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ÚSTAV AUTOMOBILNÍHO INŽENÝRSTVÍ

VEHICLE THERMAL BATTERY HEAT RECOVERY SYSTEM ARCHITECTURE LOOP

ARCHITEKTURA SYSTÉMU ZPĚTNÉHO ZÍSKÁVÁNÍ TEPLA Z TEPELNÉ BATERIE VE VOZIDLE

MASTER´S THESIS

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Pursuant to Act no. 111/1998 concerning universities and the BUT study and examination rules, you have been assigned the following topic by the institude director Master´s Thesis:

Vehicle thermal battery heat recovery system architecture loop

CONCISE CHARACTERISTIC OF THE TASK:

OEM's are pushed to achieve stricter emission standards. At present we still loose more than one third of total energy in exhaust gases. As one of the possibilities how to help to fullfill future standards is to develop thermal storage unit, which in the case of need of the cold start will improve the engine efficiency, when emissions and consumption are the highest. These thesis will deal with appropriate incorporation of the heat storage unit and further optimization. We can deliver the stored heat to the coolant circuit, engine or transmission oil circuit.
Practical part of these thesis will contain the design of the model, where effects of system architecture of the heat storage unit to consumption, emission and other important parameters will be investigated, its evaluation and also results interpretation on hybrid vehicles which have specific needs on exhaust heat recovery systems.

GOALS MASTER´S THESIS:

To analyze thermal battery needs and this thermal battery influence efficiency on vehicle as a whole.
To do this both for conventional and hybrid vehicles.
To design vehicle model with various thermal storage unit incorporations and to investigace the influence of engine overheating.
To evaluace results related to hybrid vehicles.

RECOMMENDED BIBLIOGRAPHY:

STONE, Richard. Introduction to internal combustion engines. 3rd edition. Warrendale, Pa.: Society of Automotive Engineers, 1999. 641 s. ISBN 0768004950.

Deadline for submission Master´s Thesis is given by the Schedule of the Academic year 2018/19

In Brno,

L. S.

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ABSTRACT

This thesis deals with the importance and possibilities of exhaust heat recovery, which helps to accelerate engine warm up at start and thereby reduce emissions. The theoretical part deals with emissions and the effort to reduce them by previous design solutions over the years. The practical part is devoted to creating the models with implemented systems of heat recovery and their impact on the temperature of the coolant and oil as well as the total vehicle consumption.

KEYWORDS

Emissions, fuel consumption, exhaust heat recovering, diesel, hybrid, EHRS

ABSTRAKT

Táto práca sa zaoberá významom a možnosťami rekuperácie tepla výfukových plynov, ktoré pomáhajú pri štarte urýchliť zahrievanie motora a tým znižovať emisie. Teoretická časť pojednáva o emisiach a v snahe znížiť ich o predošlých konštrukčných riešeniach v priebehu rokov Praktická časť je venovaná vytvorení modelov s implementovanými systémami rekuperácie tepelnej energie a ich dopad na teplotu chladiacej kvapaliny a oleja ako aj na celkovú spotrebu vozidla.

KĽÚČOVÉ SLOVÁ

Emisie, spotreba, spätné získavanie tepla, diesel, hybrid, EHRS

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DECLARATION

I declare, that I have elaborated this master´s thesis independently under the supervisor *Ing. Jiří Bazala*. All used sources have been properly cited in bibliography.

In Brno, 24th May 2019 …….……..…………………………………………

Michal Stanko

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INTRODUCTION

Cars have been for a long time considered a significant source of air pollution. These concerns have spread regularly until the 60s of the 20th century, when California as the first state in United States of America introduced the first emission standards. This important decision was driven by scientific research from Ajhaägen-Smit Company. The atmospheric chemistry company has demonstrated that the photochemical reactions of hydrocarbons and nitrogen oxides lead to many secondary pollutants that reduce visibility and cause irritation to eyes and nose. *"Emissions from road transportation by itself are causing around 50 000 early deaths per year only in the United States."* [5]

These emissions are highly dependent on energy transformation. Energy losses occur every time energy moves from one system to another. Internal combustion engine is only able to transform around 1/4 of total energy input from fuel to movement. Although efficiencies can be improved, they can only be increased to some degree because of the principles of thermodynamics. Better solution is to take this wasted exhaust heat and use it for additional recovery heating.

1 EMISSIONS

1.1 TYPES OF EMISSIONS

If we look at the composition of exhaust gas, the largest part is created by nitrogen N_2, water vapor H_2O and carbon dioxide CO_2. In a smaller way, exhaust gas contains undesirable and mostly toxic substances like carbon monoxide CO, hydrocarbons HC, nitrogen oxides NO_x and particulate matter in a form of soot. Percentage of each substance in composition can vary depending on the type of engine (gasoline or diesel engine), type of injection (direct or indirect) and many other attributes.

1.1.1 CARBON MONOXIDE

CO is a product that results from incomplete combustion, where the process of oxidation does not finish completely. Concentration of CO is heavily dependent on air/fuel mixture and the highest values occur where the excess-air factor (λ) is less than 1.0. That is classified as rich mixture and it can be caused especially at the time of starting the engine or instantaneous acceleration where the richer mixtures are required.

Carbon monoxide is colorless, odorless and tasteless which makes it even more dangerous. Inhaling CO from air can reduces the blood's ability to carry oxygen as it binds to hemoglobin and overexposure may be fatal. Poisoning from carbon monoxide is the most frequent cause of air poisoning in many countries. Around 55% of all carbon monoxide emissions are created by mobile vehicles in the U.S. [1], [2]

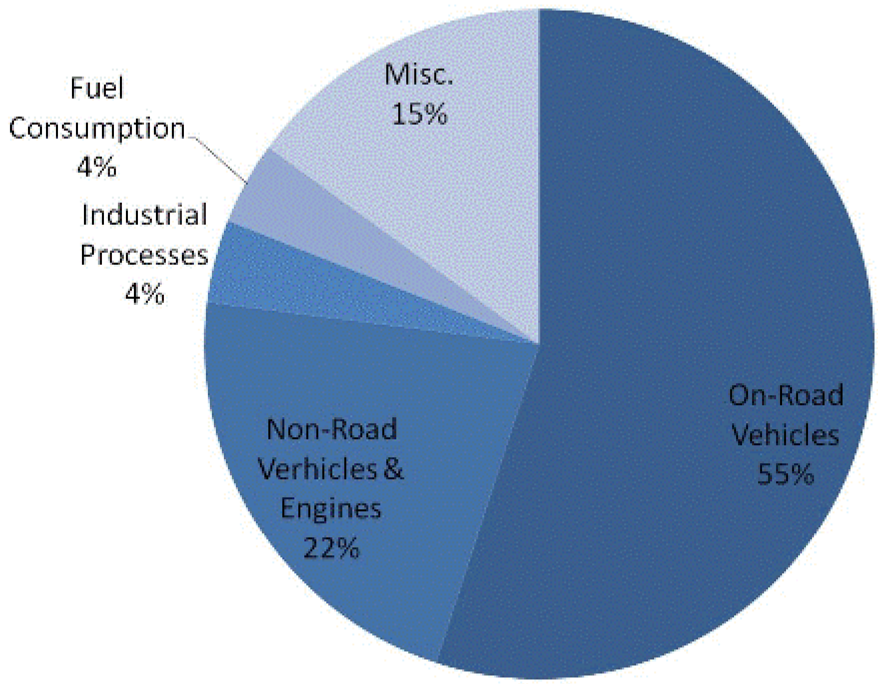

Figure.1 Contribution of various sources to the CO emissions [1]

1.1.2 CARBON DIOXIDE

It is very stable gas without smell or color. CO_2 emissions are directly proportional to the quantity of fuel consumed by an engine. They are products of perfect oxidation. In high doses they are dangerous to humans as they push the oxygen out. According to majority of scientists, this greenhouse gas contributes to climate changes (heat waves, floods, droughts and storms). China, United States and India as the largest emitters of energy related CO_2 emissions are shown separately to highlight the ratio of CO_2 to their continents. [1], [2]

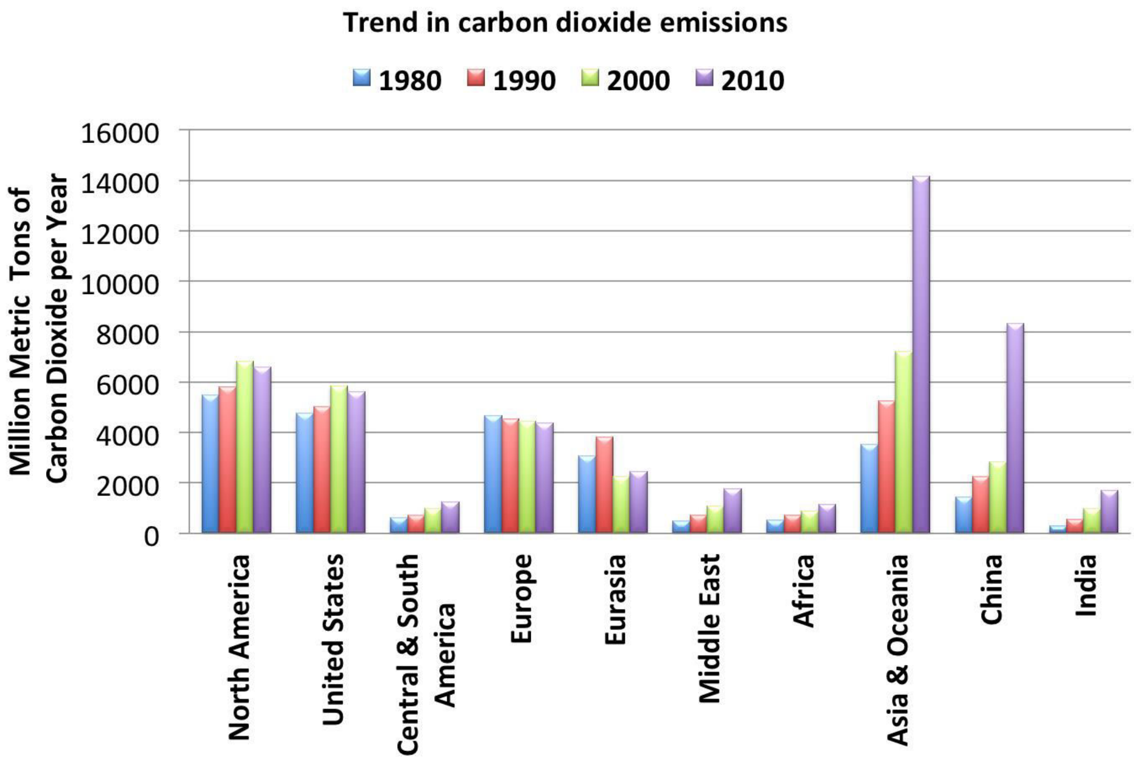

Figure.2 Trend in carbon dioxide emissions [1]

1.1.3 HYDROCARBONS

Hydrocarbon emissions are creations of unburned fuels as a result of insufficient temperature which usually occurs close to the cylinder wall. Because the air–fuel mixture temperature is significantly lower than the center of the cylinder, unburned hydrocarbons still continue to react in the exhaust, but only if the temperature is above 600 °C and oxygen present. It means that hydrocarbon emissions from the tailpipe may be significantly lower than the hydrocarbons leaving the cylinder.

Hydrocarbon emissions do not occur only in the vehicle exhaust, but also during fuel distribution and dispensing from atmospheric venting of vapors or in the engine crankcase and the fuel system. Crankcase hydrocarbon emissions and evaporative losses of hydrocarbon emissions have, respectively, 20–35% and 15–25% while tailpipe hydrocarbon emissions have 50–60% of total hydrocarbon emissions. Hydrocarbons have harmful effects on environment or human health. But with other pollutant, they are main contributor to smog, ground-level ozone. [1], [2]

1.1.4 NITROGEN OXIDES

Nitrogen oxides (NO, NO_2) are a group of highly reactive gases. The amount of produced NO_x is a function of the maximum temperature in the cylinder, oxygen concentrations, and residence time. Most of the emitted NO_x is formed early in the combustion process, when the piston is still near the top of its stroke. This is when the flame temperature is the highest. High temperatures above 1600°C in the cylinders cause the nitrogen to react with oxygen and generate NO_x emissions. Increasing the temperature of combustion increases the amount of NO_x by as much as threefold for every 100°C increase.

Nitrogen oxides emissions from vehicles are responsible for a large amount of environmental and health hazard. NO_x emissions contribute to acidification, formation of ozone, nutrient enrichment, and smog formation, which have become considerable problems in most major cities worldwide. NO and NO_2 are considered as toxic; but NO_2 has a level of toxicity five times greater than that of NO and it is also a direct concern of human lung disease. Nitrogen dioxide can irritate the lungs and lower resistance to respiratory infection (such as influenza). NO_x emissions are important precursors to acid rain that may affect both terrestrial and aquatic ecosystems. [1], [2]

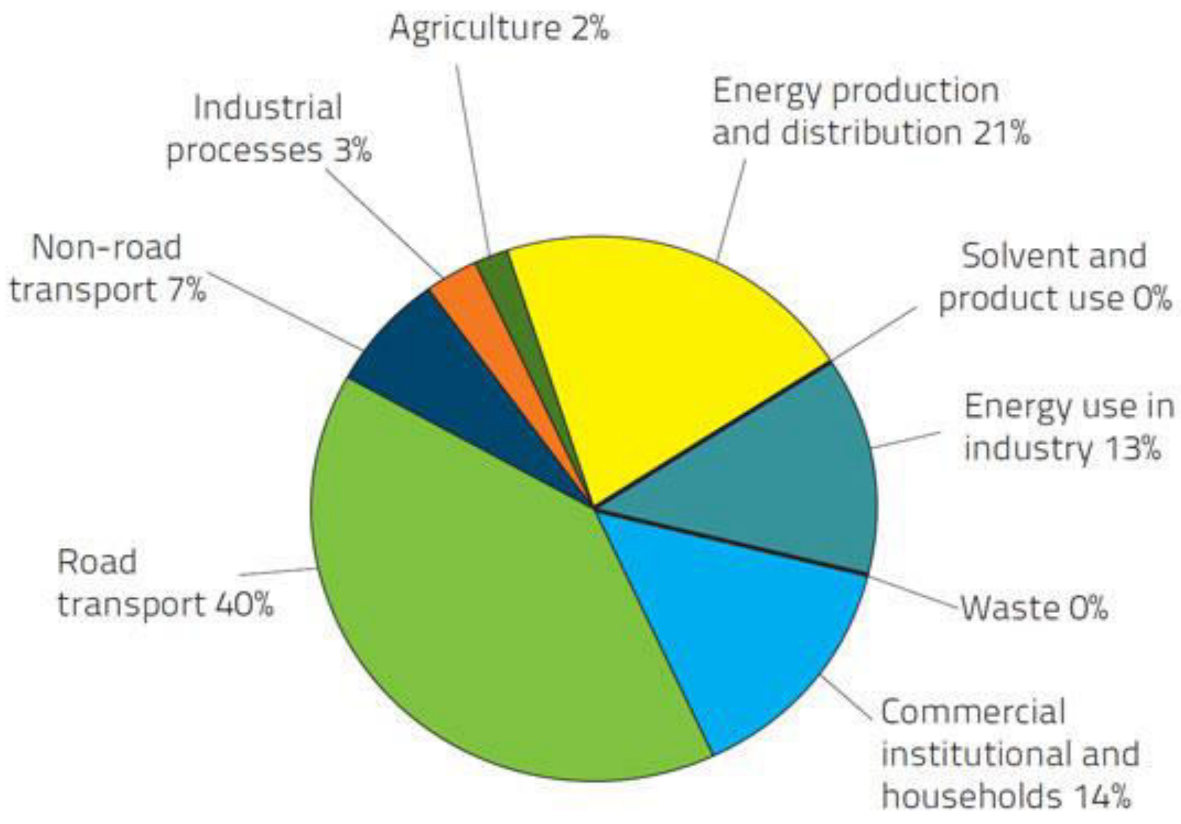

Figure.3 Sources of nitrogen oxides emissions [2]

1.1.5 Particulate matter

Particulate matter emissions in the exhaust gas are resulted from combustion process. They may be originated from the agglomeration of very small particles of partly burned fuel, partly burned lube oil, ash content of fuel oil, and cylinder lube oil or sulfates and water. Most particulate matters are resulted from incomplete combustion of the hydrocarbons in the fuel and lube oil.

Inhaling of these particles may cause to important health problems such as premature death, asthma, lung cancer, and other cardiovascular issues. These emissions contribute to pollution of air, water, and soil; soiling of buildings; reductions in visibility; impact agriculture productivity and global climate change. [1], [2]

1.1.6 Sulfur oxide

Sulfur dioxide is part of the sulfur oxide gases (SO_x), which means that these gases can easily dissolve in water. It prevails in all raw materials like crude oil or coal.

SO_x emissions occur when fuel containing sulfur is burned and gasoline is extracted from oil. SO_2 dissolves in water vapor to form acid and interacts with other gases and particles in the air to form sulfates and other products that can be harmful to people and their environment. [1], [2]

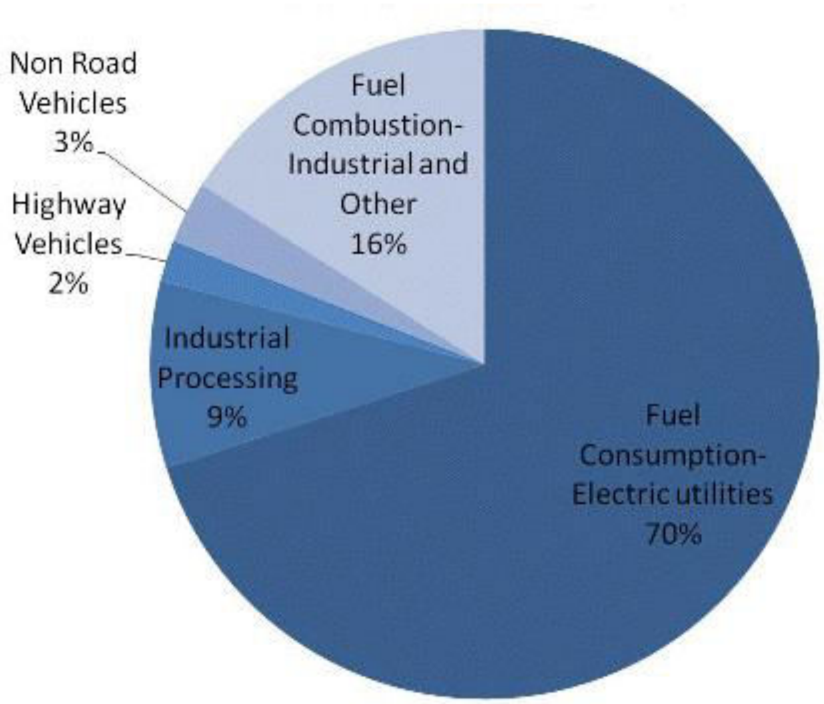

Figure.4 Sources of sulfur dioxide emissions [1]

1.2 Emission control

Vehicle emissions are made from three different sources: exhaust gas, fuel system (evaporation) and gas crankcase ventilation. For the determination of standards, which means, maximum permissible emission level in grams per mile, two essential aspects must be defined: the driving cycle and the sampling method.

With modern technologies and improvement in engine design, engine efficiency has been steadily improving. Advanced and more precise electronic ignition timing, fuel metering or computerized engine management helped reduce toxicity of exhaust gas. Despite that, these methods alone have generally been proved insufficient to meet emissions goal. [3]

1.2.1 Air injection

One of the first developed exhaust emission control. Originally, secondary air injection system was used to inject fresh air into the engine's exhaust ports to provide oxygen. Unburned and partially burned hydrocarbons in the exhaust would thanks to it complete burning.

Air injection is used to support the catalytic converter oxidation reaction, and to reduce emissions when an engine is below optimal temperature. After a cold start, an engine needs an air-fuel mixture richer than what it needs at operating temperature, and the catalytic converter does not function efficiently until it has reached its own operating temperature. The air injected upstream of the converter supports combustion in the exhaust head pipe, which speeds catalyst warm-up and reduces the amount of unburned hydrocarbon emitted from the tailpipe. Once the catalyst is warm, air is injected to the catalytic converter itself to assist with unburned hydrocarbons. [3], [4]

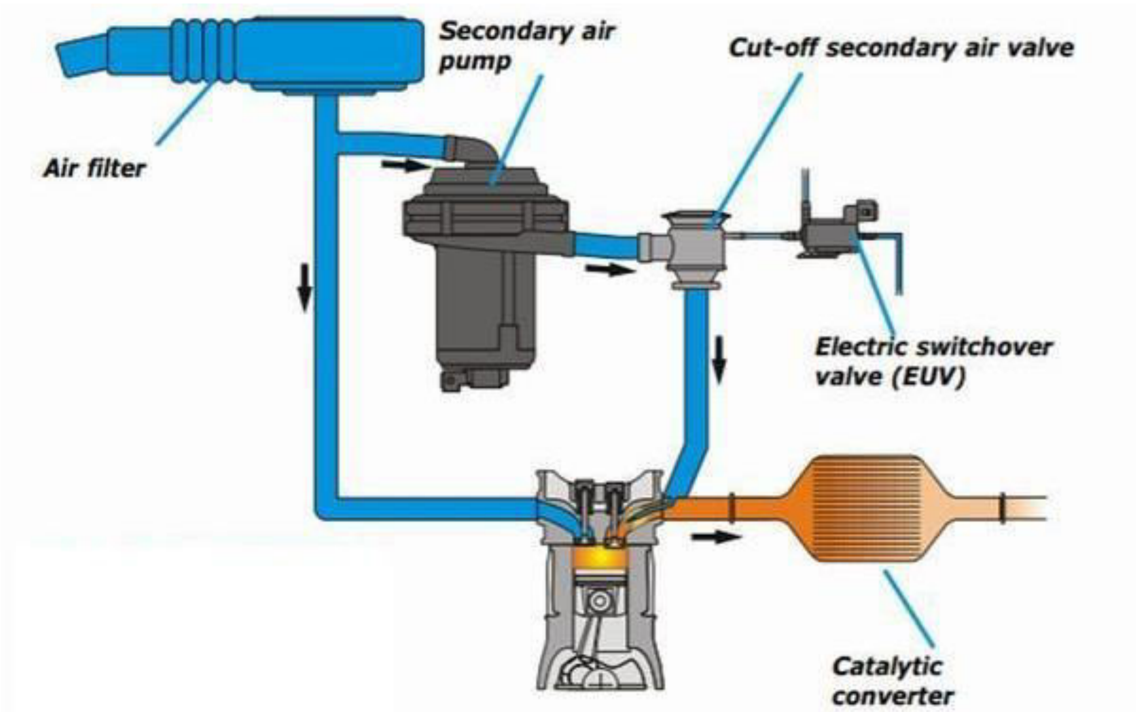

Figure.5 Air injection [4]

1.2.2 EXHAUST GAS RECIRCULATION

EGR is an emissions reduction technique used in internal combustion engines of gasoline and diesel engine to decrease the amount of nitrogen oxide NO_x. EGR works by recirculating a certain portion of an engine's gas back to the cylinders. This changes the percentage of the oxygen O_2 in the incoming air stream and overall helps to reduce temperature peak inside cylinders. It is important, because NO_x is produced in high temperature mixtures of atmospheric nitrogen and oxygen, usually at cylinder peak pressure.

In case of a spark ignition engine, EGR valves can increase efficiency as charge dilution allows a larger throttle position and reduces associated pumping losses. Also, the EGR valves can become clogged with carbon particles so they have to be cleaned to work properly or replaced in case of fault.

Diesel engines work with excess air. Adding EGR reduces the specific heat ratio of the combustion gases in power stroke. This reduces the amount of power that can be extracted by the piston. EGR also tends to reduce the amount of fuel burned in the power stroke and it can be noticed by the increase in particulate emissions that corresponds to an increase in EGR. [6]

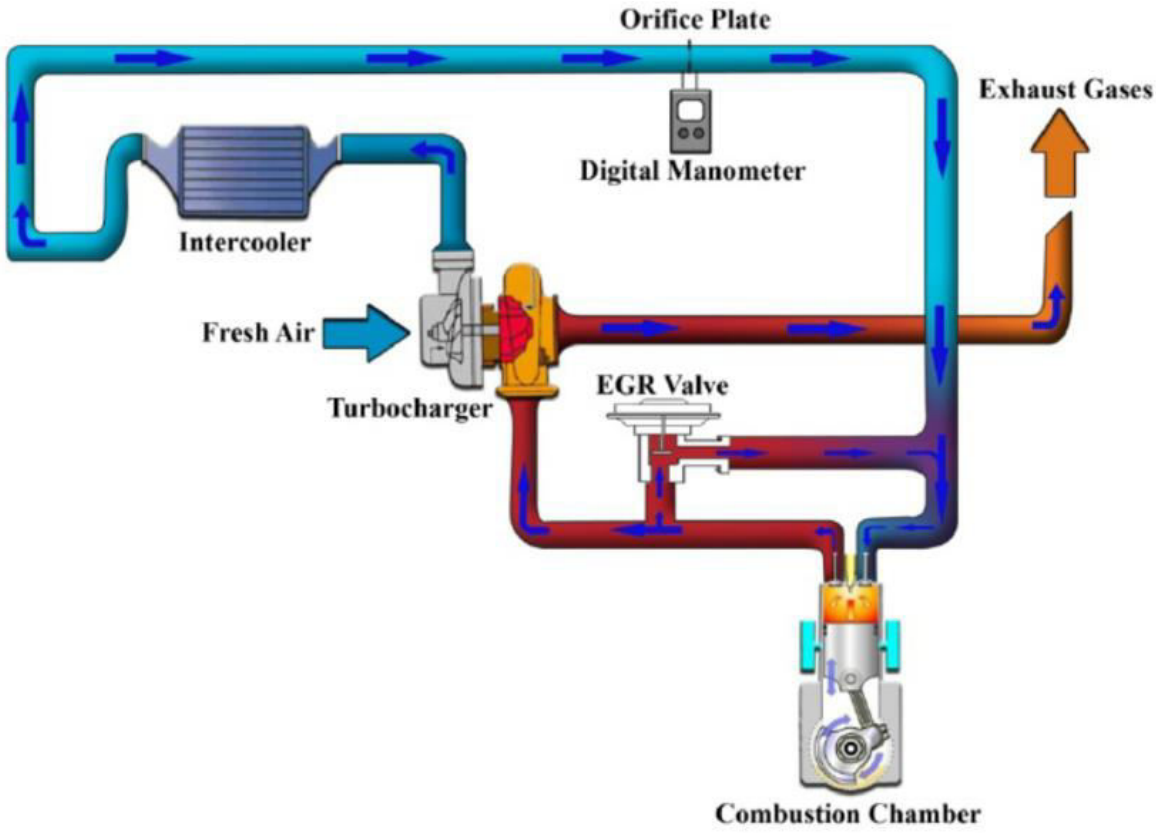

Figure.6 Exhaust gas recirculation [6]

1.2.3 CATALYTIC CONVERTER

Exhaust emission control that converts toxic gases and pollutants in exhaust gas from an internal combustion engine into less toxic pollutants by catalyzing a redox reaction. Catalytic converters are usually used with internal combustion engines fueled by either gasoline or diesel.

The first catalytic converters were placed close to the engine, to ensure fast heating. However, such placement can cause several problems. One of these is vapor lock - which may occur several minutes after the engine is shut off, as radiant heat from the catalytic converter causes fuel in surrounding fuel lines to first boil and then aerate. This subsequently leads to a non-start condition, which lasts until the engine and fuel in the lines cool down. As an alternative, catalytic converters were moved to a third of the way back from the engine and were then placed underneath the vehicle. [7]

1.2.3.1 TWO-WAY

Two-way catalytic converter has two simultaneous tasks:

- Oxidation of carbon monoxide to carbon dioxide:

  $2\,CO + O_2 \rightarrow 2\,CO_2$ (1)

- Oxidation of hydrocarbons (unburned and partially burned fuel) to carbon dioxide and water:

  $C_xH_{2x+2} + [(3x+1)/2]\,O_2 \rightarrow x\,CO_2 + (x+1)\,H_2O$ (2)

Diesel oxidation catalyst (DOC) is the type of catalytic converter widely used on diesel engines to reduce hydrocarbon and carbon monoxide emissions. *"A minimum exhaust temperature of about 200°C is necessary for the catalyst to light off."* [31] For that purpose, DOCs contain palladium, platinum and aluminum oxide. [7]

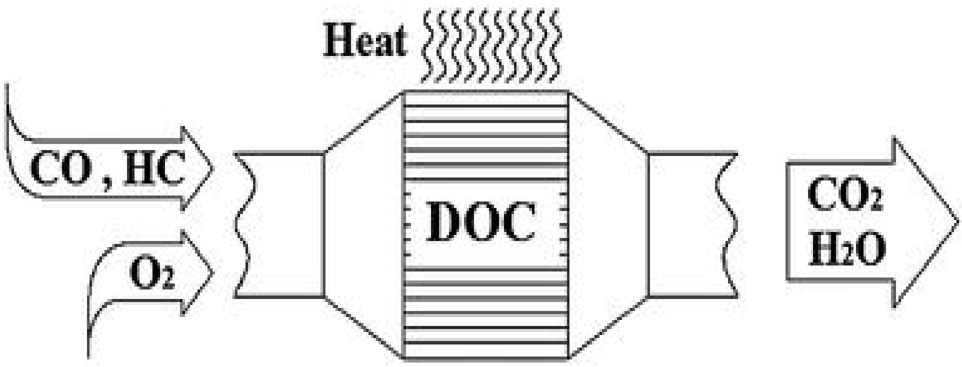

Figure.7 Diesel oxidation catalyst [7]

They were also used on gasoline engines in American and Canadian market until 1981. Because of their inability to control oxides of nitrogen, they were superseded by three-way converters.

1.2.3.2 THREE-WAY

Three-way catalytic converters (TWC) used for gasoline combustion have the additional advantage of controlling the emission of nitric oxide (NO) and nitrogen dioxide (NO_2) which are precursors to acid rain and smog.

The reduction and oxidation catalysts are typically contained in a common housing; however, in some instances, they may be housed separately. A three-way catalytic converter has three simultaneous tasks.

Reduction of nitrogen oxides to nitrogen (N_2)

- $2\ CO + 2\ NO \rightarrow 2\ CO_2 + N_2$ (3)
- $\text{hydrocarbon} + NO \rightarrow CO_2 + H_2O + N_2$ (4)
- $2\ H_2 + 2\ NO \rightarrow 2\ H_2O + N_2$ (5)

Oxidation of carbon monoxide to carbon dioxide

- $2\ CO + O_2 \rightarrow 2\ CO_2$ (6)

Oxidation of unburned hydrocarbons (HC) to carbon dioxide and water, in addition to the above NO reaction

- $\text{hydrocarbon} + O_2 \rightarrow H_2O + CO_2$ (7)

These three reactions occur most efficiently when the catalytic converter receives exhaust from an engine running slightly above the stoichiometric point. For gasoline combustion, this ratio is between 14.6 and 14.8 parts air to one part of fuel, by weight. The ratio for autogas (liquefied petroleum gas LPG), natural gas, and ethanol fuels is slightly different for each, requiring modified fuel system settings when using those fuels. In general, engines fitted with 3-way catalytic converters are equipped with a computerized closed-loop feedback fuel injection system using one or more oxygen sensors. [8]

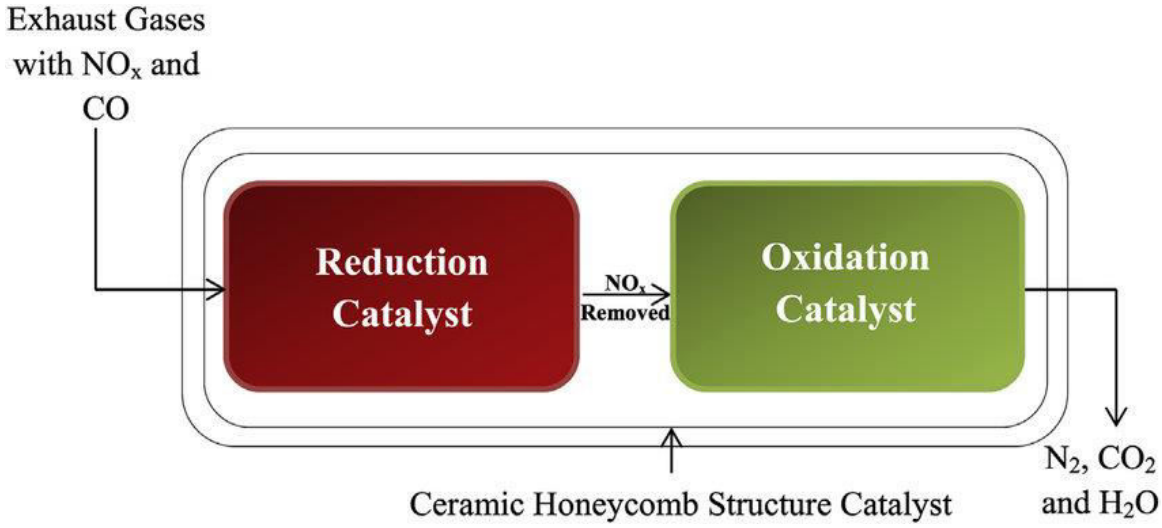

Figure.8 Three-way catalytic converter [8]

1.3 EMISSION STANDARDS

Emission standards are the legal requirements governing air pollutants released into the atmosphere. They set quantitative limits on the permissible amount of specific air pollutants that may be released from specific sources over specific timeframe and are generally designed to achieve air quality standards and to protect human life and environment.

An emission performance standard is a limit that sets thresholds above which a different type of vehicle emissions control technology might be needed. While emission performance standards have been used to dictate limits for conventional pollutants such as oxides of nitrogen and oxides of sulfur (NO_x and SO_x) this regulatory technique may be used to regulate greenhouse gasses, particularly carbon dioxide (CO_2). [9]

1.3.1 EUROPEAN EMISSION STANDARDS

In the European Union, emissions of nitrogen oxides (NO_x), total hydrocarbons (THC), non-methane hydrocarbons (NMHC), carbon monoxide (CO) and particulate matter (PM) are regulated for most vehicle types, including cars, trucks, locomotives, tractors and similar machinery, barges, but excluding seagoing ships and aero planes. For each vehicle type, different standards apply.

Compliance is determined by running the engine at a standardized test cycle. Non-compliant vehicles cannot be sold in the EU, but new standards do not apply to vehicles already on the roads. No use of specific technologies is mandated to meet the standards, though available technology is considered when setting the standards. Newly introduced models must meet current or planned standards, but minor lifecycle model revisions may continue to be offered with pre-compliant engines. Along with Emissions standards, the European Union has also mandated a number of computer on-board diagnostics for the purposes of increasing safety for drivers. These standards are used in relation to the emissions standards.

Following table shows evolution of emission standards for passenger cars. EU regulations changed emission limits from Euro 2. CO standards have stringent more, opposite to NOx emissions which were allowed higher. Vehicles with petrol engine were exempted from PM standards through to the Euro 4 stage. Direct injection engines are regulated to limit of 0,005 g/km from Euro 5. [10]

Stage	Date	CO	HC	HC+NOx	NOx	PM	PN
		g/km					#/km
Positive Ignition (Gasoline)							
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	-	-
Euro 2	1996.01	2.2	-	0.5	-	-	-
Euro 3	2000.01	2.30	0.20	-	0.15	-	-
Euro 4	2005.01	1.0	0.10	-	0.08	-	-
Euro 5	2009.09[b]	1.0	0.10[d]	-	0.06	0.005[e,f]	-
Euro 6	2014.09	1.0	0.10[d]	-	0.06	0.005[e,f]	6.0×10^{11} [e,g]
Compression Ignition (Diesel)							
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	0.14 (0.18)	-
Euro 2, IDI	1996.01	1.0	-	0.7	-	0.08	-
Euro 2, DI	1996.01[a]	1.0	-	0.9	-	0.10	-
Euro 3	2000.01	0.64	-	0.56	0.50	0.05	-
Euro 4	2005.01	0.50	-	0.30	0.25	0.025	-
Euro 5a	2009.09[b]	0.50	-	0.23	0.18	0.005[f]	-
Euro 5b	2011.09[c]	0.50	-	0.23	0.18	0.005[f]	6.0×10^{11}
Euro 6	2014.09	0.50	-	0.17	0.08	0.005[f]	6.0×10^{11}

* At the Euro 1..4 stages, passenger vehicles > 2,500 kg were type approved as Category N_1 vehicles
† Values in brackets are conformity of production (COP) limits
a. until 1999.09.30 (after that date DI engines must meet the IDI limits)
b. 2011.01 for all models
c. 2013.01 for all models
d. and NMHC = 0.068 g/km
e. applicable only to vehicles using DI engines
f. 0.0045 g/km using the PMP measurement procedure
g. 6.0×10^{12} 1/km within first three years from Euro 6 effective dates

Figure.9 Emission standards for passenger cars [11]

From a real-life perspective, emission standards do not fully reflect everyday usage of the vehicle. Manufactures are allowed to make numerous adjustments before testing. Lightening vehicle by removing unnecessary weight like back seats, improving aerodynamics or switching off the headlights and therefore reducing load on generator which leads to better results.

1.4. Driving cycles

The driving cycle is a fixed test of performance of vehicle that allows to measure emissions under reproducible conditions. Driving cycles are usually defined in terms of vehicle speed and choice of shifting as a function of time. A trained driver is used to monitor the driving cycle on the chassis dynamometer and driver assistance ensures that the driving cycle is as close as possible to the predefined cycle (for example, within the set tolerances).

Emission levels depend on many parameters, including factors related to the vehicle, such as model, size, fuel type, technology level and mileage and operating factors such as speed, acceleration, gear selection and road gradient. Therefore it is no surprise, that for a different type of vehicles such as cars, vans, trucks, buses and motorcycles have been developed multiple driving cycles. [12]

1.4.1 NEDC

New European driving cycle was used as a reference for homologation of vehicles in Europe until Euro 6 norm. It consists of ECE urban cycle, which is repeated four times and one EUDC extra urban part.

Reason for replacement was criticism from expert, that cycle does not represent real life driving conditions. For an urban cycle, there are numerous constant speed cruises and very soft accelerations. Also, with idle events, cycle made it impossible to obtain representative values. [12]

1.4.2 WLTP

Worldwide Harmonized Light Vehicles Test Procedures combines WLTC (World Harmonized Light Vehicle Duty Test Cycle) and RDE (Real Driving Emission). New driving cycle replaces NEDC which was first introduced in 1970 and his last modification was 20 years ago.

There are considerably more differences compare to the NEDC driving cycle, starting with the mass of measured (tested) cars. While NEDC driving cycle works with a single test for all cars, the WLTP driving cycle has developed and counted WLTC driving cycle, that measures cars on a cylinder test. The WLTC driving cycle works with three categories of passenger cars, depending on their power output and maximum speed.

The first category contains less efficient (powerful) cars with a power weight of less than or equal to 22 Watts per kilogram of weight [W/kg]. This category is measured in three modes – low, medium and high load. The second category with a power weight between 22W/kg and 34W/kg is calculated with four modes – low, medium, high and extra high. The last third category, where are majority of cars sell in European Union, works with a power weight of 34W/kg and more. They are further divided into cars with a maximum speed of 120km/h and cars over 120km/h. The test modes are similar to those in the second category, meaning four different modes.

RDE serves to confirm WLTC results in real life, thereby ensuring that cars deliver low pollutant emissions not only in the laboratory, but also on the road. For this road test, it is used Portable emissions measurement system (PEMS) that provides a complete real-time monitoring of the key pollutants emitted by the vehicle. From 1.9.2019 it will apply to all new registered vehicles. [13]

The WLTP driving cycle test is more complex and longer than the NEDC driving cycle. When the third-category vehicles are tested, the whole test, consisting of four parts takes up to 1800s and the total traveled distance is 23266 km. The maximum speed is limited to 135km/h and currently selected transmission gear changes depending on the vehicle.

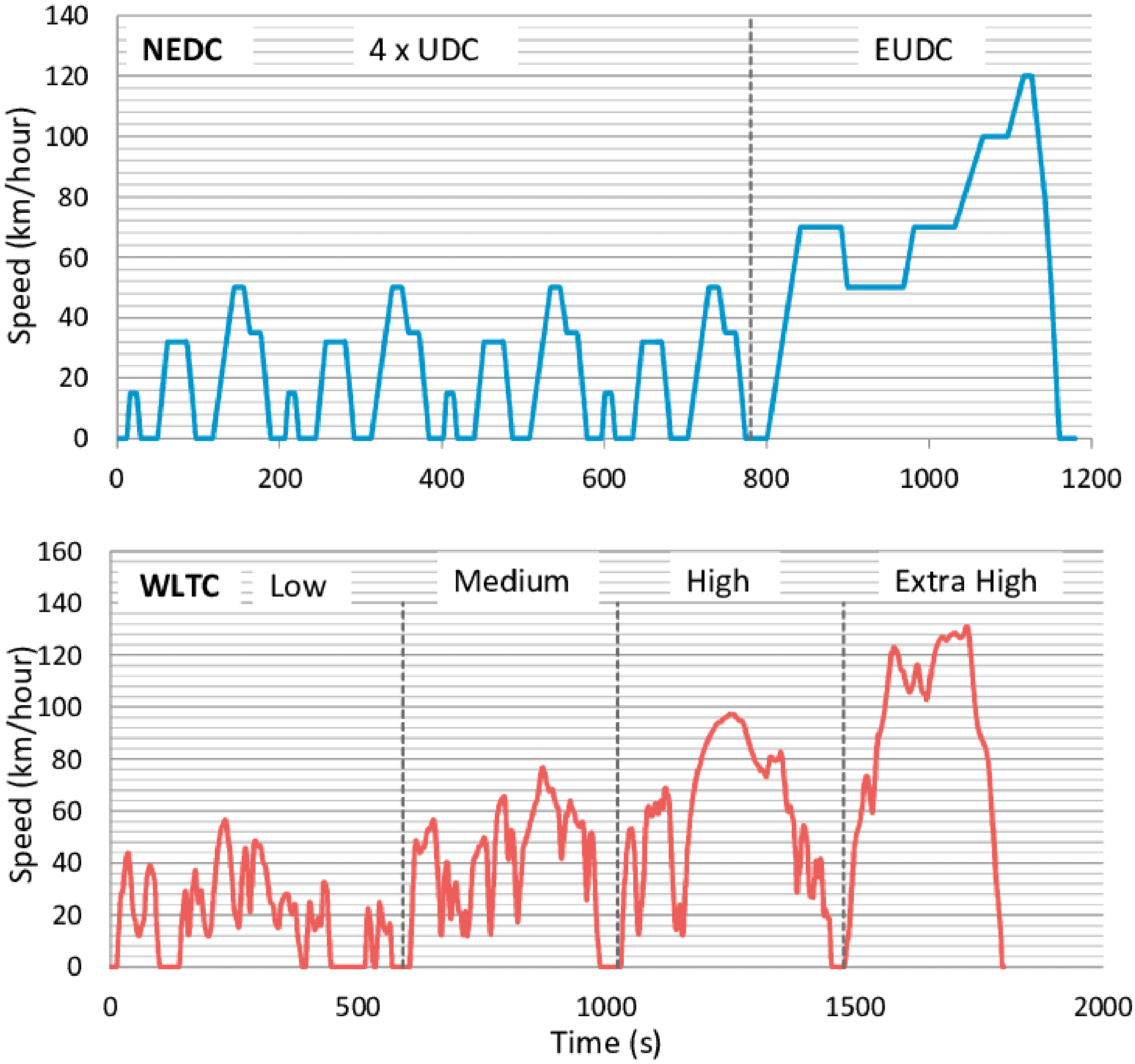

Figure.10 NEDC and WLTC driving cycle [12]

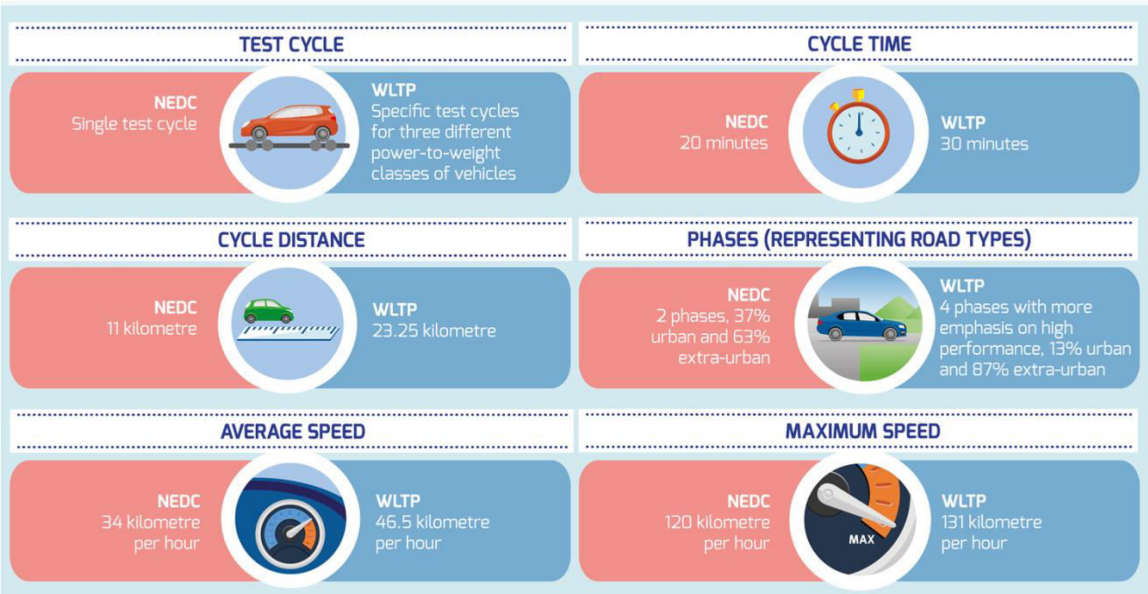

Figure.11 NEDC and WLTP comparison [13]

1.4.3 WLTP FOR HYBRID VEHICLES

Electric and hybrid vehicles will also have to obtain type approval. Just as with the fuel consumption figures, range specifications of electric and plug-in hybrids will be more representative. As a result of this more realistic driving profile, it may be expected that the electric range as well as the fuel consumption will be closer to what is observed by vehicle owners in everyday driving conditions.

The new driving cycle present a larger range of vehicle operating points than the NEDC. WLTP for hybrid vehicles now consists of one defined test including both the depleting and sustaining operations. Initial state of charge is set to its maximum. Driving cycles are repeated until the minimum allowed SOC for depleting mode is reached. After that, one whole cycle is performed in sustaining operation mode. [14]

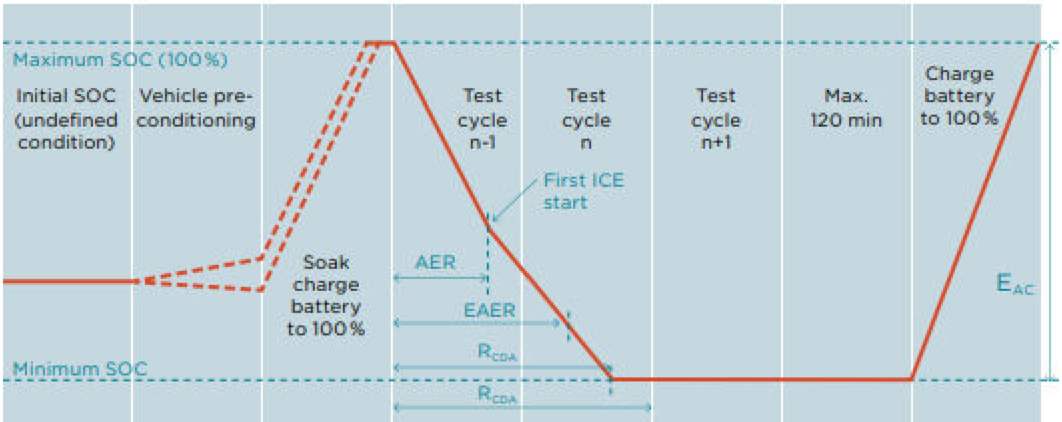

Figure.12 WLTP for hybrid vehicle [14]

1.4.3.1 State of Charge

The SOC defines available capacity of battery, usually current value at the latest charge or discharge cycle. Because of the reduction of cell caused by age, the preferred state of charge reference should be rated as the capacity of new cell comparing to current capacity. Effectiveness of battery can be also reduced by temperature or discharge rate. To keep batteries within a safe operating window, electronic battery management is needed. It is particularly important for lithium batteries. The BMS monitors evaluate the SOC of each individual cell in the battery to check for uniform charge in all the cells. The SOC is not just needed for showing the fuel gauge indication but is also used to determine the end of the discharging and charging cycles. In any hybrid electric vehicle, function of the SOC level and the battery can be in several states: charge deplete, charge sustain and charging. [15]

Battery as the only source in EV must have capacity to achieve required range but with margin of 20% to prevent undesirable discharge. An additional margin of about 5% is also needed to receive any regenerative braking charge when the battery has just been charged. The battery for HEV should be able to deliver the same power, but because the energy requirements are shared with ICE, the capacity is much smaller. Overall, the size is usually one tenth of EV battery so to produce the same power, HEV battery must be capable of delivering continuous currents of 10C or more. Because of the low capacity, battery can undergo the equivalent of a hundred charge-discharge cycles per day and with deep discharges would be worn out in few weeks. However battery cycle life is exponentially increased as the DOD is reduced so HEV battery must run at partial DOD in order to extend the cycle life. PHEV needs to operate part of the time as an EV in the charge depletion mode and part of the time as an HEV in charge maintenance mode. Therefore there must be a compromise between an energy storage and power delivery. [16]

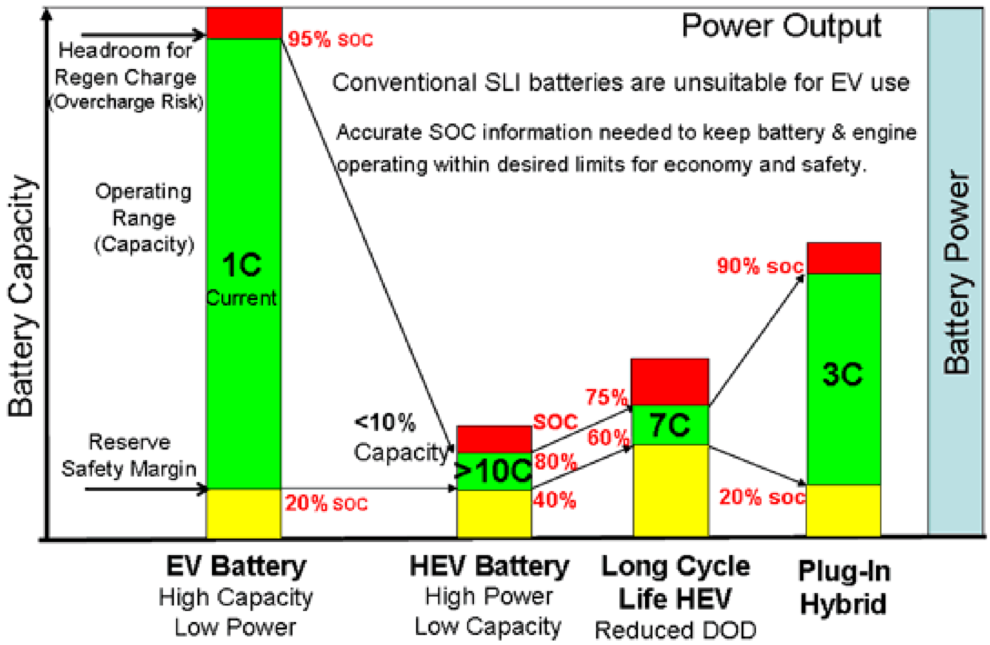

Figure.13 Battery operating requirements [16]

1.5 Homologation

Automotive homologation is the process of certifying and approving vehicles or a particular component in a vehicle that it has satisfied official standards set by their destination countries. These standards are applicable to all kinds of automobiles, the most importantly in the areas of environment and safety. It is necessary and mandatory for approval to export any products. Homologation test is performed either on the representative sample in the case of vehicle type and same vehicle´s components approval or on the concrete vehicle in the case of the single vehicle approval. All conditions for set-up are predefined alongside with the testing and final processing of results. The homologation certificate is given to the manufacturer after approving new components or systems. These approvals are based on test reports made by an officially recognized testing organization. At the end of the procedure technical service issues a technical report. When a new emissions standard enters into force in the EU, a manufacturer has a period of one year until all of its future production would have to meet this standard. [17], [18]

The number of rules and norms applying for automobiles has drastically increased all over the world due to awareness of global warming problems and environmental protection. For the European market, there are two types of vehicle homologation:

- European Union directives - since 1998 individual national type approvals of the EU member states are progressively replacing with whole vehicle type approval (WVTA). It is simplification of process, where the manufacturers only have to have vehicle type approved in one-member state and then be allowed to market and sell the vehicle in all other member states without any additional tests.
- United Nation Economic Commission for Europe regulations - tests according to ECE regulations opens the gate to the worldwide markets, because of the EU members and also many others from Japan, Russia, South Africa and Turkey. [17]

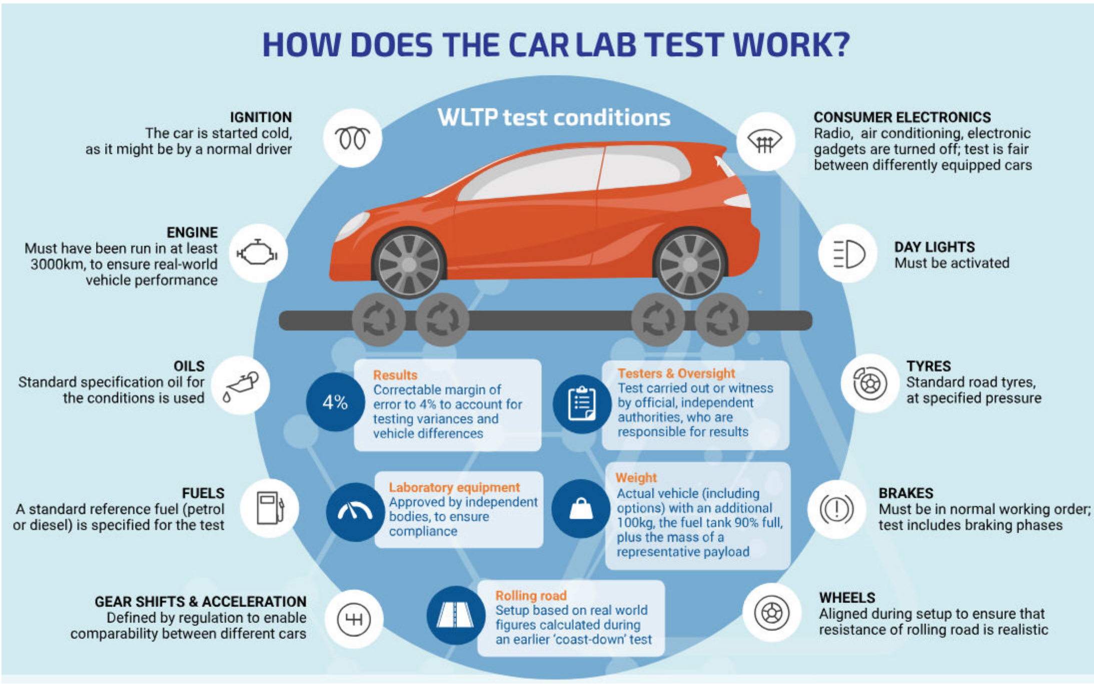

Figure.14 Laboratory test procedure [18]

2 ENERGY RECOVERY SYSTEMS

Energy losses occur every time energy moves from one system to another. Internal combustion engine is only able to transform around 20% to 25% of total energy input from fuel to movement. Chemical energy from gasoline or diesel as a fossil fuel is converted into heat energy. Pressing on pistons in engine, heat is transformed into mechanical kinetic energy which drives the wheels. Rest of the energy is lost throughout the process as a source of water pump or alternator. However the most of it is lost through exhaust pipe as heat. Some of this kinetic energy is further lost to the sound of the engine, light from combustion, and to heat energy from the friction between the road and the tires. Although efficiencies can be improved, they can only be increased to some degree because of the principles of thermodynamics. Better solution is to take this wasted exhaust heat and try to recover it for additional heating. With growing importance in vehicle fuel economy there has been several techniques of thermal energy recovery. [27]

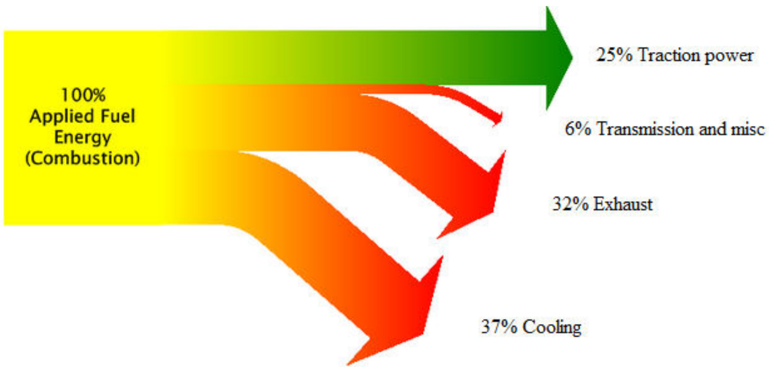

Figure.15 Diesel energy distributions [19]

2.1 COOLANT HEAT STORAGE SYSTEM

Heat storage tank is used to collect and store engine coolant that has been heated by the engine. Then the coolant is later available for starting of cold engine to preheat the intake port. As a result, system provides more efficient fuel injection during cold start, reduces the adhesion on surfaces of intake port wall and decreases emissions of hydrocarbons (HC). [28]

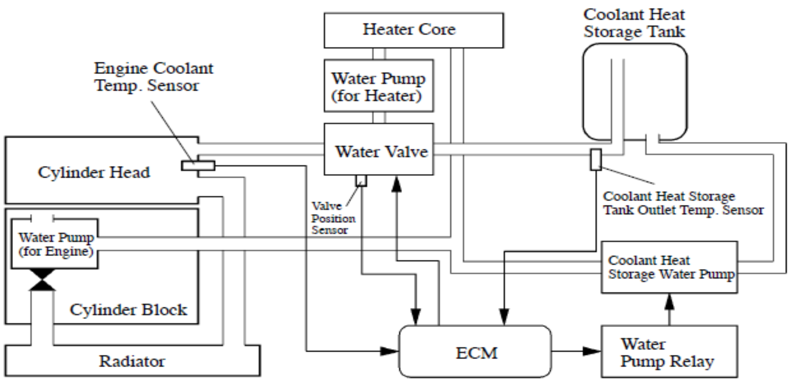

Figure.16 Coolant heat storage system from Toyota [28]

ECM affected preheated control and hot coolant recovery control by actuating main components. Coolant heat storage pump supplied coolant from tank on the cold start. Later recovered and stored coolant from engine to the heat storage tank. These passages were switched by the water valve depending on the system control conditions like temperature. It was measured by sensor which was located at the coolant heat storage tank, to be more precise at its inlet and outlet. Whole system worked on a simple base. Stored hot coolant was delivered from the tank to engine before starting it to preheat the cylinder head. That means that only the hybrid system was started, and car could be driving only in electrical mode (EV). Whole process of preheating took several seconds. [28]

2.2 Exhaust heat recovery system

The fuel consumption and emission are dependent on temperature of fluids. Modern vehicles using direct or spark ignition have high thermal efficiency which causes low heat transfer to the engine components, especially at low ambient conditions. As a result of regulations of emissions, cold start problems and passenger comfort, there is an opportunity to recover more than 1/3 of energy lost through the exhaust.

The cooling system is connected to a heat exchanger placed in the exhaust gas transferring the thermal energy from the exhaust gas to the cooling system. It is regulated by double valve providing two operating modes. Recovering mode where exhaust gas flows through heat exchanger and bypass mode.

Normally, the cabin is heated with engine losses to coolant. But in modern vehicles, especially hybrids, which they are trying to work in the most efficient way, this can lead to a deficit of energy from coolant to cabin. Using energy given by EHRS can shorten warm-up procedure, in case of hybrids also warm the battery, and most importantly save fuel. [20]

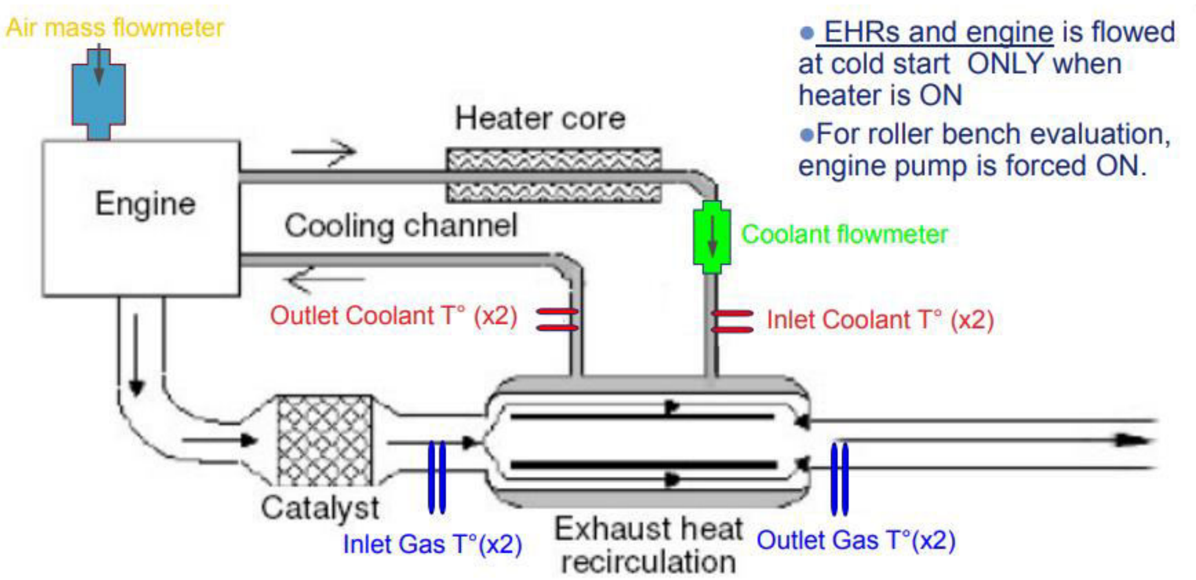

Figure.17 Exhaust heat recirculation system [19]

2.3 Latent heat storage

BMW came up with an idea of using latent heat thermal energy especially for cold climates countries. They only appeared in older 5-series models (E39) as optional equipment.

The principle was simple. Only thing that was needed was storage material connected to the radiator. As a material it had to be used phase change material (PCM), where the chemical bonds under a rise of a temperature cause break up. Material changes from solid to liquid and this is when the heat is stored (endothermic process). In this case, BMW was using salt mixture Mg (CO_3) H2O and $LiNO_3$. Process started when engine was operating in normal condition and temperature, then heat was stored and later used for starting of cold engine and its quick heat-up. This could reduce unburned hydrocarbons and CO by 30%. It also could be used for heating the interior or defrosting windows. [21]

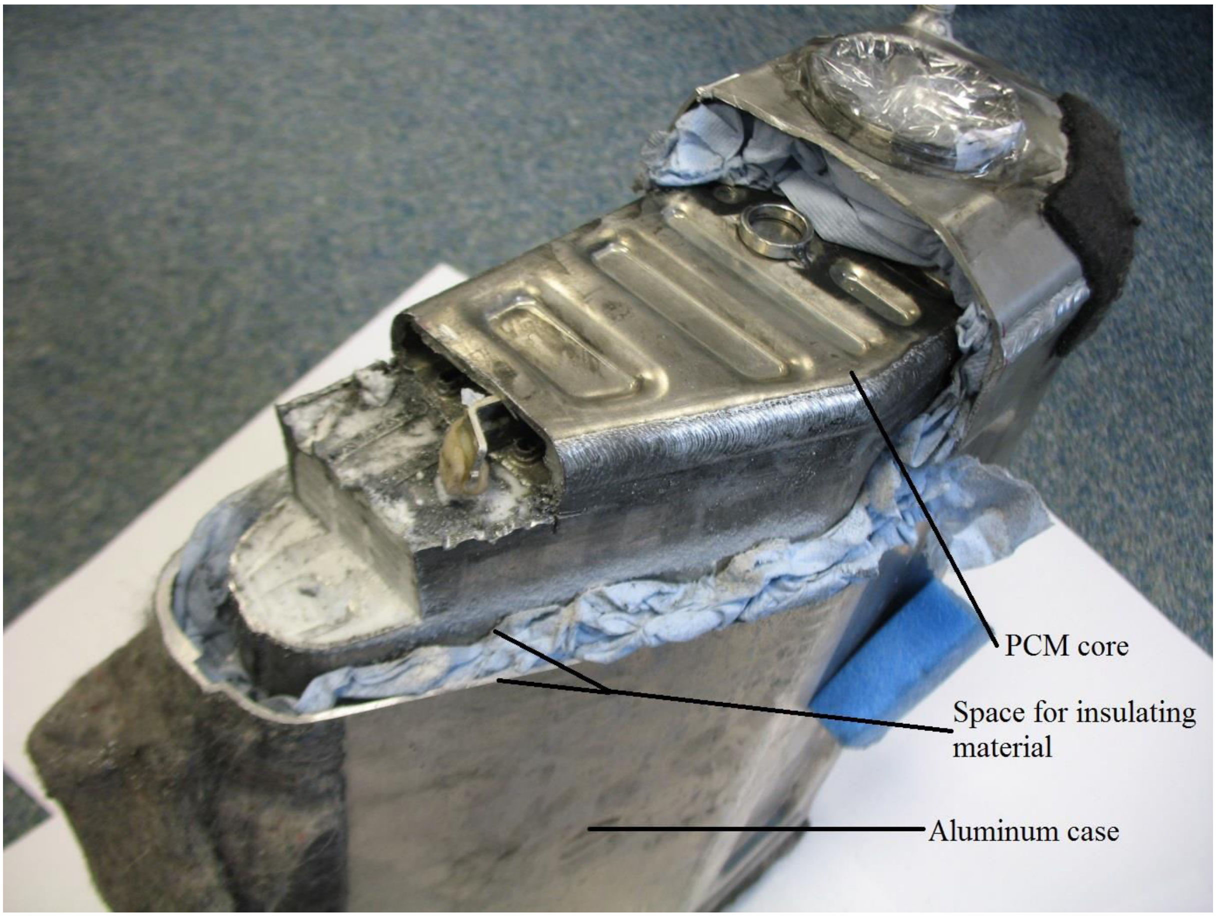

Figure.18 Latent heat storage design

2.4 VEHICLE INTEGRATED POWERTRAIN ENERGY RECOVERY

The key component of this method is a thermoelectric generator (TEG) placed in the exhaust system downstream of the catalytic converter. The aim is a recovery of 300 watts of electrical energy from a wasted heat of engine after completing the World Harmonized Light Vehicle Test Procedure (WLTP).

The TEG consists of several thermoelectric modules, each one with a hot side and a cold side. The exhaust gas leaving a catalytic converter is very hot and has to pass down on one side of the TEG´s gallery and can only exit the component by passing through these modules first.

Every module of the TEG also involves two thermoelectric semiconductor materials, one positively and the other negatively charged. When heat is delivered at one side of a pair of semiconductors, the temperature difference between the hot and cold parts of the module generates a direct electric current.

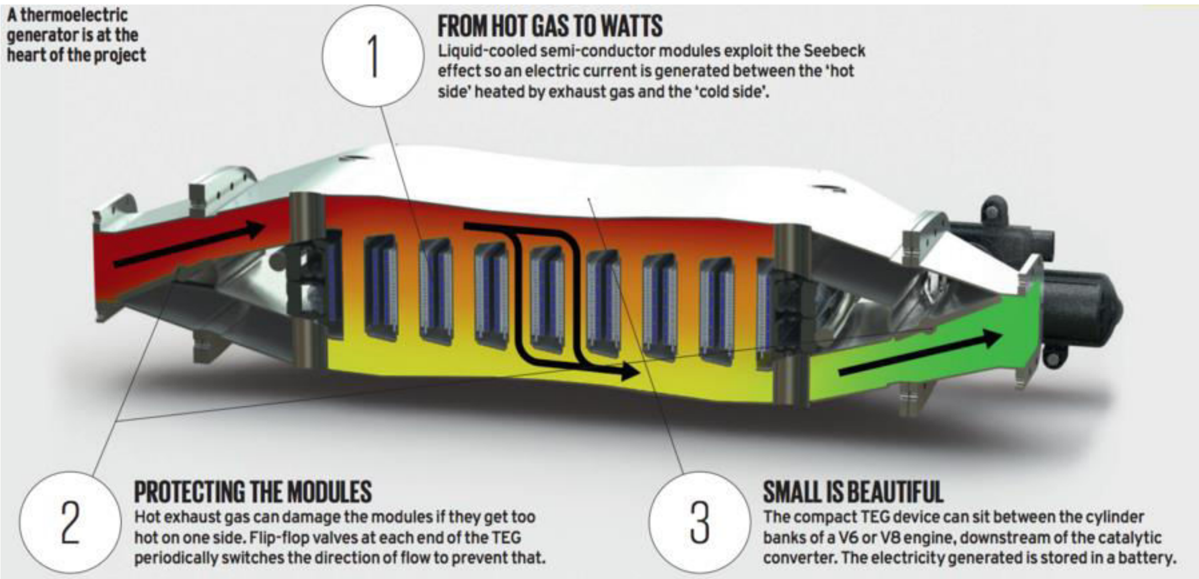

Figure.19 Thermoelectric generator [22]

The modules are cooled by liquid to maintain the temperature difference. The greater the difference between the two sides, the higher the current, so for better results. Because the temperatures of exhaust gas in petrol car gets significantly high, the TEG has to have a flip-flop valve at each end to periodically change the flow of the exhaust from one side to avoid the modules overheating. The valve has also option to bypass the TEG altogether. [22]

3 GT-SUITE

GT-Suite is the leading 0D/1D/2D multi-physics CAE system simulation software developed by Gamma Technologies. It provides numerous sets of components allowing simulating the physics of fluid flow, thermal, mechanical, electrical, magnetic, chemistry and control systems. With all of this, we are capable of creating accurate models of numerous engineering system, most importantly whole vehicle with engine, driveline, thermal management, cooling, aftertreatment and much more.

GT-SUITE works as a typical all-in-one CAE tool. Firstly, it is well known in high-level modeling of 0D/1D, but what is unique, is a detailed 3D modeling tool with built-in structural and thermal 3D FEA (Finite Element Analysis) and also 3D multi-body dynamics with flexible bodies and 3D CFD (Computational Fluid Dynamics). All of this is complemented by CAD (Computer-aided design) modeling.

Integration of high-fidelity 3D models into 0D/1D models allows simulating accurate transient multi-physics boundary conditions with two-way interaction between all the sub-systems. Also, for the CAE activities, GT-SUITE provides quick 0D/1D modeling solutions for real-time, software/hardware and control system simulations. [23]

4 DIESEL MODEL

For the needs of my thesis, I started with exampled model from GT-Power demonstrating a fuel economy drive cycle (WLTC) of conventional diesel vehicle, including drivetrain, engine, coolant, oil, under hood air, the engine cylinder and block structural mass. They are all created as subassemblies of detailed models. Therefore, there are suitable for necessary changes of required systems, parts and their connections during simulations. Some of the attributes were left untouched with their pre-set values as the whole exampled model worked and showed reasonable results. As a great starter point, several changes had to be made considering attaching heat recovery systems with additional components and their needs.

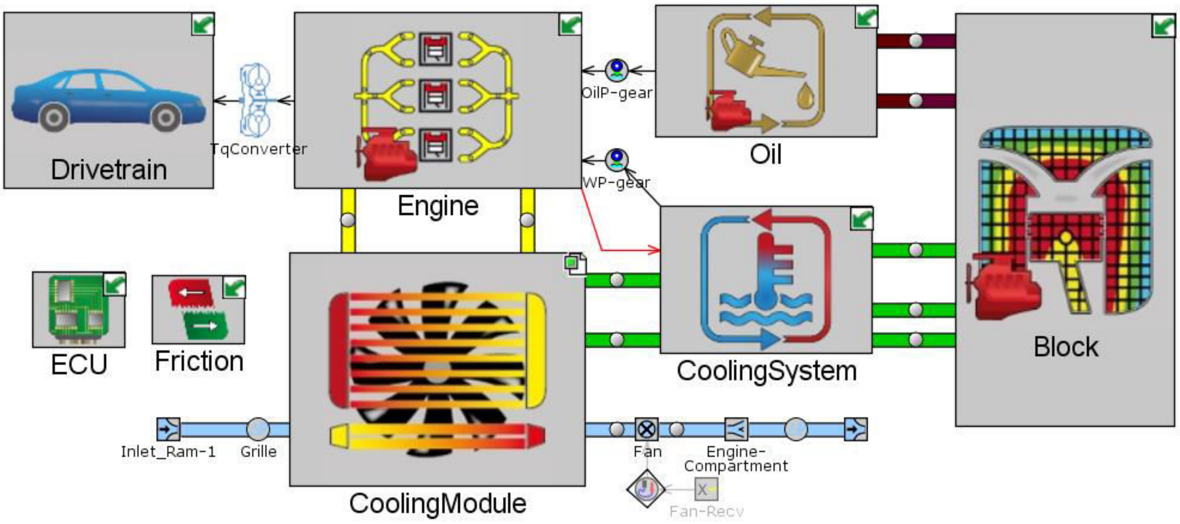

Figure.20 Exampled model of diesel vehicle

Simulation of the complex model showed compute time of nearly two weeks so to get faster results I simplified the model as much as it was allowed. Underhood circuit was replaced with independent heat exchangers for engine and coolant circuit similar to one in oil circuit. These heat exchangers were set to be air cooled, where air velocity was provided from vehicle. They differ with heat transfer data bonded to particular circuit and with inlet/outlet diameters.

Pipes connecting parts included in engine, coolant and oil circuit had to undergo some changes as well. Basic geometry, surface and initial conditions were left with recommended values corresponding to the circuit and solving method, but thermal characteristics were simplified. As I am not interested in thermal properties and boundary conditions of the pipe walls, they were solved with faster adiabatic method.

Tab.1 Main specifications of diesel vehicle

Specifications			
Vehicle		Engine	
Drive wheels	Rear wheel drive	Displacement	3.1L
Wheelbase	2700 mm	Configuration	4-cylinder straight
Transmission	6-speed manual	Forced induction	Turbocharger
Weight	1853 kg	Injection	Direct

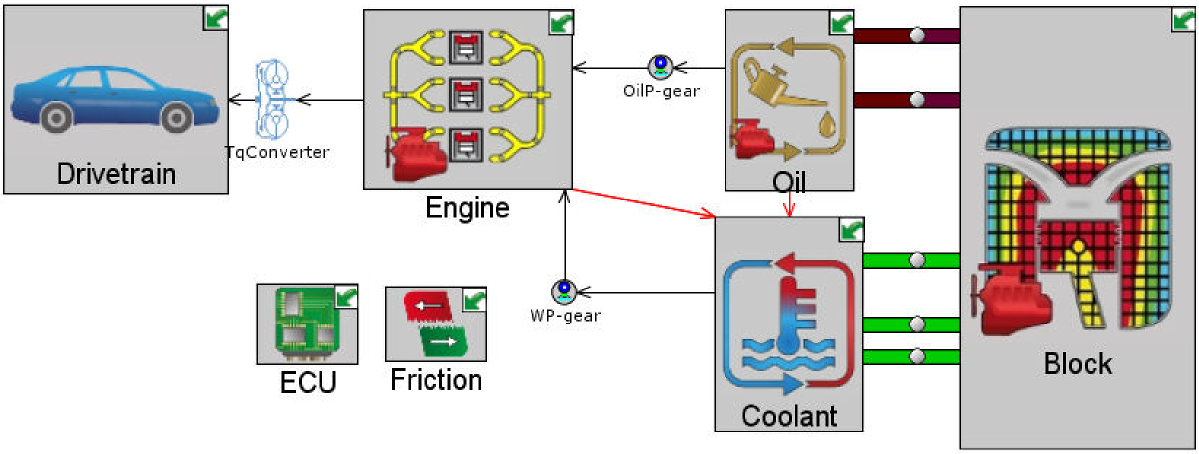

Figure.21 Simplified model of diesel vehicle

4.1 DRIVETRAIN

This assembly includes vehicle, transmission, differential, axle and connection between them, but overall it is not significantly important considering preparing adjustments. Simulations made while testing thermal heat storage unit did not affect this part of the car, meaning model did not required any great changes in attributes comparing to exampled one.

One attribute was added to support driving cycle simulation. Weight class object was given a value, which selects a vehicle mass representative of a given weight class to be used for the model. The mass selected will replace the vehicle mass and passenger and also cargo mass in the model.

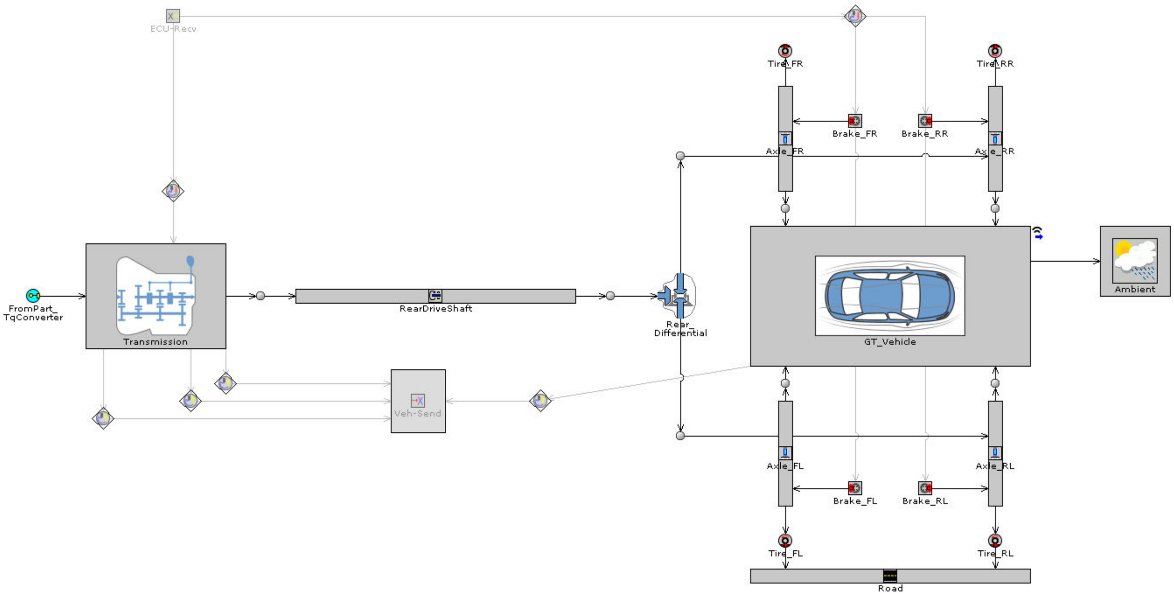

Figure.22 Drivetrain assembly

4.2 ENGINE

Assembly with the cylinders and valves that are modeled in detail in the same way which would be built typical engine performance model. Crain train allows setting main characteristics of engine, which in this case are used to model the kinematics and rigid dynamics of common reciprocating ICE engine crank train configurations. It sends signals about revolution per minute and indicated mean effective pressure. But it also receives signal about friction mean effective pressure from different subassembly. Cylinders as well are using pre-set values describing initial state, heat transfer, flow and combustion. EGR Cooler is discretized to acceptable level and with other components set to recommended values. During the simulations, some of these components stayed untouched as the changes did not affect them. [29]

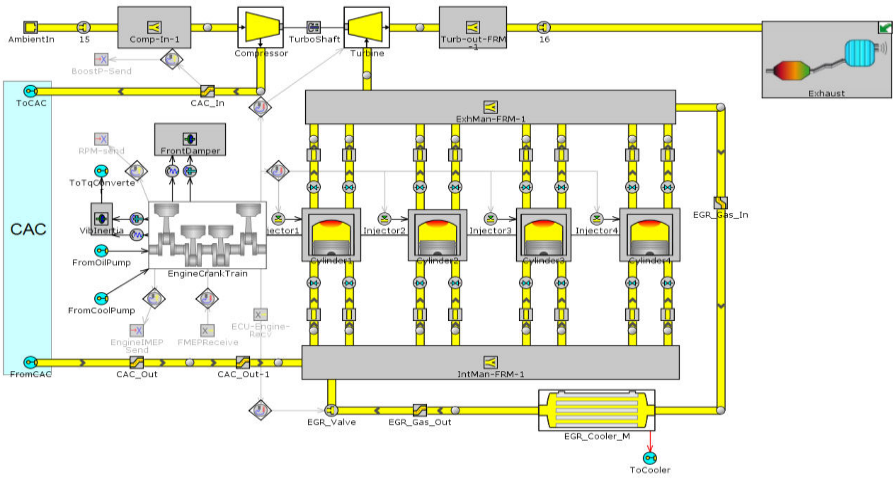

Figure.23 Engine assembly

4.3 EXHAUST

Aftertreatment system was completely added into model. It includes components of Diesel oxidation catalyst (DOC) and Diesel particulate filter (DPF). However, my goal is not to get best results of emissions using exhaust system with catalysts, but to investigate warm-up effect of the recovered heat on them. Therefore, all chemical connections were removed and even so the sensors monitoring emissions were placed right behind catalyst, they don't have to work properly. Their function is to showing the difference depending on heat storage system.

DOC main attributes were set to recommended values depending on engine displacement and also diameter of connected pipes. Having 3L engine means having at least 75mm diameter pipes as it was necessary due to high velocity and mass flow rate. Frontal area of catalyst had to be bigger comparing to area of connected flow split volume object and also with reasonable values of cell density, substrate wall thickness and wash coat thickness it forbids negative pressure. The wall temperature method specifies thermal characteristics like material properties, density and specific heat of substrate and wash coat. It is important as it is used to calculate wall temperature. In additional thermal options it was only required to set heat input location to gas as I was not using any advanced adaptive chemical solver. [30]

I proceeded to particulate filter with similar approach. Main attributes were set inside the range of recommended values and depending on the previous failed simulations because of the negative pressure or temperature. After all, this part doesn´t play a big role in simulations.

Several sensors were attached behind the exhaust. These sensors measure mass flow rate of emissions. Connecting to integrator with respect of time, I am allowed to display cumulative emissions of CO, HC, NO_x, Soot and CO_2. Also attaching these integrated values alongside with vehicle distance limiter to template that produces an output signal which results into RLT creator showing cumulative emissions in g/km. Exhaust system was ended with object that describes end environment conditions of pressure, temperature and composition.

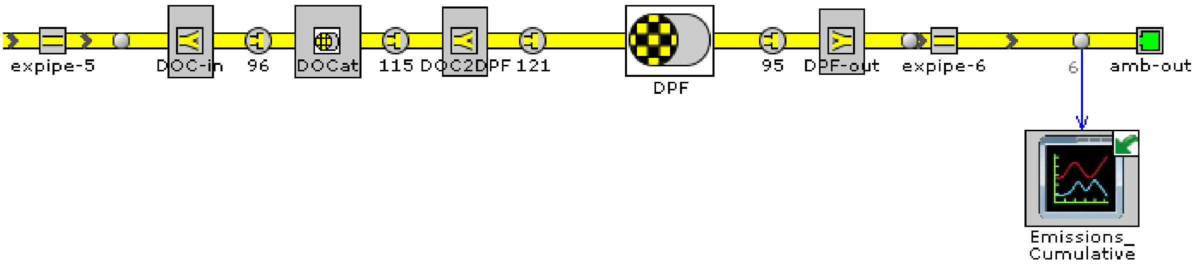

Figure.24 Exhaust assembly

4.4 COOLANT

The coolant circuit is imported from CAD using pre-processing tools where it was modeled with great importance to details. The water jackets and head coolant passages are modeled using flows splits in a way that one is for block and two are for head. It is due to extra outlet to EGR circuit. This leads to a great simplification of the geometry in the block, which means that the model does not try to predict the flow through the water jackets from geometry. Pressure loss connections are used to impose the flow distribution to the two block outlets. Connections are placed at each outlet with the characteristic curves obtained from 3D CFD. CAD geometry allows determining the volumes of flow splits, and the heat transfer areas between the coolant and structure. The heat transfer coefficients between coolant and structure are imposed as a function of overall coolant flow. [29]

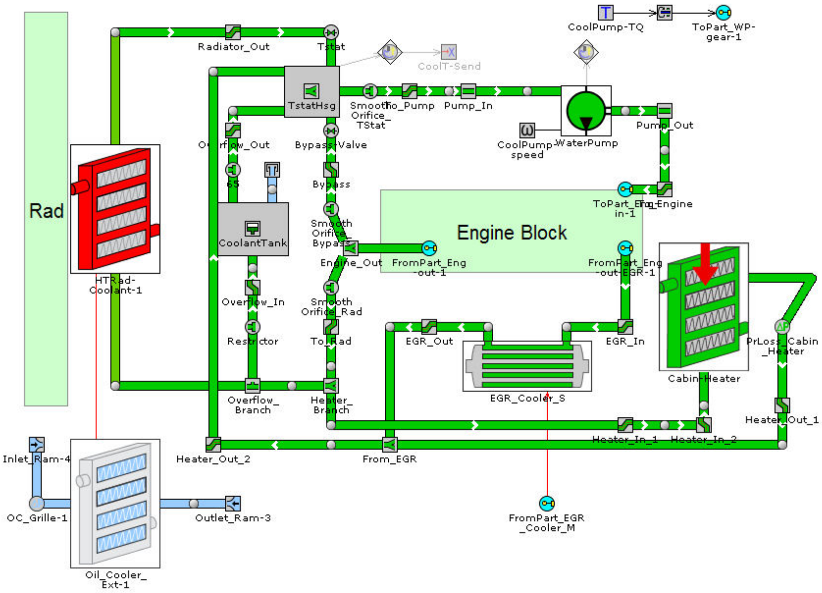

Figure.25 Coolant assembly

4.5 Oil

The complete engine oil circuit is modeled with all of the pressure losses of internal bearings and other oil consumers lumped into a single pressure restriction. The internal oil drillings are not modeled in detail, but rather are simplified into one volume that provides a temperature boundary condition for the cylinder structure. Oil pump is powered by mechanical connection with crankshaft. [29]

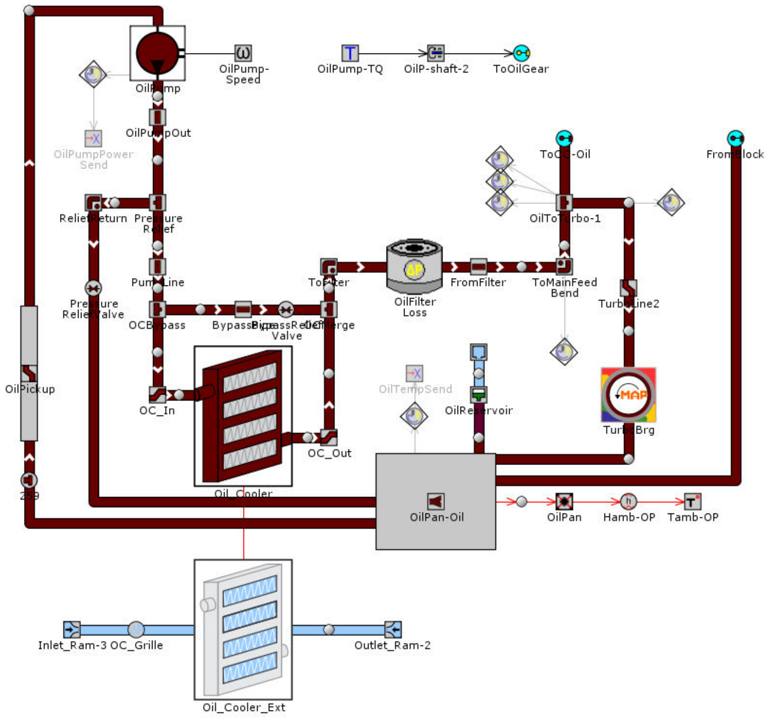

Figure.26 Oil assembly

4.6 Cylinder structure

This model is thermally connected to the gas side of engine cylinder, the coolant volume in block and head, the oil contacting the piston bottom and liner inside surface, as well as to the "external" block structure. The outer block/head structure and the oil pan are modeled using thermal masses. These masses are interconnected via conductance objects and also transfer heat to the ambient via convection. Overall this assembly did not require any additional changes corresponding to my task. [29]

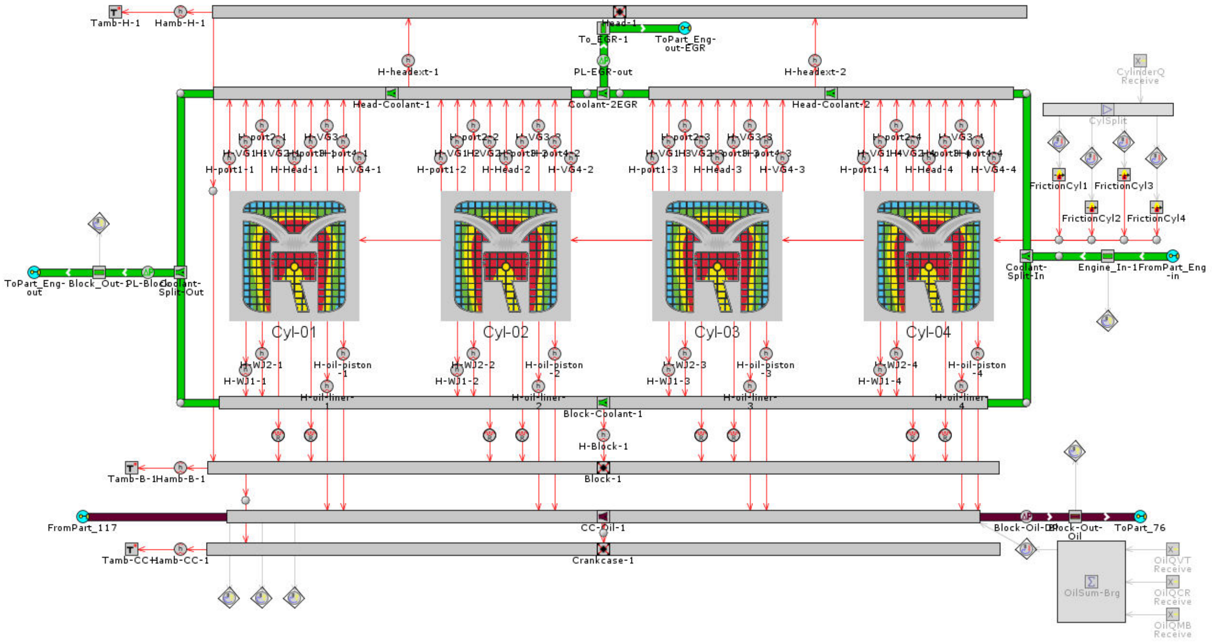

Figure.27 Block assembly

4.7 Electronic control unit

ECU assembly consists of several controlled subassemblies that are connected together and are dependent to each other.

- engine controller for turbine rack, fuel and EGR
- fan controller
- vehicle controller
- transmission controller
- idle controller

4.8 Friction

Assembly that simulates engine friction from predefined maps depending on receiving signals from oil, cylinder temperature and IMEP. Equations convert components FMEP to heat energy and send values to engine parts.

5 Hybrid vehicles

Hybrid vehicles can be distinguished by using two or more types of power. The basic principle and the main advantage is different usage of motors for situations, where they work the best. [24]

- Parallel hybrid - internal combustion engine and electric motor are designed to power the vehicle either together or separately. The most common solution is connection of engine, electric motor and gearbox together by automatically controlled clutch. [24]

- Series hybrid - main difference comparing to parallel hybrid is that combustion engine is primary used as generator to charge battery and extend its range. Vehicle is driven by an electric motor. The battery of series hybrid is commonly charged by being plugged-in but can also work only for regeneration purposes. [24]

- Plug-in hybrid - general fuel-electric, parallel or serial hybrid with higher energy storage capacity thanks to lithium-ion batteries. These batteries can be either recharged by plugging into an external electric power source or by on-board engine and generator. [24]

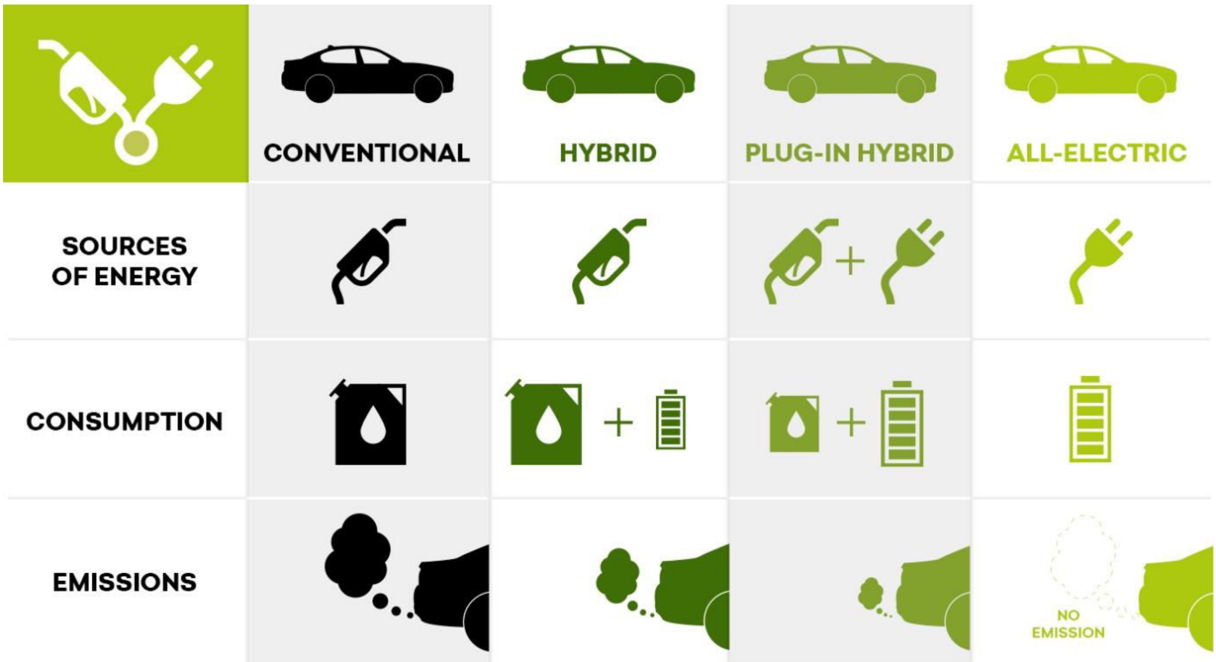

Figure.28 Types of hybrid vehicles [24]

5.1 Energy management

Electric motor is more efficient at turning power or producing torque, while engine works better at maintaining high speeds. Combining both benefits and switching motors at proper time increases energy and fuel efficiency. Also electric energy can be recuperated and either used immediately or stored for later. [25]

- Electric driving - powerful electric motor can drive vehicle in electric mode. Combustion engine is entirely switched off and electric motor is providing all the necessary power and torque. Full hybrid vehicles are only capable of electric mode up to 10km/h due to limited energy available in the battery. Plug-in hybrids containing high voltage battery with higher capacity are possible to speed up to 100km/h in electric mode. [25]

- Regenerative braking – energy recovery system that usually involves an electric motor as generator. Kinetic energy is transforms into electric while braking vehicle and can be either used immediately or stored in a battery or capacitor in hybrid vehicles for later. Hybrid vehicles switch electric machine into generator mode during braking. Negative torque enhances the braking capability of the powertrain. Kinetic energy spins the generator and generates electric energy. Electric vehicles use the motor as a generator, so it is operated as a generator during braking. The amount of electrical energy capable of dissipation is limited by either the capacity of the supply system to absorb the energy or on the state of charge of the battery or capacitors. One of the objectives of brake energy recuperation strategy systems is to keep the battery at a state of charge that allows you to use the electric motors more often. [25], [26]

- Stop/start system - internal combustion engine is switched off without the intervention of the driver when the vehicle is in stationary position. After pressing clutch pedal or releasing brake pedal the engine is restarted automatically. Energy management function optimizes the consumption of battery energy. When the engine is running, energy is supplied to the consumers. Alternator does not require producing electrical energy and at the most efficient points, the battery is recharged. Vehicles that have idle stop/start and energy management functions are called micro hybrids. [25]

- Battery charging - apart from the charging during driving, PHEV can also be charged by connecting into a power socket. Rectifier contained in the power electronic control converts the alternating current into direct current and stores it in the high voltage battery. [25]

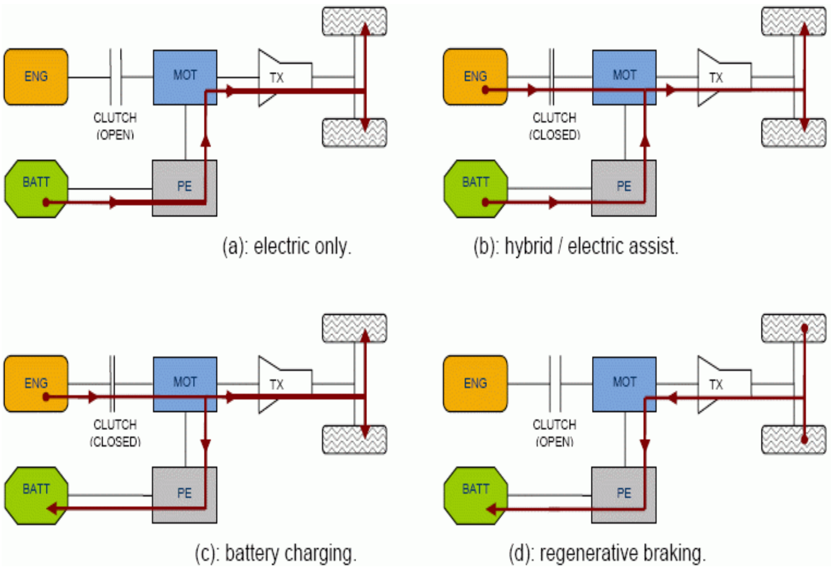

Figure.29 Hybrid vehicle energy management [25]

6 HYBRID MODEL

The model represents a through-the-road hybrid electric vehicle. It is alternative parallel hybrid with diesel engine, belted-starter generator (BSG) and 6 speed manual transmission power the front axle, while a larger electric motor (RTD) propels the rear axle. It is different model requiring similar approach while implementing recovery systems but suitable for comparing their thermal effectiveness.

Tab. 2 Main specifications of hybrid vehicle

Specifications	
Drive wheels	All-wheel drive
Wheelbase	2700mm
Transmission	6-speed manual
Weight	2000kg
Engine type	4-stroke
Engine displacement	3L
Battery capacity	22.5Ah
RTD power	27kW
BSG power	8kW

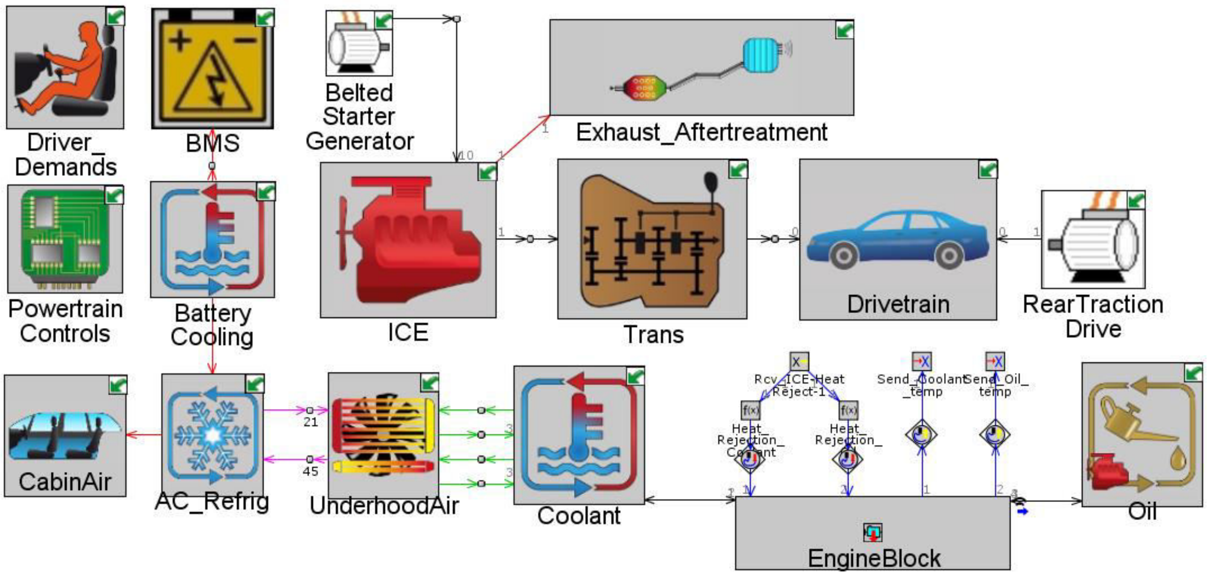

Figure.30 Model of hybrid vehicle

6.1 Drivetrain

Assembly is almost identical to diesel model with obvious changes of rear differential that is used for translating power from electric motor. Transmission connected to front differential is also using clutch system engaging or disengaging engine depending on hybrid power request.

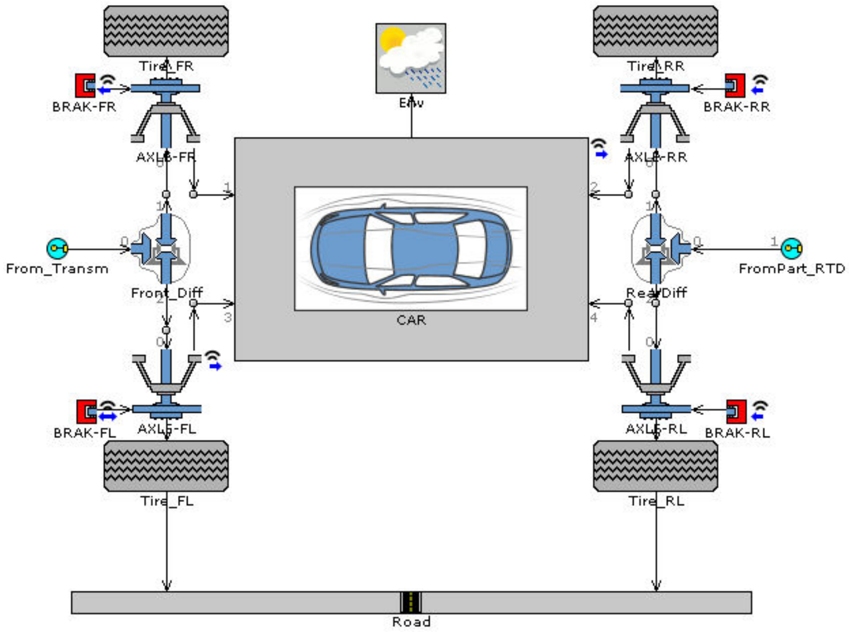

Figure.31 Drivetrain assembly

6.2 Engine

Instead of whole engine circuit I used mapped engine that describes engine performance (power output and friction), fuel consumption, heat rejection, emissions and other characteristics. Overall, it is utilized as the source of power and heat for HEV or thermal system simulations. From main attributes, it could be selected only engine type (4-stroke/2-stroke) and displacement as a total volume of all cylinders in one revolution. Rest of the important attributes were defined by primary maps (BMEP, FMEP), secondary maps of (fuel consumption, heat rejection, air flow) and emission maps. Engine is mechanically connected to transmission trough flywheel and to BSG with accessory drive connection and operating mode is determined by received signals of engine pedal position and ignition. [29]

Output signals measuring fuel and air flow rate are connected to limiter which sets minimum limit of total engine mass flow rate and also prevents it to be divided by 0 when engine speed is zero.

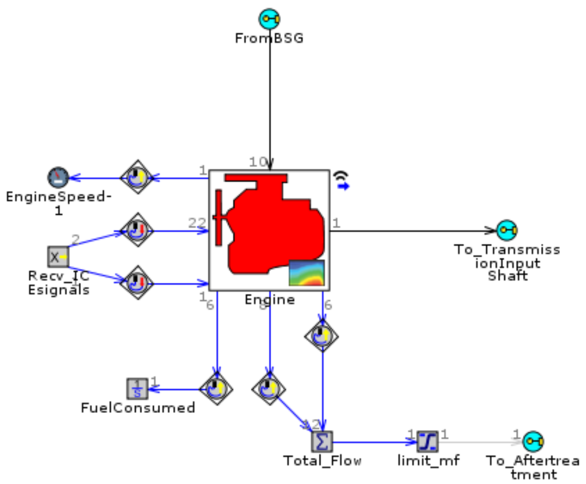

Figure.32 Engine assembly

6.3 Exhaust

Exhaust system assembly is almost identical to diesel model. However, I had to adjust connection with engine circuit because of the different engine representative, which did not allow mechanical connection. This was solved with wireless signals sent to exhaust receiver and sensors measuring total mass flow as a sum of air flow rate and fuel rate. Received signals of engine speed and BMEP go as variables to maps to determine exhaust gas temperature, O2, NO and NO2 mass flow rate. Alongside with CO, CO2, soot and HC mass flow rate, they are connected with total mass flow through converters and limiters to exhaust inlet that has specified composition table for emissions. In this case only DOC was included, placement and set up of EHRS, Combo or ETMU heat exchangers with emission sensors were identical to diesel model.

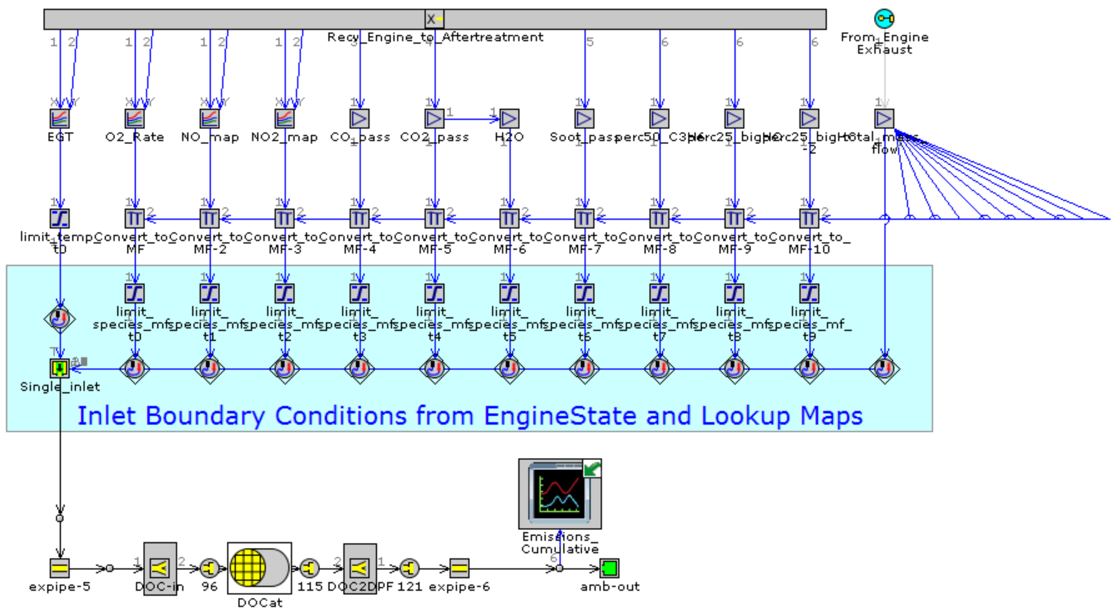

Figure.33 Default exhaust assembly

6.4 OIL

Missing circuit had to be added into hybrid model, because it has connections with coolant circuit and also is necessary while applying Combo cooler. Everything is dependent to each other and therefore creating one big circuit. This circuit is a copy from diesel model with following slight changes.

Since the oil pump could not be mechanically connected through shaft with crank train like in previous model, I used RLT sensor allowing me to create control signal from any variable value. In this case, it was engine speed with initial output of 100RPM taken from engine state part. Multiplier value of 1.2 representing gear ratio was taken from diesel model. Output signal was connected through angular velocity to pump. However oil pump could also be electrically controlled to satisfy different needs in case of a hybrid vehicle. These cases will be mentioned later in HSU conditions with adjusted pump controller.

6.5 CYLINDER STRUCTURE

As I tried to simplify model, instead of including whole cylinder structure I used engine block template that models the coolant and oil volume within the engine block, as well as the engine structure into a single volume. Most attributes were set with recommended values depending on the fluid as well as the external convention and conduction attributes.

Thermal connection with engine was secured by receiver of engine heat rate and splitting it with math function between coolant and oil inner mass by 9:1 ratio. This ratio is an approximate value taken from typical engine heat distribution. Additional sensors measuring temperature of coolant and oil were used to send values into warm up control for examination.

6.6 COOLANT

Overall, circuit is similar to one on previous model apart from missing EGR, but with additional need for cooling of electric motor. Also the hybrid vehicle is using electrical pump and not mechanical one connected to engine because of the previously mentioned electric motor. Its operating speed is determined from engine temperature and vehicle speed which covers the needs of all modes. Placement of HSU, Combo and ETMU is identical to previous model and followed the similar set-up.

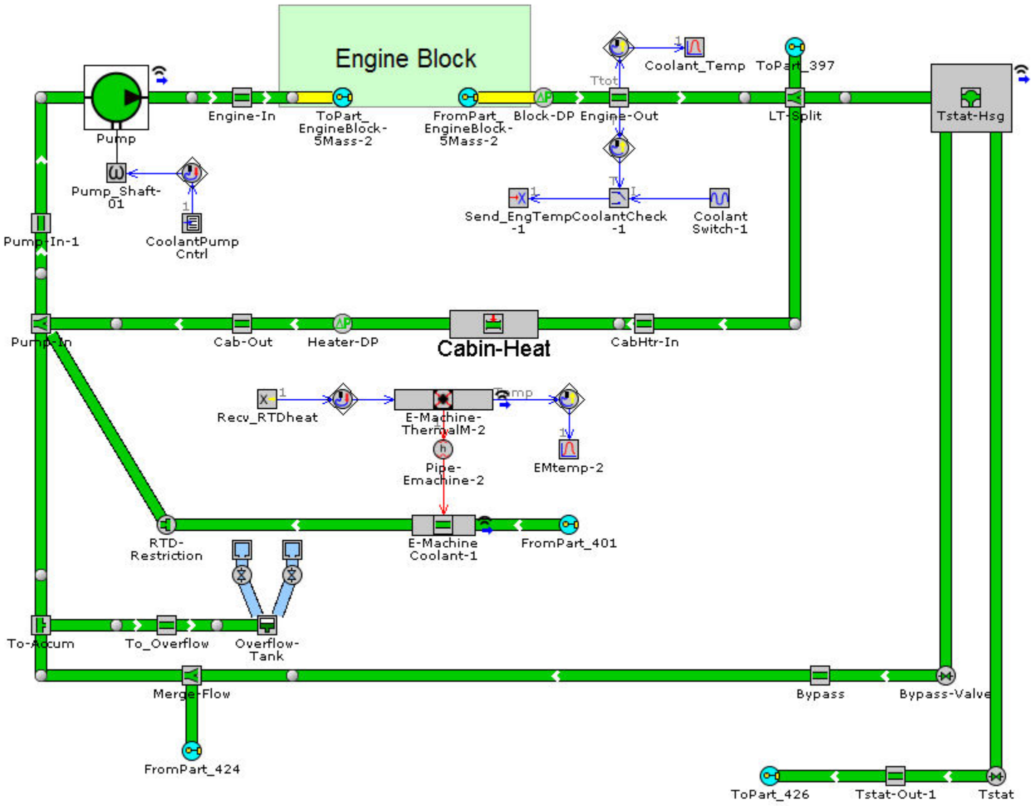

Figure.34 Coolant assembly

6.7 Others

These assemblies are important parts of hybrid vehicle and ensure working of it as a whole part. Throughout the simulations, they did not highly interfere with heat exchanger systems or did not require changes that would significantly affect them. There were some slight adjustments that support the simulations, but overall predefined attributes would still secure representative results and possibility to compare effect of different heat exchanger solutions.

6.7.1 Battery Cooling

Hybrid model required two coolant circuits, one additional for battery cooling. It is mainly defined by battery coolant pump, heat exchanger, additional heater and battery plate. Thermal connection with battery is solved through battery plate which is simple round pipe. Battery heater controls heat rate at cold starts. Circuit is thermally connected with AC circuit which is controlled by temperature of coolant and determining whether the cooling valve is open to heat exchanger or directed different path. [29]

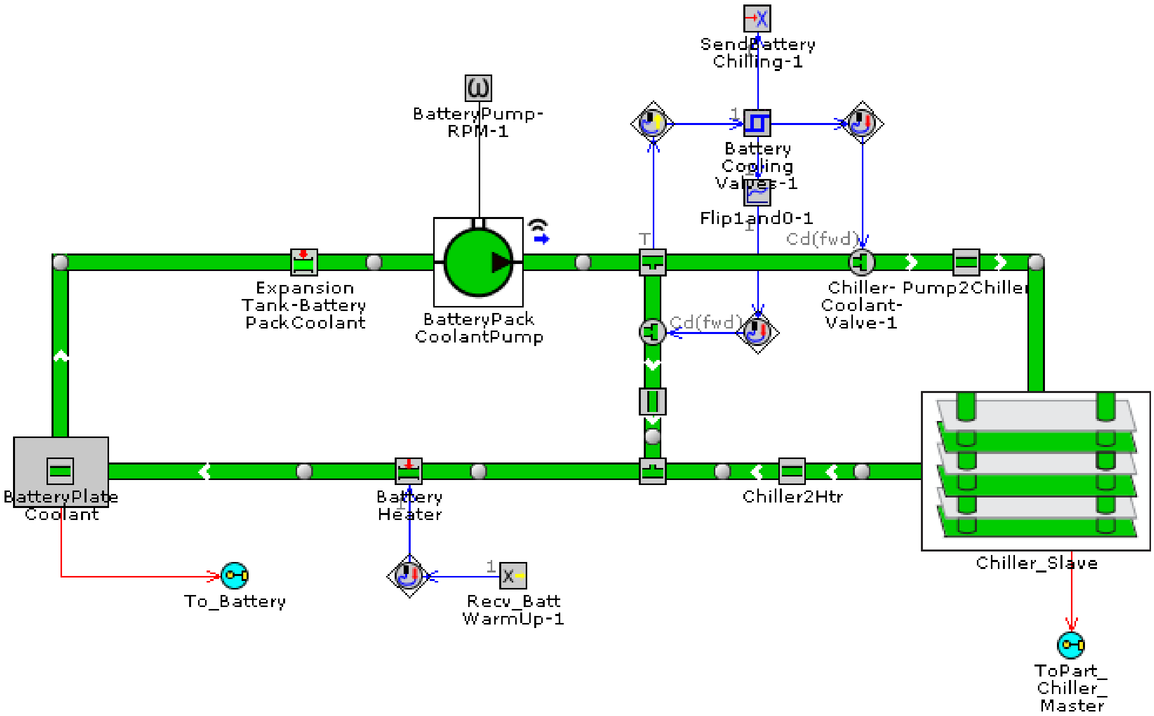

Figure.35 Battery cooling assembly

6.7.2 Air conditioning

AC circuit is thermally connected with battery cooling and cabin air circuit. Depending on the requirements and received signals, it is determined compressor speed and how much are connected circuit affected. But as it did not directly affect my set up, it was left with predefined values and left for possible comparison with different models.

6.7.3 Underhood air

Circuit is created with external cooling module with connections for AC circuit and coolant circuit for engine and electric motor. Fan input is determined from receiving signals of fan control. These signals are from connected circuits of engine with electric motor cooling and air conditioning.

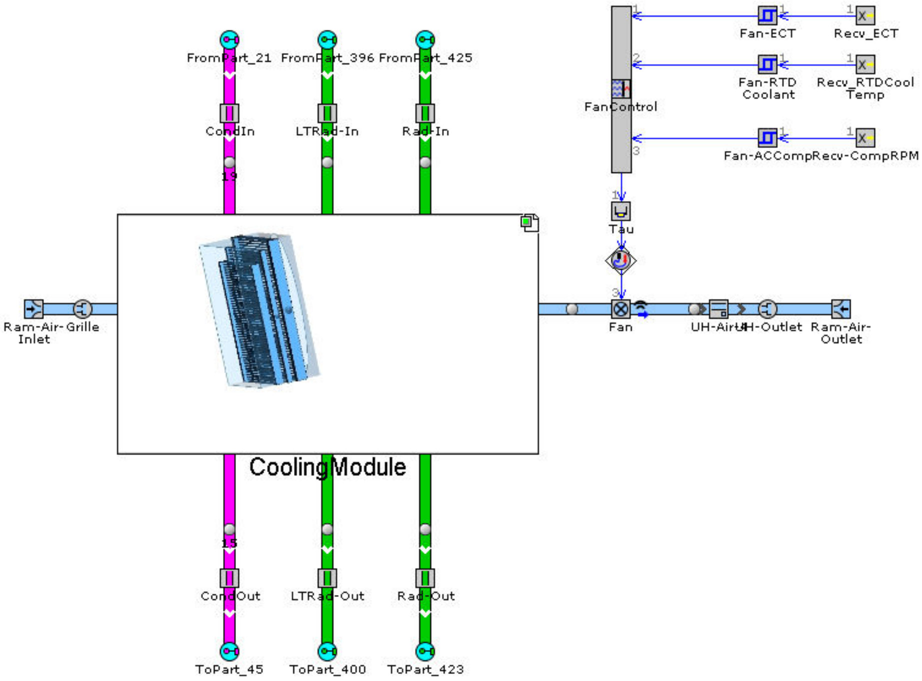

Figure.36 Underhood assembly

6.7.4 Cabin air

Model represents vehicle cabin with additional smaller circuit enabling to connect heat exchanger from air conditioning. Also, this circuit includes cabin heater and blower powered by battery, but overall it did not require any changes from exampled model.

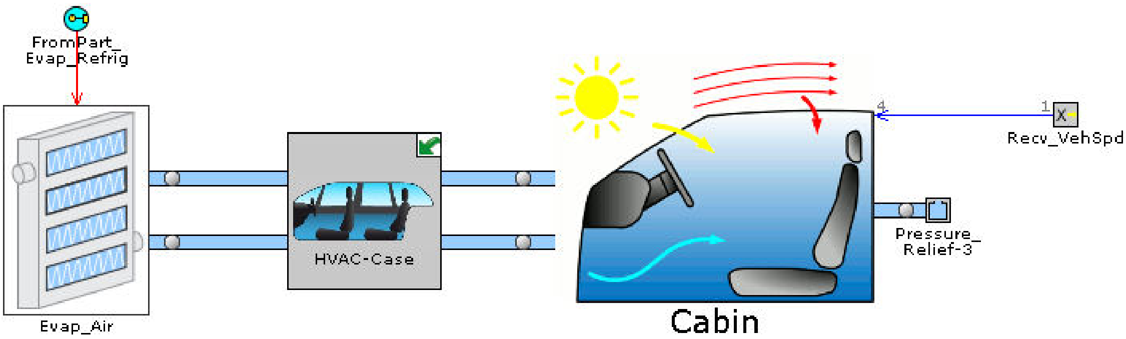

Figure.37 Cabin air assembly

6.7.5 Battery

Battery power consumption is dependent on of auxiliary loads. It is a sum of total power of fan, predefined accessory load, pump of battery, AC and cooling circuit and blower of cabin. Power request is determined by the calibration table based on the difference between the current and target SOC.

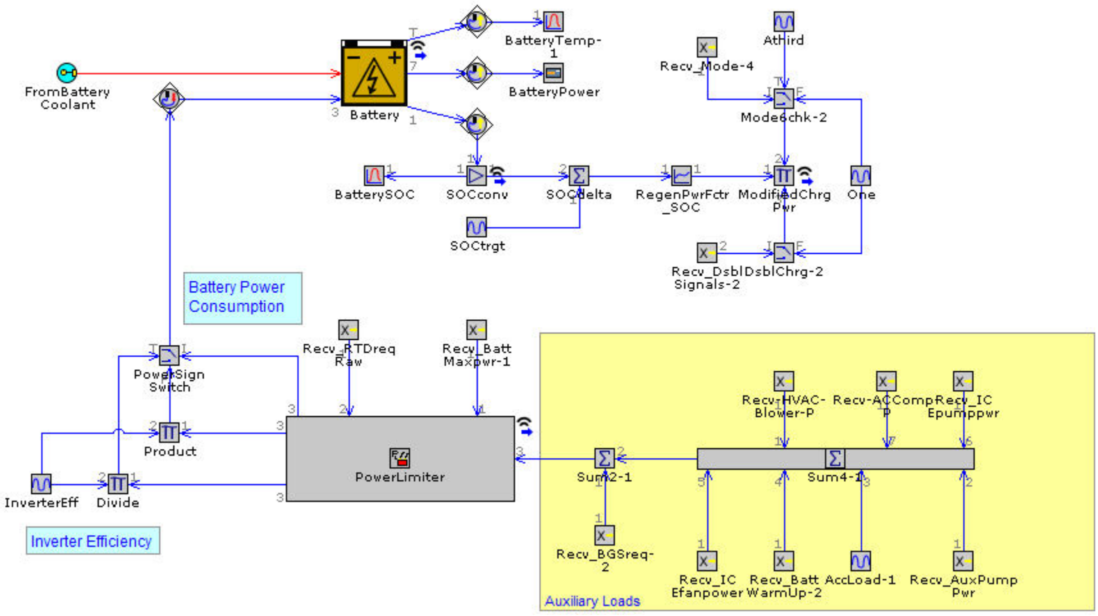

Figure.38 Battery assembly

6.7.6 Rear Traction Drive

Electric motor with power of 27kW propels the rear axle. It is defined by electromechanical conversion efficiency between electrical and indicated mechanical power. Electrical power and brake torque are calculated from imposed mechanical brake power. Maximum and minimal brake torque limitations are pre-set as XY table where X represents the motor speed in RPM. Other values in power control may be ignored as the load control option has power-brake value. The same principal works for torque control. Working of electric motor is actuated by drive request and by temperature received from thermal mass connected with E-machine coolant in cooling circuit.

When the RTD is working in operating mode 1, 2 or 3, power determination is responsible for providing the output power request. In all other modes, the RTD is simply fulfilling the braking demand with regeneration depending to its limit.

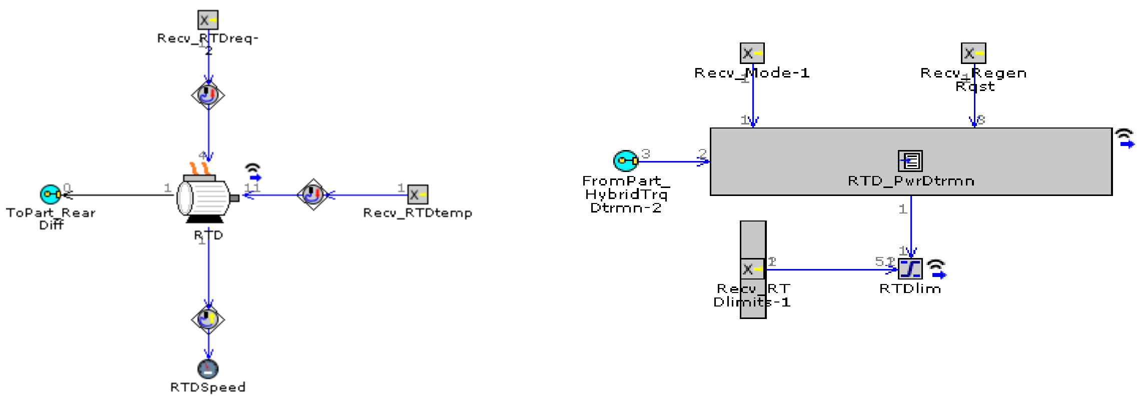

Figure.39 Rear traction drive assembly (left) with its power determination assembly (right)

6.7.7 Belted Starter-Generator

This gear is representative of the belt assembly that exists on the vehicle. Provided the amplitude and phase match, such a simplification is justified for controls development. Multiple requests may be made at any point during operation depending on the actual mode Typical function includes engine start, battery charging or engine boost to provide additional torque power.

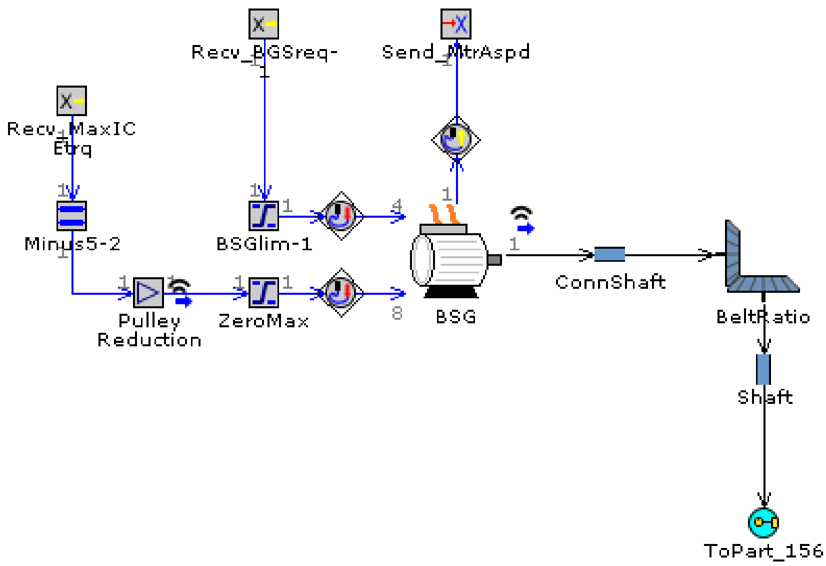

Figure.40 Belted starter-generator assembly

6.7.8 Powertrain controls

Hybrid models can work in different modes (CD, CS) depending on the requirements of the driver, vehicle speed target, battery state of charge and others. The controls determine what mode the vehicle should operate in. To prevent any unrealistic scenarios, it had been ensured, that the limits of the battery and rear electric motor are not exceeded and shift the state of the powertrain.

6.7.8.1 Hybrid operating mode determination

Based on the received signals from state of charge, output power request, vehicle speed, system constraints and other metrics, the operating mode is determined according to the first table. Initial SOC was set to 0.4% of total power. Target programmed to switch from electric mode to including of diesel engine was set to 65% of SOC. This provided enough time for electric drive and also engine and its warm-up phase. Current operating mode determines torque request as it follows in second table.

Tab. 3 Operating modes

Mode	Description	Main source of propulsion
1	Electric Only	Rear Traction Drive (RTD)
2	Engine Start	RTD while the engine is being started with the BSG
3	Series	RTD with Engine providing electrical power via BSG
4	Engine Off	Vehicle at rest with sufficient SOC to allow engine to start/stop
5	Engine Idle	Vehicle at rest, but battery state of charge is being recovered
6	Normal	Diesel Engine

These power requests are either send to BSG, engine or RTD control.

- BSG – determining the function depending on multiple requests during operation
- Engine – determining speed target, pedal request and ignition control according to multiple attributes
- RTD – depending on the operation mode, electrical power is provided, or regenerative breaking is applied

6.7.8.2 System constraints

Receiving power request signal and determining outputs to following controls.

- Engine warm up control – determining if and how long a warm up period is required
- SOC recovery mode – turning engine on in case of low value of SOC
- RTD power limits – determining the power request depending on RTD mechanical power, electrical power and temperature
- Battery temperature – controlling power request for battery warm up and power limits depending on the temperature
- BSG power limits – controlling mechanical limits with operating map and electrical from battery power constraints
- Fault diagnostics – ending simulation if fault occurs on one of the previous constraints

6.7.9 Driver demands

Circuit controls behaving of the vehicle depending on preset parameters, received values and demands of the driver.

- power request – comparing target speed with actual and calculating output power and torque
- shift control – determining gear with basic shift map using vehicle speed and accelerator pedal position
- launch control – engaging the clutch during vehicle launch according to slip target
- break control – comparing maximum regenerative breaking with requested and filling with mechanical breaks if needed or using the mechanical breaks only

7 HEAT STORAGE UNIT

Phase of using HSU takes place after engine start, with cold coolant, cold exhaust gas and cold engine block, creating higher mechanical friction which results in increased fuel consumption and CO_2 emission. Faster engine warm-up is obtained by transferring accumulated heat from the latent heat storage unit to the coolant or oil. To optimize the effect of the HSU, flow is directly diverted to the HSU without flowing through the exhaust heat exchanger using valve. It was placed right behind water or oil pump, depending on the circuit.

7.1 HEAT SOURCE

Storage heat can be directly delivered to the coolant circuit or engine oil circuit. For demonstrating a heat storage unit in GT-Power I used a component “Heat addition” to simulate a transfer of heat rate directly going to the fluid flowing through the component, with options for modeling the pressure drop. This object may be placed between any two pipes and typically it is used to model component for which heat transfer is significant, typically heat exchangers or engine block, but for which the heat transfer rate does not need to be predictive. It also allows the pressure drop characteristics of the component to be imposed without need of modeling the actual geometry. Heat input rate specified in this component is applied directly to the fluid, not to any wall or other structural material, which meets the necessary requirements. To make it work properly, there had to be set all values of attributes. Most of them were provided by Hanon Systems as a result from their test laboratories. Most importantly the profile of heat input through time to determine how it affects the fluids. [29]

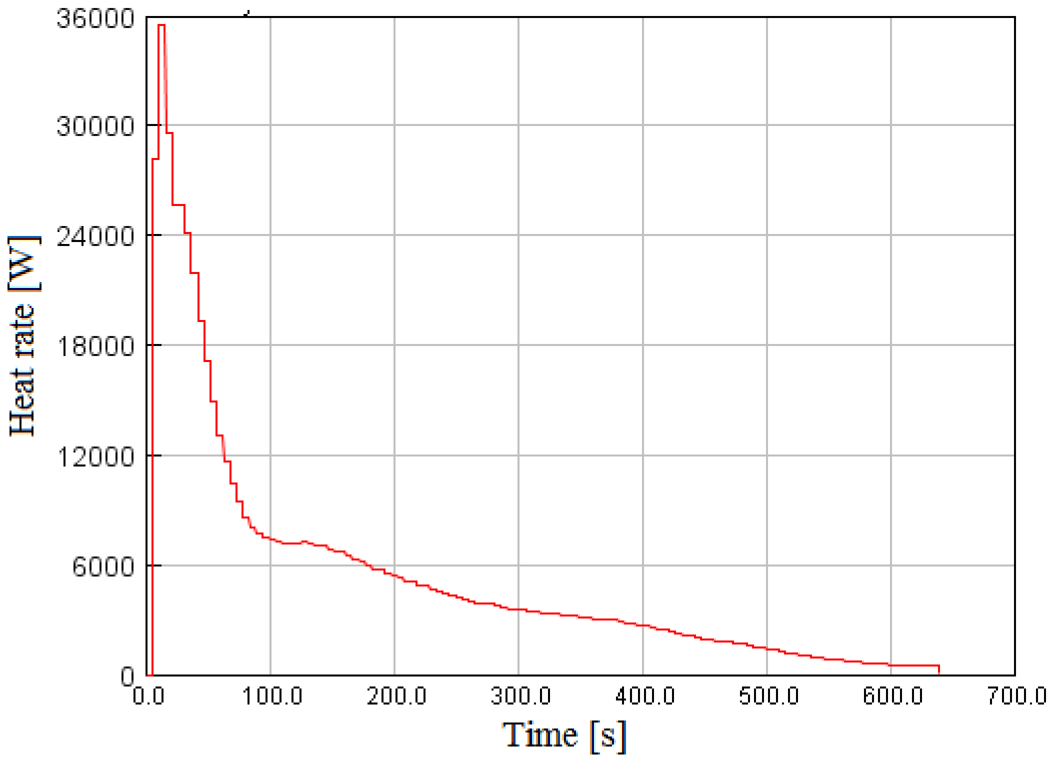

Figure.41 Heat input rate

Initial state name describes components initial conditions. Setting coolant initial value means, that the egl-5050 coolant will defines the composition at the start of the simulation. In case of oil heating, it is Oil-5W30-62-10cSt. Initial pressure and temperature conditions will have the same values as selected fluid. Volume of fluid inside component was set to a value of expected unit design.

Pressure Drop Reference Object defines the pressure loss through the component. If it is used, then the downstream connection must include a default orifice connection component. It demonstrates an orifice placed between any two flow components and it represents the plane connecting them. Values of pressure losses were also provided by company as results from testing.

7.2 SETTING

After a simulation of default model, it was recognized that the optimal temperature for coolant was escalating around 350-355K and for oil 340-350K. After fluids reached their optimal temperature, additional heating was not needed anymore. Overheating fluids would act contra productive and in those situations, it should be turned off and fluid transport different way. However, in cases where fluid temperature decreases below optimal, it should be ready to turn back on and be able to continue with remaining heat source if available.

Heat input rate was set as a time-dependent profile instead of a constant value, so to be able to turn it off, it had to be controlled and actuated by creating several conditional statements that determined required outputs. Usage of thermal unit is mainly dependent on temperature so the sensor was placed at the pipe behind pump as the closest place where flow will be continuous for the whole simulation and therefore temperature will be changing. This sensor is connected to the mentioned conditional statement but through averaging template which prevents thermal unit to unnecessary turn on or off in temperatures escalating close the optimal. [29]

If the criterions were met, heat input is initiated but to be able to pause this heating, it had to be controlled with event timer. This template tracks the time and depending on the criterions determines when to start and stop, additionally when to continue again at the last value. Using of limiter was precautious, where the maximum limit was set to total time storage unit delivers heat. However, input rate profile had to be transformed into one-dimensional table as I needed to control time, in this case X values.

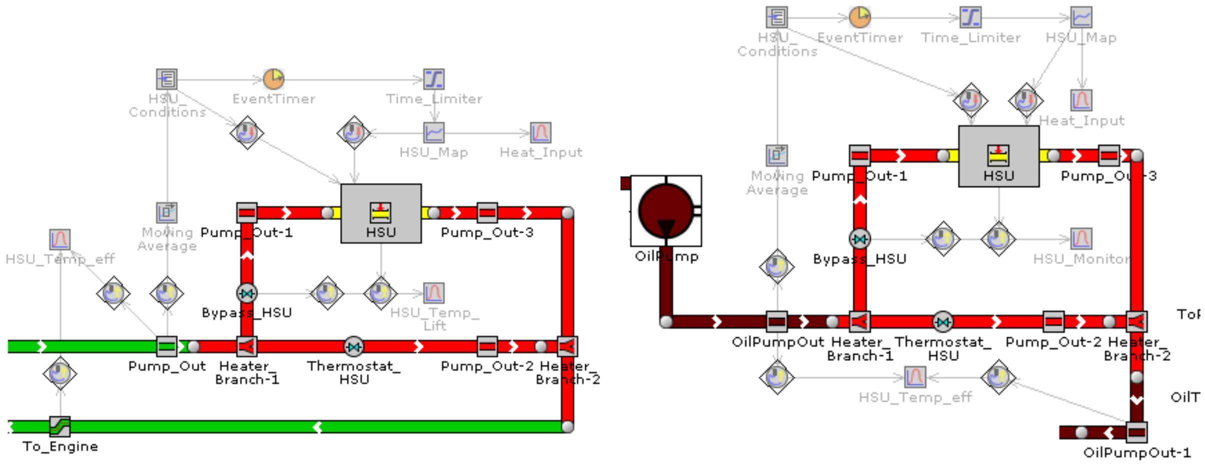

Figure.42 Diesel heat storage unit assemblies for coolant (left) and oil (right)

Coolant circuit of hybrid vehicle is slightly different and also had to have one additional condition included. Exhaust recovery systems should not work from the start of the simulation as the vehicle is running on electric motor, but to copy diesel model, it should be turned on simultaneously with engine which had to be additionally included into HSU conditions.

But because of the fact, that hybrid vehicle is actually running on electricity only and HSU is using stored exhaust heat, it can be modified to warm up water and oil sooner before the engine actually starts. Therefore HSU conditions can be adjusted where they don´t take engine state into account, but instantaneous battery SOC. Also in case of HSU inside oil circuit, oil pump had to be changed from mechanically controlled to electrically with dependency on battery SOC.

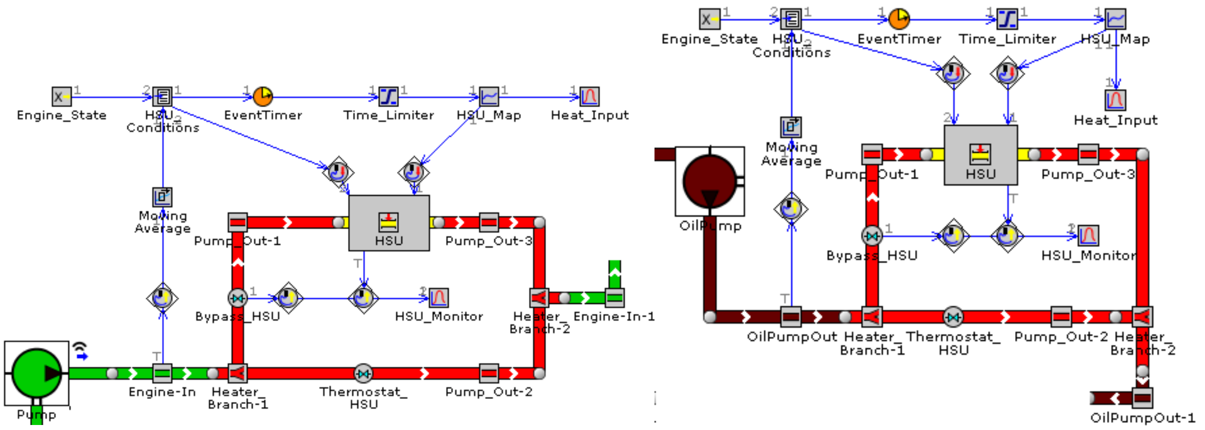

Figure.43 Hybrid heat storage unit assemblies for coolant (left) and oil (right)

7.2.1 THERMOSTAT VALVE

As previously mentioned, coolant or oil not having anymore the need for additional heating should be transfer different way. Thermostat component is used for directing these fluids and it can be described as an imposed lift thermostat valve, or a single temperature-activated thermostat valve. Lift cannot be a function of time in my case, because of the changing initial ambient conditions and therefore of time needed for thermal storage. Thermostat had to be activated depending on the temperature and at the same pipe as it was with conditional statements.

After few simulations, results showed that it is optimal to select place to sense temperature at pipe behind pump. This pipe is outside unit assembly and has continuous fluid flow throughout the whole simulation. Initial thermostat state was set to be closed, and bypass opened. The reason is in course of temperature-lift chart (0mm fully closed and 10mm fully open). Values for opening and closing were adjusted to my temperature range and area calculation depending on the diameter of pipes. [29]

8 COMBO COOLER

8.1 DEFINITION

EGR Combo cooler is a three-way heat exchanger and therefore more advanced system of preheating the coolant and oil at the same time. It doesn´t have any storage system because instead of storing heat and then later using it, we transfer exhaust heat into coolant and oil. System works in real time and its effectiveness doesn’t decrease when vehicle is longer in no use.

Figure.44 Combo cooler

System is designed by Hanon Systems with intention to be mounted at the exhaust system behind catalyst. So, after the engine starts, exhaust gas goes directly through heat exchanger where it heats coolant. Oil is heat-up through coolant in heat exchanger, to obtain faster warm-up of engine block through combined oil/coolant heating. The position of the valve enables to split the mass flow between heat transfer to the coolant and exhaust bypass. All of this helps to accelerate the temperature of fluids, reduce pressure losses and therefore increase overall performance of the car.

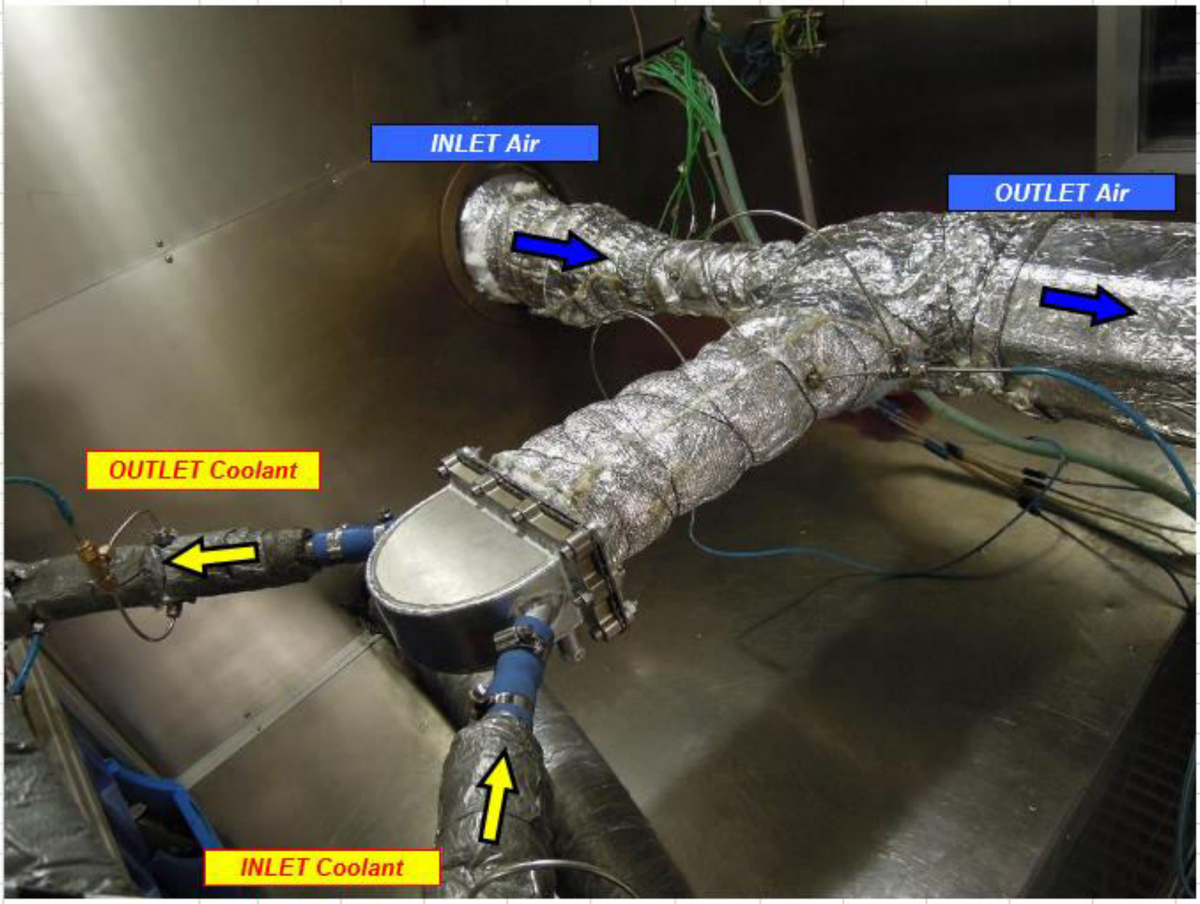

Figure.45 Laboratory test of Combo cooler

8.2 SETTING

HxMaster heat exchanger is a component to model heat transfer between the fluid and the wall of heat exchanger or by thermal connecting HxSlave exchanger component, the fluid boundary conditions on the opposite surface of the heat exchanger mass. In my case, master exchanger will be placed at exhaust system as I was trying to transfer heat from there. Heat exchanger is made up of thermal mass and flow volume so the configurations and options available for characterizing depend on the geometry of object. In this case, it was unknown as a component in development process, therefore set up as general. Heat transfer performance was described by map that consists of measured data of inlet and outlet temperature and pressure, flow rate of both master and slave fluids and total effectiveness of heat transfer. These data were received from laboratory tests provided by Hanon Systems.

Internal and external pressure data object were enabled to use map only. The resulting temperature and pressure distribution of the Nusselt calibration will be used as an input to the pressure drop calibration. This method closely mimics the behavior of the forward run for the best accuracy to the preprocessed data. [29]

GT-Power only allows creating two-way heat exchanger. That means Combo had to be adjusted to meet the requirements. Master heat exchanger placed behind exhaust system and connected to slave heat exchanger in coolant circuit behind water pump was completed with another identical slave, placed right behind and connected to master exchanger in oil circuit. Between two slave components there is orifice object as it represents connecting of two flow components. Initial state name and wall temperature are bonded with flowing fluids describing conditions of exchanger at the start of simulation.

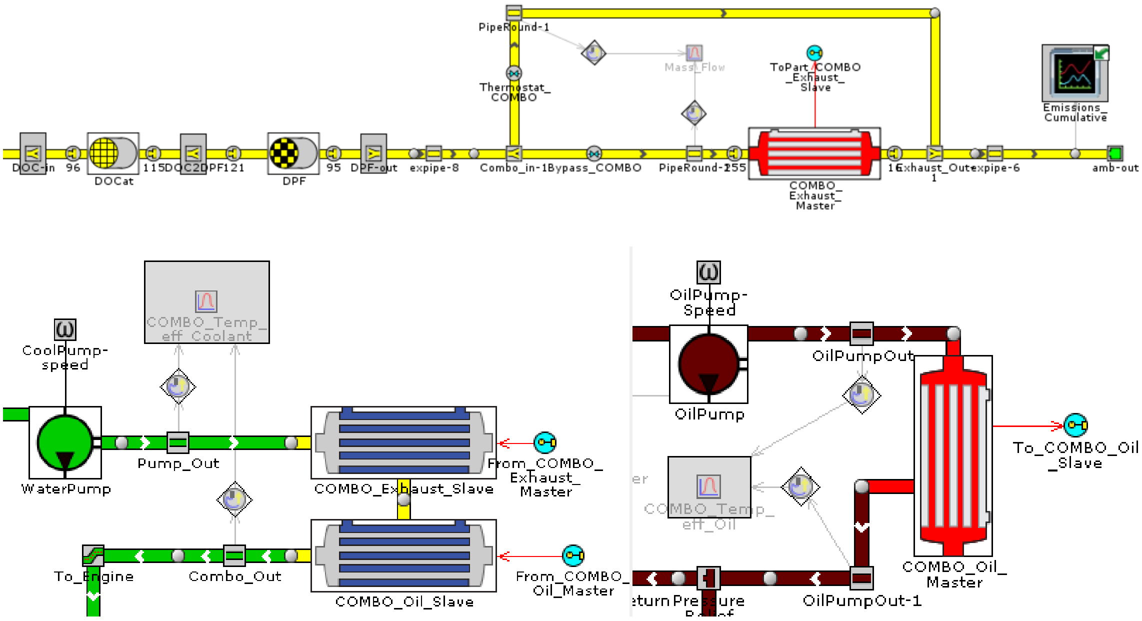

Figure.46 Combo assembly at exhaust (top), cooling (bottom left) and oil (bottom right) circuit

9 EXHAUST THERMAL MANAGEMENT UNIT

Idea of using both HSU and Combo cooler is that at the start the exhaust gases are not high enough to provide coolant and oil heating from heat exchanger. So with the assist from HSU this problem could be minimized. Exhaust gas directly heats coolant in heat exchanger; oil is heated up through coolant in heat exchanger to obtain faster warm-up of engine block through combined oil/coolant heating. During this phase, full exhaust gas flow is directed through heat exchanger thanks to the valve and provided maximum heat transfer to the coolant.

Heat storage unit will again use bypass system sensing temperature on the pipe behind pump in coolant circuit and also conditional statements. Its placement and function are similar to previous models as a design solution requires it.

Recovering of heat was not modeled in any way and simulation always starts with same amount of heat rate, but it would be designed in way that coolant transfer energy to the Heat Storage Unit, where it is accumulated under sensitive and latent forms.

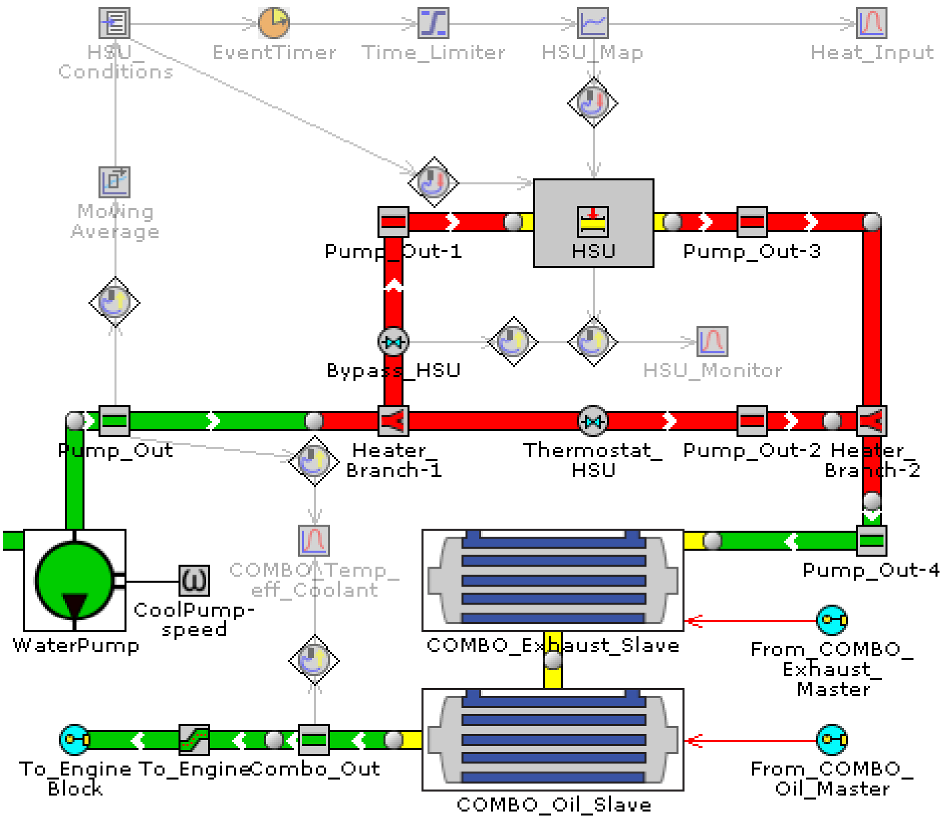

Figure.47 ETMU assembly in cooling circuit

Similar to HSU system only, hybrid vehicle can initiated ETMU before diesel engine starts to shorten warm-up time of coolant and oil at the same time. That again meant adjustment of oil pump to be powered electrically.

10 RESULTS

For better comparison it was also created another model with EHRS heat exchanger. Placement and settings were identical to heat exchanger on Combo Cooler between exhaust gas and coolant, so it offered a better look on effectiveness of additional oil cooling. For evaluation, I chose results that were affected by additional heating and could lead to better results of fuel consumption. Mass of recovery systems was also taken into account and added to overall vehicle mass.

Tab.4 Vehicle mass

	Diesel vehicle	Δ	Hybrid vehicle	Δ
	[kg]	[%]	[kg]	[%]
Default	1853	-	2000	-
HSU	1856	+0.16	2003	+0.15
EHRS	1856	+0.16	2003	+0.15
Combo	1857	+0.22	2004	+0.2
ETMU	1860	+0.38	2007	+0.35

10.1 DIESEL VEHICLE

10.1.1 FLUID TEMPERATURE

Simulations showed interesting results. In case of heat input of storage unit, it is obvious that maximum possible power of 36kW is enormous and even if it helps to accelerate the coolant or oil warm up, it also causes overheating inside HSU. Fluids are not capable to absorb that much heat. This cause significant rise of temperature in short time periods. This problem would be solved by decreasing the power or changing the profile of heat rate depending on the fluid and its specific heat capacity. However, in real life situation, fluid won´t be able to absorb so much energy and also energy lost to the wall has to be taken into account which wasn´t able to simulate.

First, I wanted to compare effect and usage of HSU additional heating on fluids. These results suggested that it should be more beneficial to heat coolant rather than oil. Coolant with higher thermal capacity could use a potential of HSU much longer. As it was mentioned previous, oil could not absorb all heat energy, which resulted in sudden rises and drops of oil temperature with possibility of overall negative impact.

Chart below shows HSU usage directly on the coolant (blue line) and its effect on oil (red) comparing to default oil temperature (black). Second chart demonstrates the opposite situation, where HSU is placed inside oil circuit showing temperature inside it (red) and again comparing effect on second fluid, coolant (blue) with default temperature (black).

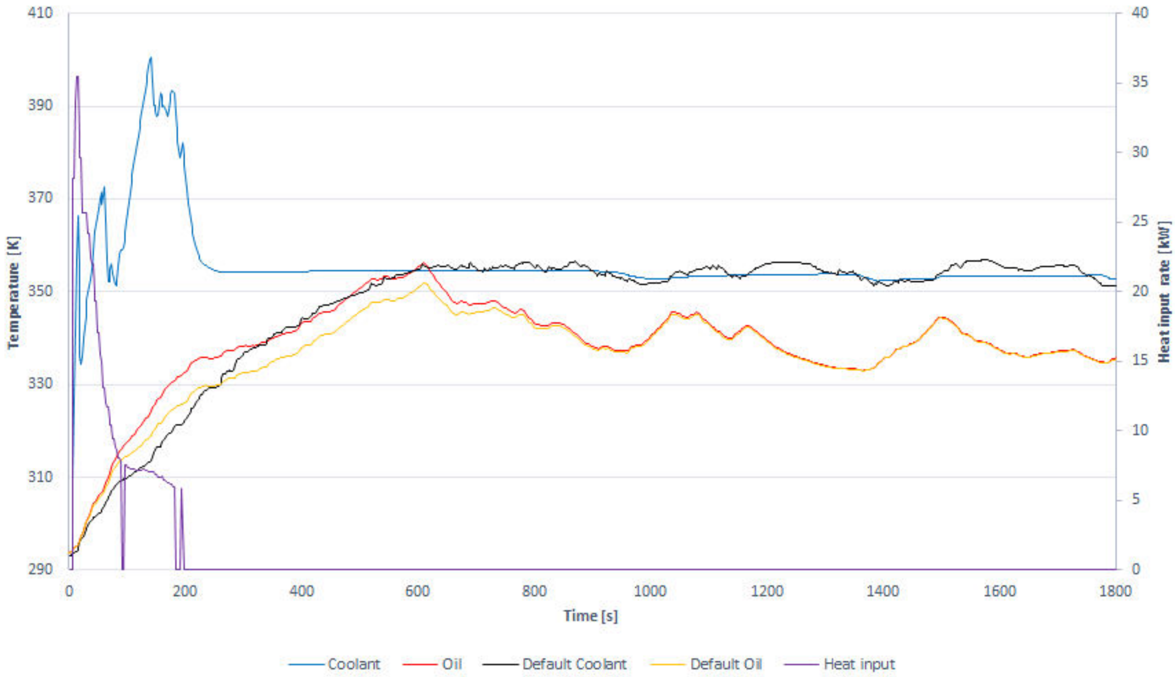

Figure.48 Diesel HSU coolant effect

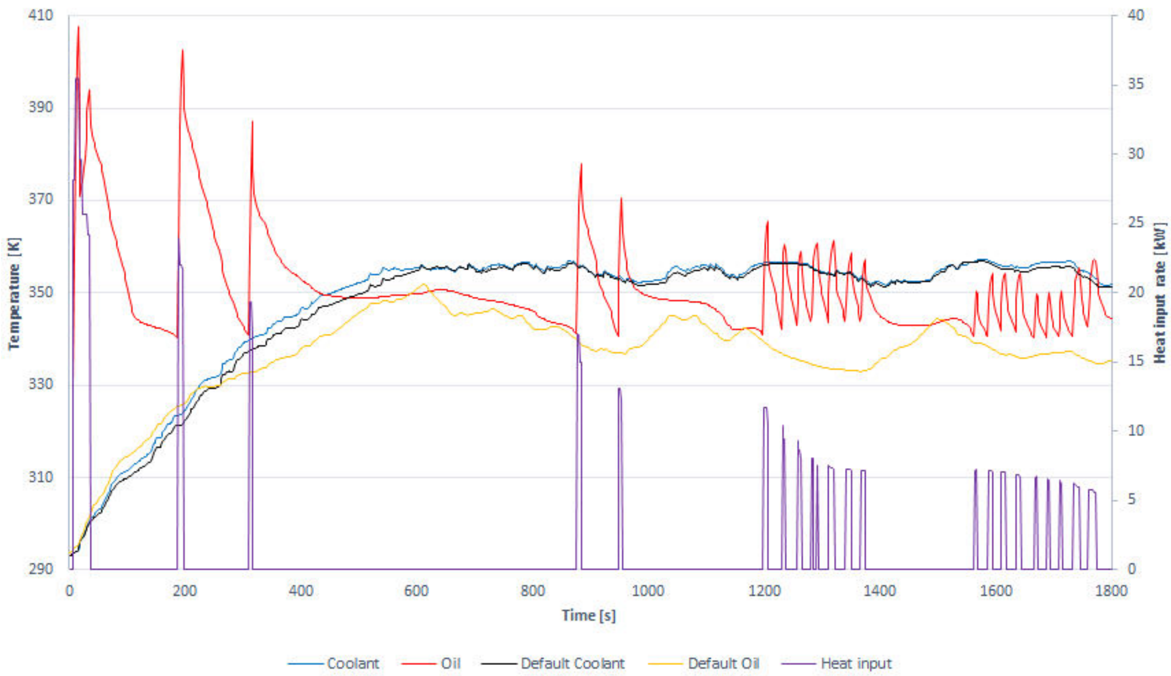

Figure.49 Diesel HSU oil effect

If I compare all the design solutions of additional coolant heating it shows that for HSU system only, it took the least amount of time to heat up the fluid. ETMU was second fastest as it also transfers some of its energy to oil. It can be also seen comparing profiles of EHRS and Combo alone or at the oil temperature profile. These temperatures were taken from the same place, pipe behind water or oil pump that was also used for HSU conditions.

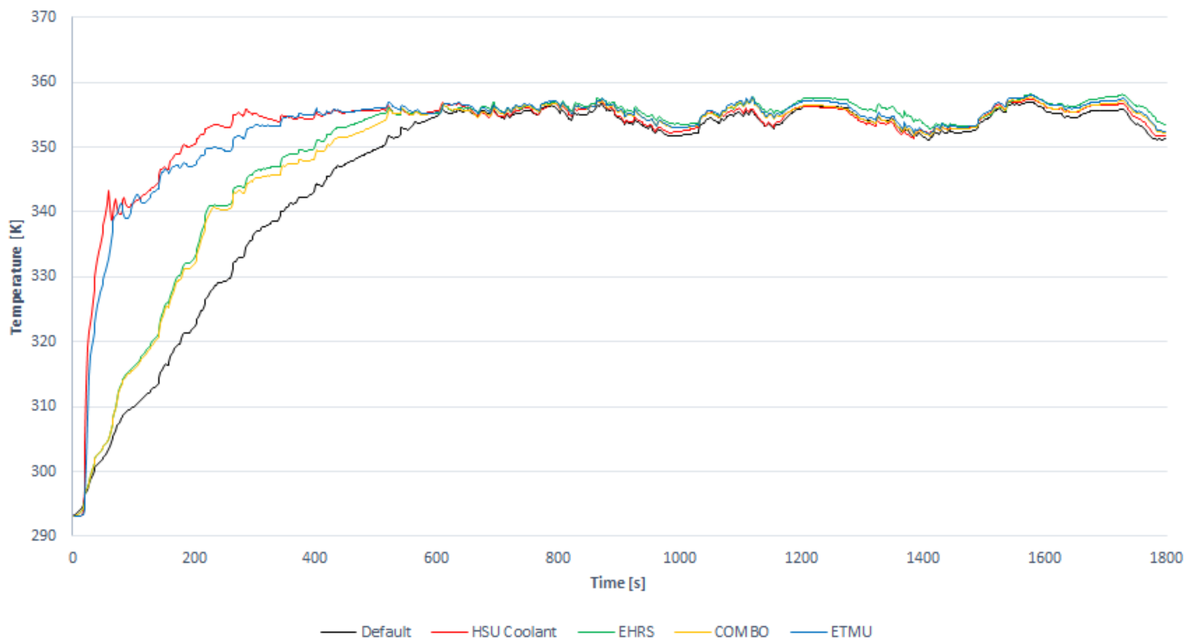

Figure.50 Diesel coolant temperature profiles

Similary, HSU inside oil circuit provided the fastest warm-up of oil, but did not act ideal. As it was set to activate in case of droping below 330K, any other heat input caused increase of the temperature. ETMU placed in coolant circuit helped increase oil temperature sooner comparing to Combo alone. These profiles would later after disabling HSU became identical. EHRS system had almost similar profile to default one with average difference of 5K. Comparing to coolant/oil heating, Combo provides sooner warm-up of oil temperature.

Figure.51 Diesel oil temperature profiles

But what could be seen from comparison of HSU coolant/oil is that energy is more used when directly imposed into coolant. Thanks to a longer and more continuous input, it had also bigger effect on second, oil temperature.

10.1.2 Catalyst temperature

Shorter warm-up time of catalyst should increase its effectiveness and therefore decrease amount of emissions as well. This can be summarized by saying that the reactions go faster at higher temperatures because the larger proportion of the molecules have the minimum activation energy needed to react. If I compare temperatures of default model to ones with HSU system only, profiles are almost identical, with slightly higher temperatures at the start of HSU placed in coolant circuit. Meaning that figures below show only first 200s where the difference is the most obvious.

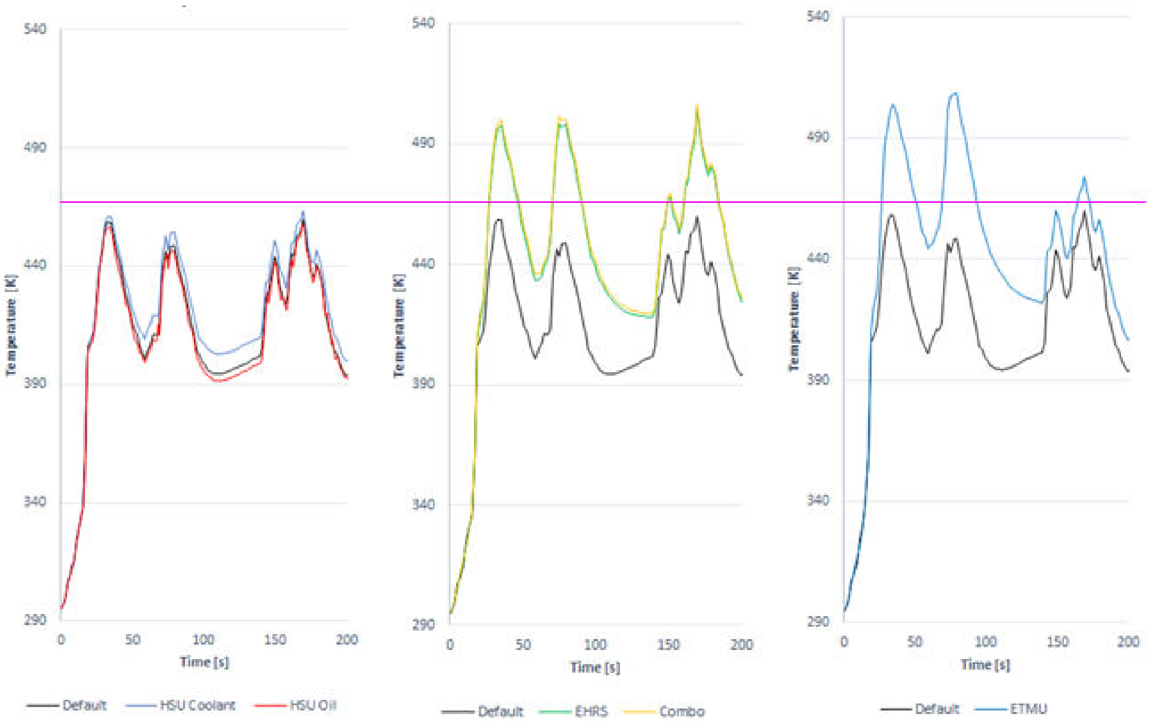

Figure.52 Diesel DOC temperature profile of default model comparing with HSU in coolant and oil (left), EHRS and Combo (middle), and ETMU (right) with minimal temperature of DOC to light off (purple line)

However, when I took results from EHRS, Combo and ETMU and compare it to default model, there can be clearly seen temperature difference mainly at the start which should have positive effect toward warming-up of the catalyst and decreasing emissions as DOC allowed to show mass conversion rate and demonstrate it.

Tab.5 Mass conversion rate difference of DOC

Mass conversion rate difference	Δ CO	Δ HC	Δ NO
	[%]	[%]	[%]
Default	-	-	-
HSU coolant	+1.943	+1.204	-1.013
HSU oil	-0.786	-1.035	-1.354
EHRS	+1.581	-0.254	-6.413
Combo	-1.177	-1.547	-5.280
ETMU	-0.731	-4.911	-14.148

10.1.3 FUEL CONSUMPTION

Engine assembly had to use explicit solver as a recommended option for the large majority of GT-Power simulations and the only one allowed for it without crashing the simulations. As it appeared, there is an exception that simulation of the thermal responses of an exhaust system from a cold start should use implicit method. In my case thermal responses points to heat exchangers which could lead to incorrect results of fuel consumption.

HSU systems as part of the coolant or oil circuit could be solved with implicit method. Inside the coolant circuit there can be seen the biggest improvement followed by HSU inside oil circuit. However, EHRS, Combo and ETMU as parts of the engine assembly were compromised and can´t take these results as representative.

Tab.6 Diesel fuel consumption

Diesel	Fuel consumption		Δ
	[g/km]	[L/100km]	[%]
Default	61.18444	7.37162	-
HSU coolant	60.65098	7.30734	-0.87199
HSU oil	60.87088	7.33384	-0.51251
EHRS	60.97043	7.34583	-0.34985
Combo	61.32022	7.38797	+0.22179
ETMU	62.48010	7.52772	+2.11758

10.1.4 EMISSIONS

This could also be said about the emission sensors at the exhaust as they only showed accurate results of default model with HSU. Because of that, I took all measured emissions from engine crank train as they weren´t compromised by heat exchangers and provided more comparable numbers. These numbers reflect what would be measured in the tailpipe of the engine.

Tab.7 Diesel emissions from engine

Diesel break specific	BSFC [g/kWh]	CO [g/kWh]	HC [g/kWh]	CO_2 [g/kWh]
Default	350.0523	0.024047118	1.4837996	1113.7529
HSU coolant	349.31152	0.023998972	1.4814583	1111.4202
HSU oil	346.81613	0.02384595	1.4703763	1103.4567
EHRS	345.33975	0.023714183	1.4647474	1098.8162
Combo	344.80997	0.023677334	1.4623228	1097.0917
ETMU	345.70065	0.023749953	1.4571128	1099.9882

The best results of BSFC and CO_2 showed Combo followed by EHRS and ETMU. These numbers are very similar with visible difference to HSU systems which also slightly improved. Combo also showed the best values of CO, however ETMU the values of HC which indicates to any unburned fuel.

I believe, that the full potential of HSU systems wasn´t discovered because of the overheating. Coolant showed better respond to additional heating than oil. But higher starting oil temperatures affected combustion process and decreased CO, HC and CO_2 emissions. Heat exchangers, having slower warm-up phase didn´t have problems with overheating which resulted into bigger improvement. Combo comparing to EHRS showed better overall results as its coolant/oil heating helped to increase oil temperature without losing too much from coolant energy. Meaning ETMU should provide the best results as its temperatures rise even quicker and it also showed cylinder temperature higher and FMEP lower comparing to Combo. But overheating from HSU compromised values and showed better improvement of only HC that suggests more sufficient burning of the fuel thanks to a quicker warm-up of fluids and overall engine temperature.

Tab.8 Diesel emissions difference from engine

Diesel break specific difference	Δ BSFC [%]	Δ CO [%]	Δ HC [%]	Δ CO_2 [%]
Default	-	-	-	-
HSU coolant	-0.212	-0.200	-0.158	-0.209
HSU oil	-0.924	-0.837	-0.905	-0.924
EHRS	-1.346	-1.385	-1.284	-1.341
Combo	-1.498	-1.538	-1.447	-1.496
ETMU	-1.243	-1.236	-1.799	-1.236

10.2 Hybrid vehicle

All hybrid models comparing to diesel models were using implicit solving method as the different engine assembly allows it. This meant more representative comparison. Simulations started with different ambient temperature of 258.15K which would show greater effect of additional heating and difference on fuel consumption and temperature of fluids and catalyst. WLTP procedure in case of hybrid vehicles were simplified due to compute time and the fact I was mainly focusing on warm-up period. It means instead of two WLTC cycles where the second one would be only engine powered, there is only one which was adjusted to have enough time for engine to reach optimal mode. Approximately, the first 640s is vehicle running only on electric mode, after that diesel engine is initiated.

10.2.1 Fluid temperature

Identical design solutions of recovery systems brought similar results. Heat input rate from HSU caused the fastest rise of temperature followed by the ETMU in both cases for coolant and oil. ETMU allowed some of the energy to be transferred into the oil. The transferred effect can be seen comparing Combo oil temperature with EHRS. Temperature was again taken from the same pipe that was included in HSU conditions.

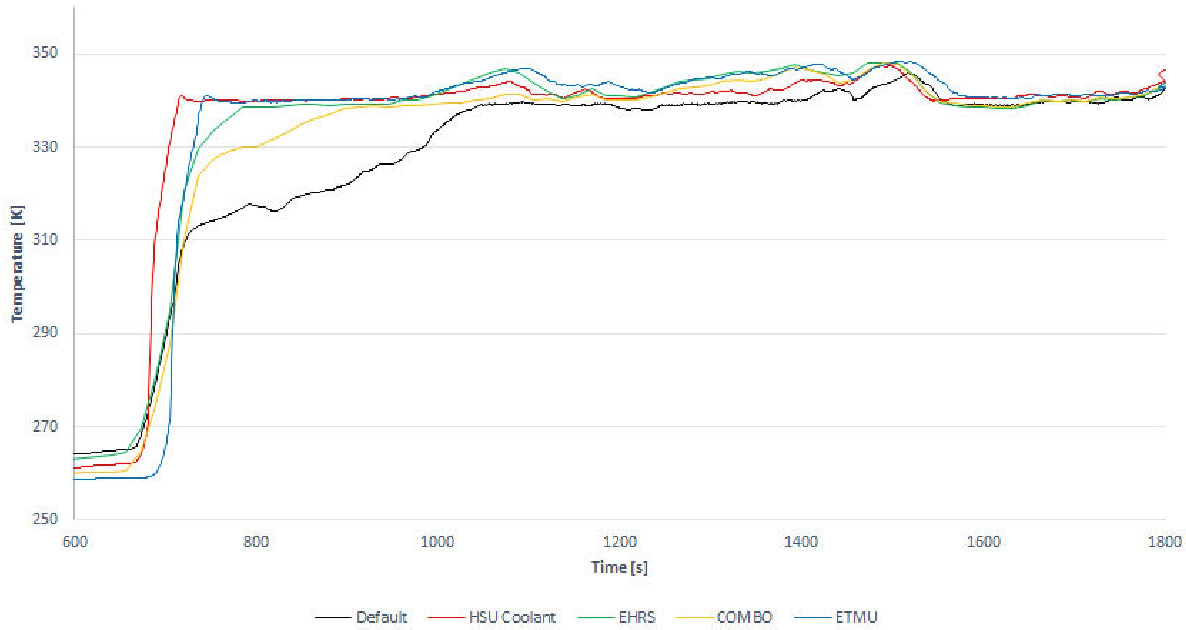

Figure.53 Hybrid coolant temperature profiles

In these cases, coolant temperature of HSU system inside oil circuit or oil temperature of HSU implemented inside coolant circuit wasn´t portrayed as it copy the default temperature profiles. This don´t have to show real situation, however it can point to differences with diesel vehicle and their effects.

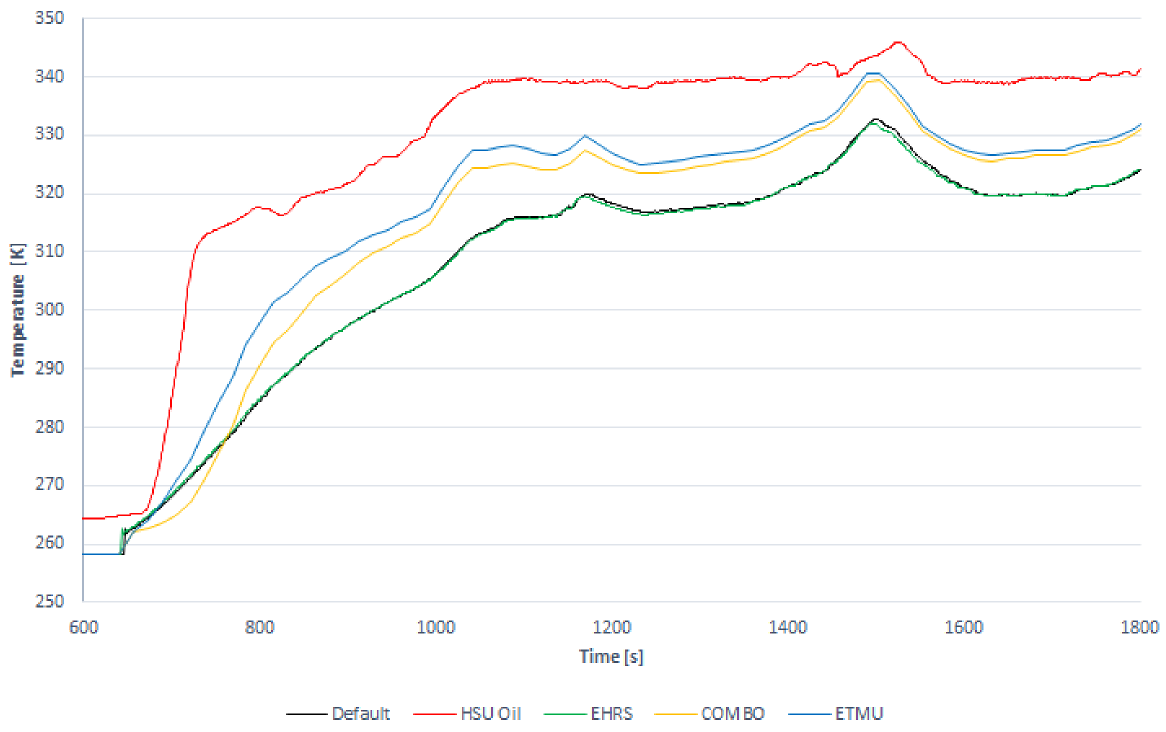

Figure.54 Hybrid oil temperature profiles

Unlike the diesel vehicle, HSU system in hybrid could have been initiated before the engine starts which meant that coolant and oil temperatures could reach their optimal stages even sooner. By examination of HSU time needed for warm-up, profile of battery SOC and previous simulations, there were determined new conditions for further comparison. Apart from engine start, HSU was also initiated at SOC=0.25 and SOC=0.26 which approximately meant 40s respectively 120s before engine start. This worked for HSU systems only as well as with the ETMU.

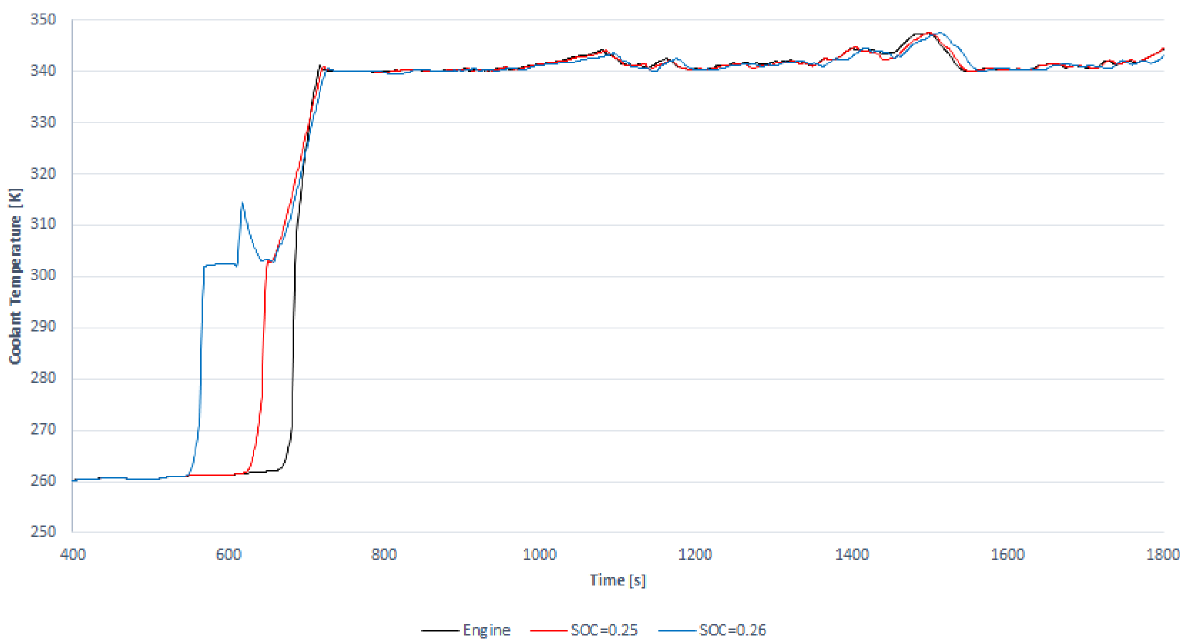

Figure.55 Coolant temperatures at different HSU coolant initiations

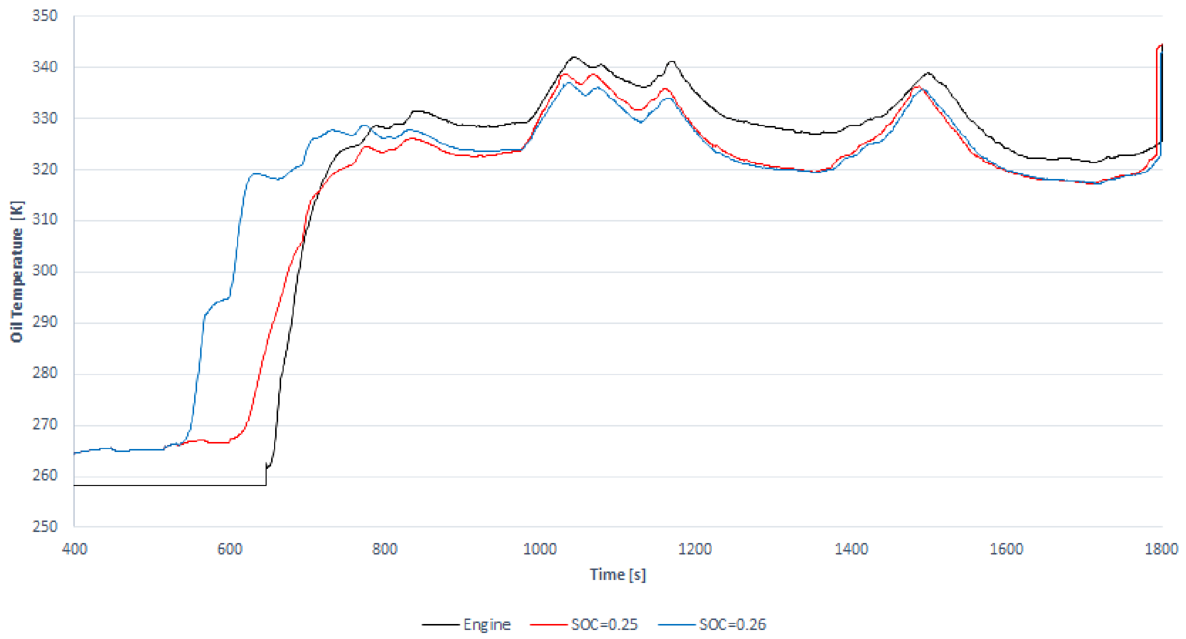

Figure.56 Oil temperatures at different HSU oil initiations

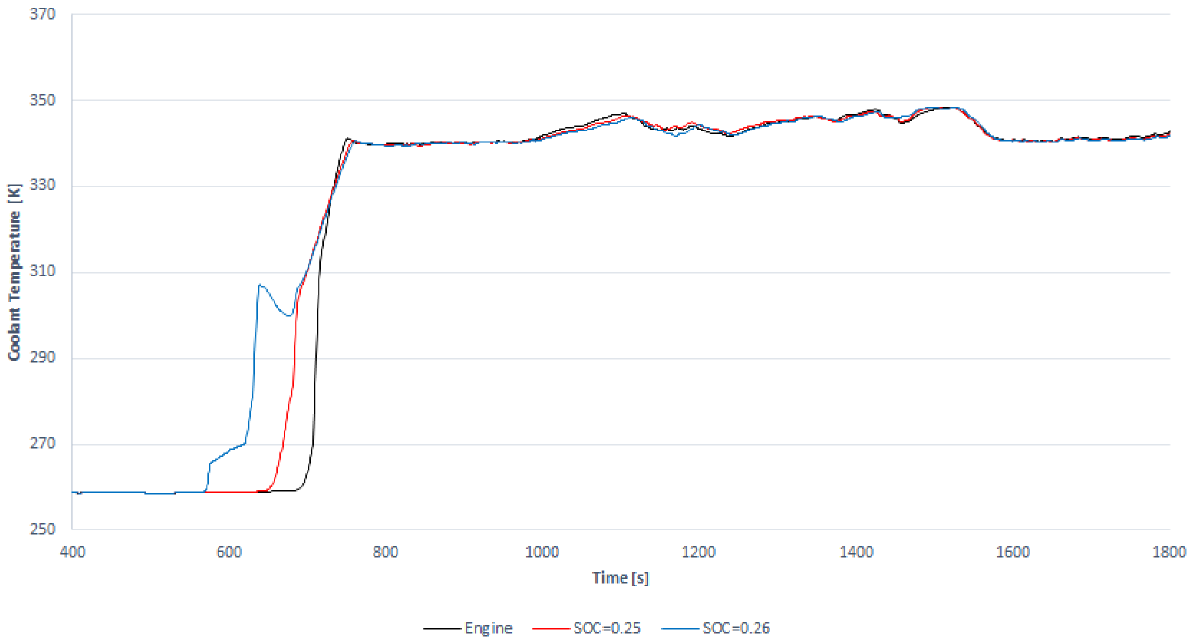

Figure.57 Coolant temperatures at different ETMU initiations

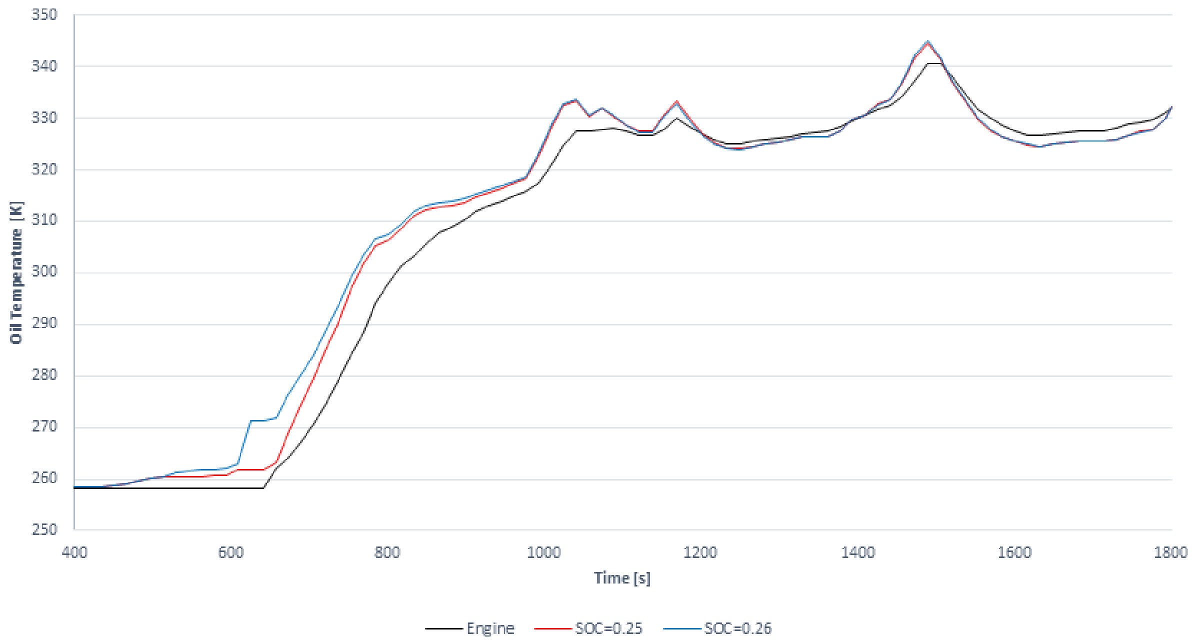

Figure.58 Oil temperatures at different ETMU initiations

10.2.2 CATALYST TEMPERATURE

Usage of recovery system in hybrid vehicle displayed different effect of warm-up on catalyst. Whole temperature profile using HSU inside oil was almost identical with small differences to default model. But in other cases, there is a sudden drop of DOC temperature approximately between 800s - 900s (160s - 260s after engine ignition) which could have negative impact. Charts below show only the section of warm-up to magnify the difference and temperature drop.

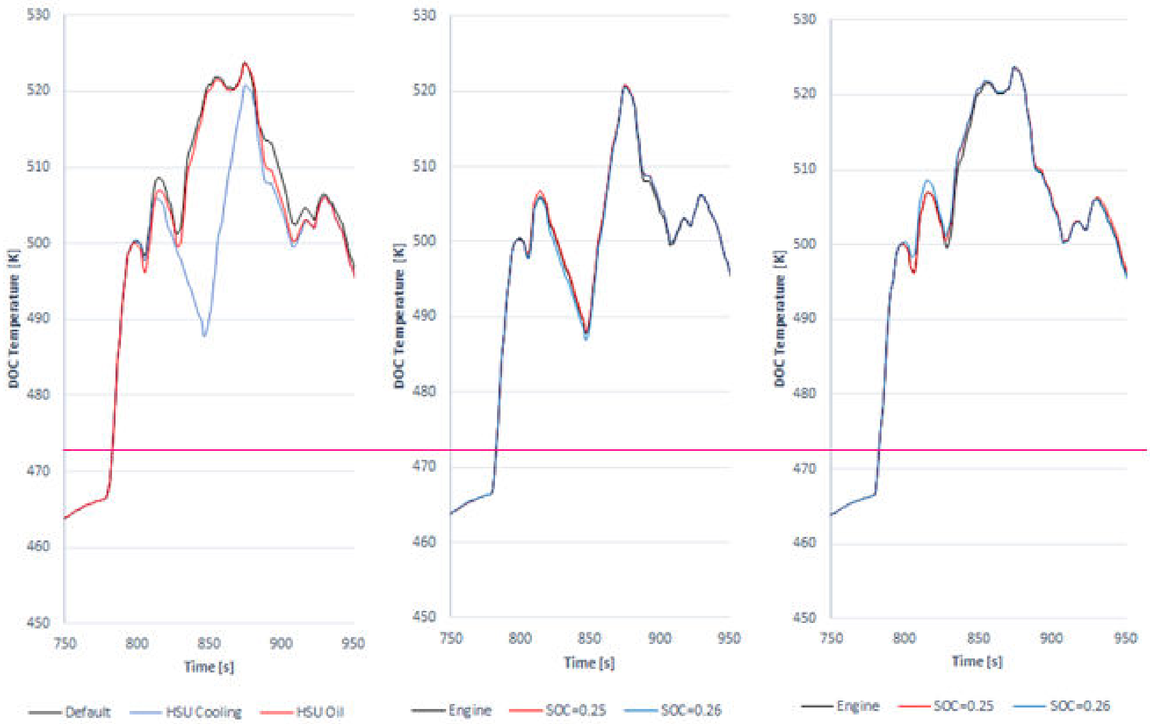

Figure.59 Details of DOC temperature profiles of HSU solutions after engine start (left), HSU coolant (middle) and HSU oil (right) after different HSU initiations with minimal temperature of DOC to light off (purple line)

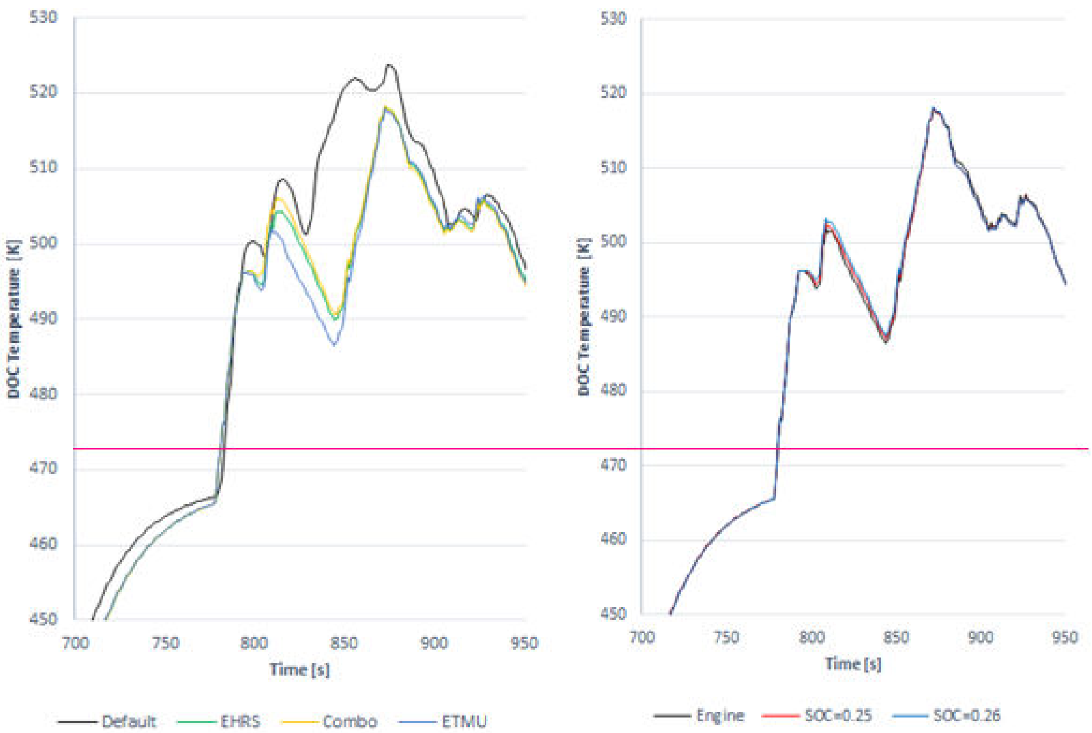

Figure.60 Detail of DOC temperature profiles of heat exchangers after engine start (left) and of ETMU after different HSU initiations (right) with minimal temperature of DOC to light off (purple line)

10.2.3 FUEL CONSUMPTION

Hybrid vehicle showed different results in terms of the most appropriate heat solution. HSU in cooling circuit both separately and as a part of ETMU showed the best fuel consumption. On the other hand, HSU system used inside oil circuit showed the worst results, following by Combo. EHRS as the last option confirms theory of the importance of pre-heating coolant rather than oil. Overheating of oil from HSU can cause fading of lubricant properties and therefore increasing friction inside the engine. Oil pump has to use more power which led to higher fuel consumption.

Tab.9 Hybrid average fuel consumption

Hybrid	Fuel consumption [g/km]	Fuel consumption [L/100km]	Δ [%]
Default	45.4350	5.4741	-
HSU coolant	44.5670	5.3695	-1,910
HSU oil	45.4172	5.4719	-0,039
EHRS	45.1288	5.4372	-0,673
Combo	45.2868	5.4562	-0,326
ETMU	44.9814	5.4194	-0,998

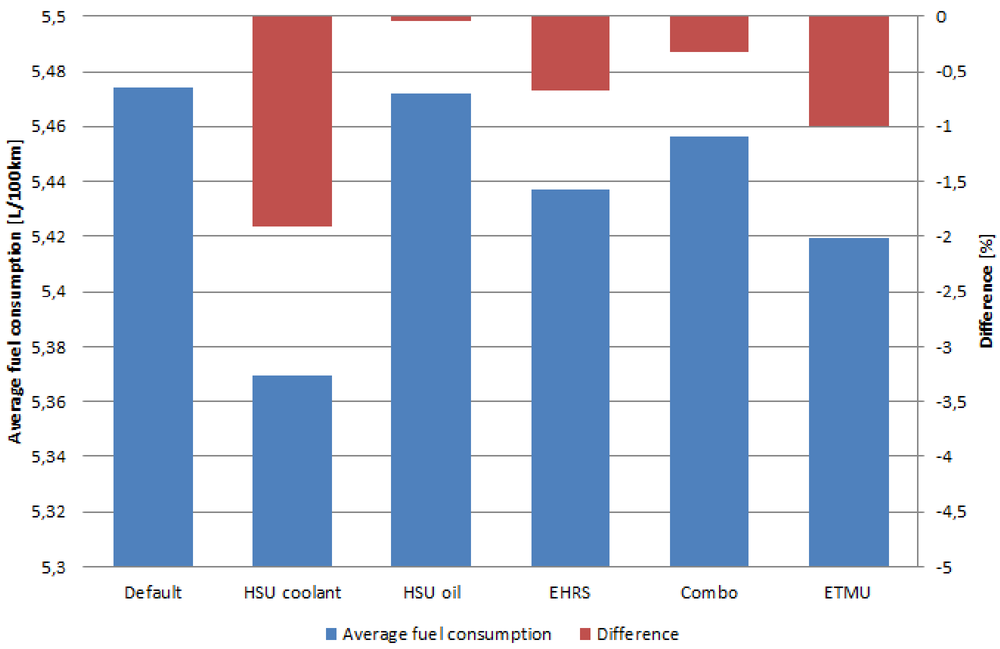

Figure.61 Average fuel consumption with percentage difference to default model

Table below shows average fuel consumption of HSU systems implemented inside coolant, oil circuit and as a part of ETMU. It compares results depending on initiation of HSU at engine start and when battery reaches SOC=0.25 or SOC=0.26. None of them are leading toward the same method but they are indicating that if I started to warm up fluid at SOC=0.26 I get the best result for HSU coolant, but the worst for other two. On the other side, they show as a more optimal solution to initiate HSU at SOC=0.25, which again points to great heat rate and its negative effect on oil and its main use. Coolant could be warm up sooner because of its greater volume inside engine and its thermal capacity that helped to transfer more heat into the engine and increase thermal effectiveness.

Tab.10 Hybrid average fuel consumption at different HSU initiation

HSU system	Coolant		Oil		ETMU	
	Average fuel consumption		Average fuel consumption		Average fuel consumption	
	[g/km]	[L/100km]	[g/km]	[L/100km]	[g/km]	[L/100km]
Engine state	44.5670	5.3695	45.4172	5.4719	44.9814	5.4194
SOC=0.25	44.5577	5.3684	45.1931	5.4449	44.9037	5.41
SOC=0.26	44.5432	5.3666	45.4551	5.4765	45.0474	5.4274

10.2.4 Emissions

Again, these results don´t represent real WLTP values as the simulation was simplified, but more the difference and improvement while using recovery heating. HSU inside oil circuit continues to show the worst overall results with improvement of HC and PM as a sight of better combustion process, but not with CO, NO_x and CO_2. Inside cooling circuit, there is significant improvement, except the PM as the only system. Combo as the only one has decreased all emissions, followed by EHRS and ETMU with slight increasement of CO. Combined coolant/oil heating system helped to transfer significantly more heat from oil to crankcase without losing almost any of coolant heat which increased thermal effectiveness.

Tab.11 Hybrid emissions

Hybrid	CO	HC	NO_x	PM	CO_2
	[g/km]	[g/km]	[g/km]	[g/km]	[g/km]
Default	5.2850E-4	8.5193E-5	1.5645E-4	1.0825E-4	0.0930296
HSU coolant	5.2455E-4	8.4872E-5	1.5350E-4	1.1099E-4	0.0907487
HSU oil	5.2853E-4	8.5144E-5	1.5844E-4	1.0746E-4	0.0932447
EHRS	5.2883E-4	8.4788E-5	1.5383E-4	1.0481E-4	0.0920227
Combo	5.2457E-4	8.4517E-5	1.5563E-4	1.0334E-4	0.0925053
ETMU	5.2958E-4	8.5032E-5	1.5631E-4	1.0579E-4	0.0923870

Tab.12 Hybrid emissions difference

Hybrid	Δ CO	Δ HC	Δ NO_x	Δ PM	Δ CO_2
	[%]	[%]	[%]	[%]	[%]
Default	-	-	-	-	-
HSU coolant	-0.7474	-0.3767	-1.8856	+2.5312	-2.4518
HSU oil	+0.0056	-0.0575	+1.2720	-0.7298	+0.2312
EHRS	+0.0624	-0.4754	-1.6747	-3.1778	-1.0823
Combo	-0.7436	-0.7935	-0.5241	-4.5358	-0.5636
ETMU	+0.2043	-0.1889	-0.0895	-2.2725	-0.6907

Tables below show emissions at different HSU initiation state. Fuel consumption results indicated that it should be beneficial to start heating before engine starts. However for HSU coolant, almost all of the emissions except for the PM at SOC=0.26 increased. PM as parts of the incomplete combustion could improve thanks to greater heat rate from coolant and therefore sooner optimal engine temperature. Oil heating at SOC=0.25 shows the best improvement of CO, NO_x and CO_2 and also ETMU produces better results at this initiation, but only in case of CO and HC.

Tab.13 Hybrid emissions of different HSU initiation

Hybrid		CO	HC	NO_x	PM	CO_2
		[g/km]	[g/km]	[g/km]	[g/km]	[g/km]
HSU coolant	Engine state	5.2455E-4	8.4872E-5	1.5350E-4	1.1099E-4	0.090748
	SOC=0.25	5.2654E-4	8.5063E-5	1.5421E-4	1.1108E-4	0.090830
	SOC=0.26	5.2809E-4	8.5176E-5	1.5507E-4	1.1076E-4	0.091173
HSU oil	Engine state	5.2853E-4	8.5144E-5	1.5844E-4	1.0746E-4	0.093244
	SOC=0.25	5.2784E-4	8.5152E-5	1.5595E-4	1.1066E-4	0.092334
	SOC=0.26	5.2882E-4	8.5217E-5	1.5525E-4	1.0853E-4	0.092383
ETMU	Engine state	5.2958E-4	8.5032E-5	1.5631E-4	1.0579E-4	0.092387
	SOC=0.25	5.2868E-4	8.4918E-5	1.5706E-4	1.0609E-4	0.092526
	SOC=0.26	5.3085E-4	8.5034E-5	1.5638E-4	1.0585E-4	0.092752

Tab.14 Hybrid emissions difference of different HSU initiation

Hybrid		CO	HC	NO_x	PM	CO_2
		[%]	[%]	[%]	[%]	[%]
HSU coolant	Engine state	-	-	-	-	-
	SOC=0.25	+0.3793	+0.2250	+0.4625	+0.0811	+0.0901
	SOC=0.26	+0.6748	+0.3581	+1.0228	-0.2072	+0.4679
HSU oil	Engine state	-	-	-	-	-
	SOC=0.25	-0.1305	+0.0093	-1.5715	+2.9778	-0.9760
	SOC=0.26	+0.0548	+0.0857	-2.0134	+0.9957	-0.9234
ETMU	Engine state	-	-	-	-	-
	SOC=0.25	-0.1699	-0.1340	+0.4798	+0.2835	+0.1506
	SOC=0.26	+0.2398	+0.0023	+0.0447	+0.0567	+0.3957

Final table is showing the most ideal usage of heat recovery systems in terms of initiation and their final percentage difference of fuel consumption and emissions. Again, it´s important to remember that values from all emission tables don´t have to show real numbers as the catalyst was simplified to mainly show temperature warm-up process.

Tab.15 Hybrid fuel consumption and emissions difference

Hybrid	Initiation	Fuel cons.	CO	HC	NO_x	PM	CO_2
		[%]	[%]	[%]	[%]	[%]	[%]
Default	Engine	-	-	-	-	-	-
HSU coolant	SOC=0.26	-1.9638	-0.0776	-0.0200	-0.8821	+2.3187	-1.9953
HSU oil	SOC=0.25	-0.5334	-0.1249	-0.0481	-0.3196	+2.2263	-0.7471
EHRS	Engine	-0.6741	+0.0624	-0.4754	-1.6747	-3.1778	-1.0823
Combo	Engine	-0.3270	-0.7436	-0.7935	-0.5241	-4.5358	-05636
ETMU	SOC=0.25	-1.1710	+0.0341	-0.3228	+0.3899	-1.9954	-0.5411

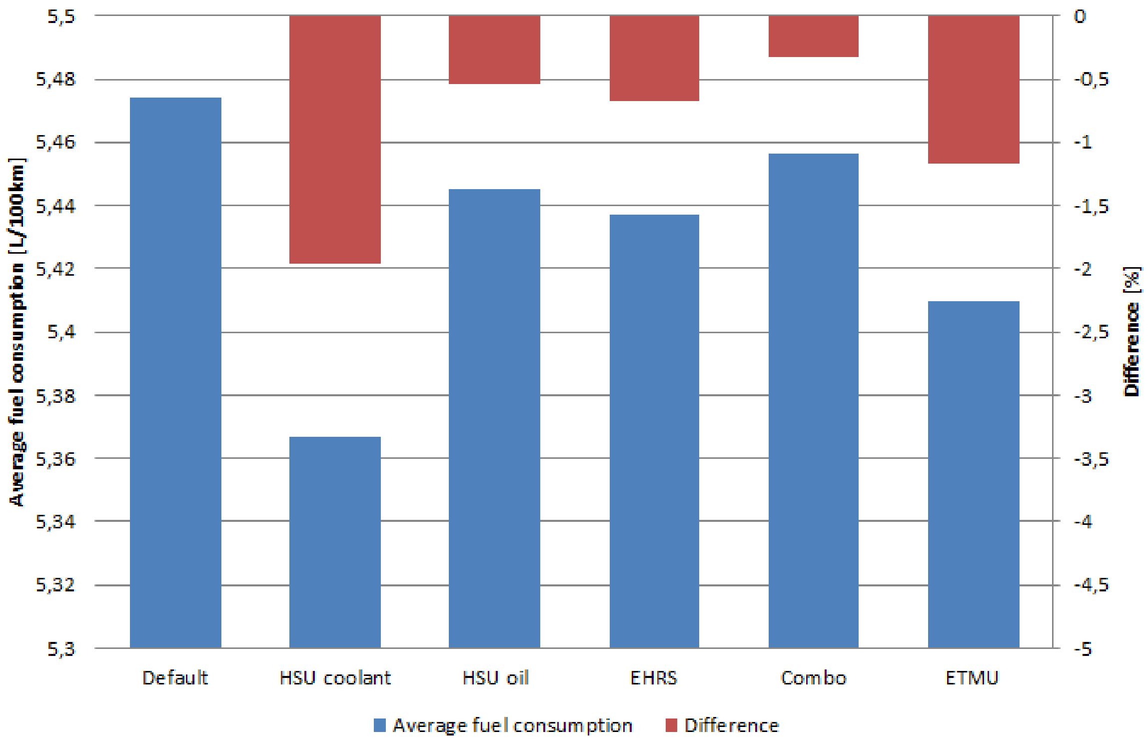

Figure.62 Average fuel consumption with percentage difference to default model

In case of a hybrid vehicle, there was also a potential of heat exchangers for positive effect on battery warm-up. However, battery already running at least for 520s (SOC=0.26), 600s (SOC=0.25) or 640s without any input from HSU managed to warm up at 78% of its optimal temperature in case of a soonest initiation (SOC=0.26). But it provided better cooling of RTD, therefore less power requirements on electric water pump and lower battery power consumption. ETMU showed even better results than Combo or HSU of coolant. Any other attempts trying to warm up battery even sooner led to increasement of fuel consumption and emissions mainly because of the unnecessary overheating with greater need from pumps to cool the fluids and losing its characteristics as oil friction and thermal capacity.

CONCLUSION

Implementation of heat recovery systems showed overall faster warming up of the coolant or oil. Models with heat storage unit offered the fastest warm-up and the best results when it was inside the cooling circuit rather than oil circuit. This could also have been caused by lower thermal capacity of oil and overheating inside HSU which won´t happened in reality due to laws of thermodynamic.

Emissions of diesel vehicle taken from exhaust were compromised due to explicit solving method required for engine assembly but not recommended for heat exchangers. This was solved by taking emissions from the engine as they better represented difference in thermal effectiveness. They showed the best improvement toward Combo heat exchanger as the potential of ETMU wasn´t fully showed because of the overheating inside HSU.

However hybrid models with implicit method showed more representative results. As hybrid vehicles with different needs, they could also use HSU system before engine ignition and therefore improve fluids heating even more. This was demonstrated with two different initiation stages with positive results towards the temperature warm-up of fluids and fuel consumption. On the other side, the temperature of catalyst wasn´t increased in any of the heat recovery system which resulted only into slight improvement of emissions and in some cases even into opposite trend. This could also be said about the battery temperature as it already reached high enough temperature before initiation of any additional system, but managed to decrease power consumption with better RTD cooling.

This leads to a conclusion that heat recovery systems for both diesel and hybrid models showed similar improvement in quicker fluid warm-up. This should be highlighted by the results of emissions and fuel consumption as it showed hybrid model. Diesel models with emissions taken from engine showed similar trend.

But taken all this into account, ideal solution would be usage of Exhaust thermal management unit (ETMU) with HSU implemented into the cooling circuit. Overall results from fluids temperatures and transferred heat indicate towards this solution. and if there wasn´t overheating of a coolant at the start. This statement is confirmed by the fact that the fluids in hybrid model behaved more optimal and led towards better results of fuel consumption.

References

[1] PISUPATI, Dr. Sarma. Products of Combustion. *Energy Conservation and Environmental Protection* [online]. [cit. 2019-04-03]. Available from: https://www.e-education.psu.edu/egee102s2/node/1951

[2] REŞITOĞLU, İbrahim Aslan. *The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems* [online]. 11 June 2014 [cit. 2019-04-03]. Available from: https://link.springer.com/article/10.1007/s10098-014-0793-9

[3] What is secondary air injection? PH Explains. *PistonHeads* [online]. 04.09.2018 [cit. 2019-05-08]. Available from: https://www.pistonheads.com/regulars/ph-explains/what-is-secondary-air-injection-ph-explains/38694

[4] Secondary air injection. *Wikipedia, the free encyclopedia* [online]. [cit. 2019-05-08]. Available from: https://en.wikipedia.org/wiki/Secondary_air_injection

[5] CHU, Jennifer. Study: Air pollution causes 200,000 early deaths each year in the U.S. *MIT* [online]. 29.8.2013 [cit. 2019-05-15]. Available from: http://news.mit.edu/2013/study-air-pollution-causes-200000-early-deaths-each-year-in-the-us-0829

[6] DENNIS A., GARNER C., TAYLOR D. (1999). *The Effect of EGR on Diesel Engine Wear*, SAE 1999-01-0839, In-Cylinder Diesel Particulate and NOx Control 1999

[7] Catalytic Converters. *ScienceDirect* [online]. [cit. 2019-05-15]. Available from: https://www.sciencedirect.com/topics/engineering/catalytic-converters

[8] Catalytic converter. *Wikipedia, the free encyclopedia* [online]. [cit. 2019-05-15]. Available from: https://en.wikipedia.org/wiki/Catalytic_converter

[9] Emission standard. *Wikipedia, the free encyclopedia* [online]. [cit. 2019-04-03]. Available from: https://en.wikipedia.org/wiki/Emission_standard

[10] European emission standards. *Wikipedia, the free encyclopedia* [online]. [cit. 2019-04-03]. Available from: https://en.wikipedia.org/wiki/European_emission_standards

[11] EU: Cars and Light Trucks: Emission Standards. *DieselNet* [online]. [cit. 2019-04-03]. Available from: https://www.dieselnet.com/standards/eu/ld.php

[12] NICOLAS, Romain. The different driving cycles. *DieselNet* [online]. 01-5-2013 [cit. 2019-04-03]. Available from: http://www.car-engineer.com/the-different-driving-cycles/

[13] What is the real driving test?. *Car emissions testing facts* [online]. [cit. 2019-05-15]. Available from: https://www.caremissionstestingfacts.eu/rde-real-driving-emissions-test/?gclid=Cj0KCQjwn8_mBRCLARIsAKxi0GI_8_VwNY2BdjNEFwH0prd9HyDM-8O5OwfDc6fBWD2qHt9jI2mFFQ0aAp8CEALw_wcB#

[14] BARTA, Pavle. Analiza: Kakve promene automobilska industrija trpi sa uvođenjem WLTP standarda?. *AutoRepublika* [online]. 09/09/2018 [cit. 2019-04-03]. Available from: https://autorepublika.com/2018/06/21/analiza-kakve-promene-automobilska-industrija-trpi-sa-uvodjenjem-wltp-standarda/

[15] Battery Management Systems. *Electropaedia* [online]. [cit. 2019-05-15]. Available from: https://www.mpoweruk.com/bms.htm#gas

[16] Traction Batteries for EV and HEV Applications. *Electropaedia* [online]. [cit. 2019-05-15]. Available from: https://www.mpoweruk.com/traction.htm

[17] European Homologation. *TUV* [online]. [cit. 2019-05-15]. Available from: https://www.tuv-nord.com/in/en/services/automotive-industry/european-homologation/

[18] *Car emissions testing facts* [online]. [cit. 2019-04-03]. Available from: http://www.caremissionstestingfacts.eu/nedc-how-do-lab-tests-work/

[19] BARRIEU, Edouard. EHRS Impact on Engine Warm up and Fuel Economy. *Energy.gov* [online]. [cit. 2019-05-15]. Available from: https://www.energy.gov/sites/prod/files/2014/03/f8/deer11_barrieu.pdf

[20] Diehl, P., Haubner, F., Klopstein, S., and Koch, F., "Exhaust Heat Recovery System for Modern Cars," SAE Technical Paper 2001-01-1020, 2001, https://doi.org/10.4271/2001-01-1020.

[21] JANKOWSKI, Nicholas R. *A review of phase change materials for vehicle component thermal buffering* [online]. [cit. 2019-05-15]. Available from: https://wiki.aalto.fi/download/attachments/91692283/a_review_of_phase_change_materials_for_vehicle_component_thermal_buffering.pdf?version=1&modificationDate=1398448565850&api=v2

[22] CROSSE, Jesse. JLR-led project to recover waste exhaust heat for 5% economy boost. *Autocar* [online]. 19 December 2017 [cit. 2019-04-03]. Available from: https://www.autocar.co.uk/car-news/design/jlr-led-project-recover-waste-exhaust-heat-5-economy-boost

[23] *GT-SUITE – A Revolutionary MBSE Tool* [online]. [cit. 2019-04-03]. Available from: https://www.gtisoft.com/

[24] Types of Electric Vehicles – Do You Know Them All?. *Škoda* [online]. 21.3.2019 [cit. 2019-05-15]. Available from: https://www.skoda-storyboard.com/en/innovation/mobility/types-of-electric-vehicles-do-you-know-them-all/

[25] Understanding micro, mild, full and plug-in hybrid electric vehicles. *X-engineer* [online]. [cit. 2019-05-15]. Available from: https://x-engineer.org/automotive-engineering/vehicle/hybrid/micro-mild-full-hybrid-electric-vehicle/

[26] Brake energy recuperation strategy systems. *AutomotiveIQ* [online]. [cit. 2019-05-15]. Available from: https://automotiveiq.wordpress.com/2011/03/31/brake-energy-recuperation-strategy-systems/

[27] STOBART, R.K., 2007. An availability approach to thermal energy recovery in vehicles. Proceedings of the Institution of Mechanica lEngineers, Part D: Journal of Automobile Engineering, 22 1(9), pp.1107-1124

[28] *PriusChat* [online]. [cit. 2019-05-19]. Available from: https://attachments.priuschat.com/attachment-files/2015/05/74972_1nzfe9.pdf

[29] GAMMA TECHNOLOGIES. *GT-SUITE: GT-SUITE Cooling Thermal Management* [user manual], v. 2016

[30] GAMMA TECHNOLOGIES. *GT-SUITE: GT-SUITE Aftertreatment* [user manual], v. 2016

[31] What Is a Diesel Oxidation Catalyst?. *NETT Technologies* [online]. [cit. 2019-05-23]. Available from: https://www.nettinc.com/information/emissions-faq/what-is-a-diesel-oxidation-catalyst

ABBREVIATIONS AND SYMBOLS

3D	[-]	3 dimensional
AC	[-]	Air conditioning
BMEP	[-]	Break mean effective pressure
BMS	[-]	Building management system
BSFC	[g/kWh]	Break specific fuel consumption
BSG	[-]	Belted starter-generator
CAE	[-]	Computer
CFD	[-]	Computer
CD	[-]	Charge sustaining
CS	[-]	Charge depleting
CO	[-]	Carbon oxide
CO_2	[-]	Carbon dioxide
DOC	[-]	Diesel oxidation catalyst
DOD	[-]	Depth of discharge
DPF	[-]	Diesel particulate filter
ECE	[-]	United nations economic commission for Europe
ECM	[-]	Engine control module
ECU	[-]	Electronic control unit
EGR	[-]	Exhaust gas recirculation
EHRS	[-]	Exhaust heat recovery system
ETMU	[-]	Exhaust thermal management unit
EU	[-]	European union
EUDC	[-]	Extra-urban driving cycle
EV	[-]	Electric vehicle
FEA	[-]	Finite element analysis
FMEP	[-]	Friction mean effective pressure
H_2O	[-]	Dihydrogen monoxide
HC	[-]	Hydrocarbons
HSU	[-]	Heat storage unit
ICE	[-]	Internal combustion engine
IMEP	[-]	Indicated mean effective pressure
LPG	[-]	Liquid petroleum gas
N2	[-]	Nitrogen

PCM	[-]	Phase-change material
PHEV	[-]	Plug-in hybrid electric vehicle
PM	[-]	Particulate matter
QS	[-]	Quasi-steady
RDE	[-]	Real drive emission
RLT	[-]	Reformulation linearization technique
RPM	[-]	Revolutions per minute
RTD	[-]	Rear traction drive
SOC	[-]	State of charge
TEG	[-]	Thermoelectric generator
THC	[-]	Total hydrocarbons
TWC	[-]	Three-way catalytic converters
UF	[-]	Utility factor
WLTC	[-]	Worldwide harmonized light vehicle test cycle
WLTP	[-]	Worldwide harmonized light vehicle test procedure
WVTA	[-]	World vehicle type approval

LIST OF ATTACHMENTS

Attachment 1 – CD with model results

- Model of default diesel vehicle
- Model of diesel vehicle with HSU in cooling circuit
- Model of diesel vehicle with HSU in oil circuit
- Model of diesel vehicle with EHRS
- Model of diesel vehicle with Combo
- Model of diesel vehicle with ETMU
- Model of default hybrid vehicle
- Model of default hybrid vehicle
- Model of hybrid vehicle with HSU engine initiation in cooling circuit
- Model of hybrid vehicle with HSU SOC=0.25 initiation in cooling circuit
- Model of hybrid vehicle with HSU SOC=0.26 initiation in cooling circuit
- Model of hybrid vehicle with HSU engine initiation in oil circuit
- Model of hybrid vehicle with HSU SOC=0.25 initiation in oil circuit
- Model of hybrid vehicle with HSU SOC=0.26 initiation in oil circuit
- Model of hybrid vehicle with EHRS
- Model of hybrid vehicle with Combo
- Model of hybrid vehicle with ETMU engine initiation
- Model of hybrid vehicle with ETMU SOC=0.25 initiation
- Model of hybrid vehicle with ETMU SOC=0.26 initiation