE and BWHR) at the optimum efficiency. The engine is allowed to operate at any points of its performance. Note that in addition to the mechanical power demand, a constant vehicle auxiliary electric power demand of 750W is also considered [30].

Dynamic programming (DP) is considered in this study in order to provide the global optimal strategy to control the APU operations [31]. DP decides on the optimal strategy for the scheduled route at each instant t while minimizing the fuel cost. Consequently, DP computes backward in time from the final desired battery state of charge SOC_f to the initial state SOC_i the optimal fuel mass flow rate in the discretized state time space. The generic DP function presented in [32] is considered where the battery SOC is the state variable and the engine speed and torque are the control variables respectively.

Table 2: Vehicle and components specifications.

Vehicle specifications	**Symbol**	**Unit**	**Value**
Vehicle mass (including driver)	M_v	kg	1210
Frontal area	S	m^2	2.17
Drag coefficient	C_x	-	0.29
Wheel friction coefficient	f_r	-	0.0106
Wheel radius	R_w	m	0.307
Auxiliaries consumption	P_{aux}	W	750
Battery maximum power	$P_{b\,max}$	kW	50
Battery capacity	C_b	kWh	2, 10
ICE system max power	P_{ICE}	kW	72 kW @ 4000RPM
ICE maximum efficiency	η_{ICE}	%	36
Generator maximum power	P_g	kW	75
Generator maximum efficiency	η_g	%	95
WHR Generator efficiency	$\eta_{g\text{-}WHR}$	%	95
Motor maximum power	P_m	kW	80
Motor maximum efficiency	η_m	%	93
Transmission ratio	i	-	5.4
Transmission efficiency	η_t	%	97
Vehicle total mass	M_t	kg	$M_v + M_b$
Fuel heating value	H_v	MJ/kg	42.5

Table 3: BWHR-system weights

Component	**Unit**	**SBC**	**IBC**	**HPIBC**	**WI-SBC**	**WI-IBC**	**WI-HPIBC**
Turbomachine	kg	4	5	5.5	4	5	5.5
Electric generator	kg	4	5	5.5	5	5.5	6
Intercooler	kg	0	2	2.5	0	2	2.5
Heat exchanger	kg	17	19	20.5	17	19	20.5
Water injection system	kg	0	0	0	5	5	5
Total system weight	kg	***25***	***31***	***34***	***31***	***36.5***	***39.5***

3. Results and discussion

In this section, the different ICE-BWHR-SHEV systems are compared to the reference ICE-SHEV in term of fuel consumption. Note that gasoline is the fuel used. In all powertrains, ICE is allowed to operate at any point of its torque-speed map. The potential of fuel savings of the different BWHR systems are carried out under two sets of simulations. The first set emulates the behavior of self-sustaining hybrids with a zero use of electric energy from the battery at the end of the cycle. Hence, the initial and final battery SOCs are set at 60%. The second set of simulations emulates the behavior of plug-in hybrids and extended-range electric vehicles, with the option of battery charging from the grid. Simulations are performed at an initial SOC of 80% and a final SOC by the end of the trip at 30%. Simulations are performed on one WLTP for self-sustained configuration and on a sequence of one to three-repeated WLTC (23 km each), for plug-in configuration, covering driving distances up to 69 km.

Figure 5 highlights the fuel saving potential of the different BWHR systems for both self-sustained and plug-in SHEVs. Many conclusions are drawn out from this figure:

1. The SBC on SHEV offers 3.2 % to 3.9% of fuel consumption saving on plug-in and self-sustaining configurations respectively compared to the ICE-SHEV basic powertrain.
2. A two stages compression with intercooler, increase the overall efficiency of BWHR. In fact, the IBC allows reducing fuel consumption about 5.3% on plug-in SHEV and up to 6.4% on self-sustaining. As described before, on one hand, the total compression work is reduced, increasing thereafter the net-work recovered, and on the other hand, the air working fluid downstream the second compression stage, enters the HEX at lower temperature which allow recovering more amount of heat from exhaust gases.
3. HPIBC offers higher fuel economy compared to IBC. In fact, the fuel consumption saving seems to be reduced to 5.6% on plug-in and up 6.8% on self-sustaining. However, this small gain compared to IBC comes over a complex machine which requires higher compression ratio and an additional turbine stage to achieve the higher expansion required.
4. Water injection upstream the HEX cold side inlet is shown to decrease the fuel consumption by 0.9 points on plug-in configuration and between 0.9 and 1.2 points on self-sustaining. However this benefits comes over more system complexity and additional cost. Adding to that, the water must be added manually or recovered from exhaust gases, that contain non negligible amount, using an additional system [33]. This adds higher vehicle integration challenges and complexity.

Finally, based on these results, the IBC seems to be a promising WHR system for automotive application as it offers the most convenient compromise between high efficiency and low integration complexity. Figures 6 (a) and (b) present the powertrain operation for ICE-SHEV and ICE-IBC-SHEV for both self-sustained and plug-in SHEVs. Note that the APU operation time on WLTC is about 26.5% on self-sustained configuration with ICE-IBC-WHR compared to 34.4% with ICE-SHEV and about 18.7% on plug-in configuration with ICE-IBC-SHEV compared to 22.1% with ICE-SHEV due to higher electric power generated with BWHR.

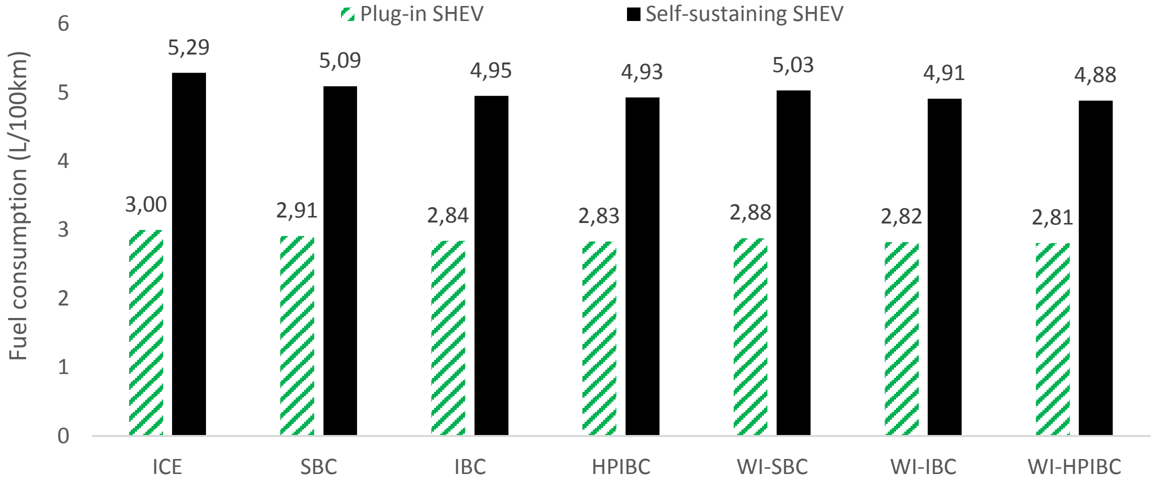
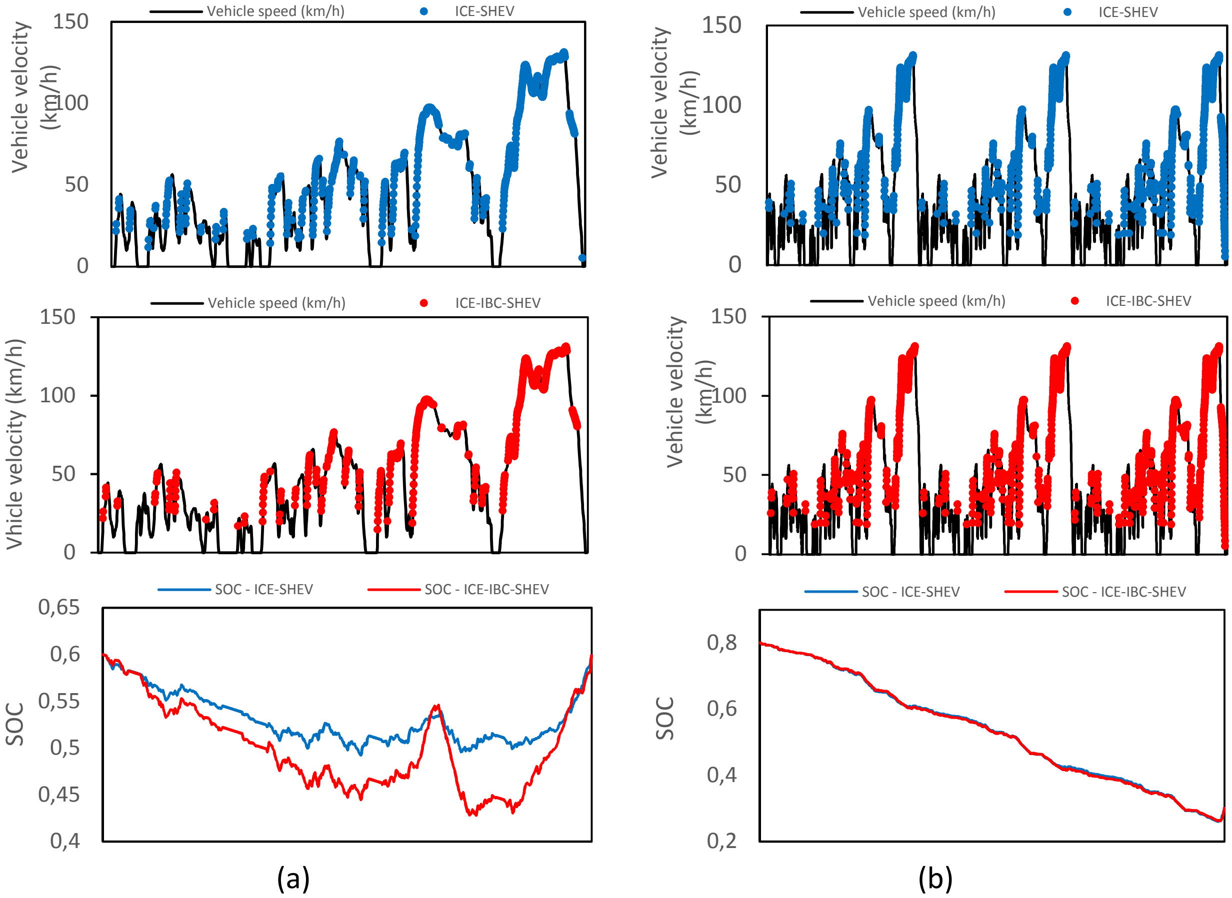


Fig. 5. Fuel consumption (L/100km) for both plug-in and self-sustaining SHEVs



(a)

(b)

Fig. 6. Power train operation and SOCs for (a) self-sustaining and (b) plug-in SHEVs

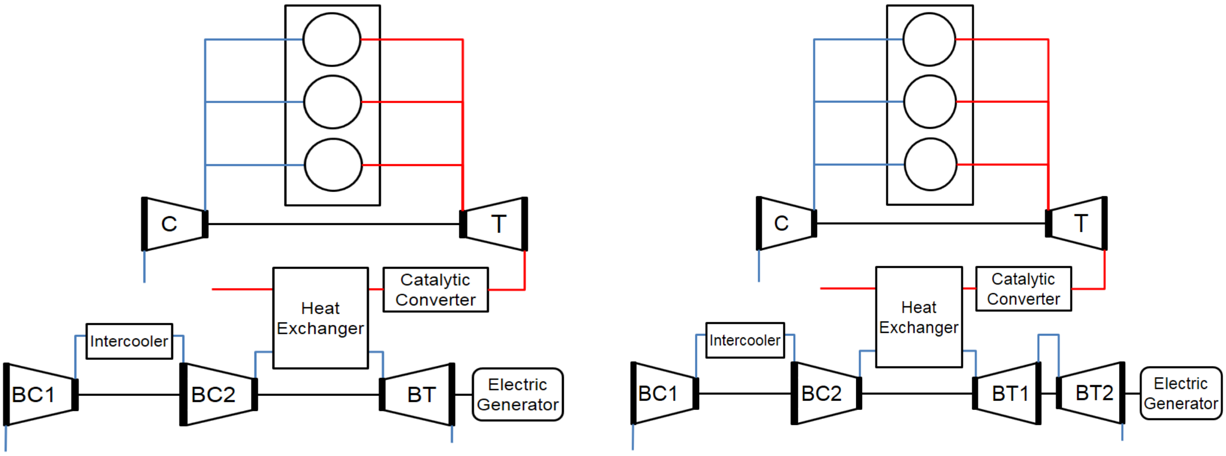
4. Conclusion

Brayton WHR systems were investigated in this study as potential waste heat recovery systems for automotive applications on Series Hybrid Electric Vehicle. Different system configurations were selected through as exergo-technological explicit selection method considering energy and exergy analysis, as well as components and automotive technological constraints. Simple Brayton Cycle, Intercooled Brayton Cycle and High-pressure Intercooled Brayton Cycle were identified. Water injection downstream the Brayton compressor on the three selected systems was also considered.

A series hybrid electric vehicle was modelled, and the different ICE-BWHR-APU systems are simulated and compared in term of fuel consumption using the DP optimal control as APU management strategy. The additional weight of the different BWHR systems was also considered in the evaluation of fuel consumption. The Intercooled Brayton Cycle (IBC) is identified as the most promising for automotive application as it offers the most convenient compromise between high efficiency and low integration complexity. It offers 5.5% to 7% fuel consumption savings compared to similar ICE configuration on plug-in and self-sustained SHEV configurations respectively as compared to similar vehicle configurations with ICE auxiliary power unit.

In addition to the fuel savings, the IBC-system offers other intrinsic automotive advantages such as reduced mass compared to other WHR systems, suitable vehicle integration, low noise, low vibration, high durability as well as the use of air as working fluid reducing therefore the system integration complexity. This makes it a potential WHR system option for integration in series hybrid electric powertrains in the future.

Appendix A



(a) IBC *(b) HPIBC*

Fig. A.1. Thermodynamic configuration of the different investigated BWHR-systems

References

[1] Khalifa H. E., Waste heat recovery from adiabatic diesel engines by exhaust-driven Brayton cycles. DOE/NASA/0304-1, NASA CR-168257, December 1983.
[2] Amicabile S., Lee J., Kum D., A comprehensive design methodology of organic Rankine cycles for the waste heat recovery of automotive heavy-duty diesel engines. Applied Thermal Engineering, 2015.
[3] Ringler J., Seifert M., Guyotot V., Hübner W., Rankine Cycle for Waste Heat Recovery of IC Engines. *SAE Int. J. Engines* 2(1):67-76, 2009, https://doi.org/10.4271/2009-01-0174.
[4] Domingues A., Santos H., Costaa M., Analysis of vehicle exhaust waste heat recovery potential using a Rankine cycle. Energy, 2013.
[5] Saxena S., Ahmed M., Automobile Exhaust Gas Heat Energy Recovery Using Stirling Engine: Thermodynamic Model. SAE Technical Paper 2017-26-0029, 2017.
[6] Aladayleh W., Alahmer A., Recovery of Exhaust Waste Heat for ICE Using the Beta Type Stirling Engine. Journal of Energy, 2015
[7] Sahoo D., Kotrba A., Steiner T., Swift G., Waste Heat Recovery for Light-Duty Truck Application Using ThermoAcoustic Converter Technology. SAE Int. J. Engines 10(2):196-202, 2017, https://doi.org/10.4271/2017-01-0153.
[8] Fritzsche J., Drückhammer J., Käppner C., Hassel E., Steiner T., Thermoacoustics as an Alternative Technology for Waste Heat Recovery in Automotive and (Heavy) Duty Applications. 24th Aachen Colloquium Automobile and Engine Technology 2015.

[9] Stobart R., Wijewardane A., Allen C., The Potential for Thermo-Electric Devices in Passenger Vehicle Applications. SAE Technical Paper 2010-01-0833, 2010.

[10] Orr B., Akbarzadeh A., Mochizuki M., Singh R., A review of car waste heat recovery systems utilizing thermoelectric generators and heat pipes. Applied Thermal Engineering, 2015.

[11] Hussain Q., Brigham D., Maranville C., Thermoelectric Exhaust Heat Recovery for Hybrid Vehicles. *SAE Int. J. Engines* 2(1):1132-1142, 2009, https://doi.org/10.4271/2009-01-1327.

[12] Arnaud L., Ludovic G., Mouad D., Hamid Z., Vincent L., Comparison and Impact of Waste Heat Recovery Technologies on Passenger Car Fuel Consumption in a Normalized Driving Cycle. Energies 2014, 7, 5273-5290; doi:10.3390/en7085273.

[13] Lua Y., Roskillya A. P., Smallbonea A., Yub X., Wanga Y., Design and parametric study of an Organic Rankine cycle using a scroll expander for engine waste heat recovery. The 8th International Conference on Applied Energy, Energy Procedia, 2017.

[14] Song B., Zhuge W., Zhao R., Zheng X., Zhang Y., Yin Y., Zhao Y., An investigation on the performance of a Brayton cycle waste heat recovery system for turbocharged diesel engines. Journal of Mechanical Science and Technology, June 2013.

[15] History of Chrysler Corporation Gas Turbine Vehicles, Chrysler Corporation, January 1979.

[16] Jung D., Park S., Min K., Study on the Application of the Waste Heat Recovery System to Heavy-Duty Series Hybrid Electric Vehicles. SAE Technical Paper 2013-01-1455, 2013.

[17] Arias D., Shedd T., Jester R., Theoretical Analysis of Waste Heat Recovery from an Internal Combustion Engine in a Hybrid Vehicle. SAE Technical Paper 2006-01-1605, 2006.

[18] Upendra K., Grauers A., Synergy and conflicts between waste heat recovery system and hybrid electric vehicle. Swedish Hybrid Vehicle Center, Chalmers University of Technology, 2015.

[19] Bou Nader W., Mansour C., Nemer M., Guezet O., Exergo-technological explicit methodology for gas-turbine system optimization for series hybrid electric vehicles. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2017.

[20] Abd El-Maksoud R. M., Binary Brayton cycle with two isothermal processes. Energy Conversion and Management, 2013.

[21] Rovira A., Muñoz-Antón J., Montes M. J., Martínez-Val J. M., Optimization of Brayton cycles for low-to-moderate grade thermal energy sources. Energy, 2013.

[22] Galindo J., Serrano J.R., Dolz V., Kleut P., Brayton cycle for internal combustion engine exhaust gas waste heat recovery. Advances in Mechanical Engineering, 2015.

[23] Song B., Zhuge W., Zheng X., Zhang Y., Yin Y., Zhao Y., Parameter Study of a Brayton Cycle Waste Heat Recovery System for Turbocharged Diesel Engines. ASME Proceedings 20th Symposium on Industrial and Environmental Applications of Fluid Mechanics, 2013.

[24] Abedin M.J., Masjuki H.H., Kalam M.A., Sanjid A., Ashrafur Rahman S.M., Masum B.M., Energy balance of internal combustion engines using alternative fuels. Renewable and Sustainable Energy Reviews, 2013.

[25] Heywood J. B., Internal Combustion Engine Fundamentals. International edition, 1998

[26] Sonntag R., Borgnakke R., Fundamentals of Thermodynamics, Sixth Edition, 2003.

[27] Moran M., Shapiro H., Fundamentals of engineering thermodynamics. 5th Edition – 2006.

[28] HORLOCK J.H., Advanced Gas Turbine Cycles. ISBN 0-08-044273-0, Pergamon, 2003

[29] Feneleya A. J., Pesiridisa A., Mahmoudzadeh Andwaria A., Variable Geometry Turbocharger Technologies for Exhaust Energy Recovery and Boosting-A Reviews. Renewable and Sustainable Energy Reviews, 2017.

[30] Liebl J., Neugebauer S., Eder A., Linde M., Mazar B., Stütz W., The Thermoelectric Generator from BMW is making use of waste heat. Thermo Management, MTZ, 2009

[31] Mansour C., Optimized energy management control for the Toyota Hybrid system using dynamic programming on a predicted route with short computation time. *International Journal of Automotive Technology*. Paper N° 220100321, vol.13, No. 2, 2012.

[32] Sundstrom O., Guzzella L., A generic dynamic programming Matlab function. *2009 IEEE Control Applications, (CCA) & Intelligent Control, (ISIC)*. St. Petersburg, 2009, pp. 1625-1630. doi: 10.1109/CCA.2009.5281131

[33] Sun Y., Fischer M., Bradford M., Kotrba A., Water Recovery from Gasoline Engine Exhaust for Water Injection. SAE Technical Paper 2018-01-0369