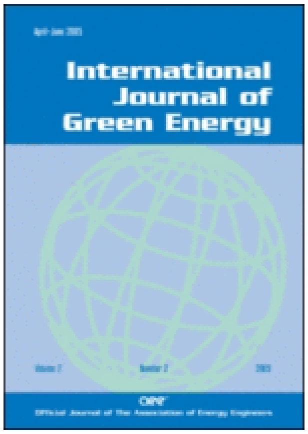

Overview of Recent Developments and the Future of Organic Rankine Cycle Applications for Exhaust Energy Recovery in Highway Truck Engines

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Keywords:	Exhaust Heat Recovery, Organic Rankine Cycle Technology, Engine Driving Profile, Daily Average Speeds, Recent Developments

Overview of Recent Developments and the Future of Organic Rankine Cycle Applications for Exhaust Energy Recovery in Highway Truck Engines

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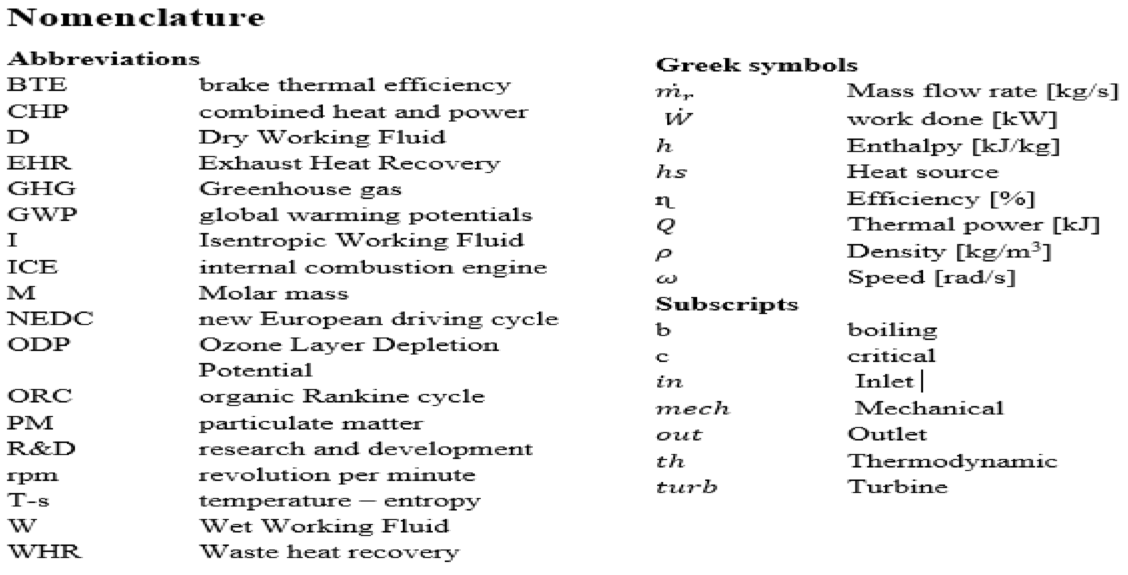
Abstract

Overall developments in internal combustion engines suggest that the ORC system recovers exhaust heat for further use, increases system performance, and decreases adverse environmental impacts, including greenhouse gas emissions, and particulate matter. This paper presents an overview of crucial advancements in the field of ORC application in commercial vehicles for WHR and continuing developments towards clean fuels and emission regulatory standards. The is review centred on the potential of ORC technology, its applications in highway truck engines heat recovery, and most notably, the bottlenecks associated with incorporating ORC technology into commercial vehicles exhaust energy recovery. Furthermore, a range of distinct engine operating patterns is reported in respect of average speeds of trucks to assess the appropriate operating points for the chosen application.

Keywords: Recent Developments, Exhaust Heat Recovery, ORC technology, Engine Driving Profile, Daily Average Speeds



Nomenclature

Abbreviations	
BTE	brake thermal efficiency
CHP	combined heat and power
D	Dry Working Fluid
EHR	Exhaust Heat Recovery
GHG	Greenhouse gas
GWP	global warming potentials
I	Isentropic Working Fluid
ICE	internal combustion engine
M	Molar mass
NEDC	new European driving cycle
ODP	Ozone Layer Depletion Potential
ORC	organic Rankine cycle
PM	particulate matter
R&D	research and development
rpm	revolution per minute
T-s	temperature – entropy
W	Wet Working Fluid
WHR	Waste heat recovery

Greek symbols	
$\dot{m}_r$	Mass flow rate [kg/s]
$\dot{W}$	work done [kW]
h	Enthalpy [kJ/kg]
hs	Heat source
η	Efficiency [%]
Q	Thermal power [kJ]
ρ	Density [kg/m^3]
ω	Speed [rad/s]
Subscripts	
b	boiling
c	critical
in	Inlet |
$mech$	Mechanical
out	Outlet
th	Thermodynamic
$turb$	Turbine

1. Introduction

Exhaust gases release from the transportation and industrial sectors have significant negative impacts on our environment and air quality. Studies indicate that the transport sector consumes much of the World's fuel, accounting for more than 67% of overall fuel consumption in the United States., [1] and 73% in the United Kingdom in 2013, [2]. The transport industry contributes to air pollution through Nitrogen oxides (NOx) and PM emissions and to global warming through CO_2 emissions. Due to the inefficiencies of ICEs, about 60 to 65% of the fuel that is supplied to the engine is released into the atmosphere in form of heat via the exhaust and cooling systems. This inefficient conversion of fuel energy to mechanical work results in a rise in entropy and causes severe negative environmental impacts; yet, technologies exist that can convert such energy in the waste heat to useful work, [3]. Today these concerns combined necessitate the development of more efficient combustion engine process as an effective way of deploying fuel sources to use. The energy in the exhaust gas could be converted to mechanical, then to electrical power for the vehicle by applying a suitable thermodynamic Rankine process (Organic Rankine Cycle).

In recent times, research and development interests are focusing on Organic Rankine Cycle Systems (ORC) as an exhaust heat recovery technology in automotive engines. The technology typically is deployed in small to modest temperature heat sources due to the low boiling point of organic fluids compare to steam which is used primarily in large scale applications. The Organic Rankine system generates mechanical energy which either delivers power directly via a belt or a gearbox to the engine shaft, or produces electricity employing an electric generator.

This study is an overview of recent developments in ORC technologies used for exhaust heat recovery in long-haul truck engines with the primary goal of improving the thermal performance of these engines, lower greenhouse gas emissions, and consequently, low systems operational costs.

2. Commercial Truck Engines

Human movement and the transportation of goods are necessities of the society today. In addition to achieving acceptance by users, any solution to these issues must follow sustainability requirements. Accordingly, approaches must adhere with requirements of safe operation, energy sustainability, environmental safety, and accessibility. Transportation infrastructure must develop with progress in powertrains and better fuel and energy options to address the above-mentioned fundamental needs of contemporary society. The need to increase energy conservation and to decrease fossil fuels dependence would lead to a more substantial use of clean energy. Advances in travel requirements and the movement of goods and services help to develop the transportation business environment, as more people are expected to travel and move goods from one location to the other and thus, need safe and efficient options.

Given the insights from industrial associates, ERTRAC's R&D forecasts that more than 60% of new commercial vehicles in Europe will continue to be powered by ICEs up to 2040: vehicle technologies will include ICE, hybrids, extended configurations and clean energy resources. Equally, due to the need for energy density in the propulsion of larger vehicles, internal combustion engines are expected to control the trucks market for some time, [4].

Diesel Engine is among the most significant emitters of carbon dioxide because it is the commonly used combustion process for heavy-duty trucks and ships applications, and, for small, medium-sized, stationary power generating plants. New environmental pollution measures on heavy-duty sectors, such as EURO VI and Tier 4 final, concerning NOx and PM, are also becoming stricter every year. Therefore, considerations on more engine innovation and performance increase have been of critical interest recently and several changes have been studied and implemented.

2.1 Truck Driving Profiles

The fundamental step in designing exhaust heat reuse devices for possible integration to automobile vehicles in a quest to improve the overall system efficiency and consequently reduce the rate of environmental pollutions is the exploration of actual driving patterns of these vehicles. The driving profile will provide insights into the regular operating points of the system and thus, its design configuration and optimal optimization points. These are critical spots at which the vehicle mostly involves in during operating periods; hence, significant in the designing process. United States NRE Laboratory has reported some commercial vehicles data regarding these points,[5]. **Figure 2.1** to **Figure 2.** report the daily driving profiles of these vehicles in histograms.

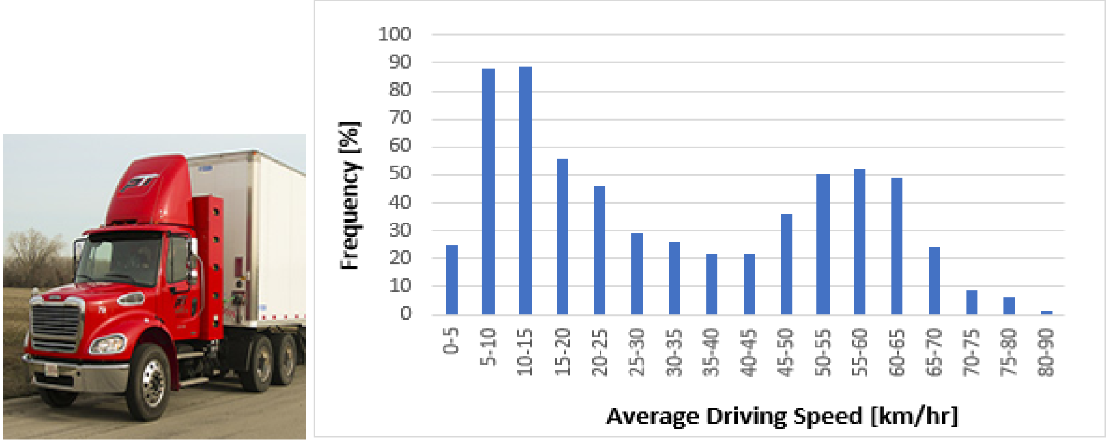


Figure 2.1. Highway Trucks Daily Average Driving Speed

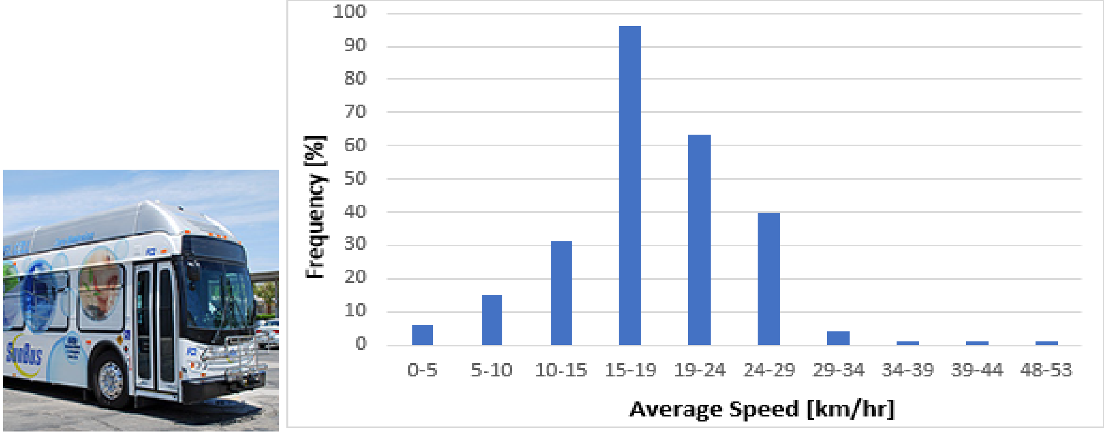


Figure 2.2. Buses Daily Average Driving Speed

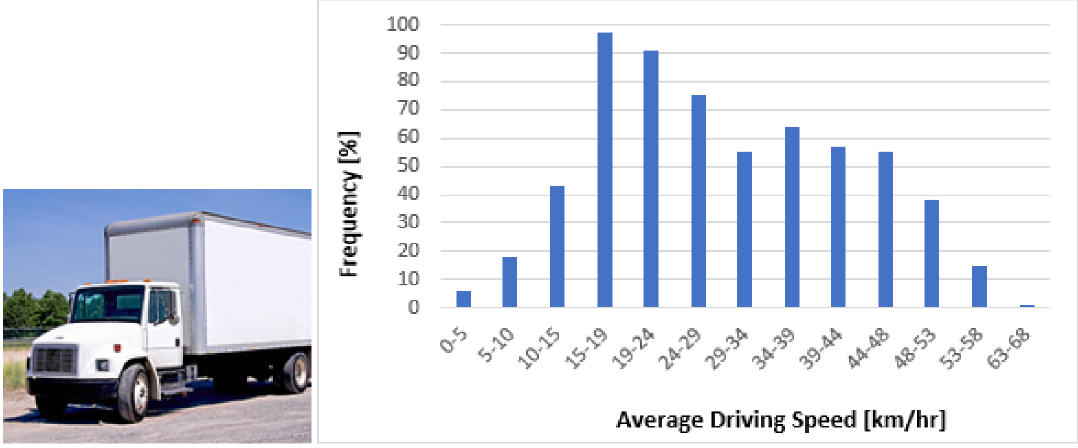


Figure 2.3. Delivery Trucks Daily Average Driving Speed

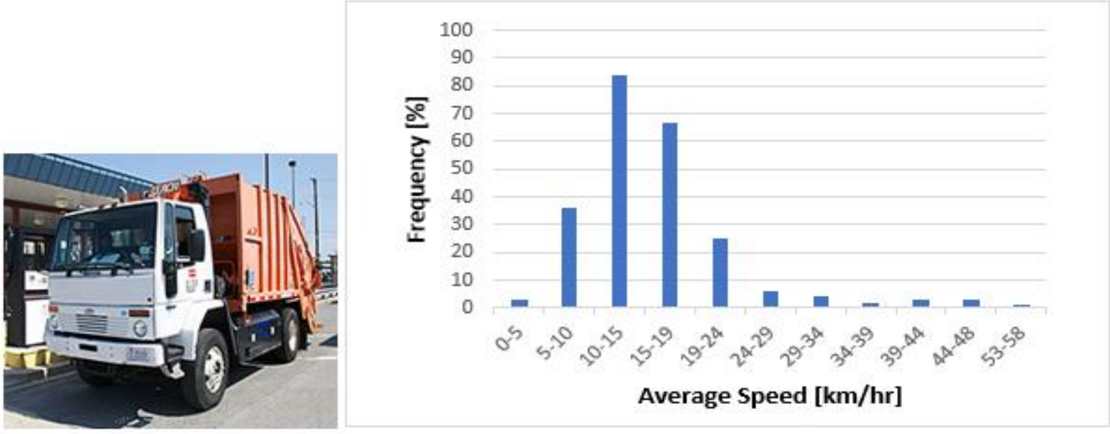


Figure 2.4. Refuse Trucks Daily Average Driving Speed

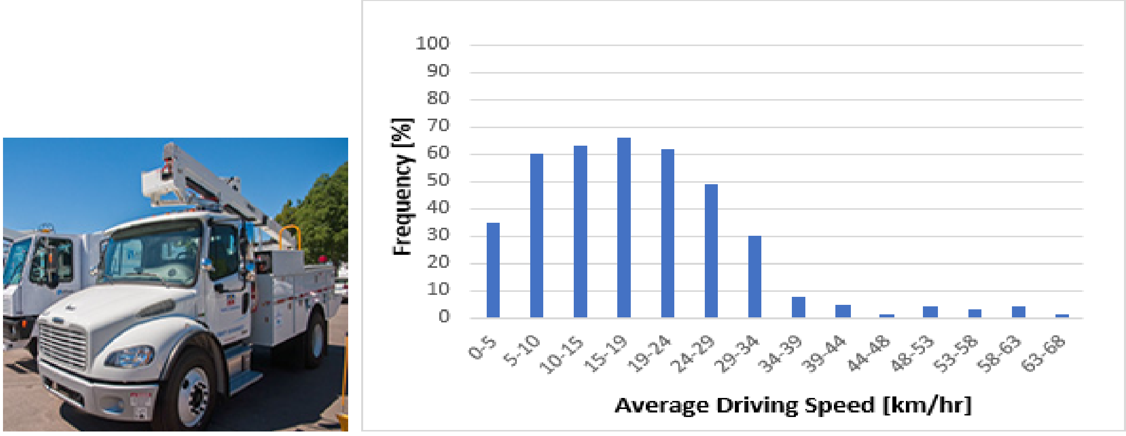


Figure 2.5. Bucket Truck Daily Average Driving Speed

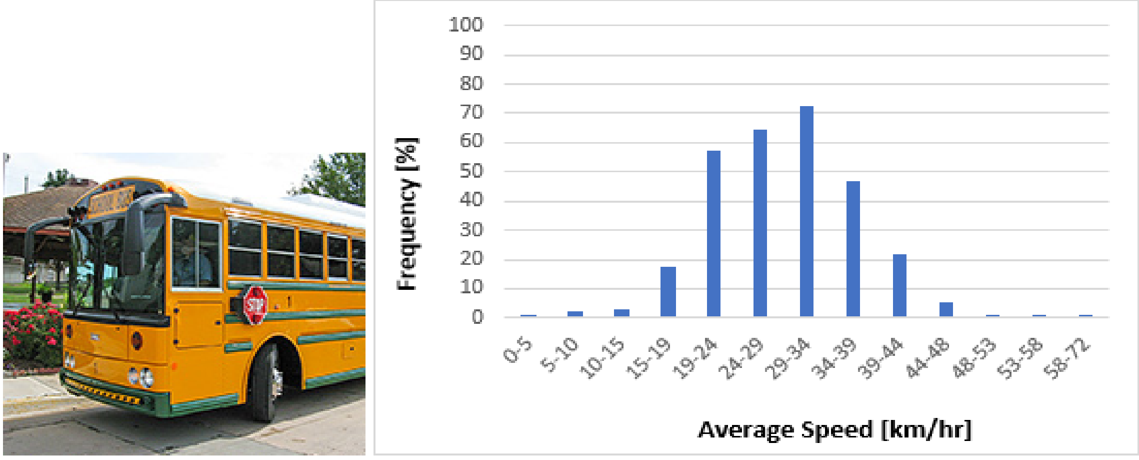


Figure 2.6. School Buses Daily Average Driving Speed

2.2 DE Sources of Heat

In diesel engine combustion, approximately 40% of energy content in the fuel is lost to the environment via recoverable heat energies which includes exhaust gas, EGR, coolant, lubricant, and Charge Air Cooling (CAC) heats. They are categorised into two, with the first category being high-temperature heat sources: exhaust gas (470-870K), EGR (470-1030K), and the second class as low-temperature heat sources: coolant (350-380k), lubricants (350-400K) and Charge Air Cooling (320-340),[6].

From different the different heat sources named above, the exhaust gas is the most promising candidate heat source for recovery. The mass flow and temperature of the EG are the major influencing factors of design process and performance of heat recovery systems. Most available reports on WHR are based on exhaust gas and EGR temperatures with minimal references to coolant, CAC, and lubricants heat recovery. The reason is based on the potential of high heat content in the exhaust gas and EGR for reuse. Exhaust heat has potentials of around 40% of the fuel heat energy content, thus, making its harvest an attractive investment in the transportation business. The possibilities of this exhaust gas harvest are dependent on its mass flow and temperature; hence, the higher their values, the greater the capacity of recovery.

3. ORC Technology

ORC system allows the use of low temperature (<230°C), medium temperature (230-650°C) and high temperature (>650°C) for power generation, [7]. This technology is promising as it recovers heat from exhaust of internal combustion engines, which otherwise are normally released to the environment as waste heat. The cycle involves using a heat source to vaporize a pressurized organic fluid, then allowed it to expand in a turbine. The power output of the turbine is converted to electricity using a generator, [8]. In organic Rankine cycle-based heat recovery systems, the heat source is the waste heat produced by some primary combustion process. The primary sources of heat from internal combustion engines are exhaust gas. Individual heat sources can be exploited separately or in tandem if the situation permits, in which case the generated power augments the vehicle's propulsion system or drives a generator that produces electricity for the vehicle's electrical systems. The ORC is not just the focus of laboratory study but an industrial feasibility, with more than 100 ORC plants in operation. Examples of ORC plants installed across the globe include the Altheim geothermal project, the Admont, Lienz and Heidelberg biomass-fired CHP plants, to name just a few, [9].

Increasingly the threat of global warming and associated outcomes is compelling energy planners to focus on developing environmentally friendly energy conversion technologies that produce electricity with fewer emissions. The utilization of waste heat reduces thermal pollutions, mitigates greenhouse gas emissions while fostering energy conservation. The challenges with ORC however are low thermal performance, limited methods to increase work production, the option of working fluids (organic) that suit existing heat sources and sink temperatures and their impact on the environment, [8]. ORC is a power cycle which transforms heat to work with ORC fluids. A schematic diagram of a typical organic Rankine cycle that consists of four main components: evaporator, turbine, condenser, and pump is shown in **Figure 3.1**. As earlier mentioned, ORC is a Rankine cycle, and hence it applies the same operating principle. The liquid is pressurized in the pump (Process 1-2) and then heated and vaporized in the evaporator (by the incoming exhaust gas from the engine in a counter current flow), which causes the fluid to change its state from liquid to vapour (Process 2-3). The now high-temperature, high-pressure vapour is then expanded in the turbine, which extracts energy from the superheated working fluid for mechanical power (Process 3-4). Finally, the vapour upon leaving the expander condenses back to liquid in the condenser (Process 4-1), and the cycle repeats.

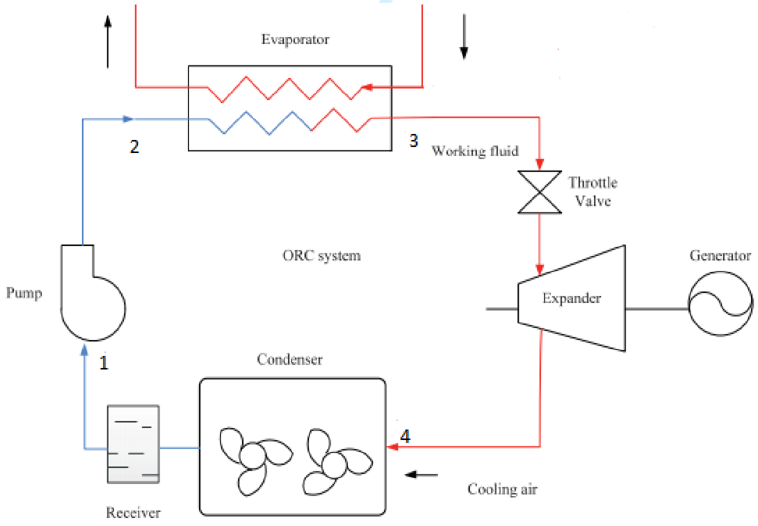


Figure 3.1. Schematic diagram of an ORC system, [10].

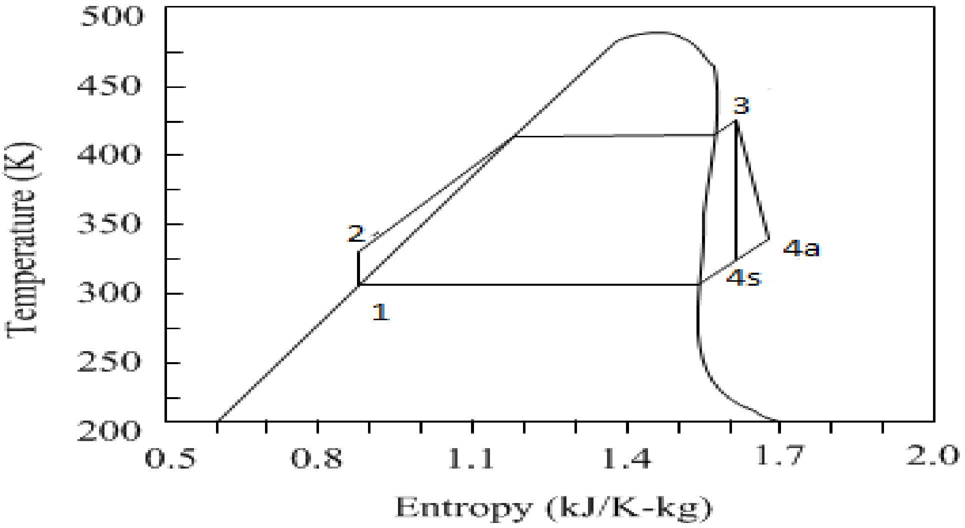


Figure 3.2. R-245fa T-s Diagram, *[10]*.

While the theoretical Rankine cycle is based on a sequence of reversible processes, real-world systems involve irreversible changes in pump and expansion equipment. Thus, real cycles do not involve any isentropic changes of state. The efficiency of the ORC unit, however, depends on the system working fluids, evaporators, expanders, pumps, or condensers. It considers that it is the most effective process for recovering waste heat from low temperatures, [11].

The thermal efficiency η_{th} of a ORC system can be calculated by considering its network output W_{net} and the heat input Q_{in} (which is supplied during stage 1-2), equation (2.1).

The network output is calculated by subtracting the and pumping consumption, W_{pump} from the mechanical output of the expansion device W_{mech}

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{W_{mech} - W_{pump}}{Q_{in}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 2.1$$

3.1 ORC Process Designs for HD Trucks

In truck installations, the ORC module is always deployed downstream of catalytic devices to prevent effects that will negate the emission control process. For possible implementation of heat recovery systems in automobiles, the architect should remain as simple as possible and take advantage of constituents that already exist in the truck design to alleviate installation costs, intricacy, and weight. Most used heat recovery system architectures for implementation in trucks are as follows:

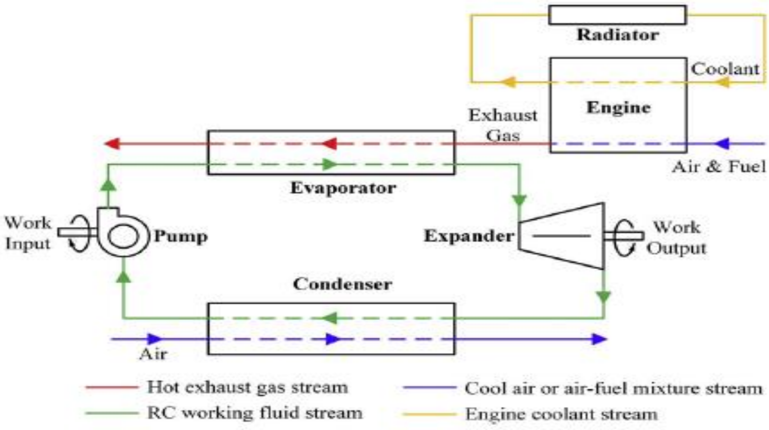


Figure 3.3. Simple ORC Design Layout

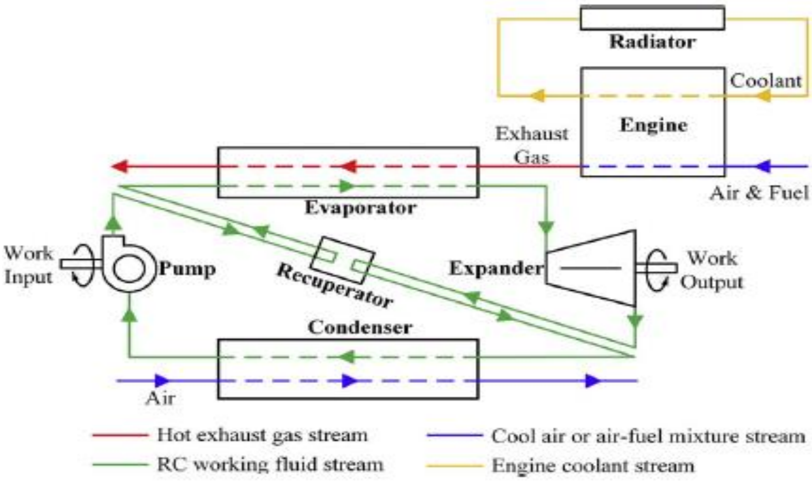


Figure 3.4. ORC Layout with Recuperate

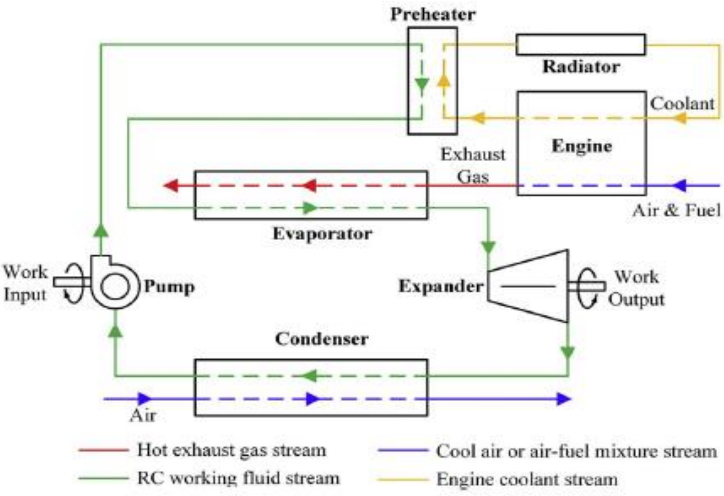


Figure 3.5. ORC Model with Preheater

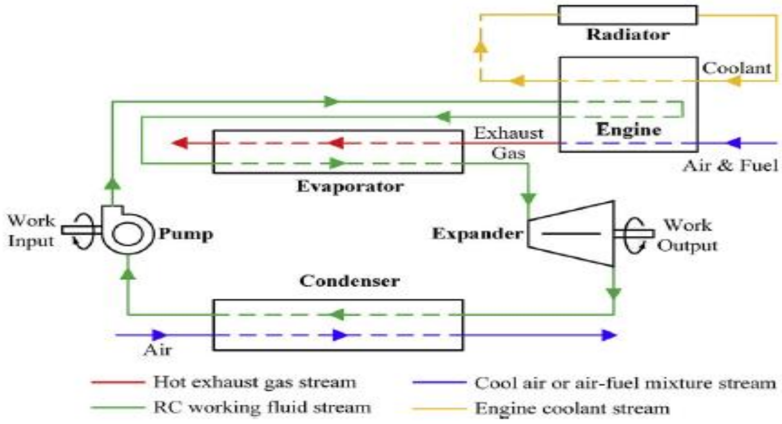


Figure 3.6. ORC Layout with Engine Block Preheater

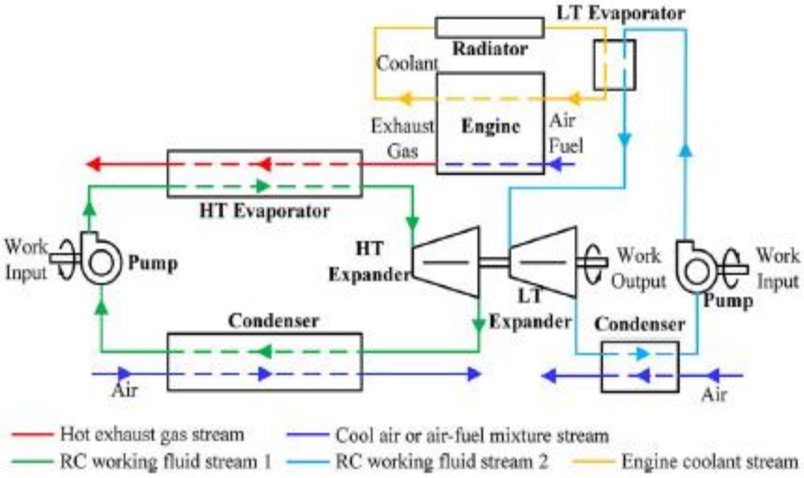


Figure 3.7. Layout with Dual Loops

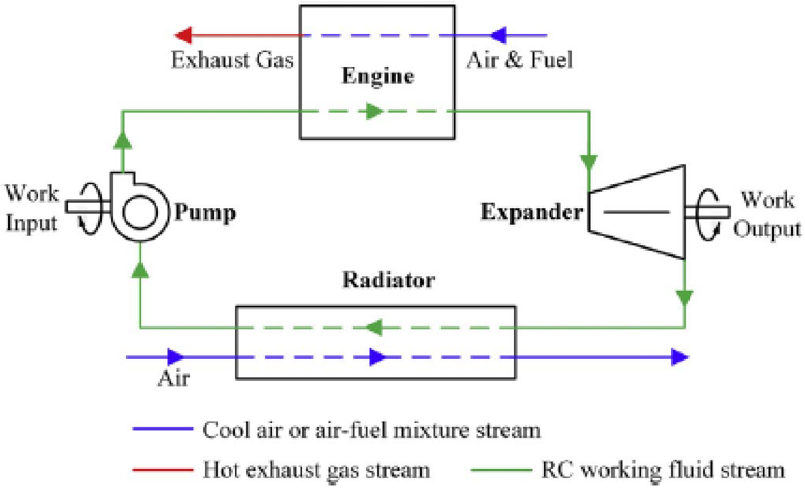


Figure 3.8. ORC Layout with Evaporative Engine Cooling System

Figure 3.3 presents the first layout, which is simple and most common used ORC layout for truck applications. Exhaust gas is the only heat source that vaporises the organic fluid, and the design consists only of the pump, evaporator, expander and air condenser. Heat rejection from the system is via the radiator. **Figure 3.4** represents an ORC architect with a recuperate for preheating the organic fluid before entering the evaporator heat exchanger with the vapour exiting the expander. This concept enhances the performance of the energy recovery unit with reduced heat input. In **Figure 3.5**, the ORC structure has preheater as an additional component which preheats the working fluid with heat from engine coolant. This module is like that of structure 2, where the preheating process is achieved by the vapour exiting the expander, thereby reducing the condenser cooling load. Few studies outline the advantages of energy recovery from exhausts and engine coolant simultaneously. A 10-35% of increased ORC net power achieved in heat recovery from EG and engine coolant as compare to the layout with only exhaust heat as Vaja and Agostino reported a heat source, (2010), [12]. Also, a 1.8% increase in engine bsfc was accomplished with a concept of exhaust and coolant heat recovery relative to the design with only exhaust gas as the heat sources, [13].

The heat recovery system layouts continue with **Figure 3.6** representing an ORC design with engine block partially vaporising the working fluid. In this case, the working fluid should not be allowed to vaporise completely, thus enter the evaporator as a two-phase vapour, [14]. **Figure 3.7** is a concept with dual loops mostly suitable for highway HD truck applications. The design uses water in HT loop and ethanol in LT loop, respectively. It has the advantage of making use of the possibilities of energy recovery in the system at the detriment of more complex module, [15]. In **Figure 3.8**, the architect adopts the engine cooling unit as an evaporator heat exchanger and the radiator as condenser. The structure has expander as the only added components to the whole module, though, the design requires moderation of the engine cooling device,[16].

3.2 ORC Working Fluids for Truck Engine Applications

Choosing the appropriate WF for Rankine cycle application is an essential step in heat recovery system designs. The approach depends on several essential requirements for such candidate fluid to have. These requirements include non-flammable, non-corrosive, non-toxic, zero ODP (ozone layer depletion potential), small global warming potential (GWP), high decomposition temperature, compatible with the system material and lubricant, excellent properties such as low freezing point, high vapour pressure, small viscosity, appropriate critical points, available, stable and low cost,[17][18].

Three types of working fluids exist for ICEs heat recovery Rankine cycle systems. These include wet, dry, and isentropic fluids, **Figure 3.9**. A negative gradient characterises the wet type fluids in t-s diagrams, and examples of wet fluids are water and ammonia. These fluids require a minimum amount of superheat at the expansion machine inlet to prevent droplets formation on the turbine blade during the expansion process, which causes cavitation effect and surface damage. High degree of superheat would consequently reduce the overall system performance and compromise the life cycle of the expansion machine material. The appropriate practice when using wet fluid is to maintain dryness fraction of above 85% without having excessive superheat,[19]. The application of the wet fluid requires frequent servicing and revamp of the turbines. Positive t-s diagrams define dry working fluids, and examples include R113, R123 and R245ca, to name a few. Dry fluids do not require to superheat in during expansion. If applied, a more considerable amount of superheat results at the outlet of the expansion machine thereby demanding a more significant amount of cooling load to bring the working fluid temperature down to sub-cooled state, thus, reduce the overall efficiency of the WHR unit. While, isentropic fluids are characterised by close-to-vertical line type of t-s diagrams, and an example is R245fa, [20]. Isentropic fluids allow expansion process to take place along the vertical line of the t-s diagram without condensation, thus, making these fluids more superior to dry fluids in ORC applications since they are not excessively superheated at the exit of expansion machines. This criterion reduces the cooling load requirement by the condenser as compared to dry working fluids.

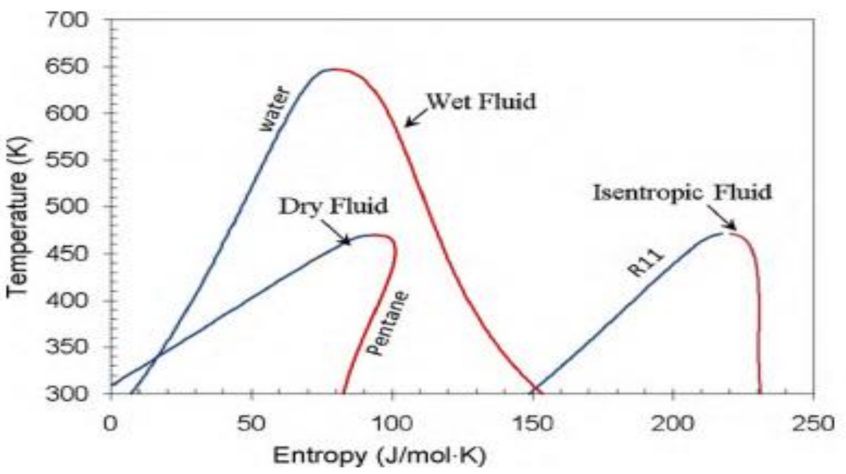


Figure 3.9. Example of the three working fluids type: wet, dry, and isentropic

Organic working fluids are also categorised into two classes based on compositions as follows:

I. **Pure Fluids**: This class of working fluids include HFCs, HCFCs, PFCs, HCs, HFOs, CFCs, and HFEs. They have the potentials of application in ICE heat recovery modules.

II. **Zeotropic Mixtures**: These are working fluid mixtures with constituents having different boiling points. Examples of the components are benzene, ethanol, toluene, and isobutane. The different boiling points criterion makes the mixture composition not to vaporised or condense simultaneously, thus making them superior over pure fluids in low-grade heat recovery.

The ORC system design in this study is for truck engine application; as such, the selection criterion would focus on properties that concern automobile applications. For selection processes based on safety and environmental concerns, NPFA 704 standards are considered,[21]. Characterising based on health, flammability and chemical reactivity, the working fluids are scaled from 1 to 4 for low to high hazards, respectively,[22]. Some selection working fluids are classified in the Table 3.1.

Table 3.1. ICE ORC Working Fluids Classification, [23][24]

W. Fluid	C.F	Group	Type	M. kg/ kmole	T_c, K	T_b, K	P_c, MPa	ODP	GWP	S. L
R11	CCl_3F	CFC	I	137.37	470.96	296.7	4.407	1	4750	A1
R12	CCl_2F_2	CFC	W	120.91	385.00	243.2	4.140	0.82	10,900	A1
R114	$C_2Cl_2F_4$	CFC	D	170.92	427.70	276.6	3.257	0.58	9180	A1
R218	C_3F_8	PFC	I	188.02	344.95	248.7	2.671	0	8830	A1
RC318	C_4F_8	PFC	D	200.03	388.20	267.0	2.780	0	10,300	A1
R236fa	$C_3H_3F_6$	HFC	D	152.04	397.90	271.6	3.200	0	9820	A1
R152a	$C_2H_4F_2$	HFC	W	66.05	386.26	259.0	4.517	0	140	A2
R227ea	C_3HF_7	HFC	D	170.03	374.80	256.7	2.930	0	3580	A1
R134a	$C_2H_2F_4$	HFC	I	102.03	374.00	247.0	4.059	0	1300	A1
R245fa	$C_3F_5H_3$	HFC	I	134.05	427.00	288.1	3.651	0	1050	B1
R21	$CHCl_2F$	HCFC	W	102.92	451.33	281.8	5.181	0.04	151	B1
R141b	$C_2H_3Cl_2F$	HCFC	I	116.95	479.96	305.2	4.460	0.086	700	-
R123	$C_2HCl_2F_3$	HCFC	I	152.93	456.83	301.0	3.662	0.012	120	-
R22	$CHClF_2$	HCFC	W	86.47	369.10	232.2	4.990	0.04	1790	A1
R142b	CH_3ClF_2	HCFC	I	100.50	410.10	263.9	4.060	0.06	2220	A2

R124	C_2HClF_4	HCFC	D	136.48	395.30	261.0	3.062	0.02	619	A1
R1234yf	$C_3H_2F_4$	HFO	I	114.04	367.70	243.5	3.380	0	4.4	A2L
R1234ze	$C_3H_2F_4$	HFO	I	114.04	382.40	253.4	3.630	0	6	A2L
HFE7000	$C_4H_3F_7O$	HFE	D	200.05	164.60	307.9	2.480	0	575	-
HFE7100	$C_5H_3F_9O$	HFE	D	250.00	195.30	332.6	2.230	0	297	-
HFE7500	$C_9H_5F_{15}O$	HFE	D	414.11	261.00	400.9	1.550	0	-	-
Propane	C_3H_8	HC	W	41.1	369.74	230.9	4.251	0	3.3	A3
Butane	C_4H_{10}	HC	D	58.12	425.00	272.1	3.800	0	3	A3
Pentane	C_5H_{12}	HC	D	72.15	469.50	308.5	3.360	0	4	-
Hexane	C_6H_{14}	HC	D	86.18	507.70	241.8	3.060	-	-	-
Heptane	C_7H_{16}	HC	D	100.21	540.00	370.9	2.730	-	0	-
Octane	C_8H_{18}	HC	D	114.23	569.20	398.0	2.500	-	-	-
Propylene	C_3H_6	HC	W	42.08	365.40	225.0	4.660	-	2	A3
Benzene	C_6H_6	HC	D	78.11	561.87	353.1	4.907	-	-	-
Toluene	C_7H_8	HC	D	92.14	591.60	383.6	4.126	-	2.7	-

Some reported studies on choosing the appropriate working fluid for heat recovery in ICEs are consulted. Wang et al. (2017) studied on the response performance of R245fa, R141b, Cyclohexane, and Toluene working fluids ICEs applications,[25]. In another study, R245fa, R141b, and R123 demonstrated high thermal performance of 21 screened organic fluids for exhaust energy recovery in IC engines,[26]. In the same vein, the screening of 31 working fluids was conducted to assess their performance in low-grade heat organic Rankine cycle systems,[27].

Despite the number of studies on selecting working fluid for ICE ORC systems, no single fluid can be defined as the most appropriate for all ORC applications. The selection process depends heavily on the field of usage, power scale, heat source and heat sink temperature. The goal is to select different optimum fluids based on the maximisation of the cycle power generation, environmental considerations, or economics.

3.3 ORC Applications

The typical advantage of the ORC over the steam (Rankine) cycle is its ability to transform low-heat sources into mechanical power more effectively. This technology opens a broad array of possibilities that would not have been possible with the steam cycle with higher boiling point. A general overview of the various possible uses of ORC technology is provided with focus on small to medium-scale in biomass / CHP, geothermal, ocean-thermal and waste heat recovery, [28].

3.3.1 Application in Automobiles

In the transport sector, the exhaust heat recovery device transforms exhaust thermal losses into power. This exhaust reuse technology is up-and-coming for light and heavy-duty vehicle manufacturers as an optimal way to save fuel and reduce CO_2 emissions. Automotive engineers are increasingly looking at ways to make fuel-efficient vehicles amidst rising global air pollution. The technology recycles the exhaust before they leave the vehicle, which also helps to reduce emissions from the vehicle. The primary source of greenhouse gases release in the United States is CO_2 emission from fossil fuel for power generation and transportation, (**Figure 3.10**).

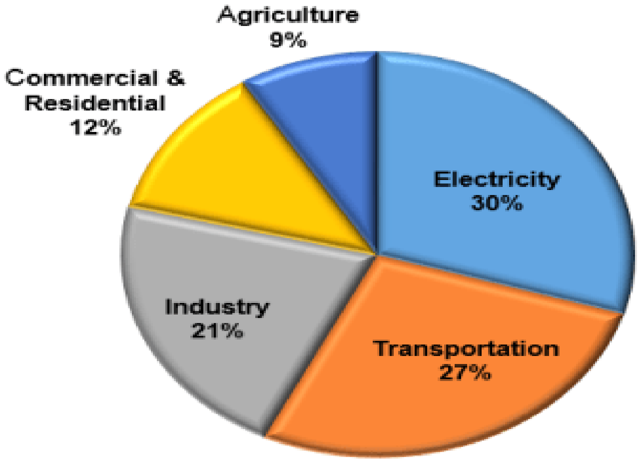


Figure 3.10. GHG Emissions by Sector **[29]**

BMW's turbosteamer was reported as the first demonstration prototype system in 2005 to use the application of the RC system for WHR from the exhaust gas to increase the thermal performance of the automobile combustion process. The cogeneration concept reduced fuel consumption in stationary operating conditions of the 4-cylinder SI engine by 10% at high-way speed, [30]. In 2012, the second-generation turbosteamer of BMW was reported to have been further simplified to ensure effective vehicle integration of the RC system for WHR, [31].

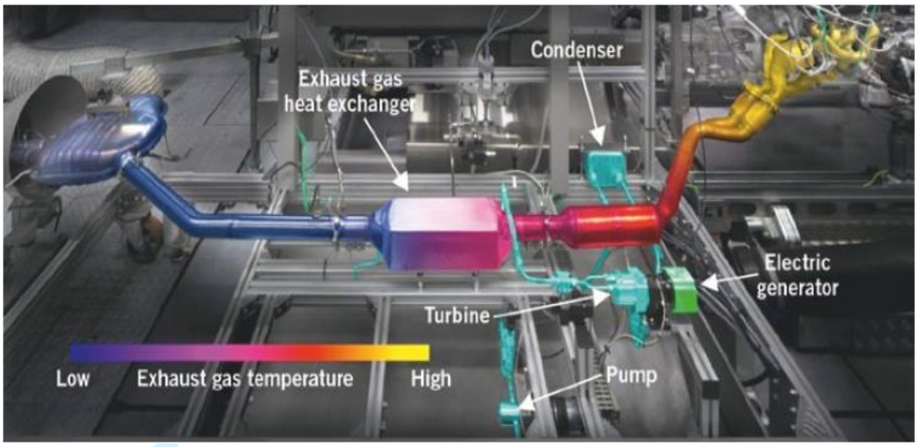


Figure 3.11. Turbosteamer Mounted on Test Rig, **[31].**

In 2005, Cummins undertook a concept of WHR for Class 8 truck which was funded by U.S Department of Energy. The project demonstrated an initial promising result, [32]. In 2013, Cummins again announced a milestone achievement in the WHR project of 50% improvement in thermal brake efficiency (BTE) and consequent increase in fuel savings of ~6%, [33].

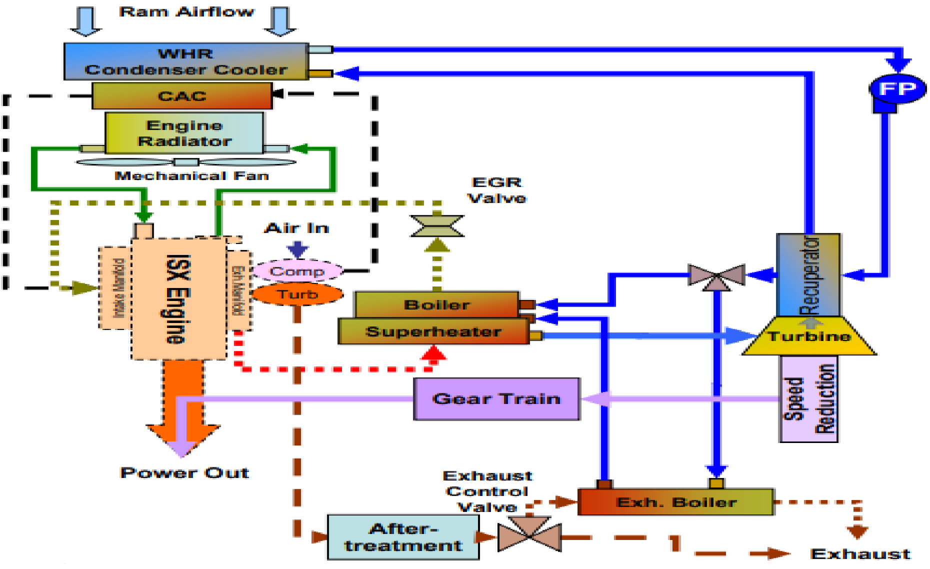


Figure 3.12. Cummins WHR Layout, **[33]**

In 2008, Honda reported a prototype Rankine cycle system installed in a hybrid vehicle for possible WHR from the engine (see **Figure 3.13**). Testing the vehicle at 100km/h constant speed resulted in a 13.2% increase in thermal efficiency. The newly designed cylinder head structure integrated with the evaporator generated a high-temperature steam with a heat quantity of 400°C, 8MPa, and 14.3kW, [34]. However, the company is not going further with production until higher efficiency is achieved, [35]

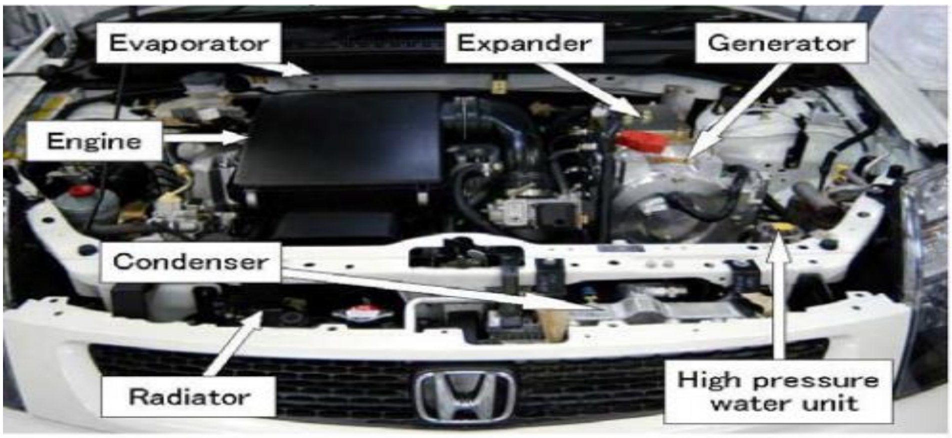


Figure 3.13. Rankine Cycle Prototype Layout, **[34].**

He et al (2011). proposed a combined ORC and Kalina thermodynamic cycle for WHR to enhance the performance of the Toyota 8A-FE gasoline engine. The steady-state experimental result revealed more exhaust heat recovery with the combined cycle compared to the traditional cycle configuration,[36]. A steady-state test on a TOYOTA 8A-FE gasoline engine working under different conditions has also been published. The performance parameter and power output of the ORC system was measured, and the results showed a thermal efficiency of 14.44%,[37].

Boretti in 2012 examined the recovery of exhaust and coolant heat in a hybrid passenger car engine with R245fa as working fluid. The findings showed that the fuel efficiency of the exhaust ORC system increased by 3.4% with a maximum improvement of 6.4%., the coolant ORC presented a maximum fuel efficiency improvement of 2.8%, and the combined system a maximum fuel efficiency of 8.2% with the engine operating at steady state, [13]. In 2013, Domingues et al. reported a model simulation of the RC for potential exhaust energy recovery from vehicle exhaust gas engines using water, R123 and R245fa as working fluids. It involved both thermodynamic and heat exchanger algorithms to achieve the goal of heat recovery. The study shows an increase of 1.4 - 3.52% and 10.16 - 15.95% in thermal and mechanical efficiency of ideal heat exchangers using the organic working fluids, respectively,[38]. Kunte and Joerg (2013) explored the suitability of a partially admitted single-stage impulse turbine in the ORC for HD truck and small car applications at three separate operating points. The turbine pulse showed the highest efficiency and allows the use of variable partial admission based on boundary conditions. The possibility to open and close stator passages allows the operation of the turbine at off-design conditions close to the design pressure ratios and maximizes the power output,[39].

Tilmann et al (2014). developed an ORC model for predicting waste heat recovery performance and fuel-saving potentials in vehicles which was validated with test rig measurements of the cycle components. The EHR system showed improvement of fuel economy by 3.4%. WHR, therefore, plays an essential role in overcoming the challenges of increased electric power demand in future vehicles,[40]. Daccord et al (2014). developed a piston expander prototype with oil-free hot parts using ethanol as working fluid to determine the effect of various parameters on the performance of the EHR system for passenger cars and heavy commercial vehicles. The built prototype showed promising results, and the expander suits the mobile applications perfectly,[41]. The design of the variable geometry turbine (VGT) of the ORC system model for the recovery of exhaust energy from a 1.25 l gasoline engine was proposed by Thaddaeus et al (2016). to assess the benefits of the variable geometry turbine. Results show that VGT increases ORC thermal efficiency and turbine output respectively by 5.6% and 3.07kW, [42]. Arise et al. reported the modelling of the ORC system integrated into the engine model in 2016 to evaluate its application opportunities and challenges. System simulations were conducted using different driving conditions, and the results achieved substantial fuel economy improvement with CO_2 savings of up to 4% on standard driving cycles, [43].

Furthermore, Rongqi et al (2016), using the Active Disturbance Rejection Control (ADRC) approach, reported the design of the ORC system for WHR of unstable exhaust heat from automotive engines. The results show that the designed model operates reliably with an evaporative pressure control with an error of less than 0.1% and a superheating fluctuation of less than 1^{o}C compared to the basic ORC system. The additional advantage of the model is that the architecture is simple, since no other thermodynamic cycle or operating fluid is required,[44]. Galindo et al (2017). present a 1D simulation model of an ORC designed with swash-plate expander coupled to 2L gasoline engine using ethanol as working fluid. The model demonstrated an expander power output of 800W, offering a potential 2.5% improvement of fuel conversion efficiency and a 23.5g/kW reduction in bsfc when operating at 120km/hr NEDC,[45]. Robert et al (2017). studied the economic feasibility of applying the organic Rankin cycle in the transport sector. The study reported a comparison of the maximum permissible mass and the volume of ORC to that of the commercially available ORC product. The results show that for trains, the weight and volume of the ORC must be reduced by 13% and 59% respectively. For trucks and buses, the reductions need to be higher,[46].

More so, Amin et al (2017). explored the implementation of WHR on a hybrid electric vehicle under three different driving cycles, including FTP-75, NEDC and US06, to evaluate its powertrain benefits. The model simulation resulted in a significant decrease in the overall bsfc of the vehicle,[47]. Zhao et al (2017). designed the ORC recovery system and compared its performance with that of the basic organic Rankine cycle for use in vehicle waste heat recovery. The steady-state results show that the cooling heat decreases with an increase in the net output of the recuperative ORC compared to the basic ORC. According to the report, compared to basic ORC, backpressure and engine performance do not affect recuperative ORC. However, more refrigerant charges and more extended response time are disadvantages,[48]. Yue et al (2019). suggested a method for the harvesting of exhaust energy from vehicles. Model simulation results showed that three efficient ways to increase turbine output power and save fuel are to reduce the LMTD in the evaporator, lower the ambient temperature and increase vehicle speed. The maximum power yield and fuel-saving rate of the model are 14.8kW and 0.23, respectively under the working conditions of the model,[49]. Yang et al (2019). reported a thermo-economic review of the implementation of the ORC system for on-road waste heat recovery vehicles. The study showed the potential for the application of waste heat recovery technology in vehicle engines and the need for cost assessment of the integration of this technology into on-road vehicles,[50].

3.3.2 Applications in Trucks

Cars, light-duty vehicles, and motorcycles account for nearly 60% of GHGs release from the transport sector (**Figure 3.14**). Medium to heavy-duty trucks contribute 24% of greenhouse gas emissions, which equates to around 6% of overall U.S. GHG emissions. It is evident from figure 2.4 that the trucking sector emits a total of 41% of air pollutions from the transport sector in the United States. Therefore, a possibility exists for the trucking industry within the sustainability movement. The public sector also can support sustainability goals that lead to improvement of technology and road conditions through funding for R&D programmes, financial incentives, good regulatory practises, and investment in infrastructure.

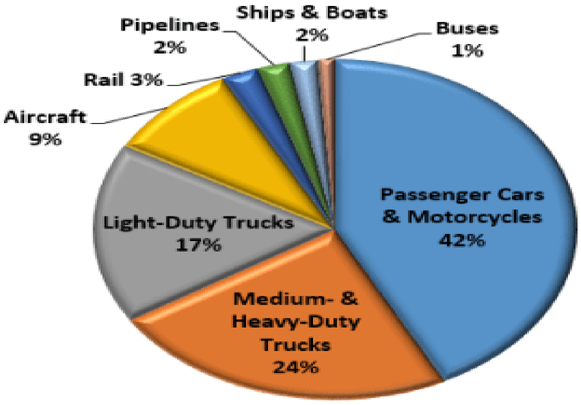


Figure 3.14. US GHG Emissions in the Transportation Sector, **[29]**

Some recently reported works in applying ORC for exhaust recovery in heavy-duty diesel engines are also reviewed. Teng et al (2017). researched on an ORC method for EHR in heavy-duty engines using a highly pressurized dry working fluid. Results showed that the WHR system could achieve up to 20% increase in engine power without increased fuel consumption and an ORC output of 18% improvement,[51]. Teng, (2010) reported a study on WHR of heavy-duty engines in a view to reduce emission and cost of operation. The outcome demonstrated ethanol as a right candidate working fluid for use in the Rankine cycle model because of low vapour pressure which in turn makes it relatively cheaper as compared to R245fa mostly used in ORC, [52]. Yu et al (2013). developed a model based on a diesel engine's ORC bottoming method with R245fa as working fluid; the system was formulated to recover energy from the exhaust gas and water jacket. Under the designed conditions, ORC output resulted in an expansion capacity of 14.5kW, a recovery efficiency of 9.2% and an exergy efficiency of 21.7%. When combined with bottom ORC, the diesel engine's thermal system output can exceed 6.1%,[53].

Again, Lang et al (2013). examined the feasibility of WHR from a HD truck engine based on ORC turbo-generator system with siloxane as working fluid. The simulated result gave an addition of 9.6kW at 150kW engine power output and 1500rpm design point,[54]. Fubin et al (2014). developed a dual-loop Organic Ranking Cycle (ORC) model for the reuse of exhaust energy in a diesel engine using R245fa as a working fluid for both loops. Under the operating conditions, the tests showed a maximum system output of 5.4%. The system's net power output was 27.85 kW, resulting in a 13% thermal efficiency increase and a 4% rise in bsfc,[55]. In 2014, Eaton Corporation reported an approximately 6% bsfc improvement demonstrated by a root-based expander organic Rankine cycle model testing for WHR from a 13,5L John Deere

Diesel engine using ethanol and water mixture as working. A project financed by US Department of Energy,[56].

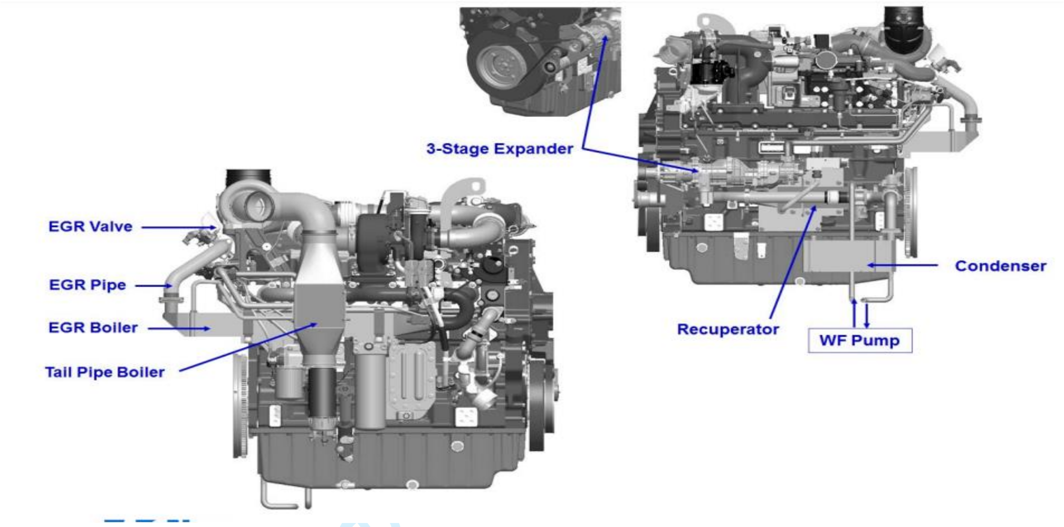


Figure 3.15. Eaton Corporation ORC Model

Amiacabile et al (2015). presented a study on the recovery potentials of EGR using ethanol, pentane and R245fa as candidate working fluids for four different ORC model layouts. Best performance was the result of a subcritical regenerative cycle with ethanol as a working fluid giving 3.3% bsfc improvement while the minimum cost of capital was from the sub-critical cycle without the recuperator using ethanol as working fluid,[57].

Pooja and Farkade (2016) carried out an experimental test on a single-cylinder, 4-stroke engine to evaluate the available exergy in the exhaust gas of a diesel engine using a shell and tube heat exchanger with water as a working fluid. In their study, they concluded that exhaust energy harvest from diesel engines could increase system performance, save energy, and reduce toxic emissions per kilowatt power generation, [58]. Also, Vijay et al (2016). reported the idea of rehabilitating diesel exhaust heat by adding a thermal transmitter to the exhaust manifold to use the exhaust gas energy for fuel preheating. For a concentrated tube heat exchanger of 130^{o}C with 25% full load and 1500rpm, the output was an increased petrol temperature. The shell and tube evaporator respectively achieved 73% and 90% of fuel temperature for parallel and counterflow temperatures at 50% load and 1500 rpm conditions. In parallel and counterflow systems, the performance of the heat exchanger was set at 75% and 81% respectively. The result ultimately concluded that the pre-heating of biodiesel fuel is beneficial,[59].

Elio et al (2017). investigated the recovery of exhaust heat from truck diesel engines using R245fa, R245ca, R134a, R11, R113 and Novec649 as working fluids in the ORC. The model analyses aimed to evaluate the optimal efficiency of the process. The study resulted in R11 and R113 as the appropriate working fluids for the ORC model, [60]. Roberto et al (2017). also explored the influence of organic working fluids on the weight and space requisites of ORC applications for EHR in truck engines. The ORC system modelled with 17 working fluids demonstrated that acetone and ethanol harvested more power while isobutane had the highest power-to-weight and power-to-volume ratios of 234W / kg and 277W / dm^3, respectively, [61]. Anh's (2018) reported a brief review of the application of ORC technology as a WHR system for diesel engines and operating fluids suitable for use as the organic working fluid,[62].

In 2019 Volkswagen and MAN integrated the WHR system into two conventional production vehicles: Golf 7, 2-1 TFSI EA888 and Demo truck D2676 LF25 Euro VI, respectively. The prototypes showed a 75% evaporator efficiency and a corresponding 3% reduction in fuel consumption. The research group is now on the lookout for a measure to increase the potential of the WHR system employing an arrangement for the combined electrical/mechanical use of expander power, [63].

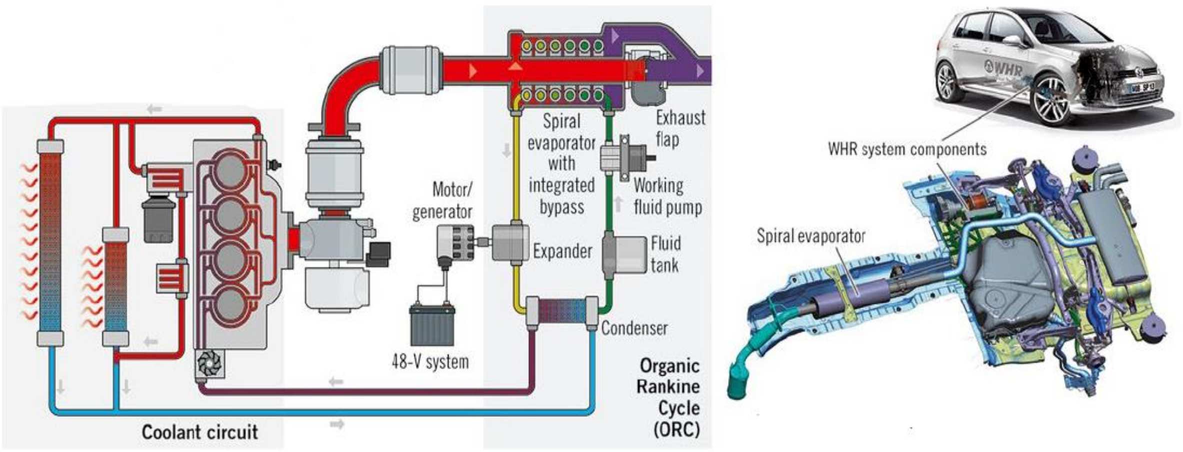


Figure 3.16. WHR System Integration to Volkswagen, **[63]**

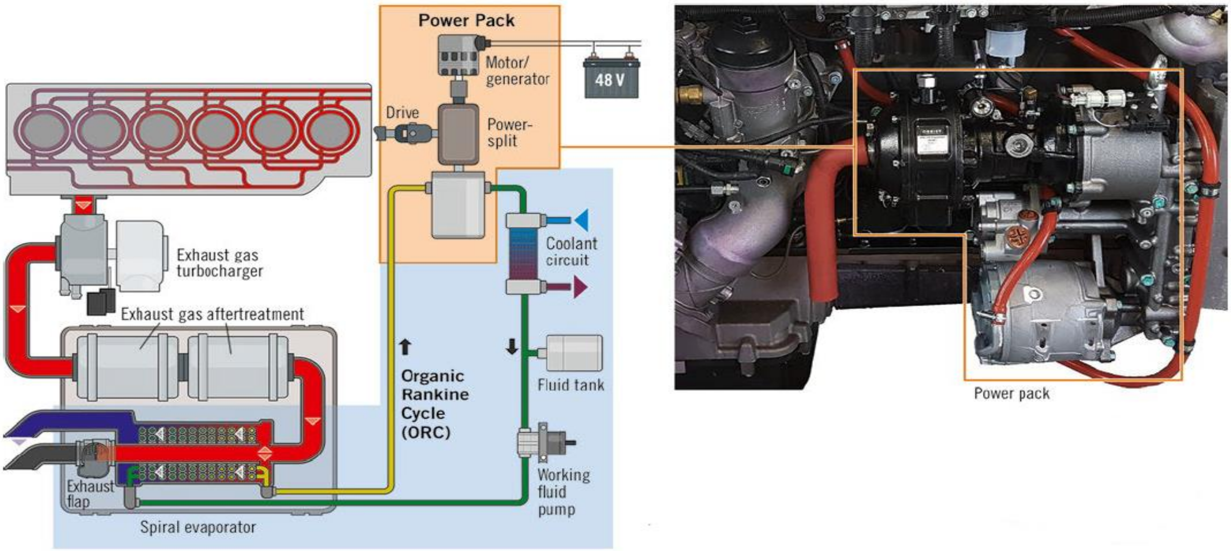


***Figure 3.17. WHR System Integration to MAN Truck,* [63]**

Table 3.2. Summary of Prototypes by Vehicle Manufacturers

Ref.	Year	Manuf.	Vehicle	Layout	Expander	W. Fluid	Result
[30]	2005	BMW 1st Gen.	3 Series	Dual loop RC	Vane Expander	Water & Ethanol	5.7% η_{th}
[32]	2005	Cummins	Class 8	RC with Recuperate	Turbine	Water	6% η_{orc}
[34]	2008	Honda	HEV	Basic RC	Axial Piston	Water	3.8% η_{th}
[31]	2012	BMW 2nd Gen.	5 Series	Basic RC	Impulse Turbine	Water	6% η_{mech}
[33]	2013	Cummings	Class 8	RC with Recuperate	Turbine	Water	55% BTE
[56]	2014	Eaton Corp.	John Deere Diesel	Basic ORC	Root Expander	Water & Ethanol	6% bsfc
[63]	2019	Volkswagen	Golf 7	ORC	Axial Piston	Ethanol	5-6kW
[63]	2019	MAN trucks	D2676 LF25 Euro VI	ORC	Axial Piston	Ethanol	4% bsfc

3.3.3 Vehicle Integration Bottleneck

The integration of ORC system onto an existing vehicle architecture for recovering exhaust heat demands a balance between the system sophistication, costs, weight. The influence of the additional ORC system on the existing components is more crucial than maximizing the power output; thus, a simple, compact ORC system is appropriate for vehicle integration. The add-on system may result in the following:

3.3.1 Increased Vehicle Weight

Increased vehicle weight (mass) due to additional system components results in more traction effort needed to accelerate the vehicle and increase the rolling resistance of the tyres. This add-on weight, however, has less effect on long-haul trucks than it does on small cars.

3.3.2 Increased Back Pressure

At increased backpressure, the engine must compress the exhausts to a higher-pressure level, which consumes additional mechanical work. The increased back pressure results in increased engine bsfc, emissions, and exhaust temperature, to mention but a few.

3.3.3 Additional Cooling Demand

The condenser heat needs to be removed, thus, increasing the cooling requirement of the automobile. The cooling of the working fluid is achieved by installing a separate air-cooled condenser or by integrating it into the existing engine cooling loop, which requires coolant recirculation at higher speeds and higher cooling air velocities.

3.3.4 Package Consideration

The ORC system for automotive applications is deployed downstream of the exhaust catalyst so as not to affect emission control. For the integration of the ORC system to be feasible for application in the vehicle, the ORC layout should remain as simple as possible and use existing components in the vehicle to reduce added weight, costs, and intricacy of the system.

Conclusion

This review presents descriptions of recent developments and researches performed in the deployment of ORC for exhaust exergy recovery system in long-haul truck engines, as reported in published journal articles. The work includes a review of ORC technology, its applications to passenger car and truck engines, and some bottlenecks associated with the integration of ORC systems to vehicle for waste heat recovery.

The outcomes show that ORC applications in trucks for exhaust gas exergy reuse is a promising technology with possibility of large-scale integration and implementation. However, not many reports exist on the dynamic operations of ORC system models for truck applications to forecast possible real-life situations if these models are adopted. More, so, few available papers report the techno-economic aspects of ORC technology in trucks application and the economic benefits of greenhouse gas reduction of implementing the ORC technology.

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