Performance and economic analysis of an organic Rankine Cycle for hybrid electric vehicles

Zlatina Dimitrova
PSA Groupe, Centre Technique de Vélizy, 78943 Vélizy- Villacoublay Cedex, France
E-mail: zlatina.dimitrova@mpsa.com

Abstract. Car manufacturers need to develop efficient technologies to reduce emissions and save fuel in order to cater of European regulations and satisfy customers’ requirements. Internal combustion engines have a main limitation on efficiency due mainly to the heat losses. Processing an energy integration, it has been shown than an Organic Rankine Cycle (ORC) can improve the overall powertrain efficiency by recovering the heat into electricity. In parallel, hybrid electric vehicles attractiveness increases as it enables important energy saving. The contribution of this article is to design highly efficient vehicles, using both Organic Rankine Cycle and hybrid electric technologies. An adapted methodology based on energy integration techniques is required to choose the best points for the integrated system design. This study applies a methodology on hybrid electric vehicles, so as to define the powertrain configuration of the vehicle that is energy integrated. The energy recovery potential of a single stage Organic Rankine Cycle for a thermal engine in combination with a mild hybrid electric powertrain is studied. The assessment is done for different drive cycles. A study of economic feasibility and fuel consumption improvement is also done, in order to characterize the integrated energy system.

1. Introduction
The efficiency gains of the energy systems for vehicles are directly related to the fuel saving and the emissions reductions. The development of efficient technologies on the driving profiles and the comfort demands is then needed. There comes the idea to define a vehicle energy system with integrated energy services for mobility and comfort. With the definition of the system we need an energy integration methodology. The energy flows are integrated into the energy system to increase the efficiency. The energy integration considers the dynamic and comfort profiles and uses technologies recovering waste energy into the energy system. Organic Rankine Cycle (ORC) is selected to recover the heat waste of the internal combustion engine (ICE). Waste heat recovery technologies and hybrid electric vehicles are briefly introduced in the following section.

1.1. Waste heat recovery and hybrid electric vehicles
The vehicle is a dynamic system. The size and the efficiency of the converters depend on the dynamic driving profile. Energy integration is used to increase the energy efficiency of the vehicle energy system. An adapted methodology is proposed in [1] to select the best points for the integrated design of the system. The method clusterizes the dynamic profile on typical multi-periods where the vehicle is used. The design of the energy system is optimized for these main multi-periods. The energy integration is applied in [1] on hybrid electric vehicles. The potential of energy recovery of a single stage Organic Rankine Cycle is studied. The ORC is considered for a thermal engine in a hybrid electric powertrain.
The contribution of the ORC is assessed for different drive cycles. After the process integration, a multi-objective optimization defines the design of a hybrid electric vehicle with an optimal waste heat recovery system. The energy balance of the internal combustion engine, for different operating points, is defined and analysed in [2]. An energy integration methodology, based on process integration techniques is discussed in [2]. It is applied on the extended energy system of the vehicle. The possibilities of an ORC to recover waste heat from a 900 kW fast passenger ferry Diesel engine are investigated in [3]. The authors analyse in [4] the feasibility of an “on-board” innovative and patented ORC recovery system. The vehicle thermal source can be either a typical diesel engine (1400cc) or a small gas turbine set (15-30kW).

Hybrid vehicles can use energy storage systems to disconnect the engine from the driving wheels of the vehicle. This option enables the engine to be run closer to its optimum operating condition. Nevertheless fuel energy is still wasted as heat through the exhaust system. The article [5] presents the model of the engine of a diesel-electric hybrid bus, coupled with a hybrid powertrain. The performances of a hybrid vehicle over a drive-cycle are analysed. This showed that including the waste heat recovery technology reduces the fuel consumption with 2.4% for a typical drive-cycle. The ORC has large applications such as agricultural biogas combined heat and power engines, biomass boilers, landfill biogas plants, small geothermal plants and concentrated solar thermal systems [6]. Most of the projects related to ORC systems, in the transport industry, discuss performance optimized solutions that include heat recovery in engine exhaust gas. The authors describe in [7] the development and exergetic assessment of a new hybrid vehicle incorporating gas turbine as powering option. A multiple heat source supercritical ORC (Organic Rankine Cycle) for vehicle waste heat recovery is studied in [8]. A vehicle energy-supplying system is proposed to satisfy energy demand of vehicle in every season in [9]. This system is based on an ORC. The authors modeled a hybrid electric heavy duty vehicle to assess energy recovery using a thermoelectric generator in [10].

Hybrid electric vehicles have two or more prime movers as energy converters (internal combustion engine (ICE) or fuel cell and electric machine) and power sources (fuel tank, hydrogen tank and electrochemical battery) on their board. The main motivation for hybrid electric vehicles (HEV) development is the efficiency increase of the powertrain in comparison to the thermal (gasoline or Diesel) engines powertrain. HEV offer as well long ranges of autonomy, comparable to thermal vehicles. HEV vehicles recover the kinetic energy during braking. However, the ICE still has thermal losses due to the waste heat when is operating. In this case, the recovery of the waste heat is possible by using an external cycle- the Rankine cycle. The ICE energy balance is showing that there are two main sources of heat: the water jacket and the exhaust gases [1, 2]. The levels of the temperature between the water jacket and exhaust gases are different from 80°C to 900°C. To value the low heat temperature, an organic fluid is proposed to be used as working fluid.

![Figure 1. ORC system to recover the waste heat of the ICE.](image-url)
An ORC presented in figure 1 will be investigated as principal utility for the energy integration. Its operation will be optimized for the operation points of the ICE, adapted for HEV. As shown in the figure 1 the turbine is linked to an electric generator and so an electricity is produced from the waste heat of the engine. The electricity can be then used for the battery fulling or to be sent the electrical network of the system, driving different accessories, devices around the engine or the consumers on the vehicle board (figure 2). The ORC receives the heat from the water circuit and the gases of the exhaust of the engine. The turbine out is related to the high-speed generator which produces electricity. The electricity is converted into DC and to the adapted voltage level and enters into the high voltage battery. The functional architecture is presented in a Mild hybrid electric vehicle is presented in figure 2.

Figure 2. Functional architecture of the ORC integration in a Mild HEV Architecture.

The target of this article is to illustrate the results from a multi-constrain optimization, which take into consideration performance and economic constrains, in order to achieve an efficient design of an ORC loop for recovery of the waste heat on a hybrid electric vehicle. The presented design is adapted and evaluated to operate on hybrid electric vehicle’s architecture. Once we perform the optimization, we should study if there is one design solution which is better than the other, or if there exists different solution which could correspond to different users’ profiles. Finally, for the best design we should perform both a study on driving cycles, and an economic study, to determine if the Organic Rankine Cycle benefit is important enough to be implemented on those existing vehicles.

The contribution of this article is to apply energy integration methodology on mild hybrid electric vehicles for optimal powertrain design of hybrid electric vehicles. The article studies the impact of an energy recovery technology, such as the ORC on the mobility performances of HEV energy system. After integration of the energy services, a sensitivity analysis on the fuel benefits is done for different real drives representative driving cycles. The results are obtained by simulation, using vehicles models containing experimental engines and vehicles data. The ORC performances are obtained by simulation.

2. Methodology - Multi objective optimization and energy integration

The optimal size of the powertrain components is defined with multi-objective optimization. The correct sizing of the powertrain is important for the operating strategies and to reach optimal fuel consumption. In this article, the multi-objective optimization is realized with the tool presented in figure 3. The tool has already been described in [11]. The vehicle simulation model including with dynamic and thermal layouts is part of the superstructure. The cost equations are defined in the economic model. The energy integration model has as inputs the results from the dynamic flows and thermal flows calculations. The genetic algorithm optimises the final solutions. The optimization considers the following parts – a master multi objective optimization (MOO), a thermo economic simulation (TES). The energy integration is incorporated in the superstructure and is a slave optimization. The optimization process ends with the techno-economic evaluation (TEE). After the identification of the typical operating points, the energy
balance is obtained from the thermal layout of the engine. The energy system to be integrated is then defined in the part “Energy Integration” of energy integration model, by listing the “cold” and “hot” streams between which a heat exchange has to occur, presented in [1] and [2]. The minimum energy requirement of the system is estimated. A utility is used to close the energy balance and estimate the energy recovery potential.

Figure 3. Framework of the energy integration and optimization program [11].

2.1. Focus on the operating points
According to [1, 2], the best ORC we can implement on a car should use two streams from the vehicle for the evaporator: the water cooling system, and the exhaust gases. Moreover, the cycle has a much better efficiency if it reaches a superheating temperature.

Usually, hybridization methods are efficient at low power of the engine. These zones allow to use an additional electric motor or to recover energy from braking. However, the ORC is more efficient at full load operations, when the total quantity of heat to recover is higher. This seems interesting to add such a system to a hybrid vehicle, as the two range are different: an electric device work mainly during urban cycles, whereas an ORC works on national roads or highway. We want to emphasize this complementariness, we try to optimize the cycle for high-loaded operating points.

2.2. Economic model
The economic model is described in [11]. We consider a serial C-Segment vehicle. The vehicle is equipped with a 1.2 l 3 cylinders gasoline engine and 60 kW of power. An automatic gearbox is as well considered.

As economic indicator, the total price of the ORC is defined. Here just the investment cost is considered. This cost is a linear function to consider the parts produced on large units’ volume. The investment cost is the sum of the following equations (1-7):

\[
\text{Cost}_{\text{evaporator}} = 18.84 \times \text{Area}_{\text{evaporator}} + 14.49, \text{ Euro, area in m}^2; \\
\text{Cost}_{\text{condenser}} = 4.01 \times \text{Area}_{\text{condenser}} + 4.96, \text{ Euro, area in m}^2; \\
\text{Cost}_{\text{pump}} = 0.083 \times \text{flowrate} + 165, \text{ in Euro, flowrate in kg.s}^{-1}; \\
\text{Cost}_{\text{turbine}} = 0.015 \times \text{Power}_{\text{turbine}} – 30, \text{ in Euro, power in kW};
\]
\[ Cost_{\text{pipe}} = 26, \text{ Euro}; \quad (5) \]
\[ Cost_{\text{fluid}} = 10, \text{ Euro}; \quad (6) \]
\[ Cost_{\text{ORC}} = Cost_{\text{evaporator}} + Cost_{\text{condenser}} + Cost_{\text{pump}} + Cost_{\text{turbine}} + Cost_{\text{pipe}} + Cost_{\text{fluid}}, \text{ Euro}. \quad (7) \]

2.3. Waste heat recovery

2.3.1. Multi objective optimization settings. We want to perform an economic, environmental and technical performance optimization. To do that we should decide what indicator to use.

- Economic: the ORC investment cost is considered as an indicator, defined by equation (7).
- Performance: The net output power, used as an objective for performance. The net power is the difference of the turbine power and the pump power for a given operating time in equation (8):

\[ P_{\text{net}} = P_{\text{turbine}} - P_{\text{pump}}, \text{ kW}. \quad (8) \]

The exergetic efficiency is verified for every solution.

2.3.2. Multi objective optimization settings. We need to choose the variable of the ORC design. The system has two degrees of freedom. We choose two define two temperature to launch the energy integration model:

- The evaporation temperature of the fluid. The interval of variation is defined between 330 °K and 360 °K in order to obtain correct exergetic efficiency.
- A difference of temperature, \( \Delta T_{\text{min}} \), between the exhaust gas temperature and the superheat temperature of the cycle. The interval of variation is defined between 100 °K and 400 °K. This range is for second order for the results.

We use a simulation of a population with 200 individuals with a maximum number of evaluation of 10. The computing time is enough, and we get enough design to have a precise Pareto curve of the net output power depending on the investment cost.

3. Multi objective optimization results

3.1. Decision variables

We need to choose the variables for the ORC design:

- The evaporation temperature of the fluid \( T_{\text{evap}} \). The interval of variation is defined between 330 °K and 360 °K. The criteria is to obtain good values of the exergetic efficiency.
- The superheat temperature \( T_{\text{superheating}} \) is defined between 700 °K and 1050 °K.

The function to be optimized for the ORC design is defined as:

\[ \min(-\dot{P}_{\text{net}}(x), \text{Cost}_{\text{ORC}}(x)), \text{ with } x \in X (\text{decision variables}). \quad (9) \]

3.2. Pareto-curves

The multi-objective optimization converges on the solutions presented on the Pareto curve (figure 4). The trade-off between the ORC net power and the investment cost are illustrated to the Pareto curves. The best value of exergetic efficiency is reached at 25%. This is for investment cost interval between 350 and 700 Euros.

3.2.1. Method to get the ORC maps. As we want to get the ORC characteristics for each operating point, we should consider the new hot streams and cold streams, as defined in [1] and [2]. Firstly, we do the following assumption: the compressor power is the same for each operating point; we consider the flow rate to be the same. The heat cascades are defined in the energy integration method. By knowing the temperatures and the exchanged power, the energy integration module computes the power maps, the energy efficiency and the exergetic efficiency maps of the gasoline engine (figure 5). The ORC map comes as a solution of the energy integration method.
3.3. Simulation results on driving cycles

This study extends the methodology for design of vehicle energy systems on other drive cycles. The peri-urban cycle represents the home to work commuting. The holiday cycle is representative for long distances drives. The New European driving cycle (NEDC) is well known as reference and is as well considered. Table 1 summarizes their characteristics.

### Table 1. Drive cycles characteristics.

| Cycle | Distance, km | Duration, s | Average speed, km/h | Min acceleration, m/s² | Max acceleration, m/s² |
|-------|--------------|-------------|---------------------|------------------------|------------------------|
| NEDC  | 11.023       | 1180        | 32.26               |                        |                        |
| Peri-urban | 39 | 2440       | 57                 | −2                     | 2                      |
| Holiday | 847          | 28800       | 105                | −1.9                   | 1.9                    |

*The peri-urban and holiday cycles are based on the parts of the WLTP cycle.*

3.3.1. Comparison of different configurations. The gasoline engine in the hybrid electric powertrain obtains an additional flow of electrical power thanks to the heat recovery from the ORC. The studied architecture is a mild hybrid electric powertrain, as presented in figure 2. The hybrid electric powertrain has already an electric energy recovery system. This category of recovery system has an electric energy storage in the high voltage battery and is an effective solution for low speed drives, where the power delivered by the electric part of the powetrain is enough to drive the vehicles on purely electric drive. The fuel consumption is zero. The selected ORC design is optimized for the area with high rotation speeds and high loads. This is a complementary zone, where the mild hybrid electric powetrain is not acting. The simulations results are displayed in the table 2.

The fuel consumption result on NEDC for the basic configuration of the vehicle is 4.6 l/100 km.

The Mild HEV is a low degree electrical hybridization of the vehicles powetrains, characterized with low capacity of the high voltage battery – between 1.2 kWh and 6 kWh. The efficiency improvement of the MHEV on the NEDC and the Peri-urban cycles is around 10%, because these cycles
except the urban part, have also a large extra urban part, which is more energy demanding and where the MHEV mode is not active. On the holiday cycle, the MHEV is not used. In conclusion the Mild HEV is an adapted technology for the city drive and can be consider as effective technology for urban drives.

The ORC design proposed for the net power map of the figure 5 is optimal for high load and high speed engines operating points. For these points we have high temperature exhaust gases. Thus the waste heat recovery potential is important. The impact proposed ORC design is estimated on the different driving cycles. At first just the ORC impact is considered. From the results is table 2 is visible that on the combined cycles (with urban part and extra urban part) – NEDC and peri-urban the efficiency improvement is 24% and respectively 34%. The ORC is well used in the charged part of the cycles. The fuel consumption reduction potential on holiday cycle is around 40%. The fuel consumption is below 4.5 l/100 km. The selected ORC design is an efficient equipment to recover the waste heat in the high speed demanding drives. In these zones the engine power demand is high.

It is as well interesting to analyse the aggregation of the MHEV and the ORC. For the combined cycles the combination of a MHEV and ORC on a small downsized engine brings the best fuel saving potential – around 40%. The MHEV contributes to the efficiency improvement on the peri-urban drives and the ORC on the extra-urban drives. For the “holiday” long drive cycle, the ORC is the major contributor of the improvement.

The lowest consumption for is obtained for NEDC cycle, because of its particularity to combine urban and highway drives at very smooth and progressive speed changing conditions. By their construction, based on WLTP, the peri-urban and the holiday cycles combines more transients and higher accelerations. In all configurations, their consumption majors the NEDC consumption.

In conclusion the mix of a low degree electric hybridization technology such as the Mild HEV and a technology for the waste heat recovery as the organic Rankine cycle is efficient for mixed usages of the vehicle. For the C-Segment vehicle the aggregation of the two energy recovery options is efficient. The powertrain efficiency increase for NEDC is of around 40%. The vehicle consumption is 3.32 l/100 km.

| Driving Cycle | Vehicle type   | Fuel consumption, l/100 km | Powertrain efficiency gain, % |
|---------------|----------------|----------------------------|-------------------------------|
| NEDC          | C-Segment 1.2  | 4.72                       | -                             |
|               | C-Segment 1.2 MHEV | 4.16                   | 10.8                          |
|               | C-Segment 1.2 ORC  | 3.71                     | 24                            |
|               | C-Segment 1.2 ORC MHEV | 3.32               | 38.4                          |
| Peri-urban    | C-Segment 1.2  | 5.56                       | -                             |
|               | C-Segment 1.2 MHEV | 5.05                    | 10                            |
|               | C-Segment 1.2 ORC  | 4.14                     | 34.2                          |
|               | C-Segment 1.2 ORC MHEV | 3.98                | 39.7                          |
| Holidays      | C-Segment 1.2  | 5.94                       | -                             |
|               | C-Segment 1.2 MHEV | 5.86                    | 1.3                           |
|               | C-Segment 1.2 ORC  | 4.27                     | 38.9                          |
|               | C-Segment 1.2 ORC MHEV | 4.35               | 36.2                          |

The system is interesting to be realised and to be tested. The practical difficulty is related to the ORC installation. The Mild HEV architecture is well known in the state of the art and exists in serial production. The discussed ORC system presents challenges on the direct mechanical connexion between turbine and the electric generator, because of the high the rotation speed that they have to operate. The choice and the realisation of the small size ORC components (pump and turbine) is as well challenging.
4. Conclusions
This article presents a study of the efficiency performance and the economic optimization for a middle class vehicle with a downsized gasoline engine. Two technological options are studied for the efficiency improvement of the baseline vehicle powertrain:

- Low degree electric hybridization technology – called Mild Hybrid electric powertrain;
- Waste heat recovery system for two heat sources the engine water circuit and the exhaust gases, means an external thermodynamic cycle – ORC.

The ORC is designed on an optimal way for high load and high speed engine operating conditions. The design is optimized considering techno-economic performances indicators. For this evaluation a multi-objective optimization methodology is applied, including the energy integration. For this reason, the best fuel consumption improvement is obtained for the holiday cycle, characterised by long ways drives at high speed. For the combined cycles such as NEDC and peri-urban the combination of ORC and MHEV bring the best fuel saving potential, superior to 35% in comparison with normal ICE vehicle.

The main conclusion coming from the driving cycles evaluation is the MHEV is an efficient technology for the drives with speed variations. The selected ORC design is efficient on the cycles using the charged area of the engine. For these operating points, the small gasoline engine is highly charged, due to the high power vehicle demands. The MHEV and the ORC are complementary technologies and their combination is especially efficient on the combined cycles containing urban and extra urban part.

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