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FUEREX

Multi-fuel Range Extender with high efficiency and ultra low emissions

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Contents

List - Tables

List of Figures

1 Project context and main Objectives

1.1 Overall project objectives

The FUEREX project takes on the challenge of simultaneously meeting the tough efficiency, emission, noise vibration and harshness (NVH), integration and cost requirements for a range extender. Each of the requirements can be met separately, but the main challenge lies in meeting them all at the same time - and - at a low enough cost to be a competitive solution for the customer demands.

Further, the FUEREX project takes on the challenge to find solutions for both short and the long term that have large impact in terms of volume (market segments and number of vehicles) and ecological footprint (bio fuel compatibility, reduced (CO_2) emissions, well to wheel efficiency, *etc.*).

The **CONCEPT** of the FUEREX project is based upon:

- **Compact spark-ignition engines** as this type of engines have the largest potential to meet the customer duty requirements in terms of efficiency, NVH, fuel types, exhaust emissions, dimensions, weight and costs. Three types of spark ignition engines will be studied, representing different solutions for low cost Range Extenders and applicable for sub compact passenger cars up to light duty commercial vehicles :
    a) An innovative rotary engine concept (AVL) with the largest potential in the long term (2020+), especially regarding low specific weight, small dimensions, low NVH and low specific mass production costs potential (low number of parts).

       This engine concept fits to the demands for high volume production, especially applicable for compact size and medium size vehicles.
    b) A 3 cylinder piston engine (AVL Schrick) already developed for range extender purpose with potential in the short term (2015+) especially for compact size and medium size vehicles.
    c) A 2 cylinder piston engine (CRF) that will be adapted to range extender purpose and CNG (Compressed Natural Gas) with potential application on Light Commercial Vehicles in the short term (2015+).

- **Multifuel capability and flexibility.** All engine types will be optimized for at least one type of biofuel (bio ethanol, biomethane), at least one type of regular fuel (petrol, CNG). The possibility to switch between bio and regular fuel will also be assessed for each engine type (multifuel flexibility);
- **Vehicle integration** of the range extenders in vehicles **with state of the art battery packs** (e.g. Li-ion, nickel metal hydrids). Complete vehicle integration will be developed with special attention to the difficult NVH issues.
- **Demonstration** of the **integrated technology at a realistic scale** (3 type of test vehicles, 2 compact passenger cars and 1 light transport, performance tests).

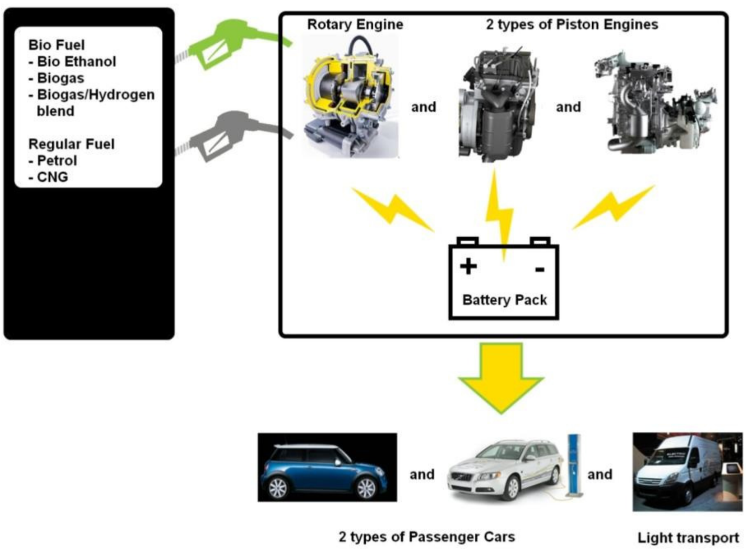


Figure 1 - Overall concept of the FUEREX project

The targeted final result of the FUEREX project is to prove the feasibility of the range extender technology for the markets for sub-compact passenger cars up to light duty commercial vehicles.

1.2 Objectives for WP 2 – System definition

- To define requirements on vehicle level both for performance and for vehicle integration. These will be used in WP 7 for studying the optimal size of the range extender, for defining optimal control and for defining driving cycles suitable for evaluation and optimization.
- To define requirements and targets for the range extender as well as methods to evaluate the concepts. These requirements will be used in WP 3-7.
- To define requirements for the vehicle integration of the range extender.

1.3 Objectives for WP 3 - Three cylinder Range Extender engine

This WP is based on WP2 requirements and targets for the range extender and the existing state of the art for 3-cylinder RE engines. It aims at RTD for multi-fuel operation, optimised fuel efficiency, multi-mode operation and ultra-low emissions:

1. Develop and optimise and 3-cylinder reciprocating piston engine for bio methanol and bio-ethanol and petrol as backup fuel with high efficiency.
2. Develop exhaust gas after treatment technologies for the specific demands of range extender operation to achieve <50% of EU6 emission levels.
3. Evaluate mechanical and thermal output as basis for the optimisation of the FUEREX CO_2 demand at customer duty.
4. Define and verify optimum operating strategies at customer duty. Customer duty specification will be carried over from WP2.

1.4 Objectives for WP 4 – Rotary engine

This WP is based on WP2 requirements and targets for the range extender and the existing state of the art for Rotary Engine RE. It aims at RTD for multi-fuel operation and overall enhanced operating strategies for multi-mode operation.

1. Develop and optimise rotary piston engine layout (thermodynamic concept, e.g injection and ignition timing and port geometry) bio ethanol and petrol as backup fuel.
2. Develop and optimise multimode operation. Three operating modes shall be considered, which can be characterised as follows: (A) base load to cover electrical power demand and heat demand for pure comfort functions. (e.g. to power the A/C compressor during vehicle standstill, or to provide a heat source for heat-up of the vehicle compartment during standstill); (B) medium load to provide electrical power demand and heat demand in NVH sensitive driving conditions (e.g. at low vehicle speeds) and (C)high load to cover the electrical power demand at extra urban travel.
3. Develop exhaust gas after treatment technologies for the specific demands of range extender operation to achieve <50% of EU6 emission levels.
4. Evaluate mechanical and thermal output as basis for the optimisation of the FUEREX CO_2 demand at customer duty.
5. Define and verify optimum operating strategies at customer duty (i.e OEM). Customer duty specification will be carried over from WP2.

1.5 Objectives for WP 5 – Two cylinder engine for light Commercial vehicle RE

The target of WP5 is the development of an environmental friendly powertrain based on a new CNG (Compressed Natural Gas) combustion engine to be integrated on Range Extender applications for Light Commercial Vehicles.

1. Definition of the subsystems specifications;
2. Development of the dedicated version of the NG two cylinders engine;
3. Development of the electric driveline;
4. Vehicle build up and RE unit integration;
5. Global assessment of the system on the validator vehicle.

1.6 Objectives for WP 6 – System integration

Main objective of this work package is to define, design and develop the necessary software/hardware interfaces and functionalities to be able to integrate the subcomponents into the Range-Extender-Concept and furthermore, to integrate the Range-Extender into the surrounding of a (demonstrator) vehicle. Key performance indicators of the concepts can be quantitatively assessed only, if complete vehicle dynamics is taken into consideration. This includes the specification of the battery system, possible strategies of customer usage, derating, diagnosis features and limp-home functionalities.

1. Definition of E-Machine layout and link to crankshaft for all three types of ICE
2. Definition of Power-Electronics features (rectifier), and design of electrical circuit, housing, cooling mechanisms and electrical/mechanical interfaces
3. Definition of control strategies for ICE with respect to battery requirements, thermal requirements, emission requirements, safety requirements and charging requirements with respect to vehicle dynamics.
4. Definition of operation strategies for whole Range-Extender-System
5. Integration of SW and HW into system, elaborating calibration guidelines

operation strategy RE

1.7 Objectives for WP 7 – Vehicle level studies

The main objective of WP7 is to use the actual performance of the Range extenders to determine how they should be controlled and how they will perform in different type of use.
The theoretical evaluation of the RE's will be an important complement to the vehicle tests as it is far too time consuming and costly to evaluate the performance during different type of driving by driving the vehicle several 100'000 km, while it is fairly easy to do it with simulations. Another result of WP7 will also be load cycles for the range extenders which will be useful as input for the design of Range extenders.
Finally results of WP7 will also be an important output of the project, as the methods used is useful for OEMs when optimizing range extender spec's for different vehicles they design.

The main parts of this work package are:

1. Creating improved driving cycles which take into account how electric vehicles with range extenders are used, including charging patterns and cold starts of Range extender. This include proposal for what type of driving cycles are suitable for future standards for fuel consumption and emission certification of range extender battery electric vehicles and discuss why these should differ from today's standard driving cycles.
2. Define optimized control strategies of how and when to use the range extender taking into account cold start, charging patterns and thermal management. Also the optimum size of the range extender will be analysed at the same time. The optimal sizing of the range extender and battery will be investigated regarding key properties like fuel consumption, all electric range, cost and weight.
3. Comparing the three range extender concepts and describe the vehicle performance, emission levels

and fuel consumption when they are used in the specified driving cycles. Since the three Range extenders are not designed for the same type of vehicles, the comparison does not aim to nominate a “winner”, but is intended to show how they can be expected to perform in their different vehicles and to illustrate that different use play an important role in the requirements on the range extender as well as how it perform.

1.8 Objectives for WP 8 – Dissemination and exploitation

Objectives for the whole duration of the project:

1. To maximise the dissemination of results and to express them in terms that are readily understandable to stakeholders (e.g. governments, industry and suppliers) in order to accelerate the implementation of the research findings.
2. To promote the dissemination of the project findings through presentations at the project workshops, scientific publications and preparing information for the project website.
3. To facilitate technology transfer and accelerate dissemination of on-going research activities.
4. To achieve an optimum knowledge management including appropriate handling of IPR’s; implementation and exploitation of the obtained results;

2 Main Science & Technological results and Foreground

This chapter describes the main Science and Technological results and foreground generated for each work package.

2.1 WP 2 – System definition

In *"Task 2.1 – Define requirements on vehicle level"* a method to describe the performance requirements for an electric power train has been defined. The method is based on describing the normalized net force which the power train shall be able to produce. By normalizing the force, by dividing it with the effective vehicle mass, values be compared between vehicles despite differences in size of the vehicle and yet show the performance experienced by the driver. The net force produced by the power train means the force the power train can produce in a certain speed minus the drag forces of the target vehicle when driving on a flat road (no gradients). The net force will thus correspond to the force which can be used by the driver to either accelerate the vehicle and to climb gradients. As a result the requirements expressed in normalized net force will directly show acceleration capability and gradient capability for the vehicle regardless of its size and its aero dynamic properties.

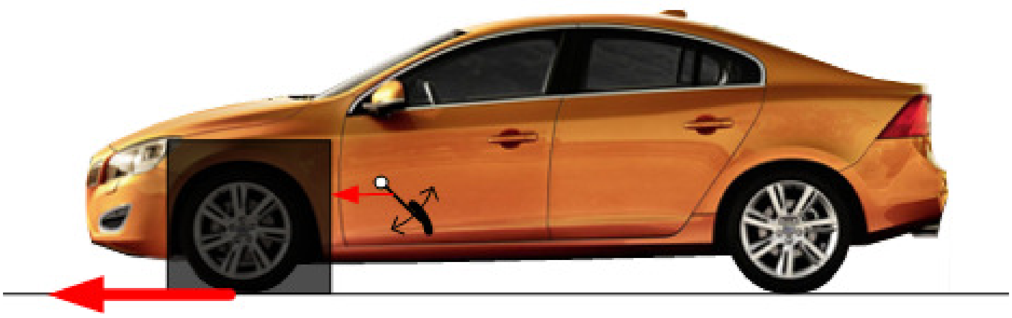


Figure 2 - From a driver perspective a drive line is preferably analysed as a black box producing longitudinal force on the vehicle.

Performance requirement can be expressed in many different ways, often by describing different driving scenarios and how the vehicle has to perform in that particular scenario. However, this type of scenarios normally does not describe all possible operating points of the power train, and therefore it is beneficial to have a way of describing the performance in all possible operating points. Also different scenarios can sometimes lead to conflicting requirements on the power train, where it is often not easy to say which requirement is the hardest, and thus it is often difficult to use these scenario based requirements in the design of a power train. Instead the performance requirements in the FUEREX project are adapted to the typical performance characteristics of an electric drive line. Thus it is possible to describe the full performance of the power train in a very short form, yet capable of including the steady state capability of the drive line in all possible situations. As a result the performance requirements can be expressed using only four main parameters.

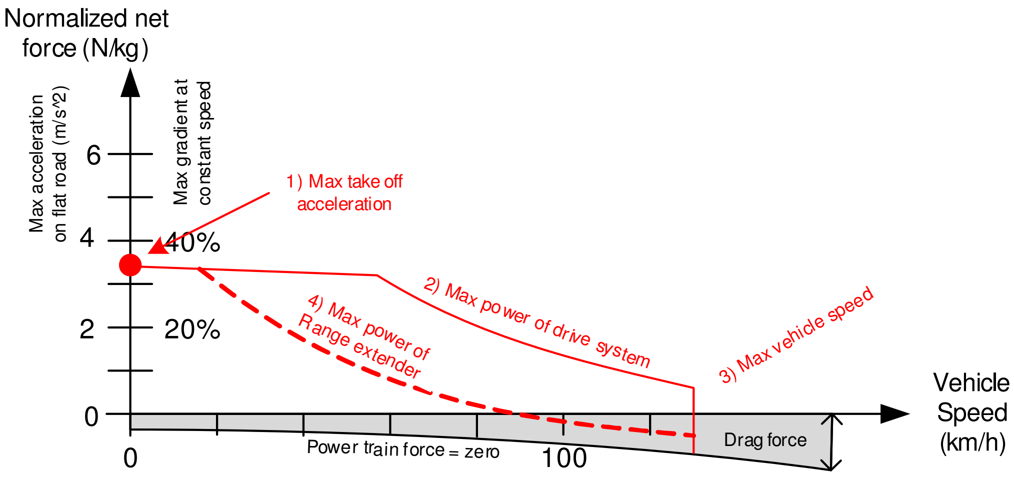


Figure 3 - The four performance parameters used in the FUEREX project.

Together with Volvo, AVL-Graz and Altra the performance requirements for the three demonstration vehicles have all been expressed in the format defined. The result reveals that there are important differences between the requirements for the three vehicle types which will influence the requirements on the range extender and how it will be used.

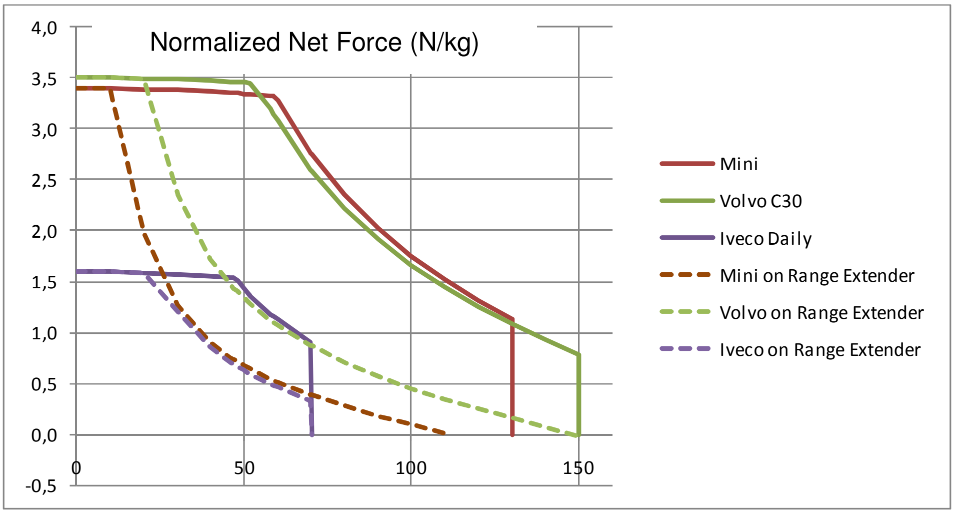


Figure 4 - The Required net normalized force for the three Vehicle speed (km/h)

The results of task 2.1 has been reported in deliverable D2.1 and D2.2.

In *"Task 2.2 – Define requirements on vehicle integration"* the vehicle integration requirements for the demonstration vehicles have been defined. The integration requirements cover mechanical, electrical as well as functional integration.

Based on the requirements from Volvo and Altra, Bosch have proposed a specification for how integration can be made. These specifications have been reviewed by Volvo and Altra and a first version has been approved. The final version will be released when the demonstration vehicles have been built, as minor changes and additional challenges are expected to be found during the build and initial tests of the demonstration vehicles.

In *"Task 2.3 – Define range extender requirements and comparison method"* the project partners have discussed and agreed on a method to evaluate the range extenders regarding their key performance measures. The evaluation include

- Fuel efficiency (by bench tests and simulated cycles)
- Emissions (by bench tests and simulated cycles)
- Noise (internal and external measurements on the demonstration vehicles.)
- Vibration (mainly from subjective evaluation of NVH experts)
- Cost and service life (through production analysis and analysis of design specification)

It is not possible to determine analytically which the most optimal solution is and which vehicle concepts will eventually win on tomorrow's market as the requirements on the range extender are very different depending on which market niche the vehicle is targeted for. Therefore the FUEREX consortium has decided to design the range extenders for three different vehicle types:

- City oriented passenger car, a Mini
- General purpose passenger car, a Volvo C30
- Light distribution vehicle, an Iveco Daily.

By this approach more knowledge is gained than if all three range extenders were to be designed for and evaluated for the same vehicle type.

Table 1 - Summary of the requirements for the three FUEREX range extenders

Requirement	Rotary piston engine	3 cylinder engine	2 cylinder natural gas engine
Maximum electrical power output	15 kW	35 kW	30 kW
Running hours (service life, B10)	800 h*	1200 h*	800 h*
Fuel efficiency	260 g/kWh	240 g/kWh	220 g/kWh
CO2 emissions	810 g/kWh	748 g/kWh	605 g/kWh
Nitrogen oxides (NOx)	0.030	0.030	0.040
Total hydrocarbon (THC)	0.050	0.050	0.100
Non-methane hydrocarbons(NMHC)	0.040	0.040	0.035
Carbon monoxide (CO)	0.500	0.500	1.100
Particulate matter (PM)	0.003	0.003	n.a.
Noise at 2 meters distance with the range extender running at full power.	< 65 dBA	< 65 dBA	< 65 dBA
Vibrations (mounted in vehicle)	Not recognized by the driver	Not recognized by the driver	Not recognized by the driver
Cost (in high volume production)	< 1,500 €	< 2,800 €	< 2,500 €

*) Preliminary targets, to be further investigated in work package 7.

The results of task 2.3 have been reported in deliverable D2.2.

2.1.1 Main results

The main results from the WP are listed below:

- A method to define performance requirements of an electric drive line in a way which allows simple comparison for vehicle performance from driver perspective.
- Performance requirements for the three target vehicles for the range extenders.
- Vehicle integration requirements documented in the specifications for the range extenders of the demonstration vehicles.
- Defined method to analyse and evaluate the range extenders.

2.2 WP3 – 3-cylinder Range Extender for all-purpose vehicles

2.2.1 Introduction

The objective of FUEREX WP3 was to develop and evaluate a 3 cylinder piston engine for range extender purpose with potential in the short term (2015+) especially for compact size and medium size all-purpose vehicles. AVL Schrick designed, provided hardware and assembled samples of the 3-cylinder combustion engine. The combustion system for multi fuels with optimized fuel consumption and a new cold start strategy was developed on an engine test bench. The engine is combined with generator, inverter and control system developed in WP6 by Bosch by an all new belt drive system.

AVL Schrick investigated the efficiency of the complete REX unit and the properties of the new drive system. The Range Extender emission development and calibration has been performed in cooperation with Chalmers University. The complete REX system is installed into a Volvo C30 electric vehicle by VCC in WP6.

2.2.2 Range extender package concept in the vehicle as basis for the 3-cylinder combustion engine design and development

Due to the additional systems which are present in a Range Extender Vehicle there are special requirements on the package of the car. In the former front engine bay the electrical drive motor is installed with drive shafts to both front wheels. Furthermore the inverter of the electrical AC motor and parts of the complex thermal management system like radiators and heaters are installed there.

The high voltage battery is installed in the center tunnel of the car. The pure electric Volvo C30 electric vehicle has a second battery of the same size under the rear end of the car.

In that position a sub frame including the Range Extender unit (combustion engine, generator and inverter) is installed with electrical connection to the high voltage battery and the control units. The small installation space of the FUEREX unit requires an extreme compact package of the engine and connection to the generator.

In all known range extender configurations which have already gone into hardware the generator is connected directly to the crankshaft of the combustion engine. In the FUEREX program an all new design has been used with the generator located parallel to the crankshaft. The transmission of the mechanical energy is done by a drive belt.

This configuration has been selected due to the following two main advantages:

- Very compact design (lower cubic capacity than standard installation)
- Freedom of generator positioning according to the package
- With an optimized gear ratio both, the combustion engine and the generator can be operated in their best efficiency range
-

To generate an optimum package situation, the engine has been inclined to an almost horizontal position. The following picture shows the integration of the FUEREX unit in the Volvo vehicle.

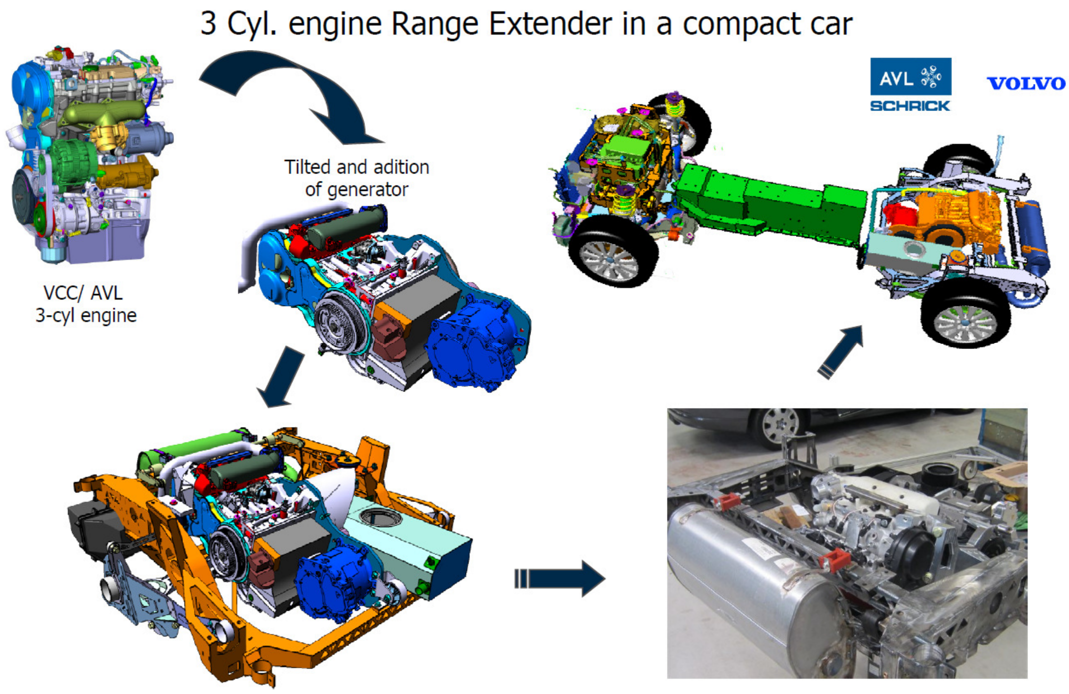


Figure 5 - Integration of the FUEREX 3-cylinder engine in the vehicle

2.2.3 3-cylinder combustion engine design

The chosen engine for the prototype is a three cylinder engine. It has been designed as a variant of an existing state-of-the art inline four cylinder engine for standard powertrains, which have a direct connection to the wheels through a gearbox.

The new design features are related to the optimization for the very narrow operational window of the range extender and for the use of liquid bio fuels (bio ethanol). All engine technologies required for achieving lowest fuel consumption in standard powertrains are questioned and deleted if possible without compromising fuel consumption and emissions in REX operation. This enables a dedicated Range Extender Engine - striped to the bone – which can be produced on an existing production line for much lower costs than the engine for standard powertrain on which it is based on.

Item	Reference engine	FUEREX	note
No. of cyl.	4	3	
Bore x stroke		82mm x 85mm	
Capacity	2.0 L	1.35 L	
Valves / cyl.	4V	4V	Valves and drive completely carry over
Cam timing	Dual VVT	fixed	No VVT required for little operation range
Camshaft drive	Belt drive	Belt drive	valve drive completely carry over
Intake ports	High Tumble for T-GDI	Adapted high Tumble	Ports adapted to incorporate port fuel injection
Exhaust ports	High Flow	High flow	Exhaust ports completely carry over
Combustion chamber	Pentroof in head for TGDI, piston bowl for cold start	Pentroof in head for TGDI, piston dome	Combustion chamber in head carry over, Piston bowl not required because no DI, Piston dome to adjust compression ratio
Turbocharging	yes	no	T/C not suitable for lowest FC
Direct injection	yes	no	DI not required for low F/C results with Miller / Atkinson

Water pump	electric	electric	Water pump completely carry over
Oil pump	Flow controlled, variable pressure	Standard G-rotor design	Friction reduction effect of variable pump is low in REX operation conditions
Mass balancing	2 shafts compensating 2nd order mass forces	1 shaft compensating 1st order mass moment	

Figure 6: Specification of the main engine systems

The cylinder block has been shortened by one cylinder. Packaging for the three cylinder engine has been made to determine which bosses need to be moved to which cylinder to enable all mounting and engine internal functionalities. In order to generate a good NVH behavior, the three cylinder engine is equipped with a new designed balancer shaft. This balancer shaft module is mounted to the engine in the same way as the four cylinder balancer on the four cylinder engine. This allows using the same assembly line for this engine, thus creating a cost efficient approach.

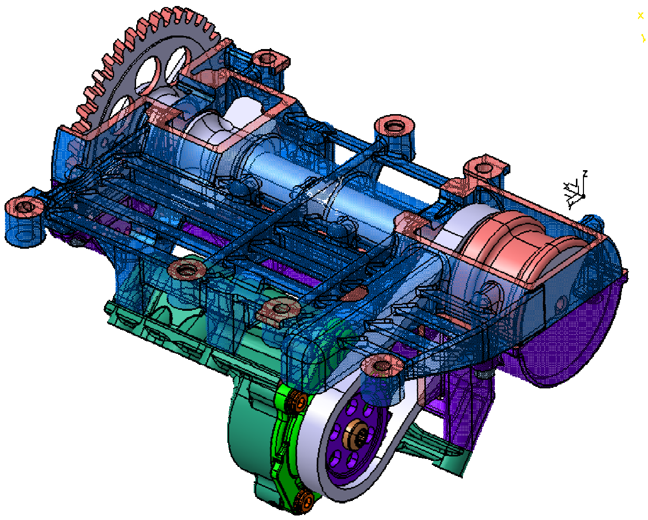


Figure 7: 3-cylinder balancer module with balancer shaft, oil pump, transmission and housing, driven by gear on timing drive side of the crankshaft

To generate a good package situation, the engine has been inclined to an almost horizontal position. The oil system for this engine has been adjusted to the new engine orientation. It was possible to create a good oil supply with a wet sump system. This system is less cost intensive than a dry sump system but still allows big accelerations in all directions.

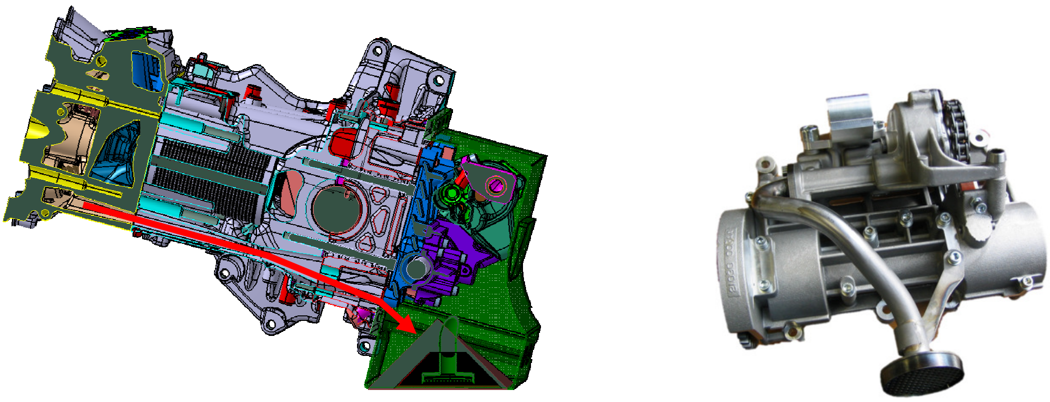


Figure 8: Oil return path of inclined engine with "oil pyramid" in tilted condition - balancer shaft / oilpump module prototype

During the mechanical development improvements have been made on the engine hardware for friction reduction and functional improvement of the oil and cooling system:

- Additional oil drain passages in the cylinder head
- Implementation of an oil separator to reduce the oil content in the Blow-by gas

- Reduction of the oilpump size and oil pressure for reduced friction.

Due to the fact that the engine derived from a turbocharged engine, a new gas exchange system is required. Intake and exhaust system are very compact due to the package limitations.

Of course all standard engine components which could be used from the existing four cylinder engine are re-used to keep the prototype engine costs acceptable and demonstrate that even with a high rate of carry-over parts such good results can be achieved.

2.2.4 Combustion system for multi fuels with optimized fuel consumption

The engine size and combustion system concept selection shows that the use of a relative large (compared to other demonstrated concepts) 1,35L engine based on a state-of-the art TGDI engine has significant benefits:

- **The intake and exhaust** ports and combustion chamber of all state-of-the-art TGDI engines like the reference engine are designed in such way that high Tumble air charge motion is established creating a stable combustion process. As a results knock sensitivity is low and high compression ratio can be tolerated resulting in good efficiency
- A 3 cylinder with 1.35L capacity is enabling 35kW power already at very moderate engine speed.
- All gasoline engines achieve the lowest fuel consumption in the speed range of 2000 – 3000 rpm. The speed range is selected in a way that it covers the range of the best fuel consumption with just little deterioration at low or peak power.
- In the standard approach for naturally aspirated engines in standard powertrains the air charge system and cam timing are designed for highest possible volumetric efficiency, but knock limitation sets limits to the compression ratio and thus the thermodynamic efficiency. The solution is the selection of an alternative combustion system, which could be the Atkinson cycle or the Miller cycle.
- Due to high torque and power the reference baseline 2.0L TGDI engine is built in a much more robust way than required for the REX causing much higher friction than a dedicated all-new engine. Nevertheless fuel consumption deterioration is much less than the fuel consumption benefit of combined approach of right-sizing, optimized engine speed and Atkinson / Miller-cycle combustion system.

For both Atkinson and Miller cycle new cam profiles have been specified and investigated by 1D air charge simulation.

The Miller Cycle (early intake valve closing before BDC) and the Atkinson cycle (late Intake valve closing after BDC) both reduce the volumetric efficiency and thus the knock sensitivity. 1D air charge simulation results show that both enable to increase the compression ratio from 10.5 to 12.5 resulting in reduced fuel consumption compared to the standard approach.

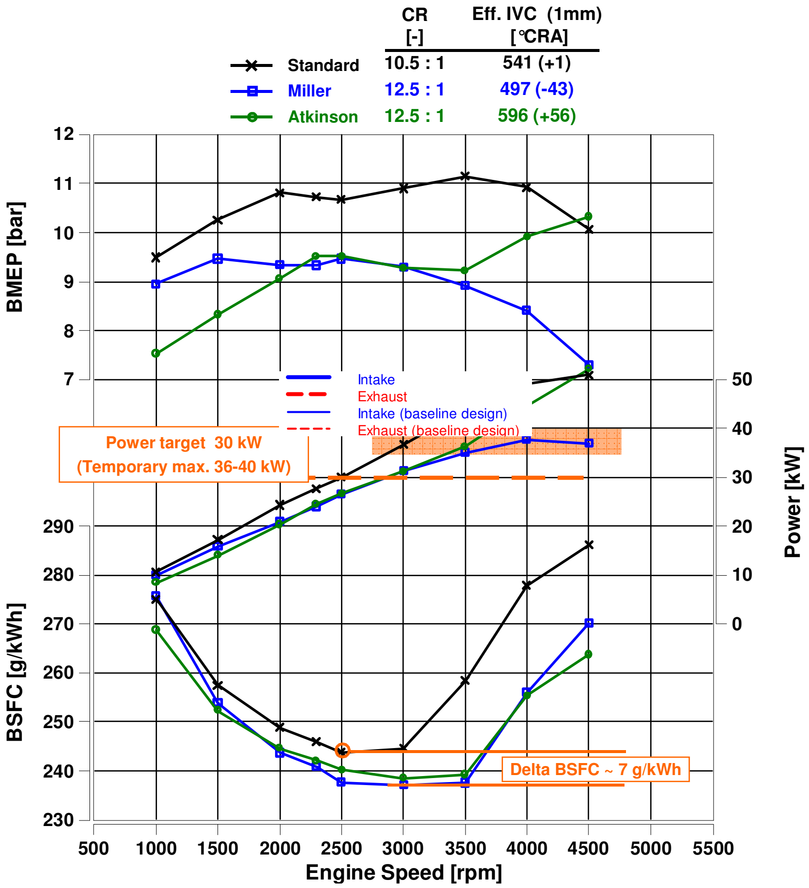


Figure 9: 1D air charge simulation of conventional, Miller and Atkinson cycle

The valve drive of the reference engine with flat tappets is limiting the power of the Miller cycle. Just very small valve lift can be achieved for typical Miller event length due to limitation in valve deceleration, cam tip radius and local contact pressure. For future applications roller finger follower valve drives with a radius contact on the cam follower should be selected. They enable much higher deceleration and thus a significantly higher valve lift.

New intake ports are based on general port shape (angles, orientation, valve and port size) from the TGDI reference engine, but siamesed (the intake channels from both intake valves join already in the cylinder head). The focus is still on high air charge motion due to lowest knock sensitivity for using high compression ratio and high thermodynamic efficiency. This is done by a straight, flat inlet port with a separation edge to focus the flow to the upper port area and generate a high tumble motion.

The optimized Miller cycle version achieves a power peak of 35kW close to 4000 rpm, 40 kW cannot be reached. The fuel consumption optimum is 230 g/kWh. The program target of 240 g/kWh is overachieved in a range from 2000 to 4000 1/min WOT which means between 20kW and 35kW. The torque characteristic with higher low end torque requires throttling the engine below 3000 rpm in order to achieve the optimum fuel consumption.

The test results with Atkinson cycle match perfectly with the simulation results. A very flat torque curve with peak power of 35kW at 3500 rpm was achieved, 40 kW at 4000 rpm can also be realized. Due to the low volumetric efficiency at low engine speed the engine is only slightly knock limited and fuel consumption along the full load curve is very low with a minimum of 233 g/kWh. The program target of 240 g/kWh is overachieved in a wide range from 1600 – 4000 1/min which also means between 15kW and 40kW power.

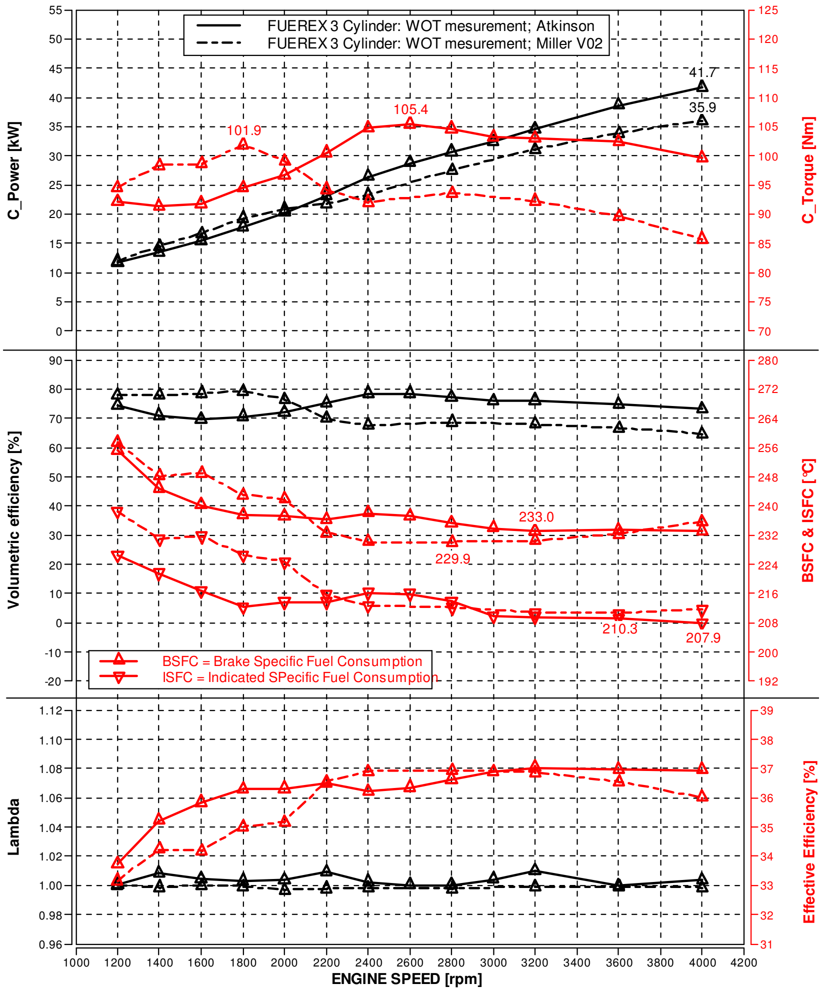


Figure 10: Comparison of Miller cycle and Atkinson cycle at WOT

The effective engine efficiency of both combustion systems versions is 37%. Due to the higher peak power and the wider range of low fuel consumption the Atkinson cycle combustion system is the slightly better choice. The Fuerex engine has been developed for full bio-Ethanol E85 capability. Due to its reduced knock sensitivity the effective engine efficiency is further improved to slightly more than 37% in a very wide operation range. The fuel consumption optimum of 334 g/kWh is related to the lower heating value of the E85 fuel of 29.2 MJ/kg.

The compression ratio has been developed to an optimum of 12.5 for RON95 gasoline. Bio-ethanol E85 would enable to further increase the compression ratio and reduce fuel consumption, but deficits in HC emissions are expected and RON95 fuel consumption would suffer severely from such a measure. In addition the expected main fuel for this REX application is still RON95.

2.2.5 Emission reduction concept – new cold start strategy

During that combustion development it has already been considered that high Tumble air charge motion which creates a stable combustion process with reduced knock sensitivity also improves the cold start emission capability. With both alternative combustion systems, the Miller Cycle (early intake valve closing before BDC) and the Atkinson cycle (late Intake valve closing after BDC) the demanding fuel consumption targets are met, so both shall also be investigated concerning their emission capability.

For low emissions of gasoline engines a fast catalyst light-off is mandatory. After the light-off the tailpipe emissions are close to zero because the catalyst efficiency is very close to 100% during Lambda 1 operation with a 3-way catalyst. The contribution of the emissions after heat-up to the whole cycle emissions is low. In order to reduce accumulated emissions before catalyst light-off the time must be reduced to a minimum by maximised heat flux into the exhaust and the HC (which is the most critical emission) flow must be minimised. CO and NOx emissions are typically far below the given limits. They are evaluated as well but they are not the driver for the new strategy. Particulate emissions are also limited for Euro6, but just for engines with gasoline direct injection. The chosen 3-cylinder engine with minimized cost and thus technology content is using port fuel injection, which is not limited concerning PM emissions because this type of engines generally shows much lower particulate emissions.

Based on long term experience and correlation with **CSWUP** (**C**old **S**tart **W**arm **UP**) tests AVL developed a steady state test which enables continuous testing of catalyst heating operation condition without stops and cool down phases. For this **CHEOPS** (**C**atalyst **HE**ating **O**perating **P**oint **S**teady state) test an exhaust heat flux vs. HC flow target range is defined. Most of the typical operation conditions for catalyst heating of a standard powertrain can be carried over:

- Lambda: 1,0 ... 1.1 (the optimum is depending on the combustion system)
- Ignition timing: retarded as much as possible, limited by the combustion stability
- Temperature: coolant forced cooled and stabilized to a level below 30°C

The range extender operation enables additional degrees of freedom at cold start operation. Due to the presence of the generator there is nearly no limitation of engine speed and load. The engine speed is tested in the range of 1200-2400 rpm whereas in standard powertrains the driver NVH expectation limit the engine speed to 1200 ±100 1/min. The engine load is not limited at all and has been investigated in a wide range during the catalyst heating investigations. For standard powertrains the CHEOPS test is always operated at 1 bar BMEP, simulating idle with no load as in the in the first seconds of the NEDC cycle. Due to higher friction at a real cold start compared to steady state forced cooled conditions the load is increased from 0 to 1 bar.

Early tests of ignition timing loops at different Lambda and load show similar results as known form engines for standard powertrains:

- The HC-flow shows its minimum with maximum ignition timing retardation.
- The heat flux shows its maximum with maximum ignition timing retardation due to highest exhaust mass flow and exhaust temperature
- The combustion stability is deteriorating with ignition timing retard.
- The NOx emissions show two maxima on each curve when spark is maximum advanced and maximum retarded.
- Increased engine speed improves HC mass flow and heat flux.

Due to the new Fuerex engine design and potential operation modes the following new results could be obtained:

The **Atkinson cycle** and the **Miller cycle** show very similar behavior but for the first one the results are better: under identical conditions there are more operation points in the CHEOPS target corridor, even down to 1400 1/min which was not possible with the Miller cycle. The achievable heat flux is also on a higher level

With **increased engine load** the heat flux can be increased to nearly twice the level at similar HC flow level compared to the previous tests with standard load of 1 bar BMEP. This will improve the catalyst light-off time, but the NOx level has increased to three times higher values. In standard powertrain application the focus is mainly on HC emissions, but when running at higher load also NOx must be considered in more details.

A complete BMEP / spark advance map has been investigated with one of the improved injectors. The lowest HC emissions have been achieved with maximum retarded ignition timing. Increased BMEP does improve the heat flux, but the HC flow is worse. When comparing operation points with identical air mass flow, such as on the WOT line, it is obvious that the lowest load on this line which requires the maximum spark retard achieves the highest heat flux.

Injectors with improved targeting (no. 2 and 3) could reduce the THC emissions by 50% and improve combustion stability.

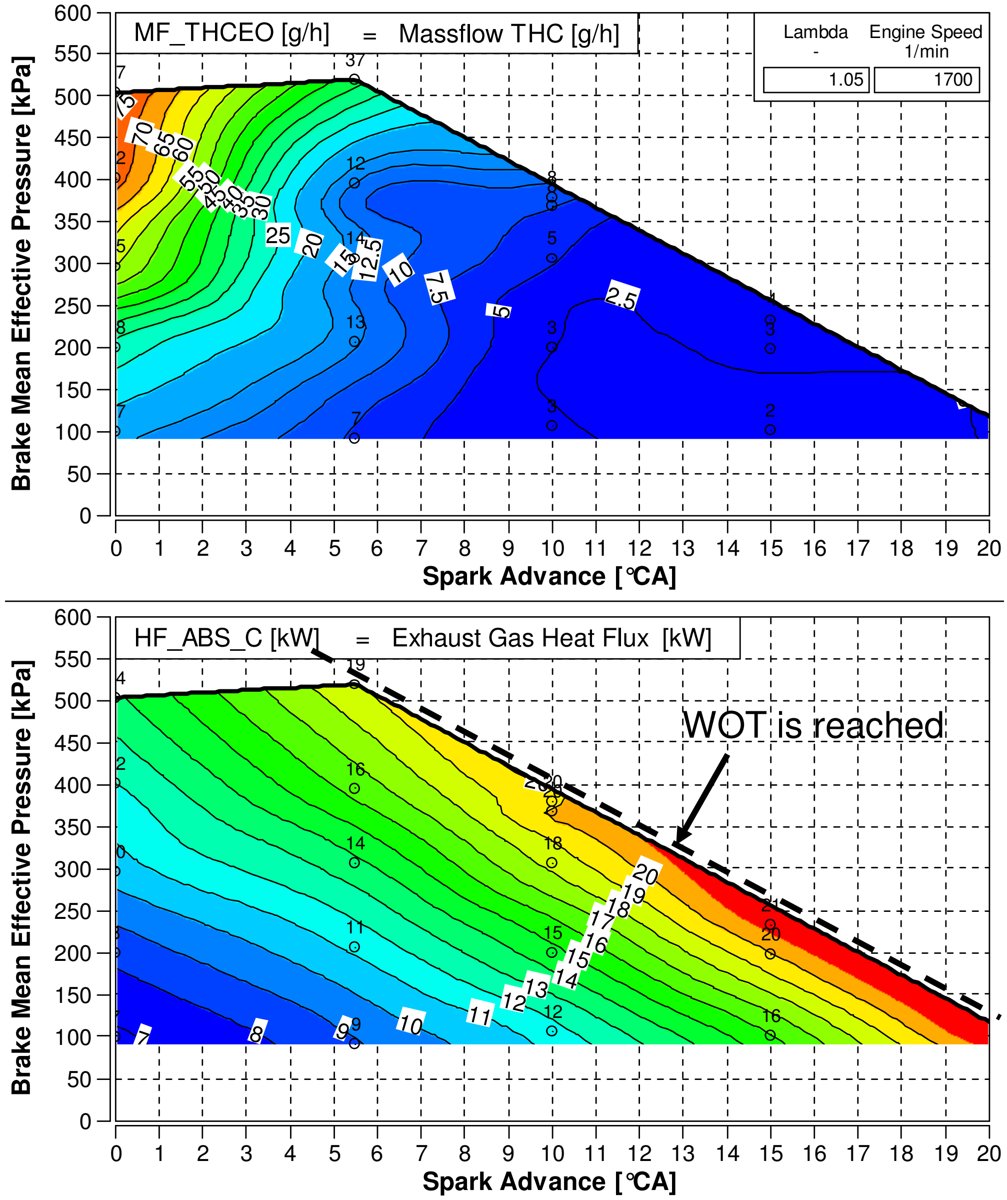


Figure 11: THC mass flow and heat flux map at 1700 1/min

For the selection of the best operation points all CHEOPS measurements are taken into account. The following table shows an overview of the measured variations.

Combustion cycle	Miller Cycle	Atkinson Cycle
Engine speed	1200 – 2400 1/min	1200 – 2400 1/min
Engine Load - BMEP	1 – 5 bar	1 – 5 bar
Fuel injectors	1 type (no. 1)	3 types (no. 1, 2 & 3)
Ignition timing	10 ° BTDC – 25 °CA ATDC	10 ° BTDC – 25 °CA ATDC
Lambda	1 ; 1,05 ; 1,1	1 ; 1,05 ; 1,1

All measurement points are evaluated in diagrams of heat flux as a function of THC mass flow. A third variable is shown as z-value by coloration to make a pre-selection of operation points limited by standard deviation of IMEP and NOX as well as THC emissions.

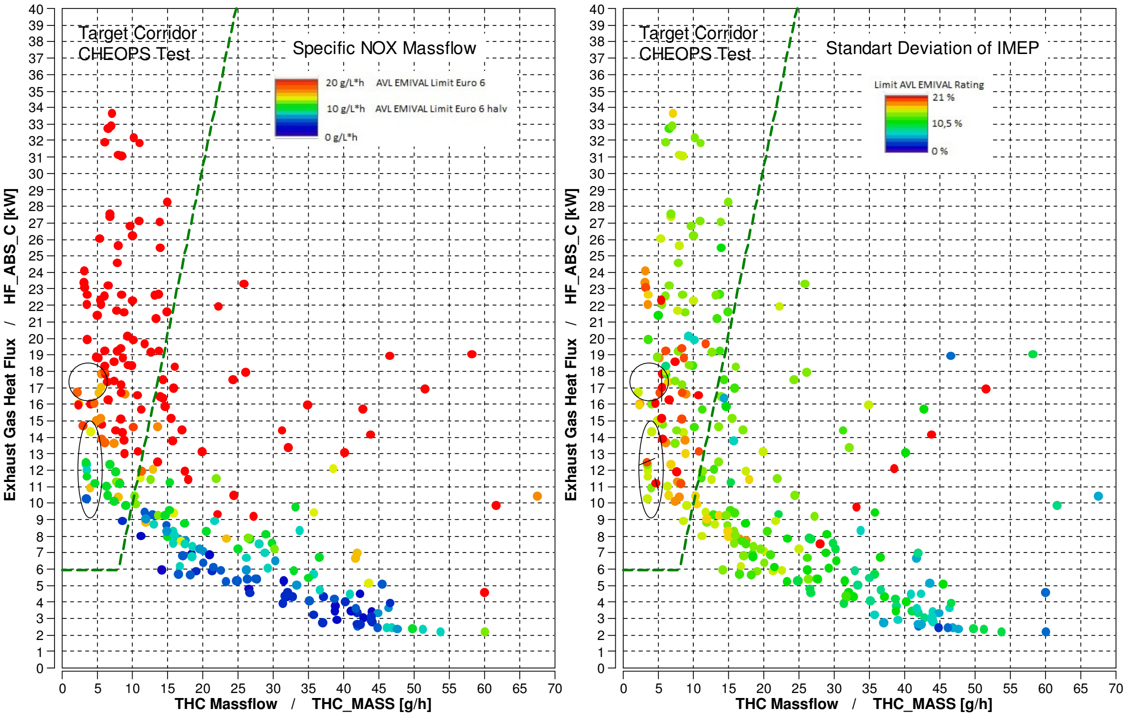


Figure 12: Heat flux vs. THC mass flow of all measured configurations

The 6 best operation points with lowest THC mass flow, a heat flux significantly above the target, acceptable NOx and combustion stability have further been evaluated with the AVL EMIVAL™ rating tool.

Operation Point [-]	Engine Speed [1/min]	BMEP [bar]	Ignition Timing [°CA after TDC]	Injector No. [-]	Combustion Cycle	Lambda [-]
1	1400	1	15	3	Atkinson	1,05
2	1400	1	15	2	Atkinson	1,05
3	1400	1	10	2	Atkinson	1,05
4	2000	1	10	3	Atkinson	1,05
5	2000	1	5	2	Atkinson	1,05
6	1700	1	10	2	Atkinson	1,05

EMIVAL™ is a tool to evaluate engine emission behavior. It is a software tool for data acquisition & validation, based on AVL INDICOM & AVL CONCERTO. In the FUEREX project this tool is used to evaluate the CHEOPS steady state test to find best cold start operation strategy for range extender application. The evaluation criteria of the EMIVAL™ ranking are Heat Flux, HC flux, CO flux, NOx flux and Combustion stability. Due to the Fuerex emission target of 50% of Euro6, the HC and NOx targets of the EMIVAL rating are also cut by half.

The operation points 1 and 2 of the table above show too high NOX results compared to the defined minimum target for Euro 6 half. The operation point 3 is slightly worse concerning heat flux but within all minimum targets. All evaluation criteria are close to the AVL benchmark targets of NOx, HC, combustion stability and heat flux. The operation point 4 shows the best results concerning heat flux und THC mass flow, even better than the benchmark targets, but too high NOX results according defined minimum target for Euro 6 half. The operation points 5 and 6 just fulfill the minimum NOx target but with very good HC and combustion stability results and a high heat flux.

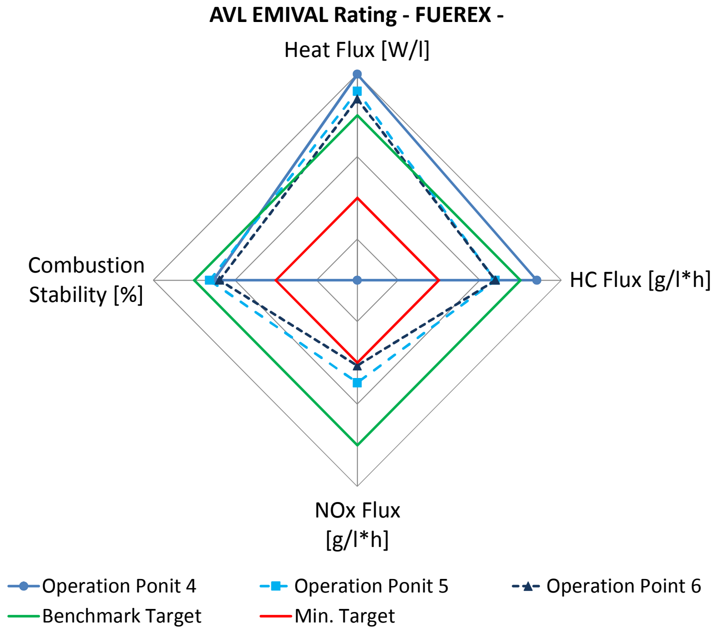


Figure 13: AVL EMIVAL rating of the operation points 4, 5 and 6

Most investigations described so far in this report have been performed with standard European RON 95 gasoline which contains 5% Ethanol. The standard ethanol fuel in Europe is **E85** with 85% ethanol and 15% RON95 gasoline and has been selected as the **alternative fuel** for the 3-cylinder in the Fuerex program. The direct comparison between RON95 gasoline and E85 Ethanol results show that the optimum operation point concerning Lambda and ignition timing is the same. The heat flux and low HC mass flow are on a very similar level; just the overall behavior is slightly different. At more advanced ignition timing the HC flow is higher for E85. As expected the NOx level is about 50% lower for E85 due to the temperature reduction during E85 evaporation and combustion. Nevertheless the heat flux is not lower, because the exhaust mass flow is slightly higher and combustion can further be retarded. Due to very similar results in the CHEOPS tests similar results can also be expected in the real cold starts.

From a big number of operation points with low HC mass flow and good heat flux in the CHEOPS target corridor the operation points 3, 5 and 6 out of 6 pre-selected points show the best results with the best chance for lowest emissions in real cold starts.

2.2.6 Test bench results of complete Range Extender - Efficiency

Before the cold start development could be started the combustion engine must be integrated with the generator. As described above a belt drive system is used for package and efficiency reasons. An all new system layout, design of the main components and the development of an assembly procedure with suitable measurement tools has been created by AVL Schrick Afterwards the complete Fuerex system is installed on a test bench. The overall efficiency of the Fuerex and the efficiency of all sub-systems are investigated. The analysis of the rotational oscillations shows if the belt drive has weak points and if it is generally suitable to handle the drive power.

In order to match the optimum speed range of the combustion engine with the optimum efficiency area in the generator map of the Bosch SMG 180x120 a transmission is required. A belt drive with a gear ratio of 1 : 1.95 shifts all operation points of the combustion engine full load curve into the sweet spot with 94% generator efficiency. Without the transmission the generator efficiency at low speed would be around 86%.

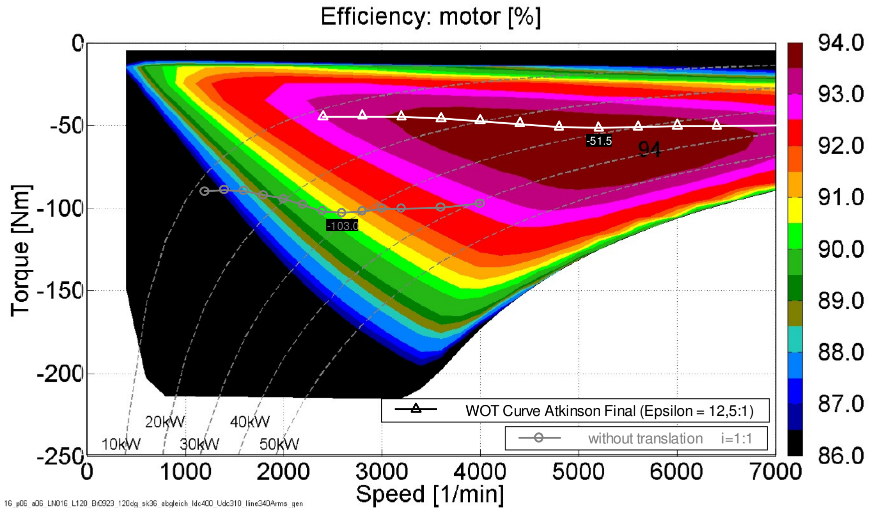


Figure 14: Combustion engine operation lines in the generator efficiency map of the BOSCH SMG 180x120

Due to the large distance between engine and generator (there is the oilsump in between) also relative large pulleys can be used, which reduce the belt force. The idler and the tensioner are positioned close together to achieve a large deflection angle of the belt around the pulleys, which increases the transmittable force of the belt. Under these conditions an 8 PK belt (Poly-V-belt with 8 rips) will cover all operation conditions between cold start at -30℃ with 150 Nm motoring torque and the above mentioned full load with a calculated lifetime close to 3000 hours.

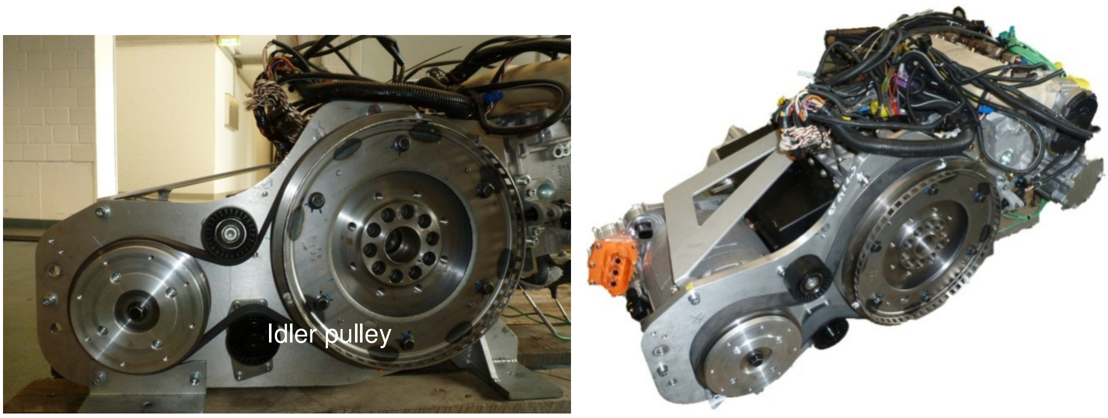


Figure 15: Fuerex belt drive and unit with ICE and generator

For this early prototype a belt drive without self-tensioning mechanism is used. The mechanical tensioner wheel, after once been adjusted, is then fixed and acting as an idler. Different belt tension measurement tools have been tested and an assembly procedure has been developed. The belt drive has been designed with support from INA Schaeffler (belt layout, idler and tensioner hardware) and Contitech (Belt calculation and hardware).

The commissioning and testing of the complete FUEREX system has been performed at AVL Schrick on a regular engine test bed which is prepared for combustion engine analysis in combination with high voltage electrical system. The generated AC electrical power of the Bosch generator is inverted to DC by the Bosch inverter and forwarded to an original battery from a Volvo C30 electric vehicle.

The performance and efficiency investigations of the FUEREX system show a maximal total efficiency of 32,5 % at 2400 1/min engine speed with RON95 fuel. This is the efficiency from chemical energy input (fuel) to electrical power into the high voltage battery. The current battery has a limited charging power of 23kW which is just reached at 2400 1/min engine speed.

The efficiency of the single energy conversion systems between the combustion energy and the energy input into the battery are investigated in more detail (data at 2400 1/min):

- 100% chemical energy in the fuel is converted into 40% energy in the cylinder pressure which is operating the piston engine.
- The mechanical efficiency of the 3-cylinder combustion engine is 93%.
- The efficiency of the belt drive is better than 96%
- The generator efficiency of the SMG 180x120 is slightly above 94%.
- The Bosch INV 2.2 which inverts the high voltage alternating current (AC) to a direct current (DC) for the Volvo battery shows an efficiency slightly below 98%

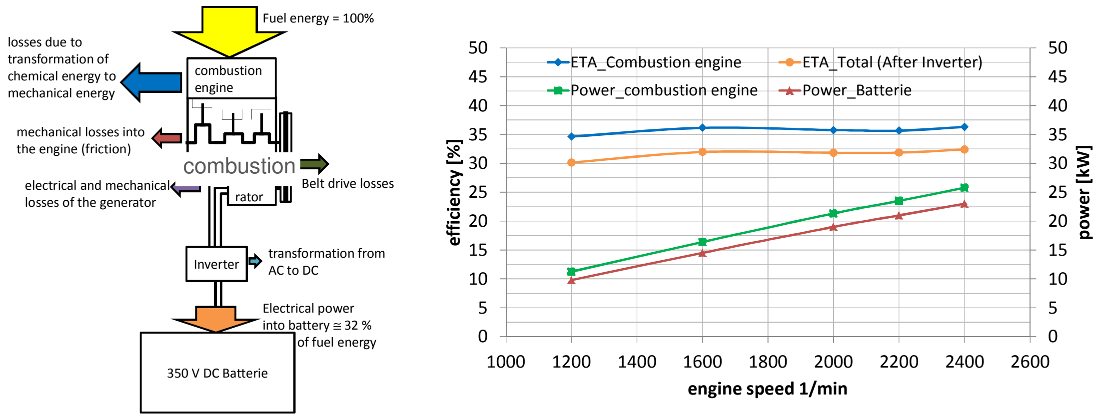


Figure 16: FUEREX losses and efficiency curve

A rotational oscillation analysis of the belt drive shows uncritical conditions in all operation points with slightly higher belt drive load at low speed, full load. Steady state and transient measurements as well as load steps have been were performed in generator mode at different engine speed and engine load. The detected maximal is uncritical for the belt. The rotational oscillations are also within normal values.

The all new belt drive of the Fuerex system is a robust energy transmission system which enables a perfect match between combustion engine and generator performance and efficiency. For the Fuerex components this advantage is in the same order of magnitude as the friction losses of the belt drive.

The belt drive has advantages by more freedom in the packaging of the generator with the combustion engine. Even the first prototype fulfills the demand of the Fuerex program. In the future a detailed efficiency optimization must follow to minimize the losses of the belt drive. For series production application an automatic tensioning system must be developed which is not yet available.

2.2.7 Cold start emission calibration and cycle fuel consumption

For the cold start calibration and emission development the Fuerex with ICE, generator, belt drive and all vehicle-like intake and exhaust system parts was installed in the same type of subframe which is also used in the Volvo C30 prototype vehicle. The whole Range Extender unit is installed in a hybrid test cell at Chalmers University. A battery simulator enables the full flexibility of electrical input and output without the limitation of the battery which was used before.

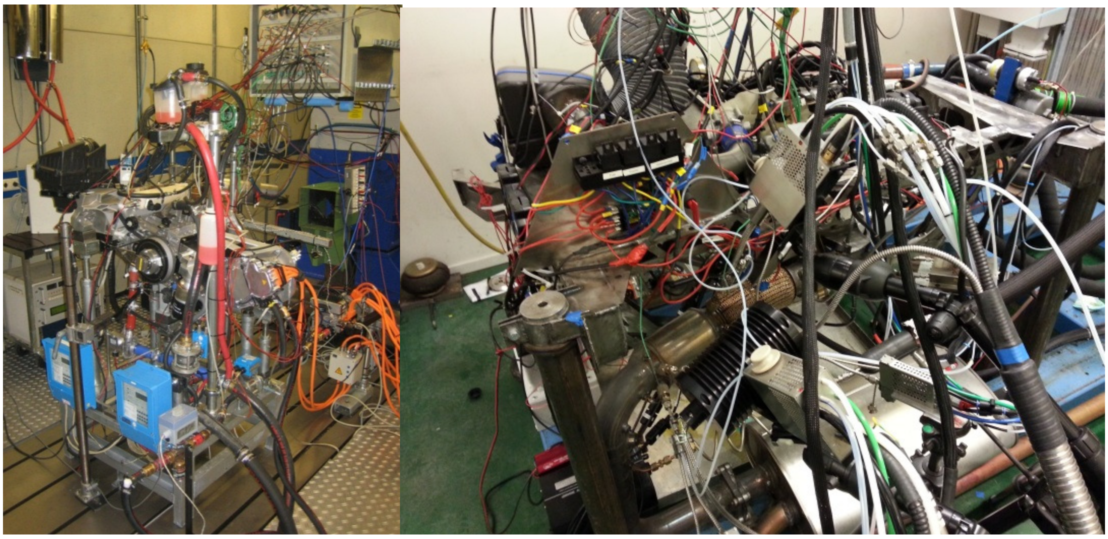


Figure 17: Fuerex engine mounted on engine dyno at AVL Schrick (left) and in the C30 sub frame at Chalmers (right)

A cold start was defined as a start at 20°C ambient and engine temperature. The engine was conditioned before the cold start by running it until it reached normal operating temperatures. It was then cold down to 20°C and left to rest for at least three hours. The result of the cold start presented in this report was acquired after the engine had been resting overnight

Early in the tests it was realized that most of the emissions from the engine during a cold start was released during the first seconds when the engine speed is ramped up and combustion is initialized and stabilized. Therefore most of the effort on cold starts within the project has been focused on calibrating the startup procedure.

The concentration of emissions was found difficult to affect during the first combustion cycles. The strategy has therefore been to start the engine at low intake manifold pressure using a very small throttle opening angle. This results in low mass flow and even though emission concentrations are high, the mass flow of emissions is low. Injection is started when the desired intake manifold pressure is reduced to satisfying levels which occurs at an engine speed of 800 rpm and the acceleration of the engine is gradually changed from being performed by the electrical motor to the combustion engine. After the first few combustion cycles the throttle is opened quite fast in order to reach the target intake manifold pressure of just below ambient pressure. At the same time, the ignition angle is progressively changed from spark advance to the target spark retard of the catalyst heating tests above in order to provide high temperature exhaust gases.

Lambda was tuned to be close to one for the first cycles and then rapidly changed into the target value. This strategy ensured that the first critical cycles show stable combustion and that the target catalyst heating operating point with large mass flows of high temperature exhaust gases is reached fast. Starting the engine at low intake manifold pressures is also more beneficial from an NVH perspective.

The selected operating point has a speed of 2400 rpm, an IMEPnet of 3.9 bar, a Lambda value of 1.1 and a spark timing of 5 CAD aTDC. This point was chosen after a pre-selection since it provides fast catalyst light-off and low emissions while at the same time producing electrical energy output from the range extender unit.

Figure 18 shows the concentrations, mass flows and accumulated mass of total hydro-carbons (THC) and nitrogen oxides (NOx) measured before and after the catalyst during the cold start. Here, it is shown that most of the emissions are accumulated before the stable catalyst operating point is reached. The accumulated hydro-carbon and nitrogen oxides emissions before catalyst light-off were 0.165 g and 0.03 g respectively, which is less than 25% of the NEDC NMHC emissions. There are some uncertainties in these values because they are based on the total mass flow in the exhaust which is based on fuel flow measurements and the transient behavior of the fuel flow measurement device and the fuel system was not entirely known.

In the figures shown, the engine was not switched into normal operation after catalyst light-off and therefore accumulated NOx emissions further increase. When the strategy is implemented in the vehicle, the engine would switch to stoichiometric (Lambda=1) operation and conversion of NOx would also start.

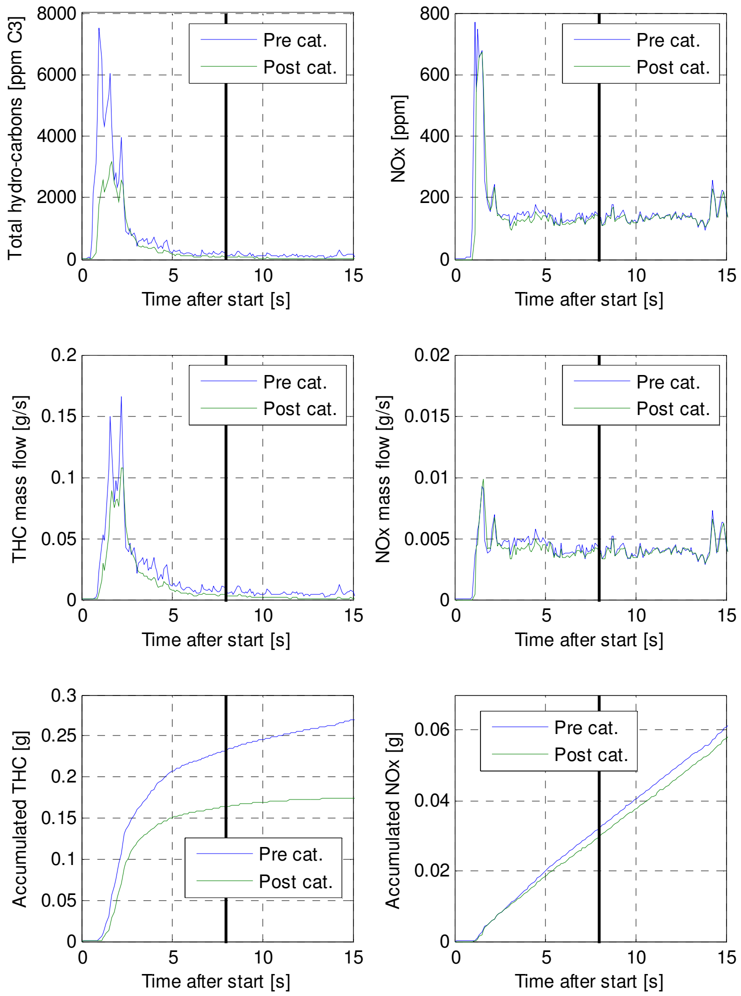


Figure 18: Concentrations, mass flows and accumulated mass of total hydro-carbons (THC) and nitrogen oxides (NOx) measured before and after the catalyst during a cold start.

In Figure 19, the measured exhaust temperature starting at the first revolution of the engine is displayed. It can clearly be seen that the engine out (close to the ports) temperature increases very rapidly with the chosen strategy. There is a delay in the temperature increase observed downstream of the ports where the three exhaust pipes merge and before the catalyst. This is due to the cold exhaust pipes absorbing some of the exhaust energy. The temperature after catalyst looks much different. The reason is that the catalyst brick is absorbing most of the energy from the exhaust gases during the warm up phase. When catalyst light off is reached the temperature after the catalyst is only 155°C. This might seem like a very low temperature for catalyst light off but it only reflects the temperature in the downstream part of the catalyst brick. The temperature in the first parts of the catalyst is higher.

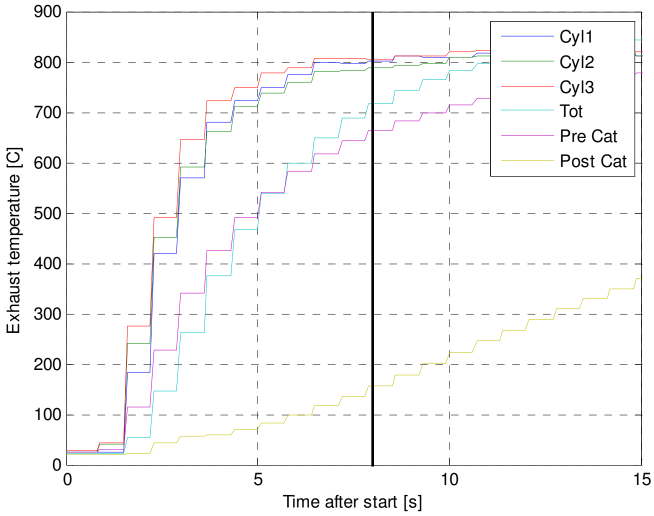


Figure 19: Measured temperatures in the exhaust system at different positions

An electric vehicle with range extender enables further operation freedom when using pure electric respectively battery mode or combined with the range extender if necessary. The main advantage of this concept is to operate the vehicle only with electric energy with the possibility to use the combustion engine as range extender if required. Furthermore, if the combustion engine is required for range extending, it could be operated at best efficiency due to the freedom of operation point definition.

In order to achieve comparable results test to a passenger car with standard powertrain, the required work of the vehicle which is necessary to run the NEDC electrically has to be generated by the range extender during the test. That means the SOC of the battery at the end of the test like at start.

For NEDC test on engine test bed the required drive work for NEDC of the range extender is defined by vehicle measurements of the Volvo C30 electric passenger car.
The operation strategy of the FUEREX is defined to operate the range extender at different power stages depending on vehicle speed. With increasing vehicle speed the interior noise increases. Due to NVH reasons the high power stages are defined at higher vehicle speed to reduce the noticeability of the range extender operation for the vehicle driver and passenger.

Two power stages with 20 kW and 26 kW have been defined. The range extender starts first time when 60 km/h are exceeded. The second power stage is activated when 80 km/h are exceeded. At the first start (vehicle speed > 60 km/h) with cold engine the engine operates in cold start mode about 15 seconds until catalyst operation temperature is reached. After cold start the engine ramps to the operation point.

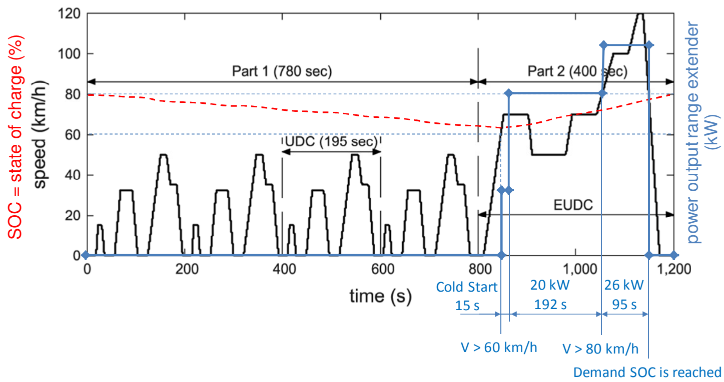


Figure 20: FUEREX operation strategy for NEDC driving cycle

Figure 21 shows accumulated emissions during the NEDC cycle using the proposed operating strategy of 15 s cold start, 192 s operation at 20 kW and 95 s operation at 26 kW. The dashed lines show the target for emissions according to half euro VI levels. Note that carbon monoxide was measured using an instrument with slow response time and therefore only provides accurate values during stationary operation.

It is obvious that the emissions produced during the cycle are higher than the limits for all measured species. It also can be seen, that this does not occur because of the cold start, transient power changes or Lambda deviations but due to a catalyst defect which causes the slip of emissions through the catalyst.

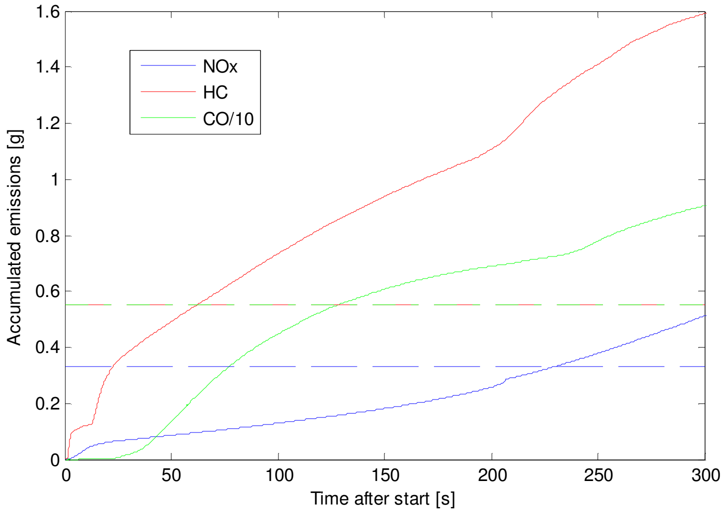


Figure 21: Accumulated emissions after the catalyst during the proposed NEDC operating strategy. Dashed lines show the emission targets.

Due to the limited time at the end of the project it was not possible to prepare a new catalyst for further tests. By investigating different speed / load points it was found out that with lower power the post-cat emissions were on a lower, even acceptable level.

The table below shows the emission results of the previously proposed operating strategy compared with further tests at lower speed and load after catalyst heating, The lower power is compensated by longer operation time, but accumulating the same work at the end of the test. The operation point of 2000 rpm / 10 kW which is approximately 50% load reduces the NEDC emissions to a level safely below the EUROVI half targets.

Power [kW]	Speed [rpm]	Time [s]	HC [g/km]	NOx [g/km]	CO [g/km]	Fuel [g]
20/26	2150/2700	15+192+95	0.145	0.047	0.824	535.4
15	2000	15+430	0.097	0.034	0.047	559.7
10	3000	15+636	0.036	0.015	0.179	710
10	2000	15+636	0.026	0.018	0.080	615.1

Results from NEDC tests (including cold start) with different operating strategies. Boxes highlighted with green shows levels below the target and boxes highlighted with red shows levels above the target.

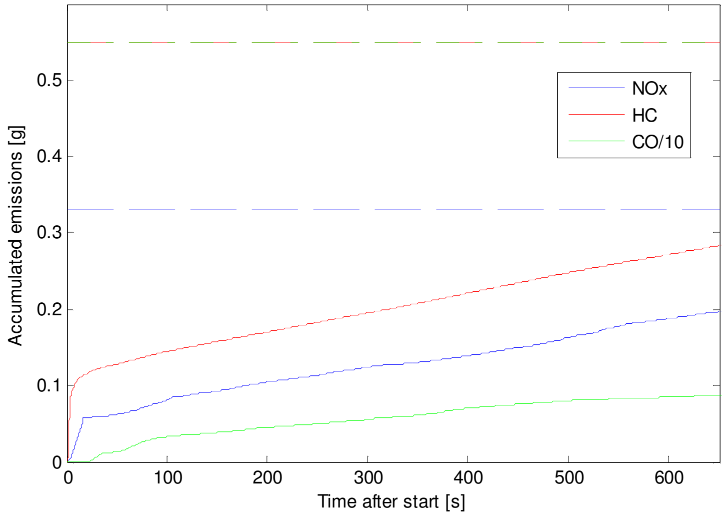


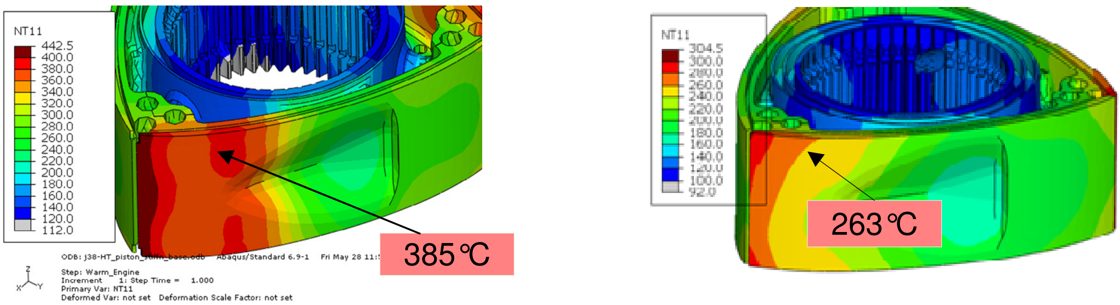
Figure 22: Accumulated emissions after the catalyst during NEDC with the REX engine operating at 2000 rpm and 10 kW. Dashed lines show the emission targets.

It can be assumed that with a new catalyst the emissions will also be achieved at higher load. If a new catalyst is still not sufficient a resizing (=larger volume) of the catalyst must be considered.

2.3 WP4 – Rotary engine

The focus of the FUEREX project was on emission, fuel consumption, noise vibration and harshness and durability development of the rotary engine. The development was done as planned in the DOW by simulation and verification at the engine test bed, at the chassis dynamometer and on the road with the vehicle:

- Design updates were defined, simulated and implemented. Component and material selection made sure, that bio fuels can be used without restrictions.
- Since the rotary engine has to exceed EURO6 emission standards, it was mandatory to minimize oil consumption in the combustion process.
- Counter measures were defined, calculated and developed mainly to improve cooling and rigidity of the RE unit.
- A reduction of rotary piston surface temperature by more than 100° in critical areas was achieved, which leaded to essentially reduced deformation and improved combustion process.
-



- Piston Surface temperatures (old and updated design)
-
- To avoid deposits especially in the spark plug area, the cooling system of the trochoid housing was re-evaluated in simulation for improved heat transfer.
- Due to further optimization of the water jacket flow combined with analysis of mechanical stress caused by the assembly process, a reduction of planar distortion of liner and reduced deformation of housing due to bolt load is expected.

Performance and emission development on the rotary engine which leaded to the best fuel consumption while keeping the EU6 emission regulations for passenger cars:

- Detailed investigations were carried out on ignition process and piston bowl design.
- This investigation did lead to the implementation of a modified design for the orifice of the first spark plug in rotating direction which improved the combustion process.
- Hardware investigation were made for different injector types and spray patterns, different high fuel injection pressures, different catalyst locations and catalyst inlet cones as well as heated catalytic converter. Also injector position, air intake and exhaust system variant were optimized.
- Performance development was performed for both test fuels, gasoline and ethanol (E85).
- A dedicated algorithm was developed to calculate the adjustment of injection volume and timing. A range of selected injectors made sure that the requested injector valve flow rates due to lower calorific value of ethanol can be met.
- The injection timing and volume are controlled continuously until the λ=1 level is reached and stabilized again.
- Test results proved that HC and particle emissions are reduced compared to standard fuel without loss of engine power for typical range extender operating areas.

The development of aftertreatment system was performed for petrol and bio ethanol. The real world fuel consumption is influenced by the thermal management requirements for the aftertreatment system. The development work was structured in hardware optimization and operating strategy to fulfill under real world range extender conditions EU6 emission level with reasonable engineering margins.

- Dedicated fast light-off strategies were implemented, taking into account the specific characteristics of the rotary engine and of the vehicle inertia. This was also managed by the system layout, in order to ensure the highest temperatures after the engine crank up avoiding us much as possible increase of fuel consumption.
- Individual tests were performed for injector types, injector targeting, injector positioning, intake and outlet geometry and other design features as well as for impact of operating strategies.
- Cold start development fulfilling the special requirements of range extender application
- Beside injection and air path, the focus was on catalyst setup. In a specific approach to initiate conversion as soon as possible, an optimized catalyst intake has been designed and tested.
- Catalyst heating @ 4500 rpm did allow fast warm-up due to increased heat input to Catalytic converter.
- The installation of a relatively small starter catalyst did lead to a reduction of HC Peak in start phase due to fast conversion start because of the reduced diameter
- With the final test setup it was possible to demonstrate, that the EURO6 targets for HC and particles can be met with a rotary engine with a reasonable development margin.
-
- Development of Noise Vibration and Harshness (NVH) for engine and for the complete RE in the vehicle:
  - Acoustic layout of mounts for housing and internal components
  - Acoustic refinement of acoustic damping performance (noise radiation surfaces)
  - Acoustic layout of air filter box and low frequent resonators and subsequent fine tuning
  - Acoustic layout of muffler, low frequency resonators and high frequency resonator and subsequent fine tuning
  - improvement of airborne noise damping to vehicle interior
  - Due to the fact that the engine operates in well-defined speed load areas the system was optimized in a very specific manner using narrow band / high damping features.
- A key element to reduce the sound pressure to acceptable levels was the encapsulation of the range extender module. The core generator-engine unit up to the exhaust manifold was installed inside a module housing which was using sound absorbing materials to reduce airborne sound radiation.
- Sound deadening material was also applied to the ventilation air duct, which was Exhaust - Silencer System Design Optimization
- The intake system, exhaust system and the damping elements of the module mounts have been optimized by detailed acoustic simulation to accomplish an averaged outside 1m-sound pressured of 65dbA at the back of the vehicle and an interior level of 58dBA at the drivers right ear.
- Combined counter measures lead to sound levels for real-life vehicle operation, which enable the use of RE at dedicated operating points with no noticeable negative impact on sound pattern of EV.
- With a strict continuation of the high load point operation below speeds of 60 km/h the RE becomes the dominant issue for acoustic convenience. The subjective noise perception can be improved by some degree of tracking the vehicle speed by definition of different RE load points according to vehicle speed and energy requirements. For high-speed driving the general vehicle noise level allows a dedicated high-power load point by increasing engine speed and mean effective pressure to avoid HV-battery depletion also at highway driving speeds.

Vehicle integration and test of the rotary engine RE system in a demonstrator vehicle based on chassis dyno tests and real world driving. For real-life testing, an improved RE system with 15kW electric power at 4500rpm was integrated into a demonstrator vehicle which has been built on the BMW Mini basis. This electric vehicle is specified and designed for use as a City car and has been equipped with a 12kWh Li-Ion HV-battery, which allows an all electric range of 50km city driving. The described 15kW RE module and a fuel-tank of about 12l guarantee independency for an additional range of at least 200km. Propelled by a permanent magnet synchronous motor with 75kW peak power, the vehicle accelerates from 0-100km/h in about 12 seconds (0-60km/h in 5.4 seconds) and accomplishes a continuous maximum speed of 100km/h with a peak vehicle speed exceeding 130km/h. The RE integration was performed under main aspects:

- No restriction to passenger compartment and trunk
- Utilization of stiff chassis areas to support a low acoustic chassis excitation by the RE system
- Reduction of auxiliary components like mounts, high voltage cables, connectors, cooling lines, …
- Low impact on vehicle chassis design to avoid expensive additional tooling
- Integration of system assembly process with assembly of drivetrain alternatives
- Vehicle crash requirements
- Vehicle system safety and electro-magnetic-radiation (EMR) requirements
- Axle-load distribution requirements

Comparison of the range extender vehicle to a state of the art combustion engine setup including start-stop strategy and brake energy recuperation.

- A real world driving route was utilised as major bases for fuel consumption optimisation. It shows a representative combination of city, extra urban and highway profile. A very important fact is that there are typical gradients which are influencing the driving strategies of EVs significantly.
- For the direct comparison with conventional drivetrain concepts an identical BMW Mini with 1.4l NA engine with fully variable valve train, start-stop strategy and intelligent battery management to recuperate brake energy were defined. To compare the CO2 emissions of both concepts the electric energy of the plug-in charging was considered according to the German power-plant mix with 625grCO2/kWh.
- For cold start at ambient temperatures of 0℃ and city driving conditions the FUEREX car shows even with battery electric cabin heating significant CO2-emissions advantages.
-

System assessment and optimisation. Based on the test bed and real life operation of the FUEREX vehicle additional fuel consumption improvement potentials were identified be vehicle simulation in summer and winter operation

- Advantage of the REEV is its ability for recuperating the brake energy. For city driving, 20 - 25% can be achieved.
- A CO2 reduction potential up to 35 % for the vehicle resulted in the NEDC cycle by vehicle and drive train optimisation such as reduction of air resistance, weight, power of electric drive or additional transmission. The same methodology has been applied to the AVL test cycle, which is much more representative for real world driving conditions than NEDC.
- Although total energy consumption is higher than in ideal NEDC cycle, the potential savings in the range of 30% confirm the severe impact of combined counter measures for realistic driving conditions and the according CO2 reduction potential.
- The results of the reduction potential evaluation performed for NEDC and a real world cycle give a clear indication for future steps in the development towards lower CO2 emissions.

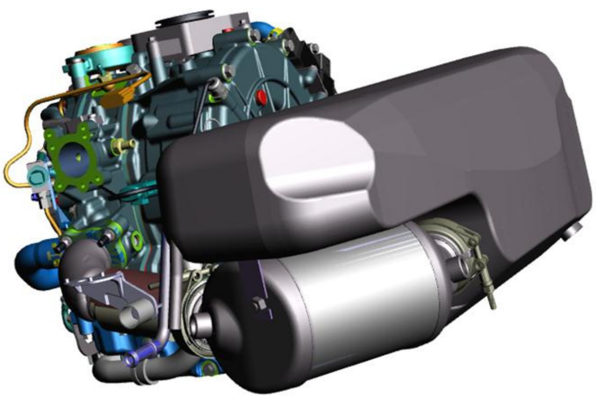


Figure 23 - Arrangement Engine – Intake System – Exhaust System

2.5 WP 5 – 2-cylinder NG RE based powertrain

The activities performed in two year of the project mainly focused on:

- Definition of the subsystems specifications;
- Development of the electric driveline;
- Development of internal combustion engine (engine calibration, engine control system adaptation)
- Evaluation of the potential in using hydrogen/natural gas blends
- Development of power electronic and RE management system
- On vehicle engine calibration
- Emission optimisation
- Validator vehicle final assessment
-

2.5.1 Definition of the subsystems specifications

The specifications have been derived starting from both the vehicle targets and the RE-Unit architecture definition. The subsystems have been identified and described in term of electrical, mechanical and fluidic interfaces. A first packaging analysis of the RE-Unit has been performed in order to identify the main mechanical constraints to be considered during the next design phase. The figure below shows in a schematic format the complete system and its components.

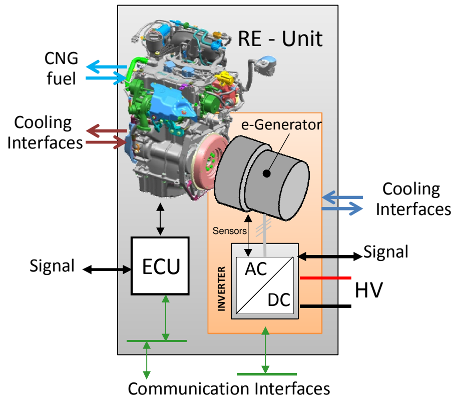


Figure 24 - RE-Unit

The main results of the activities performed in the specification phase, are about the definition of:

- the Internal combustion engine configuration and its target working points
- the electric machine required performances
- the electric machine mechanical interface requirements
- the inverter unit required performances
- the electric and electronic architecture of the RE-Unit
- the cooling requirements for the power electronic
- the complete I/O interface definition of the RE-Unit

2.5.2 Development of the dedicated version of the NG two cylinders engine

The ICE configuration optimization activities consisted mainly in Fluidynamic optimization performed at engine test bench supported by engineering (design, simulation and laboratory) activities. This development activity had the aim to optimize the engine specific fuel consumption with a particular attention to the area of the two main working points chosen: 20kW and 40kW.
In order to increase efficiency in these two working points some development of combustion has been done.
Two main modifications were studied and experimented: the compression ratio increment and combustion chamber modifications.
The use of CNG as fuel allows to increase compression ratio (there is no particular problem for knock). The Compression Ratio has be increased of 2 points being fixed in 12:1 from the initial 10:1.
The final result of this modification is an increase of engine efficiency of about 4% both at 20kW (main benefit thanks to Compression Ration increase) and 40KW (main benefit coming from masking elimination).

2.5.3 Development of the electric driveline

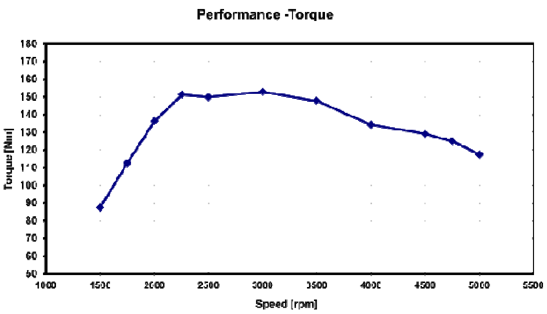
The development of the electric driveline covered both the mechanical expect and Electric generator functionality.
The Electric generator is supported by an interface bolted to the internal combustion engine crankcase. This interface is made of two parts: an aluminum alloy support derived form a gearbox housing, and a plate that also provides the attachments for the Range Extender suspension mounts. This interface will prevent dust to enter in the area where there are the flywheel (modified from base the engine) and the torsional connection to the electric Generator.
To be sure that E-gen support is properly designed the complete Range Extender global modes has been calculated.

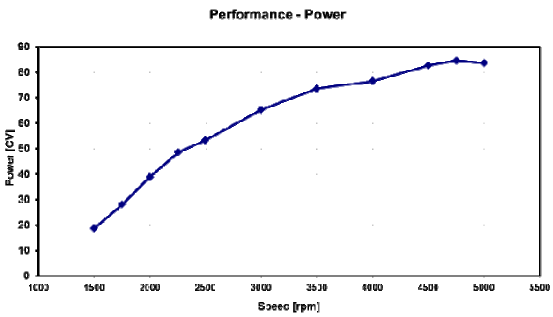
The torsional connection between ICE and E-gen has been designed in order to fulfil the requirements of transmit the torque and recover little misalignments between flywheel and electric motor axis. The final configuration of the transmission is based on a dual mass flywheel.

The Electric machine has been delivered by Bosch on the base on the given specification. The machine has been preliminary tested at the electric traction laboratories of CRF.

2.5.4 Engine performance at test bench

Main scope of this activity is the characterization of the engine in terms of performance, emission and fuel consumptions.
This purpose is pursued through the regulation of the engine parameters: ignition advance, fuel injection, Multiair valves command, turbocharger regulation system. In the same time a specific after-treatment management for natural gas engine is tested to improve the pollutant emissions conversion.
The Range Exterder application need to optimize the engine specially in the high efficiency zone, however sometimes it's necessary a fast regulation of the energy produced by RE in order to fulfil the requests from vehicle or battery management. Therefore an accurate calibration of the engine is required in an extended zone of operation.
The engine used to realize the Range extender is the FIAT TWINAIR TC 85CV modified in the combustion chamber and Compression ratio (12 vs. 10). Maximum performance have to be reached respecting the following thermo-structural constraints of the components.





2.5.5 Evaluation of the potential in using hydrogen/natural gas blends

The potential in using hydrogen and natural gas bland has been evaluated considering the potential benefit on fuel consumption/emission and the impact on the systems. Blending H2 in NG is a technically viable solution to introduce a growing fraction of renewables lowering fuel carbon content.
A 30% H2 by volume blend is an appealing compromise between emission/combustion benefit and vehicle range reduction due to the lower energy density in the blend. Under the same engine efficiency the correspondent CO2 reduction is 11% compared to pure NG, while the resulting vehicle range is 20% shorter.

The use of NG/H2 blends asks for 2 action lines:

1) Adapting engine control parameter

2) Adapting materials of the storage and feeding system to prevent embrittlement phenomena due to hydrogen.

Calibration data set must be adapted mainly in order to:

- Set the corresponding stoichiometric A/F ratio;
- Set new gas injector model (to transform fuel mass into injection pulse width);
- Set spark ignition timing (check of knocking under full load conditions);
- Adapt the control parameters on the lambda probe to optimize catalyst conversion efficiency.

Being hydrogen (H2) a carbon free fuel, a reduction in “Tank to Wheel” CO2 emissions is achieved at the same engine efficiency and with the same amount of energy entering the engine, as shown in Figure 7.1. For blends containing a 30% in volume of H2, more than 10% CO2 reduction is expected.

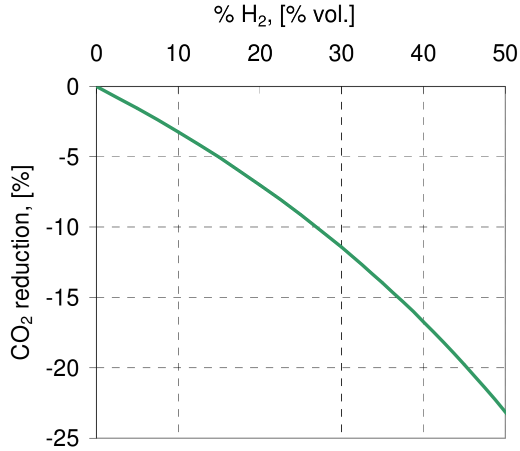


Figure 25 - Effect of hydrogen content on tank to wheel CO2 emission reduction.

2.5.6 Development of the power electronic and RE management system

During the second year of the project, two inverter samples were delivered and some preliminary test on the functionality has been done at CRF test laboratories. The main parts that compose the Range Extender are the Internal Combustion Engine (ICE), the Electric Generator, the Inverter, the Electronic Control Units and the fuel supply, as shown in Fig. xx

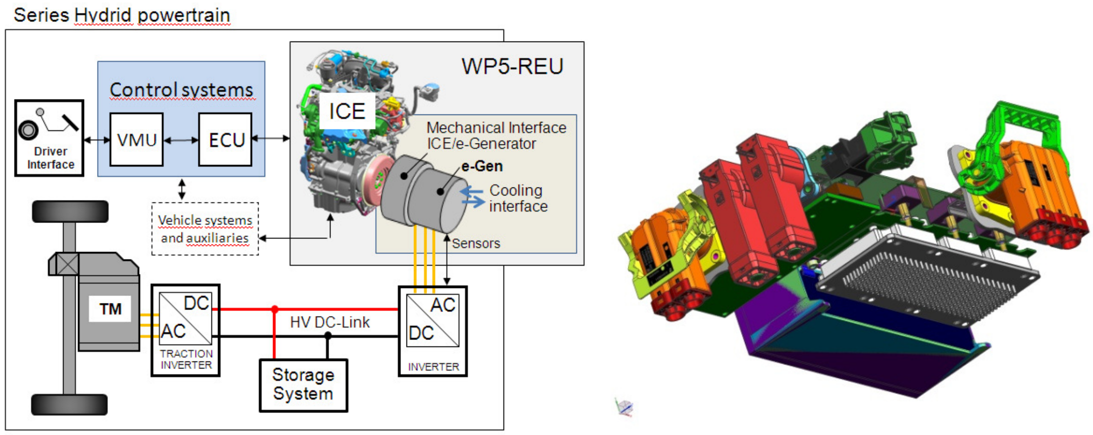


Figure 26 - Series Hybrid Powertrain overview and the Electronic assembly 3D layout

The inverter was realized according to the specification requested in the present document. In particular the inverter:

- will be electrically connected to a three phases AC e-generator (electric machine);
- will be electrically connected to a DC storage system (traction battery);
- will control the e-generator by a PWM technique at the appropriate frequency (up to 20kHz available);

- will be liquid-cooled and a dedicated cooling circuit has to be adopted at vehicle side (same circuit of the traction motor and inverter);
- will be mechanically fixed with an appropriate flange to the vehicle chassis in the engine compartment;

On the other end, the e-generator is electrically coupled to the inverter and will be used as an electric machine that acts:

a. as a generator when the thermal engine is on;
b. as a motor in order to crank the thermal engine.

The housing of the inverter has been designed in order to provide:

- electrical power dissipation through cooling fluid circuit heat-sink
- water proof case for engine compartment installation
- ruggedness against mechanical vibrations
- assembly and interconnections solutions for the electronic components and PCBs

Concerning the electronic assembly, the layout of the whole electronic assembly is provided in the following figure. The IGBT modules, the DC link capacitor and the connectors are mounted onto the mechanical box and interconnected through different bus bars. The current sensors are already mounted onto the control pcb board. The IGBT driver board and the control board are then stacked each other.

In the above figure it is possible to see the particular configuration of the PowerPACK2 module with the pin-fin structure for the direct liquid cooling.

Concerning the RE management unit, the RE electronic layout is show in the following figure.

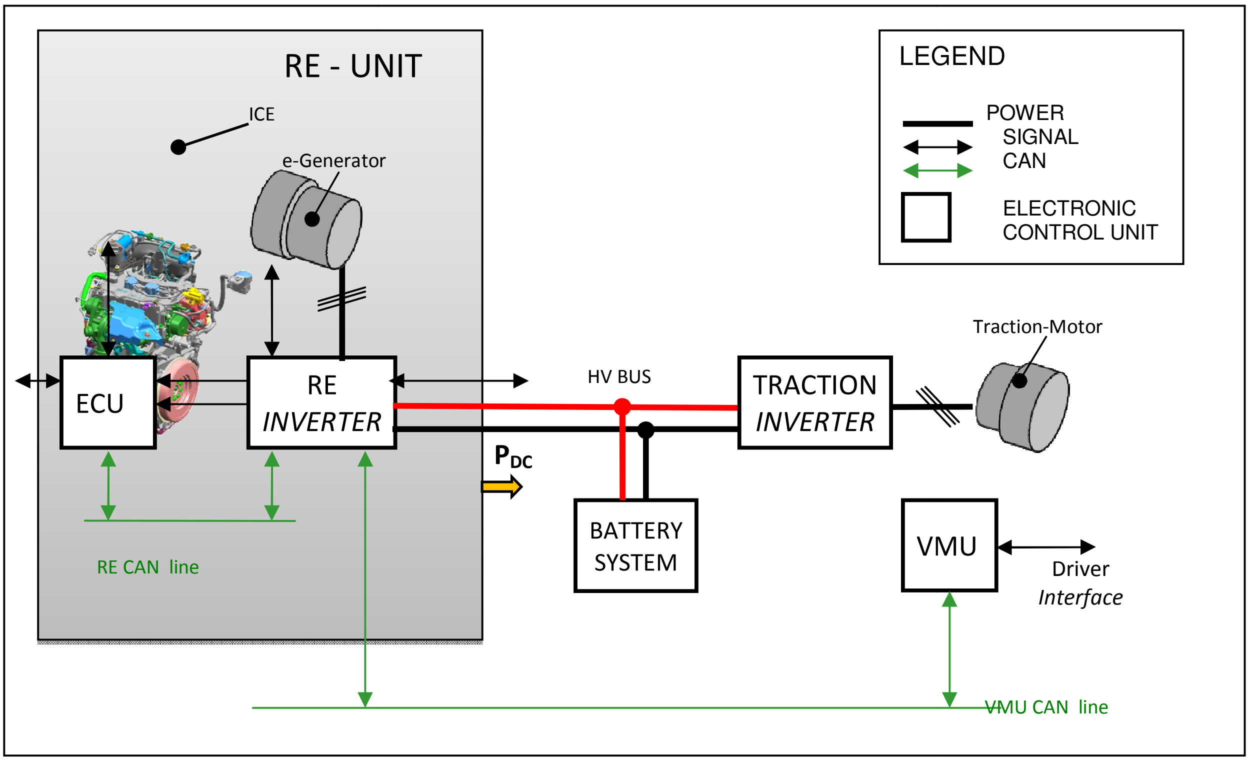


Figure 27 - RE Electronic layout

The RE-Unit has two electronic units: the Engine Control Unit (ECU) to control the thermal engine and the inverter to control the electric machine and to manage the system.
The communication between the two control units is realized with a dedicated CAN serial line.
The inverter generates also two signals in order to emulate the ignition key and gas pedal signals for the ECU.
A second CAN line on the inverter is used for the communication with the Vehicle Management Unit (VMU). VMU is the control unit that manages the vehicle and decides when and how the battery has to be recharged by the RE. The RE management unit details are well described in the Deliverable D5.5.

2.5.7 Demonstrator Vehicle Integration

The vehicle adaptation, subsystem integration and to start up and tuning of the RE system on the validator vehicle. According to the general target of the range extender vehicle the same performances of electric version with 3 Z5 batteries (50 kWh available) should be achieved:

range	120 km in urban use
max speed	70 km/h (limited)
pay load	800 kg
start ability	16% full load
G.V.W.	3500 kg

- High way capability in hybrid mode self sustaining
- 30 kWh R.E. capability
- Load follower with S&S serial hybrid mode
- Plug in capability
- ESS EOL available energy 20 kWh
- Electric mode range more than 48 km in urban use

RE (APU, Alternator and inverter) and storage system were defined and developed with the partners. Using an existing electric platform that complies above performance requirements electric storage system energy, CNG storage system and APU performance were defined.To reach 20 kWh ESS EOL available energy, storage system was reduced from 3 to 2 Z5 batteries that comply with the requirements both in terms of energy and power. To reach 30 kWh R.E. capability at DC link level, a 8 kg, 56 l CNG storage system is the lower limit.

2.5.7.1 Demonstrator build up

Buildup of demonstrator vehicle was performed as well as startup, tuning and preliminary testing of the complete vehicle

Gas tank position	Water capacity [l]	Diameter x length [mm]
E - F	28	269x670

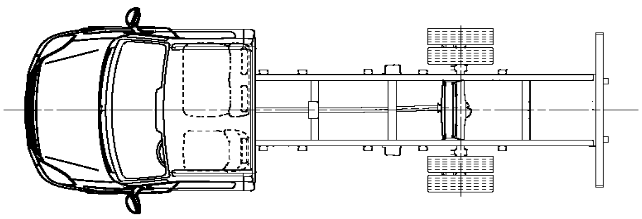


Figure 28 - CNG storage system integration

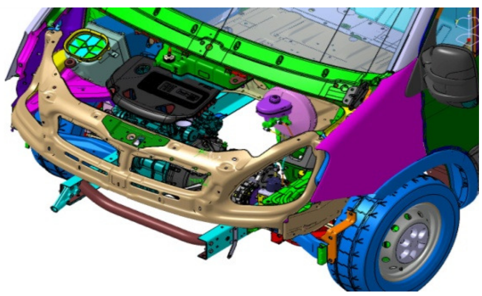


Figure 29 - Mechanical integration

On track testing with data logging was performed in order to verify and asses drive-ability and performance according to vehicle requirements, as defined in year one.

2.5.8 On vehicle engine calibration

As described in the procedures, the calibration of the engine on vehicle requires carrying out tests in a repeatable manner in many conditions of operation both on roller bench and at the proving ground. Since it was not available in CRF a bench adequate for this test on the vehicle we proceeded to the design and realization of a 'bench’ to perform these tests. The main requirements that the test bench must have are: safety requirements, functionality and reliability of testing. This test bench has been described in details in Deliverable D5.3

Scope of the vehicle test bench was the tuning of the power generation function, including coordinated control of both electric generator and thermal engine.

The vehicle has been kept at standstill, due to safety and practical reasons. This gave also the possibility to use external instrumentation.

At zero vehicle speed, generated power directly feeds the on-board batteries, which can be charged only for a limited amount of time. In order to tune the control, activity that requires to test the power generation even for long time, the generated electrical power shall be removed from the vehicle and routed to an external electrical devices able to absorb it continuously without damage.

The first tests on the APU control strategies were performed with the vehicle not moving and the high voltage battery pack connected in parallel to the external regenerative bidirectional DC power supply (AC/DC converter), just described.

The first steps consisted in the calibration of the electrical machine speed control in order to be able to set the thermal engine to different speed and torque conditions. The thermal engine control was then improved, starting from idle and low power generation and then increasing the generated power which was absorbed by the AC/DC converter. An evaluation of the thermal engine consumption was then performed with the aim of refining the speed and torque working points (for several requested power levels) to maximize the APU efficiency.

The second step was the calibration of the electric machine speed control (See D5.3 for details).

Due to the mission of this kind of system, it is not necessary to have too high performance in dynamic response (the requirement for the motor generator dynamic response was about 5kW/sec; this means a maximum derivative of about 500 rpm/sec). This allowed calibrating the speed control to a value that did not require too much power during thermal engine cranking and during speed set point transitions in general.

A speed and torque set point curve depending on the requested power level was initially determined on the efficiency map of the motor-generator. Since the efficiency of the electric motor is almost constant in the range taken into account for power generation, the curve was set following the highest efficiency path on the thermal engine efficiency map.

Alongside with the maximization of efficiency, the objectives were to reduce noise and vibrations and to avoid mechanical resonances that were calculated at about 850 and 2400 rpm: the final curve is shown in red in the figure below.

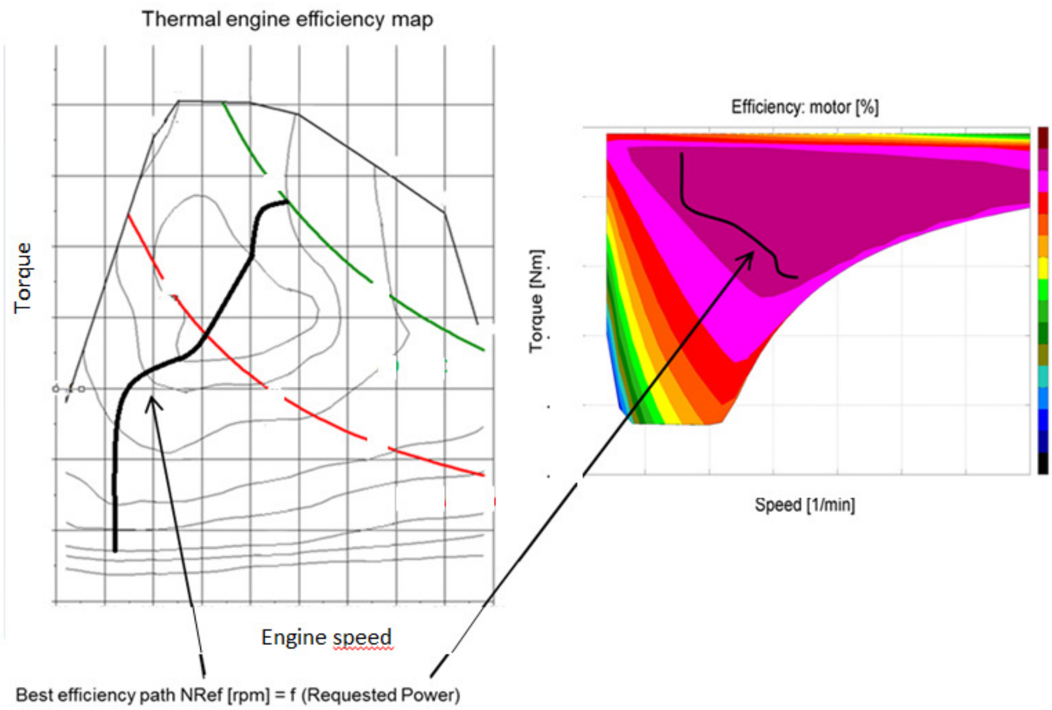


Figure 30 - Initial (in black) and final (in red) calibration of the speed set point curve, after consumption and noise evaluations

2.5.9 On vehicle calibration refinement at proving ground

Two types of tests were performed in order to assess and improve the behavior of the system in real driving conditions:

- Tests on the road. These were useful to improve the intervention of the voltage limit control and, in general, to assess the response of the whole system in real dynamic conditions. The behavior of the APU with changing power requests and the interaction with the traction motor were tested and improved.

- Tests on track with a specific urban-like mission. The mission required a maximum speed of about 40 km/h and a vehicle stop each 400 meters, with an average speed of 20-25 km/h. These were the final tests where the APU intervention strategy was refined while checking the overall behavior of the vehicle.

While the thermal engine has a torque limitation curve already defined for Normal Production applications, the inverter and electrical motor needed a dedicated calibration for the degradation strategy at high temperatures.
The following temperature measurements have been taken into account to determine the maximum available torque:

- Temperature of the electrical machine (wirings)

- Temperature of the inverter

The final calibration values were determined during tests on the road and on track, studying the available temperature measurements: these values allowed keeping the electric motor temperature below a maximum value of about 130℃ in long duration tests on track.

2.5.10 Emissions optimisation

The engine used is equipped with a 3-way catalyst and lambda control and works in quasi-stationary condition (Range Extender). In this behavior the emission are very low because the maximum efficiency window of the cat is easy to achieve.
For this reason the activity to reduce the emission is focused during the first minutes after the start of the engine when the thermal transient of the catalyst ("light-off phase") don't allow to have a good efficiency of pollutants conversion.

In NEDC cycle for a traditional ICE vehicle motored only with a CNG engine most of the pollutant emissions are produced in the acceleration maneuvres during the Light-off catalyst phase (first 100 sec of the cycle) see figure below.
Using a RE unit it is possible to have a dedicate tuning of the Light-off phase in order to avoid engine operating points with high emissions. After reaching a good catalyst temperature and conversion efficiency RE is free to produce the energy required.

The strategy followed to optimize the emission is to regulate the engine with a low combustion efficiency (low spark advance) and in self-sustaining mode during the light off phase, a lean mixture is adopted in order to produce the minimum possible of unburned hydrocarbons and CO.

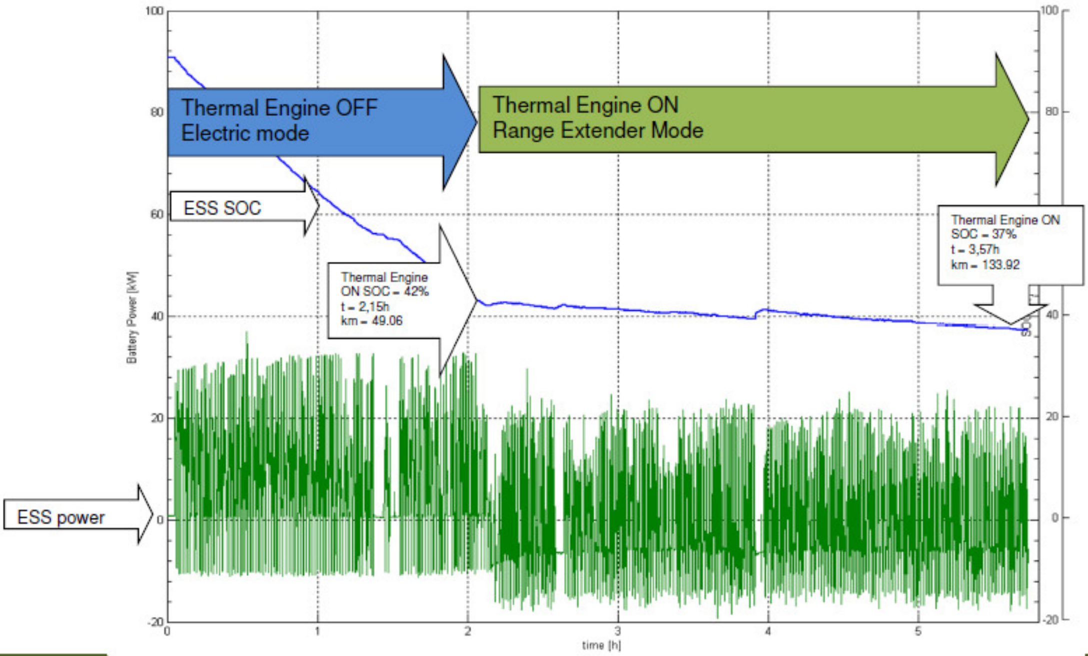
2.5.11 Control SW definition and tuning

According to system requirements and specifications a specific control sw was defined and implemented:

- Main input are: actual SOC, vehicle speed, e-drive power (ESS Voltage), e-mode requested and target SOC;
- Output are: APU requested status, OFF or ON and APU requested power;
- APU management strategy was defined according the following main drivers:
    - Smoothed load follower strategy to reduce ESS energy throughput
    - Engine stopped when vehicle is running below a fixed minimum speed
    - Engine stopped (E - mode) if SOC ≥ defined value 1
- APU requested power according optimized design point, from 5 kW to 30 kW;
- E-mode on request and if SOC ≥ defined value 2;
- Load follower strategy adjustment in order to reach / maintain a defined target SOC.

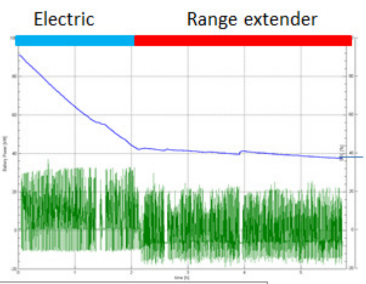
VMU Control SW for APU management was uploaded and preliminarily tested and tuned, before starting assessment tests.

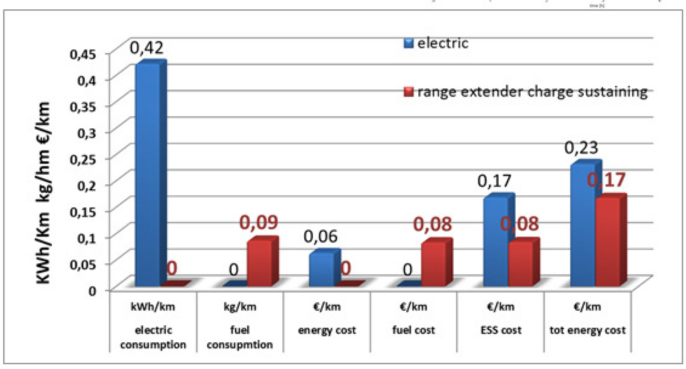
2.5.12 Tests results



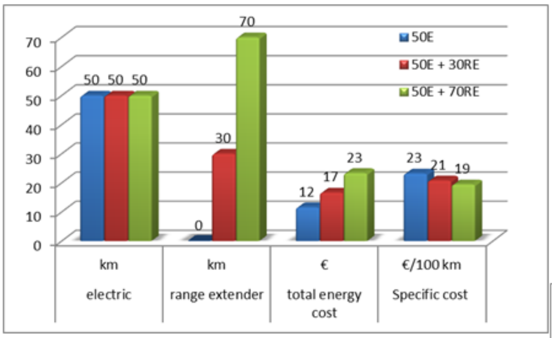
Test results

Consumption form logged data and energy costs including ESS cost
Red pillars evaluated according charge sustaining behavior in RE mode (red pillars)





CNG: 0,965€/kg
Electricity: 0,15€/kWh
Battery Energy throughput cost: 0,40 €/kWh



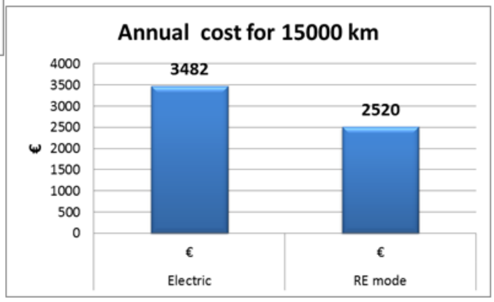
Annual mileage cost:

- 15000 km/y
- 3482€ if always electric mode
- 2520 if always in range extender cost

Daily Mode, km and total energy cost:

- 50 km in electric mode (blue)
- 50 km in EM + 30 km REM (red)
- 50 km in EM + 70 km REM (green)

Cost/km decrease with REM depending on actual ESS cost for energy throughput (ESS life time) most significant in EM



Range extender system with load follower APU has shown the following advantages:

- Allows all electric vehicle benefits
- Avoids range anxiety
- Increases EV flexibility and range
- Reduces investments costs
- Allows more than 60% EV mode overall a year
- Reduces EV TCO on the same yearly mission
- Is suitable to use renewable electric energy and fuel
- Increases energy efficiency

2.6 WP 6 – System integration

2.6.1 Introduction

The role of the Robert Bosch GmbH (Germany) and the Robert Bosch AG (Austria) was defined in WP6, to perform major activities as

- Design and delivery of an electrical machine for optimized use as Range Extender.
- Uses: to start the combustion engine and generate electrical energy by the rotational torque of the combustion engine.
- Design and delivery of power electronic unit.
- Uses: to control the E-Machine for combustion engine start up and providing a DC current for charging the battery.
- Specification of functional control of the combustion engine by the Bosch Electronic Control Unit (ECU) ME17 and development of a common control strategy for an encapsulated Range Extender system with respect to the different needs of operation, safety and charging the battery.
- Support of an Operation Strategy for an easy functional implementation of this Range Extender system into the vehicle.
-

In the following positions the complete activities and their main results for the developed Range Extender system will be described.

2.6.2 Overview Bosch Range Extender System

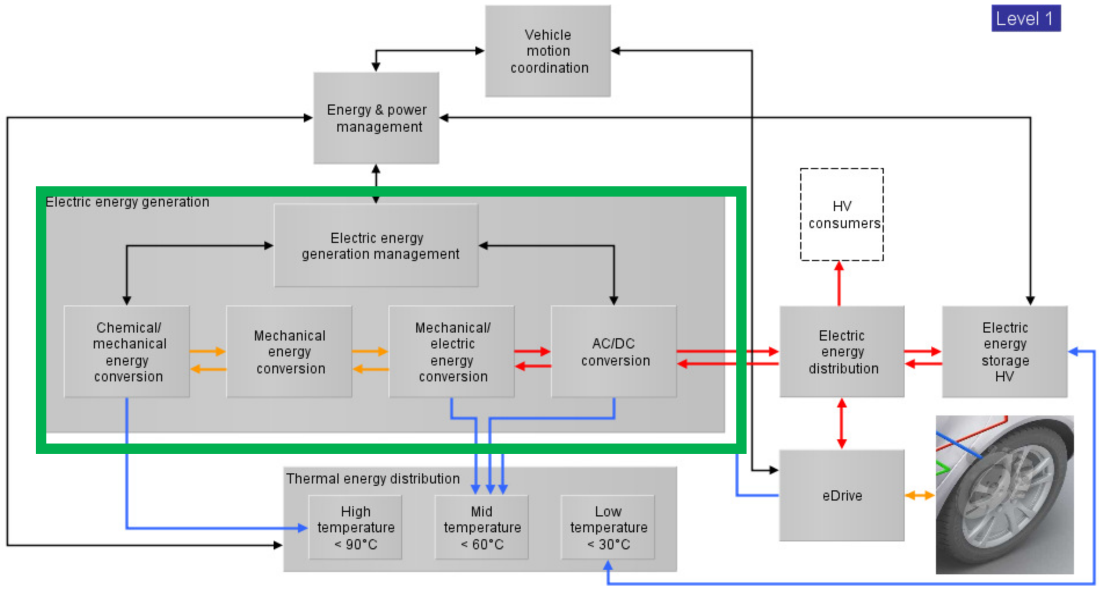


Figure 31 - Bosch Range Extender system as a part of an BEV (Battery Electric Vehicle)

All the interfaces to the BEV (**B**attery **E**lectric **V**ehicle) for a functional Range Extender system must be developed with respect to the design of the system and their components. Therefore during design of the electrical machine (marked in this report as generator) all the requirements for direct coupling (ALTRA use) and indirect coupling via belt drive (Volvo use) to the combustion engine and cooling demands must be met. The power electronic unit must fulfil all the demands of the High Voltage supply system required by the HV-battery and guarantee excellent efficiency with the electrical machine for charging the battery while meeting cooling demands. Additionally the ECU must gather data from all the needed sensors and actors to control the combustion engine for a safe and efficient operation in alignment with the generator and the power electronic unit.

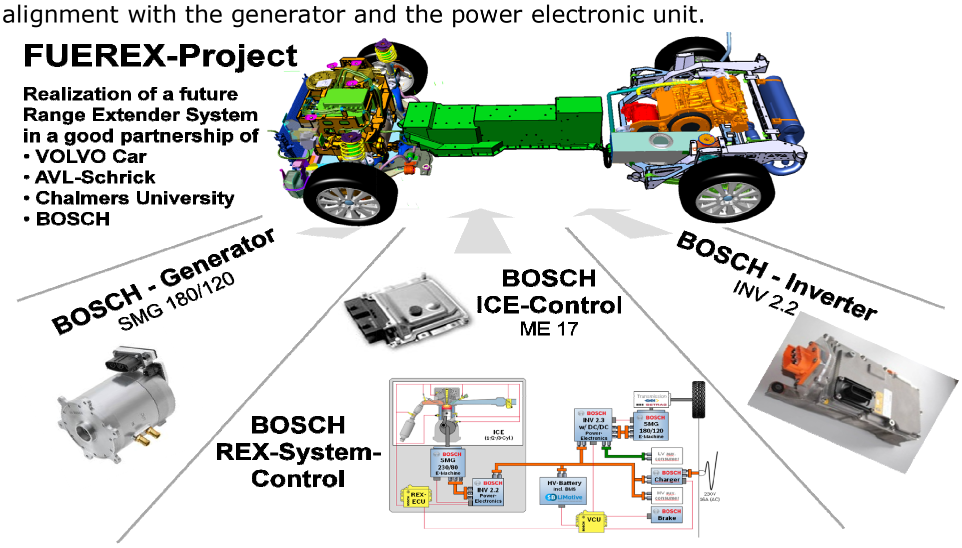


Figure 32 - Overview of components of the Bosch Range Extender System in the FUEREX project

The Bosch system is designed as an encapsulated system that regulates on one side the combustion engine with means of the Bosch ECU ME17 and on the other side the Generator SMG 180/120 (mechanical connected with the combustion engine), fully operated by the Power electronic unit INV 2.2.

2.6.3 Design and specification of the electrical machine

The requirements for the concept of the electrical machine and power electronics must fulfil the demands for rectifying the alternating current, charging the battery and starting the combustion engine. It is important to make the correct choice of the appropriate system concept, electrical and mechanical layouts, mechanical linkage and electrical connection as well as thermal cooling. The generator is designed as a 3-phase synchronous electrical machine with permanent magnets, shielded alloy housing and integrated water jacket cooling. The coupling to the combustion engine is designed in one version for a direct mounting to body parts of the combustion engine (ALTRA) and in another version by coupling via a newly designed belt drive (Volvo). The belt drive allows a ratio with best efficiency of the generator in combination with the speed range of the Volvo combustion engine.

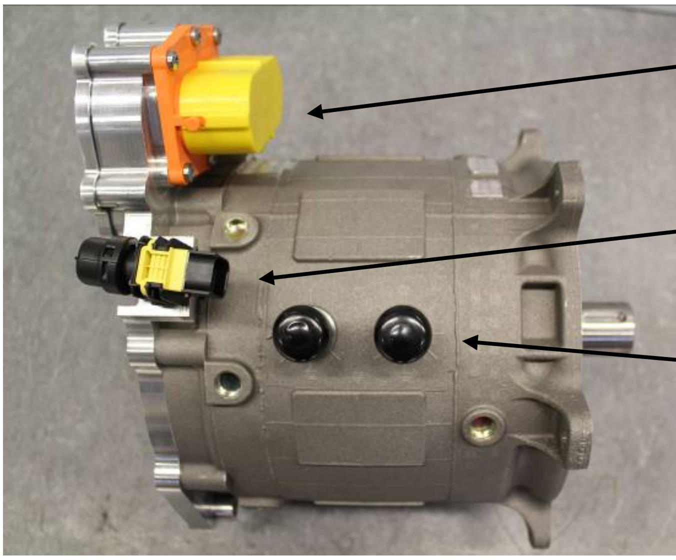


Figure 33 - Picture of the designed generator SMG 180/120 FUEREX

The electrical machine is connected to the power electronic unit by three different electrical connectors:

- 3 phase High Voltage cable to the power electronic unit.
- Temperature sensor for thermal control of the stator (measured with the help of a NTC sensor) and HV Interlock signals (to avoid electric shock caused by direct and indirect touching) in a common connector to the power electronic unit.
- Speed and position measurement of the rotor in the generator (Resolver for rotor position) for direct and efficient control of the machine by the power electronic unit.

Dimensions and weights of the designed Electric machine:

Length: 225 mm (including sensor cover / HV Cover)
Diameter: 212 mm (not including water cooling connections and flange for combustion engine)
Weight: 31 kg (without coolant)

EM-Type	PSM 3-phase synch. electrical machine with permanent magnets
Cooling	coolant: 50% water + 50% glycol
	Inlet temperature: ~ 85°C
	Flow-rate max: 8l/min @ Pressure drop < 300mBar
S1 gen. mode	Mechanical power: EM shaft @ 200V: 20kW (91Nm @ 2100rpm)

S2 - 2h gen. mode	Mechanical power: EM shaft @ 200V: 40kW (116Nm @ 3300rpm)
S2 - 3 sec. Motor mode	Transient torque for ranking = 150Nm at low rpm (transient performances)
Operating rotational range	Rotational speed: cranking at 400 rpm possible
	Rotational speed: 0 rpm to 8000 rpm
Overspeed	14 000 rpm
Protection Class	IP6k9k & IPx7 according ISO 20653.
Sensors	Thermal measurement of electric machine: NTC sensor
	Position measurement of electrical machine: Resolver for rotor position

Figure 34 - Main Specification for the designed generator SMG 180/120 FUEREX

2.6.4 Design and specification power electronic

The design of the power electronic unit must fulfil the requirements for rectifying the alternating current, charging the battery and to start the combustion engine. For this the electrical and mechanical layout takes care of the requirements for the mechanical link, electrical connection, cooling demands and the needs of the high voltage net (including battery and other components which are connected to HV).
So in the design of the power electronic unit various requirements for HW characteristics must be met in order for the design parameters, thermal limits and robustness to be optimized for all mechanical and electrical design.
The power electronic housing is made of shielded metal for mounting directly to body parts of the vehicle. The power electronic will be connected to the electrical system by three different electrical connectors. The design of the connectors for the cooling liquid of power electronic and generator is the same.

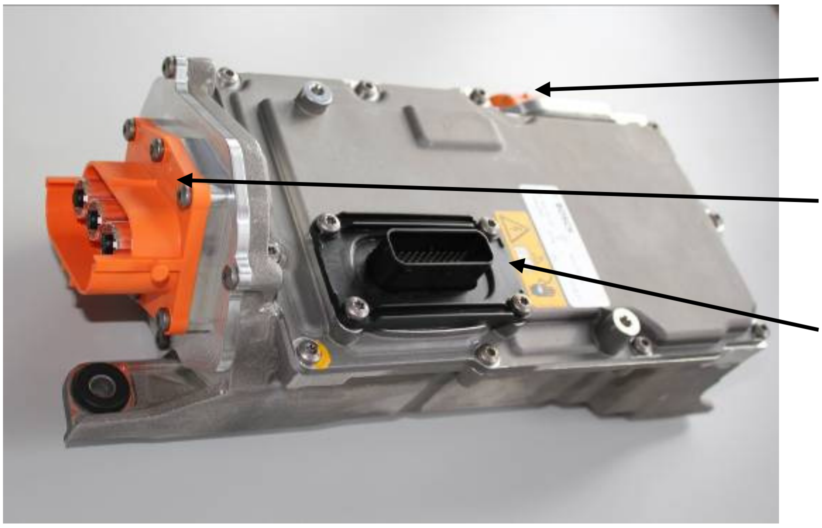


Figure 35 - Picture of the designed power electronic unit INV 2.2 FUEREX

Designation	Min	Max	Unit	Remarks
Voltage area	0	420	V	@-40..105°C ambient
Unrestricted operation at Tw<=75°C	150	400	V	@40..105°C ambient max. continuous current: 250A
Unrestricted operation at Tw<=85°C	190	400	V	@-40..105°C ambient
Range of the controlled	0	200	Aeff	Value range for the controlled output current as

output-continuous current in the unrestricted operation at Tw<=85°C				per setpoint specification at max. continuous current 150Aeff @ 40..105°C ambient
Peak current in the unrestricted operation at Tw<=65°C	200	250	Aeff	

Figure 36 - Operational limits for the designed power electronic unit INV 2.2 FUEREX

The CAN communication between the ECU ME 17 and the power electronic unit INV.2.2, implemented as a private CAN-Bus, ensures the proper and safe control between both components. The ECU receives the desired electrical power and "on/off" requests via vehicle CAN and forwards this demand on one side to the combustion engine for mechanical power (torque) and on the other side to the power electronic unit in the Range Extender system (rotational speed). To do this the power electronic unit receives the actual values for operation mode and electrical power and provides the needed electrical current via high voltage connection due to the desired limits of the battery. The feedback of the internal signals from the power electronic unit to the ECU via internal CAN is basis of an efficient closed loop control.

The SW structure of the power electronic unit will be able to operate in different operating modes:

- Torque control: a specified set point torque is set (internal torque model controlled).
- Speed control: internal power electronic unit controls a setpoint speed.
- Standby: defined as a safe state in a case of an error or shut down.
- Pre charge: pre charge status from first HV activation command till the HV battery contactors is closed.
- Discharge mode: active and passive discharge of internal capacitors in case of an error or shut down.

2.6.5 Specification Range Extender Control Strategy

The ECU ME17 is responsible to control the combustion engine and the power electronic unit. It is able to fulfil following requirements in the FUEREX project:

- The 3 cylinder Port Fuel Injection (PFI) engine shall be supported with external ignition according to the specification of the FUEREX partner Volvo.
- The combustion engine is supposed to have a simple set up (PFI, no turbo charging, no camshaft phasing and no air flow sensor). Use of Gasoline fuel or Ethanol shall be supported.
- The HW setup supports two CAN buses, one for the connection to the range extender power electronic unit and the second one to the Vehicle Control Unit (VCU).
- The design of the HW supports a normal average lifetime of a car.
- The HW shall be capable to support future EU6 functionalities.
- The cost of the range extender package shall be limited, so the ECU can handle low prices for a potential future series production.

Figure 37 - Figure of an ECU ME17 for FUEREX project

The ECU ME17 can control the combustion engine components such as electrical throttle, lambda sensors, in tank fuel supply unit, injectors, external ignition, coolant temperature, intake air pressure and ambient temperature sensor, knock sensor, crank- and camshaft sensor, canister purge valve and the electrical pumps for power electronic unit and combustion engine coolant.

The projects started with the first design of the system architecture and the control layout, followed by functional simulations of the static and dynamic capability for the control algorithm of the Range Extender system. After the implementation of the described functionality, the testing and verification at AVL-Schrick, Volvo and Chalmers University took place. As a result of the different test phases some additional enhancements were designed and implemented.

In the FUEREX project new functionality was especially developed to solve robustness issues (cranking, dynamics) and interface changes. Also an advanced starting torque/speed control of the generator, an optimization in the generator control and catalyst heating were successfully developed. The code implementation of the functionality was secured by performed integration system tests in the vehicle.

Together with the FUEREX partners AVL-Schrick and Volvo following integration and verification strategy we agreed:

- LAB CAR for ECU functionalities: Closed loop tests on a test environment within Bosch (HIL). A physical closed loop laboratory car model simulated the electric vehicle, the CAN interface to the vehicle and the power electronic unit as well as the generator.
- EMULATION TESTBENCH: For power electronic unit functionalities – here the whole power electronic software and also hardware was tested in a real environment
- TEST BENCH: A physical real world test of the complete range extender unit was done before the vehicle integration at a test cell together with AVL-Schrick. The combustion engine, the engine control unit, the power electronic unit and the generator worked successfully together and produced electrical power. The test procedure included the control of the HV battery by an emulated battery control module.
- VEHICLE: Finally, the complete REX system was mounted in the vehicle. The battery control unit as well as the vehicle control module communicated with the ECU directly via CAN. The vehicle control module calculated the "engine-on" request as well as the selection of the necessary electrical power, depending on the state of charge of the battery as well as the vehicle dynamic and NVH demands.

According to this verification plan all needed functionalities of combined combustion engine and power electronic unit operation for active battery charging and safety were demonstrated with the Bosch Range Extender system for the FUEREX project.

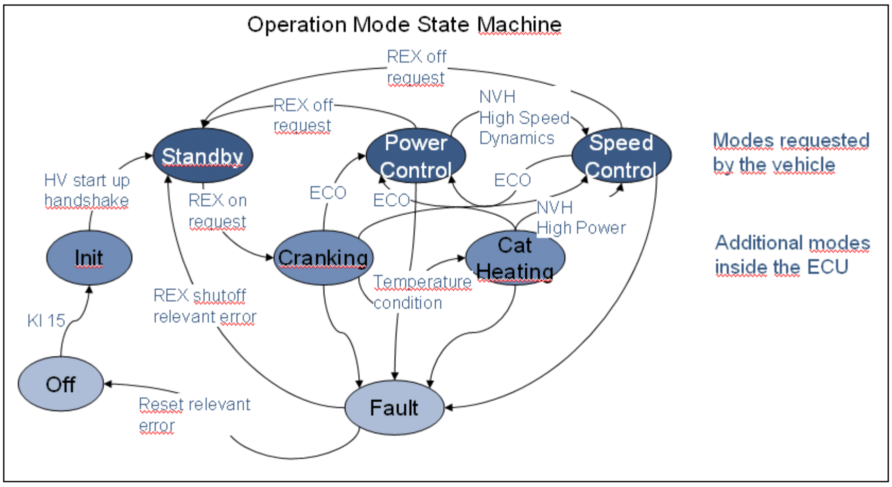


Figure 38 - Range Extender ECU state machine for the FUEREX project

In power control mode, optimal operation points are selected by the ECU control algorithm in order to achieve a highest efficiency of the Range Extender unit. Figure 9 shows the efficiency of the generated electrical power by generator/power electronic unit as a function of rotational speed and torque of the combustion engine.

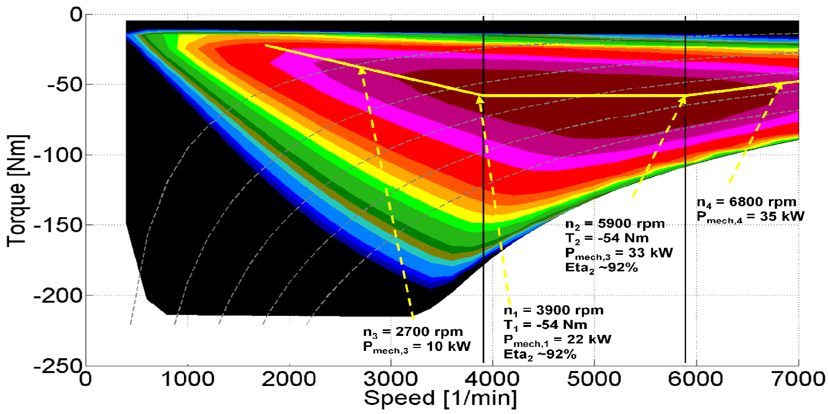


Figure 39 - Area of high efficiency operating points of the FUEREX Range Extender

2.6.6 Vehicle Operation Strategy of the Range Extender system

Together with Volvo the following functionalities could be demonstrated as a main result by implementation of the Bosch Range Extender system in the Volvo C30 BEV demonstrator.

- Communication with the Vehicle Control Unit (VCU) and the Battery Management System (BMS)
- Battery high voltage start up (connected additionally with the range extender unit)
- Engine cranking and switching to generator mode
- Cranking with start of injections at high engine speeds
- Cat heating
- Power control mode with automatically selected operation points (including control improvements)
- Speed control mode by VCU preselected operating points
- Dynamic transitions: fast response for negative power drop, ramped transition for power increase
- Combustion Engine shut down

2.6.7 Conclusion for Bosch Range Extender System within FUEREX

The Bosch system architecture supports an integration of the shown range extender unit into an existing electric vehicle. The Range Extender can be easily activated or deactivated via control of the vehicle as demanded and the desired electrical power is delivered as demanded to the vehicle.

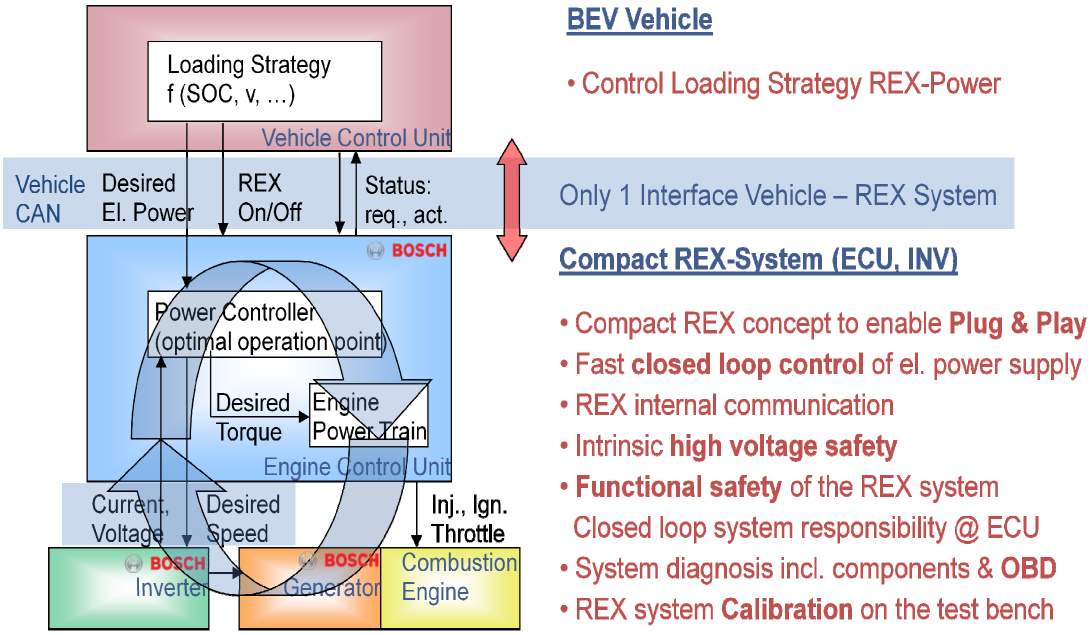
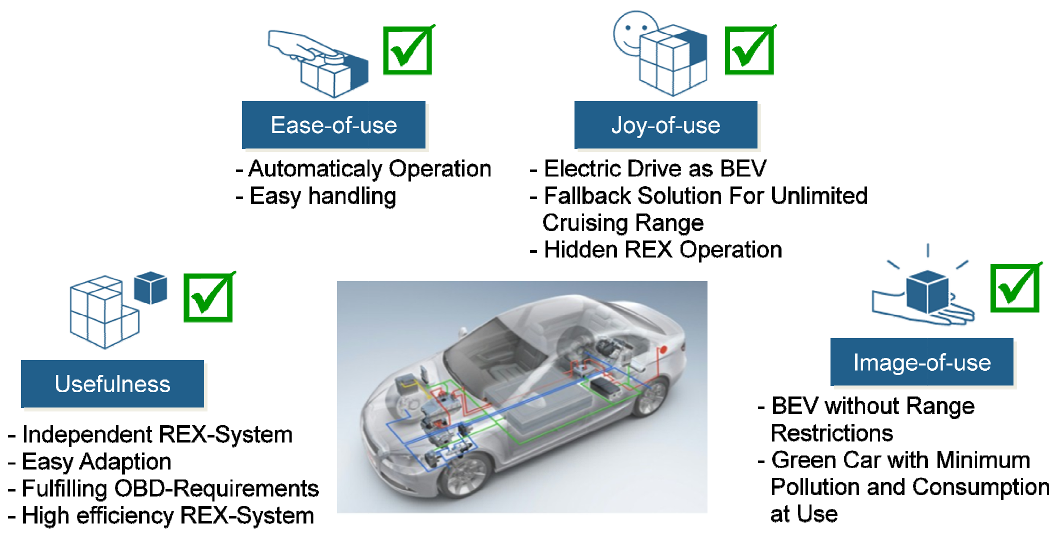


Figure 40 - Control structure of the Bosch Range Extender system for FUEREX

The Bosch Range Extender system is an intelligent solution to fulfill all user demands for unlimited electric drive using a range extender unit in a BEV vehicle and to avoid any concern about range anxiety.



This Range Extender is build-up and demonstrated in the FUEREX project and is now ready to be adapted into different series projects in future.

2.7 WP 7 – Analysis of performance, control strategy and sizing for different driving cycles

To be able to optimize the size of the range extender and the battery as well as defining an optimal control strategy it is vital to define how the vehicle will be used. Different usage will of course lead to different optimal design. However, it is important that the selected sizing is suitable for a wide spectrum of use. Therefore, several driving cycles for different types of driving is being defined to provide a robust design of the system and to be able to analyse the performance for a spectrum of typical usage profiles. I.e. it is not sufficient to describe an average driving for a vehicle type, as different vehicles of that type will experience very different types of driving. It is for instance very important to model the variation in daily driving distances accurately as that will significantly influence the required size of the battery and the real life fuel consumption significantly. Also the charging patterns must be modelled as well as cold starts of the engine. All in all this means that a large set of driving cycles are required to describe all these aspects.

The method to create the driving cycles are based on combining complete daily driving cycles by combining different shorter micro trips in such a way that the reflect a realistic variation in both driving distances, speeds and type of road as well as traffic condition. It has been decided to create the driving cycles from different cycles from the ARTEMIS project as these are well documented and cover many different categories of both road and traffic conditions.

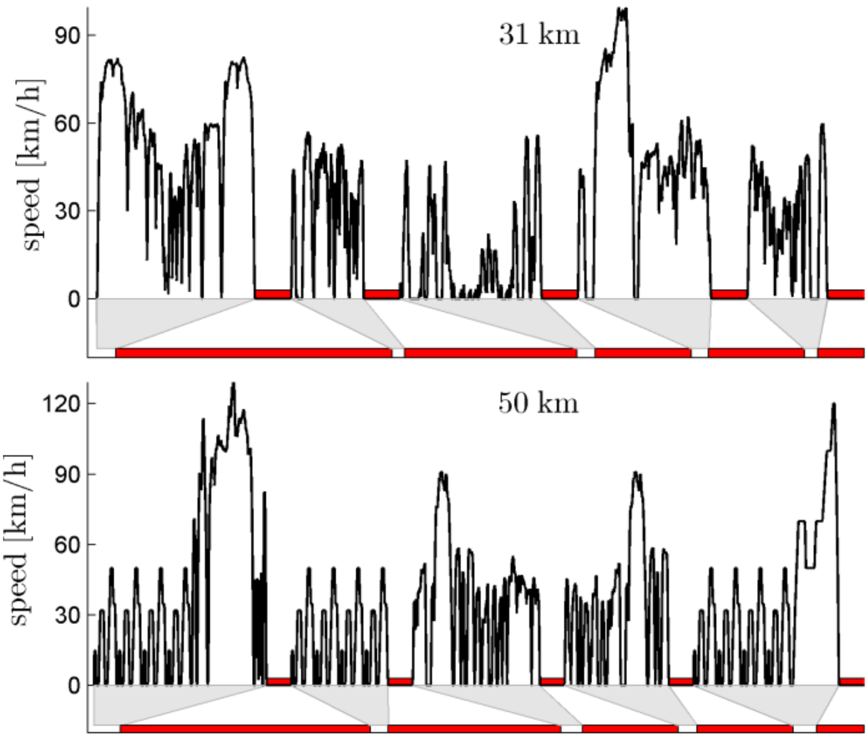


Figure 41 - Example of how daily driving cycles are created by combining micro trips from existing driving cycles. Note also that standstill periods are compressed.

The final step in the generation of the driving cycles is to adjust the cycle to the performance of the studied vehicles, as they have different performance and cannot always follow the base driving cycle. As a result the light distribution van will much more frequently use the maximum performance than the two passenger vehicles, as shown in the below figure where the operating points of three daily driving cycles of 31, 50 and 100 km are plotted.

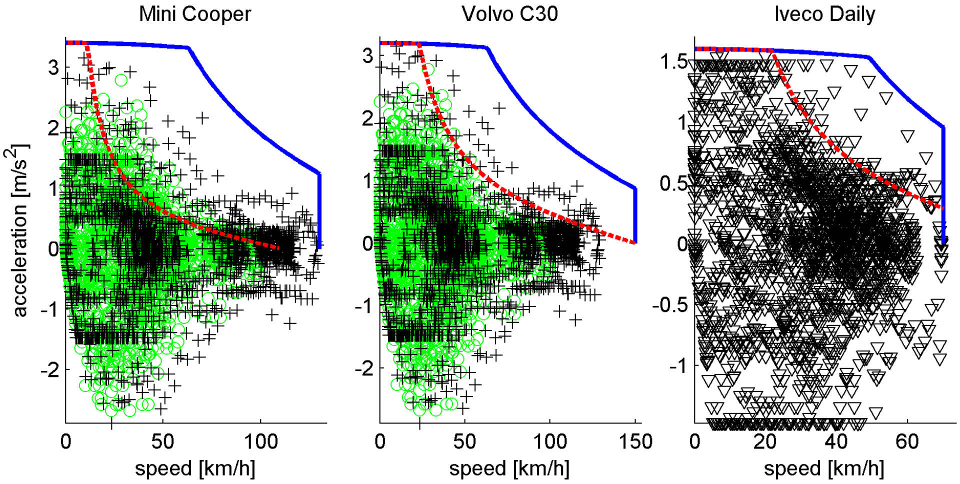


Figure 42 - Operating points of the duty cycles plotted together with the REVs performance requirements. The 31 km, 50 km and 100 km duty cycles are marked with circle, plus and triangle, respectively. The REV performance in charge depletion and charge sustaining mode is given with solid and dashed line, respectively.

The method to create the driving cycles have been defined, and when including all the aspects which are found important the total length of the driving cycle needed would become impractical long. Therefore there is a need to produce a compressed version of the driving cycles in order to have a manageable length of driving cycle which is still capable of describing all the important aspects like the variation of daily driving distances. The main methods to compress the driving cycles which has been used are:

- To use a weighting factor for different parts of the driving cycle instead of repeating parts which are frequent.
- Standstill periods are modelled as one time sample, of variable length, to be able to calculate battery charging and cooling of the engines without having to simulate in many steps.

The consequences of different sizing of the range extender power has been analysed both in terms of which possible combinations of range extender power and battery power are possible and what their consequences are, but also comparing the sizing with the real world usage of 470 cars, to see how often different small range extenders may lead to limited performance. In the Figure below it the different possible combinations of battery power and range extender power are shown. In report D 7.2 the options are discussed. In FUEREX it is concept 4 which has been chosen for all three vehicles.

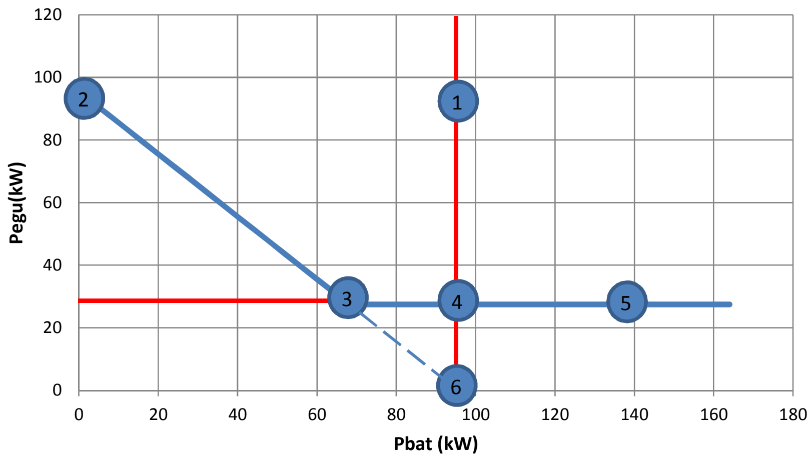


Figure 43 - Different possible combinations of battery power and range extender power.

The consequences of selecting a smaller range extender than what is needed for the extreme cases, is a significant cost saving but also a small risk that the performance expectations are not always met. The risk of reduced performance is however very small, because if there is sufficient energy left in the battery it can support the range extender and therefore overcome temporary high power demands. However, the critical situations are the ones with have average power for long times, as the battery may then be emptied. This is typically the case for high cruising speeds, which will decide the minimum range extender power. In the figure below it is plotted what percentage of the total driving distance which can be met fully with a range extender of different size, assuming that the battery is discharged and can only supply small amounts of energy for accelerations.

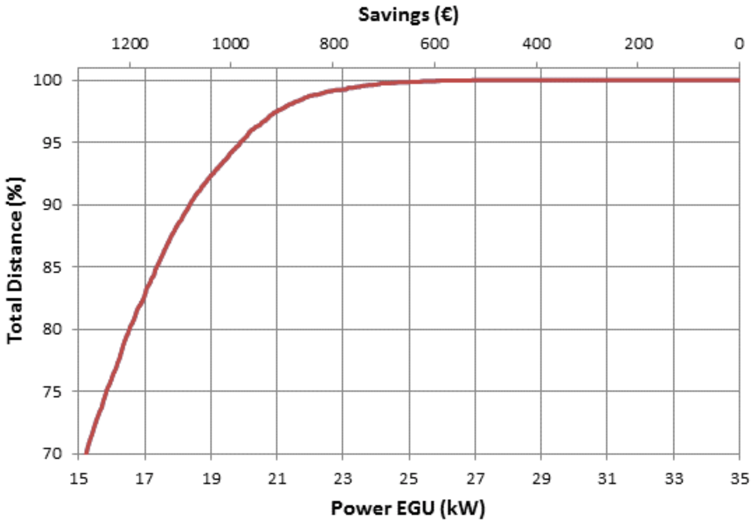


Figure 44 – Percentage of the total distance which can be met without performance limitations as function of range extender power, and potential cost saving.

In the table below the fuel consumption is presented for charge sustaining mode in the NEDC and at a constant speed, 110 km/h for the passenger cars and 70 km/h for the light distribution van.

Table 2 - Fuel efficiency for the vehicles in Charge sustaining mode (l/100 km)

	Mini	Iveco Daily	Volvo C30
NEDC	3,88	7,13	3,73
At 110 km/h	4.79	(above top speed)	4.78
At 70 km/h	----	11.48*	----

**) The range extender power needed to drive 70 km/h continuously exceeds the peak power of the range extender slightly. The fuel consumption value given is based on extrapolating the range extender fuel consumption slightly above its peak power.*

As can be seen from these results the fuel efficiency is very good even in charge sustaining mode, i.e. when the vehicles are run without energy from the battery (on average). The fuel consumption will in the NEDC cycle correspond to 90 g CO_2/km for the Mini and 87 g/km for the Volvo. Both these values are lower than the best diesel version of the same vehicles. The light distribution van emits 166 g/km which is also very good for such a big and heavy vehicle.

The vehicles are normally primarily driven on electricity until the battery is emptied. Only the remaining distance will be driven on the range extender until the next charging opportunity. This means that the average fuel consumption per 100 kilometer will be much lower than in charge sustaining mode. To estimate the average fuel consumption there is a standard for how to calculate this consumption for the certification cycle (NEDC), which has been used to calculate this average consumption in the table below. Also it has been compared with the consumption from a simulation for an optimization cycle DC5 used in the study of battery and range extender sizing in the FUEREX project. The results for DC5 agree fairly well with the average consumption for the NEDC cycle, but since the optimization driving cycle also includes some long drives, the range extender will be used more in this cycle, leading to higher average fuel consumption.

Table 3 - Mixed fuel efficiency for the vehicles in typical driving (l/100 km)

	Mini	Iveco Daily	Volvo C30
NEDC mixed	1,3	2.5	1,0
Optimization DC5	1,4	*	1,5

For the passenger cars this leads to a CO2 emission of 35 g/km or lower, which is well below the 50 g/km limit for super credits used in some countries. For the Iveco Daily this will correspond to very low CO2 emissions of less than 60 g/km.

2.7.1 Main results

The main results from WP7 are:

- A method of how to create driving cycles, reflecting not only an average drive of an electric vehicle but which is capable of modelling the main categories of different driving which a vehicle will be used in. The driving cycles reflect the variation in, for instance, daily driving distances and variation in road type and traffic conditions. The driving cycles are also defined such that they can reflect how frequent different type of driving are for different vehicle types. Reported in D7.1
- Developed the convex optimization model such that the Range extender vehicle can be modelled in a mathematically convex form, and such that the optimal control of the range extender power will be found through optimization for the developed driving cycles.
- Shown how the sizing of range extender is influenced by the driving profile of the vehicle, and how the size can be reduced if smart control is used to save energy in the battery for some extreme driving situations.
- Shown that battery electric vehicles without a range extender has a very small market niche, if the drivers are not prepared to change the driving habits, while a similar vehicle with a range extender can meet all the required driving situations for all the investigated drivers and normally also lead to a lower cost.
- Summary of the results for the three range extenders on a vehicle level.

3 Impact

3.1 Potential impact

The targeted **final result of FUEREX** is to prove **within 2 years from its start** the feasibility/viability of the RE technology for the markets for sub-compact passenger cars up to light duty commercial vehicles by delivering:

1. Three REs with multi-fuel capability demonstrating state of the art performance and integration;
2. Bench test demonstrating emissions, efficiency and performance for the total RE;
3. Vehicle test demonstrating integration/NVH and vehicle performance;
4. A study on volume production optimization (low cost solutions);
5. Design guidelines of how a RE should be optimized for a given vehicle and how the RE itself is optimized.

Environmental impact of FUEREX

In Europe, the European Union is committed under the Kyoto Protocol to reduce GHG emissions by 8 per cent by 2008-2012 compared to the 1990 level. In addition, the EU has committed to a 20% cut in its greenhouse gas emissions by 2020. The EU has also adopted a target improving energy efficiency in the European Union by 20% by 2020.
These targets were legally implemented with the adoption of the “climate and energy package” in December 2008: this package contains laws on the emissions trading scheme, “effort sharing”, carbon capture and storage, renewable energy, transport fuel quality and car emissions.

The **FUEREX concepts meet these targets** and even more important the project will address all the main obstacles for developing successful REs for battery vehicles paving the way for a broad introduction of RE-BEV’s and thus play a major role in the greening of the transport sector in Europe.

Compared to regular fuelled cars the environmental effect of introducing FUEREX powered BEV’s to the market is obvious: zero emission in city driving and capable of running on bio-fuels for longer distances.
In the environmental comparison of conventional BEV’s and RE-BEV’s, another important issue related to the battery mass is worth mentioning. The specific power density of a battery system is in the range of 0.1kW/kg, thus a nominal range (extension) of 100km requires an additional battery weight of 150 – 200 kg, which is equivalent to a surplus in fuel demand 0.4 to 0.8L /100km in customer duty. The range extension by a RE engine has a much lower weight penalty for common customer range requirements leading to only a minor fuel consumption penalty relative to an urban area BEV with a range of 50km only.

Strategic and economic impact of FUEREX

With the global requirement to reduce CO_2 emissions driving a move to the increased electrification of the vehicle, the realities of economics provide a serious challenge for electrical cars. Whereas stationary energy consumers do not require a significant energy storage capability, vehicles do and current battery technology is both heavy and expensive.

The main issue with BEV’s is that costs of batteries are too high to accommodate most customer driving range demands, which significantly limits the possibility for BEV’s to be sold in large numbers. Specific battery costs are between 250 and 500 €/kWh. It can be seen that the battery cost for a passenger BEV with 160 km driving range will be between 10,000 and 20,000 €.

If we assume a retail price of 1,500-2,500 euro for an integrated FUEREX range extender then system cost savings in the order of 5,000-10,000 euro seem feasible bringing down the selling price of a RE-BEV significantly. However, it must be noted that cost competitiveness will also highly depend on future electricity and oil prices, and consumer willingness to pay more (or possibly less due to government taxation incentives) overall for BEVs than similar ICE vehicles.

Market introduction of RE-BEV’s will be accelerated directly by the FUEREX auto manufacturers Volvo Cars and the FIAT group (represented by Altra/Iveco) but also through the RE engine manufacturers in the AVL group and 1-tier automotive supplier BOSCH that will supply other car manufacturers with integrated RE solutions. Obviously, both exploitation routes will have beneficial effects on Europe's automotive industry in terms of competitiveness and employment.

3.1.1 AVL City EV with range extender, IVECO electric Daily with CRF 2-cylinder range extender and Volvo family car with AVL-Schrick 3 cylinder range extender

The final user as a customer is requesting "green", reliable technology at affordable costs. EV technology is on a good way with promising results, but it is expected that it will need some years to overcome mainly the cost and lifetime topics. Therefore RE technology can provide an adequate offer to the end consumer for the next years. Besides the cost factor, the range anxiety is a major concern that can be overcome with RE EV. Another benefit is the (almost) "free of charge" heating, when taken from a combustion engine, which would be very expensive and associated with a significant range reduction, when taken out of battery energy of the pure BEV. For the automotive customer – typically the OEM community - a well-integrated design solution, which is respecting all constraints (e.g. energy + thermal management, package, lifetime, business case etc.) from design sources and system suppliers is a major advantage in the development and implementation of this kind of technology.

3.1.2 Chalmers Analysis of performance, comparison method

The results from the analysis of the sizing and control of the range extender vehicles has contributed to a better understanding of the influence of different car usage profiles. It is clear that the range extender vehicle should not be optimized for an average user. This knowledge will make it easier to develop more attractive range extender solutions for different types of users. Allowing a better adaptation to different users will most likely make the range extender vehicles attractive for a larger number of users and increase the market niche for the range extender vehicles.

The convex optimization method which has been adapted for range extender vehicles, and partly developed within FUEREX, is a tool which allows the optimal sizing and optimal control to be studied very effectively. The method enables the use of long driving cycles in the analysis, which reduces the risk for sub optimization and leads to more robust designs. The method requires much less computation time than other optimization methods and thus allows analysis of many different types of vehicle use and many different performance specifications without being too resource demanding. A tool which allows quick exploration of different design strategies is expected to lead to better developed REX concepts which will be more robust for variations in driving conditions and thus have a better cost-benefit ratio for both the car buyer and for the OEM who may need fewer variants.

Even though the convex optimization tool can handle much longer driving cycles than other optimization methods, there is still a need to compress the driving cycles a lot in order to handle them effectively. Within FUEREX a method which allows compressing driving cycles has been developed. It can represent different distributions of driving ranges in a relatively short cycle, by the use of weighting factors influencing the cost function in the optimization, and by altering the sampling time during charging. This method allows a reduction of the length of the test cycle of about 10-100 times, further improving the computational efficiency significantly.

3.2 Dissemination activities

To accelerate the acceptance and implementation of Range Extended Electric vehicles, which is one of the main objectives of the FUEREX project, the Dissemination activities were initiated since the beginning of the project. For this, several tools were setup and used and at the end of the project also a half day session at the eMobility conference was organised to show the final project results to a wide audience.

3.2.1 Website – www.fuerex.eu

The FUEREX website is divided in two parts; a public site and restricted area only for partners.

The public website has been designed to act as a contact point for third parties who might be interested in the progress and/or outcomes of FUEREX project. It provides a brief summary and information on the project. The partners involved in FUEREX are also presented in the website, and all their logos are linked to their web sites.
The objective of the website is to inform the general public of the ongoing and ended research activities through hosting the flyers and technical project publications, providing links to EC documents on Electrification of the European fleet and to other research activities, especially to the Green Car programme.
All the information displayed in the project website is updated and maintained on a regular basis.

Uniresearch has created an exclusive logo for the FUEREX project:

Figure 45 – FUEREX logo

3.2.2 Flyer and Newsletters

A **dissemination database** has been generated based on contact databases from the partners. The database includes person names, organisations and their contact details. It includes over 200 contacts clustered in the following categories: Car manufacturers, Suppliers, Research Groups, Academia and Others. This grouping allows for dedicated mailings to the various groups. The database is used for the distribution of the flyer, the newsletter and invitations for the public workshop.

Also via the public website: www.fuerex.eu it is possible to register for the FUEREX Newsletters and Flyer. For this there is a link on the home page to register to the newsletter:

Since the database contains contact details of many persons, the database itself is kept confidential within the consortium and will not be used for other purposes than explained above.

3.2.2.1 General Flyer

A general Flyer is created in the first month of the project and distributed to all relevant stakeholders, using the dissemination database. The flyer is also published on the website as news item and under downloads, FUEREX Public Flyer.pdf.

Figure 46 – General Flyer

3.2.2.2 Newsletters

In the project, in total four newsletter are created and published with a frequency of approxamity 6 months. All four newsletter are send to the contacts and downloadable in the public website:

- 01.FUEREX-Newsletter.pdf
- 02.FUEREX-Newsletter.pdf
- 03.FUEREX-Newsletter.pdf

Figure 47 – All newsletters

3.2.3 Final conference

The final workshop for the FUEREX project was organised as special session to the eMobility conference in Graz, 30 and 31 of January 2013.
Session: Range Extender Concepts for Electric Vehicles: results of the EC funded project FUEREX. In total one overview presentation was given (Dr Sams, AVL) and five technical presentations by the Work package leaders.

The presentations are available on the FUEREX project website.

Figure 48 – The FUEREX presenters during the panel discussion

3.2.4 Publications

The Chalmers part of FUEREX has included development of a optimization method and adapting it for a vehicle with range extender. As this method has been jointly developed with other projects, and not all information about the FUEREX range extenders and vehicles are publicly available we have selected to use other vehicle examples in in our publications. These publications explains the method developed and how it us used and also explains some of the key features which has been developed. They focus on:

- Explaining this novel optimization method and why it is necessary for efficient analysis of sizing of powertrains
- A way to find an optimal engine on-off strategy for the range extender which is possible to use in the convex optimization of the power train.
- A way to model the battery including SOC dependent no load voltage which is mathematically convex. This allows for more accurate modelling of battery losses (and also allows other storage types, like super capacitors, to be optimized).
- A way to include battery wear in the optimization. This allows the controller to adapt is use of the battery such that the battery life length can be maintained even when the battery is sized and used in different way.

3.2.4.1 Peer-reviewed articles

- N. Murgovski, L. Johannesson, J. Sjöberg, B. Egardt, “Component sizing of a plug-in hybrid electric powertrain via convex optimization”, *Journal of Mechatronics*, vol. 22, no. 1, pp. 106-120, 2012.
- In this article we present a general framework that will allow a computationally efficient design optimization of electrified vehicles. The key contribution is convex modeling steps for solving the problem of simultaneous powertrain sizing and control of electrified vehicles which have access to predictive information.
- N. Murgovski, L. Johannesson, J. Sjöberg, “Engine on/off control for dimensioning hybrid electric powertrains via convex optimization”, *accepted at IEEE Transactions on Vehicular Technology*.
- Here we present a near optimal solution for integer variables which infringe convexity of the problem of simultaneous powertrain sizing and control of electrified vehicles. The proposed strategy is based on a synergy between convex optimization and Pontryagin’s maximum principle.
-

3.2.4.2 Peer-reviewed conference contributions

- N. Murgovski, L. Johannesson, J. Sjöberg, “Convex modeling of energy buffers in power control applications”, *IFAC Workshop on Engine and Powertrain Control, Simulation and Modeling (E-CoSM)*, Rueil-Malmaison, Paris, France, 2012.
- In this paper we show steps to remodel standard battery and capacitor models as convex, without any loss in modeling accuracy.
- N. Murgovski, L. Johannesson, A. Grauers, J. Sjöberg, “Dimensioning and control of a thermally constrained double buffer plug-in HEV powertrain”, *51st IEEE Conference on Decision and Control,* Maui, Hawaii, 2012.
- We show here a strategy based on convex optimization, to simultaneously size engine-generator unit and electric buffer in the problem of optimal control of series hybrid electric vehicle. We have also presented how thermal buffer constraints can be included in the optimization problem.

3.3 Exploitation of results

3.3.1 AVL City EV with Rotary range extender, IVECO electric Daily with CRF 2-cylinder range extender and Volvo family car with AVL-Schrick 3 cylinder range extender

Before the battery electric vehicle (BEV) will become a mass product – mainly due to the battery performances and related costs – range extended electric vehicles (REEV) will be an important bridge technology.

Besides the business case topic for the OEM, the automotive application potential will play an important role for all those concepts. On the one hand OEMs will use and adapt their existing high volume engines (e.g. GM VOLT / Opel Ampera) or share their engine families; on the other hand suppliers with strong capabilities in technology, production and financial background will get additional market shares with very innovative, future-oriented solutions.
A core business of AVL is solving specific issues in the engine and drive train development. Because of this, a continuous know-how extension in the field of range extender systems is very important. The gained experience has been and will be used in upcoming R&D and customer projects.

Due to the high market demand for better solutions than pure BEVs the demonstrator has already been presented at various events to potential customers and experts.
Core elements are going to be protected by patents to have a good base for licensing in customer projects. Project results are used for the development, manufacturing and serial production of competitive modules and systems for REEV applications.

E-mobility is already a business for AVL in the field of range extenders and battery technology. R&D work for REEV is absolutely necessary to address this market which is expected to grow much earlier than the market for pure Battery-EVs. AVL will use all the structures needed for the HEV business also for the REEV business.

An innovative and successful low-cost concept for REEV is not only very attractive for European customers, but also for customers in areas with high population densities and highest pollution rates, such as megacities in China and India.

3.3.2 BOSCH integration / electric components

The Bosch system architecture supports an integration of the shown range extender unit into an existing electric vehicle. The Range Extender can be easily activated or deactivated via control of the vehicle as demanded and the desired electrical power is delivered as demanded to the vehicle.

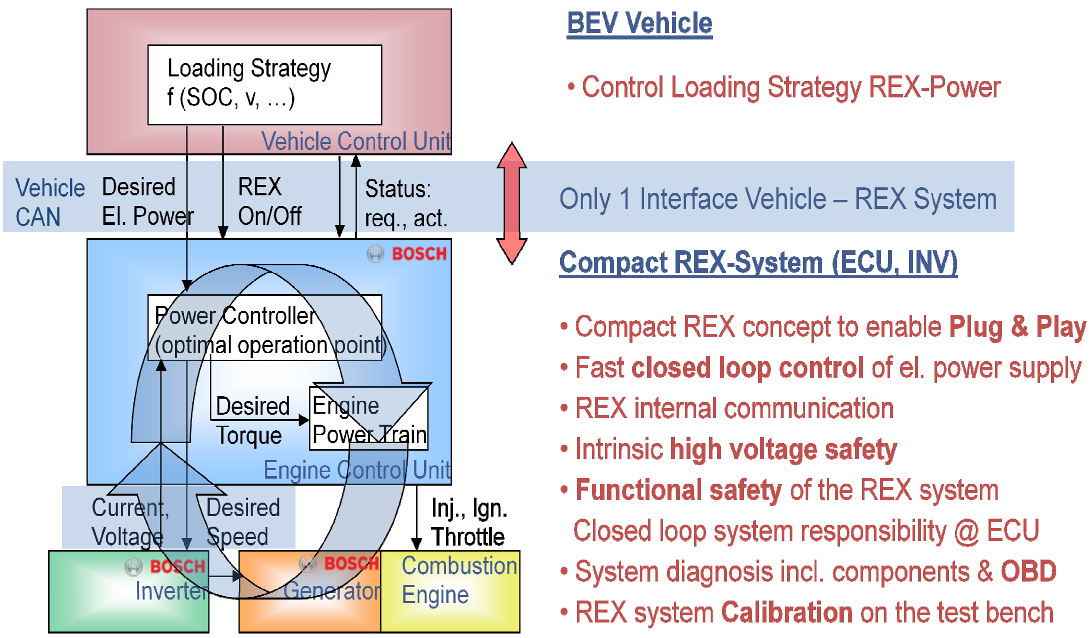
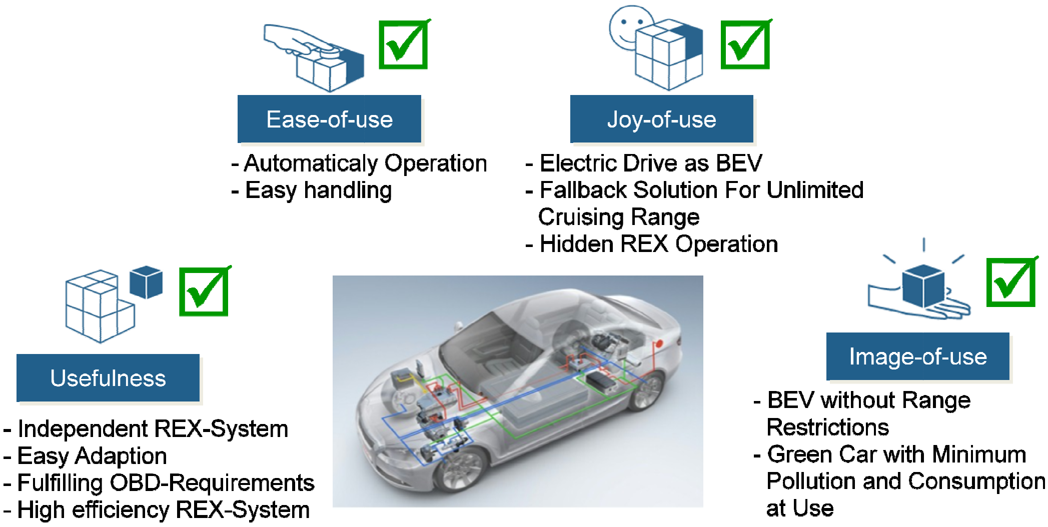


Figure 10 - Control structure of the Bosch Range Extender system for FUEREX

The Bosch Range Extender system is an intelligent solution to fulfil all user demands for unlimited electric drive using a range extender unit in a BEV vehicle and to avoid any concern about range anxiety.



This Range Extender is build-up and demonstrated in the FUEREX project and is now ready to be adapted into different series projects in future.

3.3.3 Chalmers analysis methods

The convex optimization tool, which partly has been developed within FUEREX, is a general tool and it has already found its use in several different research projects as well as design analysis studies together with vehicle OEM's. For example it has played a role in a project analysing plug-in hybrid buses with Volvo, where both the sizing of the battery in the bus but also the optimal charging infrastructure has been studied.

The method to create compact driving cycles for robust design has been one of the base components when the Swedish Hybrid Vehicle centre has started an industry-university collaboration project on tools to analyse driving and generate driving cycles for different usage like concept analysis (like in FUEREX), control design, diagnostic system development or control with preview.

4 Website and contact details

4.1 Website

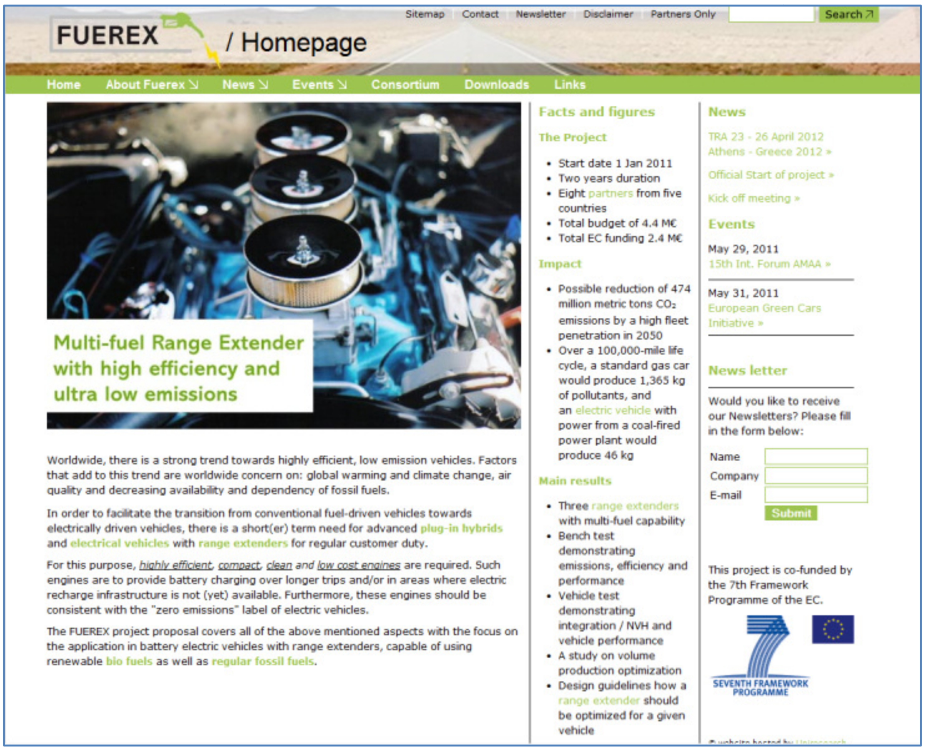


Figure 49 – Homepage of public FUEREX website

www.fuere.eu

4.2 Contact persons

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5 List of project participants

Participant no.	Participant organisation name		Country
1 (coordinator)	Uniresearch BV	UNR	Netherlands
2	AVL LIST GmbH	AVL	Austria
3	AVL Schrick GmbH	AVL-SCHRICK	Germany
4	ALTRA SPA	ALTRA	Italy
5	Centro Ricerche FIAT SCPA	CRF	Italy
6	Chalmers tekniska hoegskola AB	CHALMERS	Sweden
7	Robert BOSCH GmbH	BOSCH	Germany
8	VOLVO Personvagnar AB	VOLVO	Sweden