IMPROVED ENERGY EFFICIENCY FOR CONVENTIONAL VEHICLES THROUGH AN ENHANCED DUAL VOLTAGE ARCHITECTURE AND NEW COMPONENTS WITH AN ATTRACTIVE COST-BENEFIT RATIO

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Abstract: *EE-VERT (Energy Efficient Vehicles for Road Transport) is a project funded under the Seventh Framework Programme of the European Commission. In particular EE-VERT targets a 10-12% reduction in fuel consumption and CO_2 generation of a conventional vehicle. EE-VERT is seeking to develop marketable energy saving technologies with an attractive cost-benefit ratio that have the potential for rapid launch and market penetration to bridge the gap between standard conventional vehicles and Hybrid Electric Vehicles (HEVs) and Full Electric Vehicles (EVs) respectively. This paper will describe the system approach of EE-VERT, the component performances and will furthermore report about the progress in assembling a demonstrator vehicle.*

Key words: *Improved energy efficiency, conventional vehicles, claw pole generator with permanent magnets, dual voltage power net architecture, electrified auxiliaries, attractive cost-benefit ratio.*

1. Introduction.

Within the European Union (EU) road transport is the second largest producer of carbon dioxide (CO_2) [7], one of the greenhouse gases responsible for climate changes (fig. 1) [1]. While some improvements in efficiency of road vehicles have been achieved, continued growth in traffic and congestion mean that CO_2 emissions from road transport have grown overall.

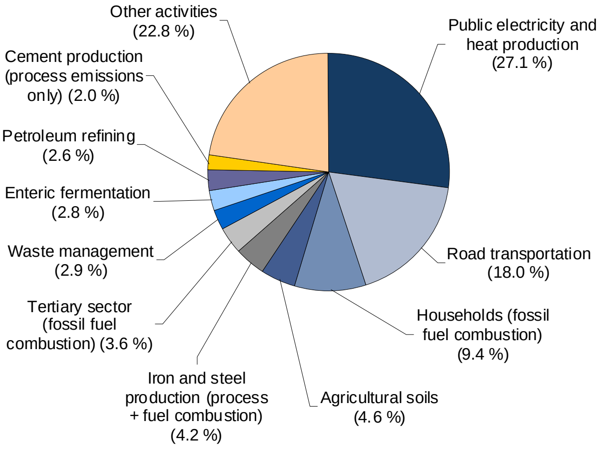


Fig. 1. Share of greenhouse gas emissions in the EU [1]

At the same time rising fuel prices and supply instability also give pressure for increased efficiency. The European Commission has a declared strategy to reduce the overall production of CO_2. Reducing the CO_2 generated by road transport is a key aspect to reduce the production of greenhouse gases. To this end binding targets have been set on the automotive industry with the objective of reducing the average CO_2 emissions from new passenger cars in the EU to 130g km-1 in 2012.

Hybrid Electric Vehicles (HEVs) have a good CO_2 benefit but only a slow market penetration. Full Electric Vehicles (EVs) are even further away from forming a significant proportion of the vehicle market. Consequently conventional vehicles will play a significant role for the next decades. But despite improvements in modern conventional vehicles, a considerable amount of energy is still wasted due to the lack of an overall on-board energy management strategy. Further electrification of auxiliary systems promises energy and efficiency gains but there is an additional need for a coordinated approach to the generation, distribution and use of energy. So there is a gap in the market between present conventional vehicles and HEVs/EVs (fig. 2).

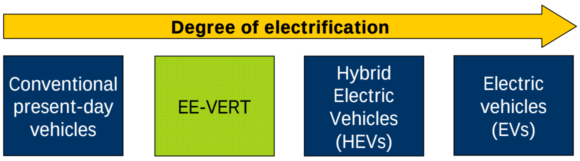


Fig. 2. Market gap between present conventional vehicles and HEVs/EVs

EE-VERT (Energy Efficient Vehicles for Road Transport) is a project funded under the Seventh Framework Programme of the European Commission. In particular EE-VERT targets a 10-12% reduction in fuel consumption and CO_2 generation. EE-VERT is seeking to develop marketable energy saving technologies with an attractive cost-benefit ratio for conventional vehicles that have the potential for rapid launch and market penetration to bridge this gap.

2. System concept

Some technologies have been deployed to the market which partially address some inefficiencies in road vehicles, for example electric power assisted steering (EPAS), electric air conditioning in currently hybrids, start-stop operation or regenerative braking [2]. Nevertheless, these technologies may be viewed as "islands" of improving energy efficiency, because they are not combined from a vehicle system point of view. For instance, regarding regenerative braking the power that can be recuperated during braking is relatively low because the power net voltage of 14V and the architecture were not adapted to this new function.

The central EE-VERT concept is the electrification of auxiliary systems, operating them demand oriented and supplying their energy by recovered and CO_2-neutral energy from energy sources such as extended recuperation of braking energy, waste heat recovery or solar cells. Fig. 3 shows the basic EE-VERT approach.

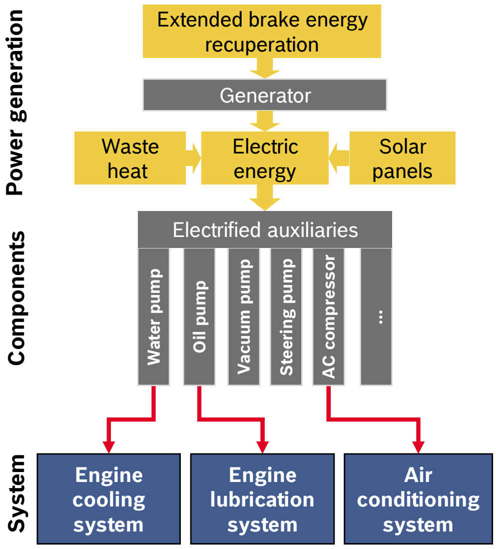


Fig. 3. The basic EE-VERT approach [3]

The (engine) auxiliaries are mainly driven by the recovered electric energy. This strategy leads to the following benefits:

- Auxiliary systems can operate on a demand-oriented basis and fulfil their tasks in an optimised way;
- Less mechanical power demand on the engine;
- Less engine drag torque, leading to a higher capability for braking energy recuperation;

The optimised operation of auxiliary systems allows the thermal engine management and the air conditioning system to be enhanced. This leads to additional benefits for the fuel demand and for the convenience of vehicle users.

3. 40V power net presentation and characterisation

In order to define an EE-VERT architecture, a number of candidate power net architectures were analysed. All of these gave special consideration to extended braking energy recuperation. The candidate architectures were analysed against a number of criteria including functional and component requirements, costs and the implications for functional safety.

Simulation studies in the project calculated that up to 8-11kW of power is the optimum power level that can be recovered during the braking phases for a standard passenger car. To collect this energy a high power and high efficiency generator coupled to a high power energy storage system is required. In addition energy can be recovered from other sources such as solar cells and waste heat in the exhaust gases.

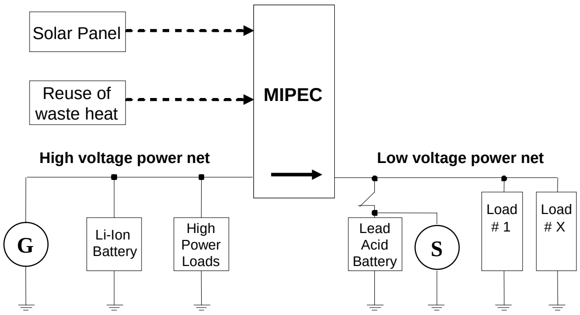


Fig. 4. The EE-VERT power net architecture

To achieve improved efficiency and increased power the generator operates at a voltage higher than the standard 14V system. To avoid introducing additional safety measures the voltage should be less than 60V. To satisfy these requirements and to connect these elements to the standard electrical system a new architecture has been devised as shown in fig. 4.

Main components of the EE-VERT approach are a generator with integrated permanent magnets, a Li-Ion battery system and a DC/DC converter with multiple inputs for interfacing between the two voltage levels and the main components (Multiple-Input Power Electronic Converter - MIPEC). Central to the EE-VERT approach is the deployment of an overall energy management strategy permitting the integration of concepts for energy harvesting whilst using smart electrical auxiliaries.

Electrified auxiliaries reduce the load on the internal combustion engine (ICE) and can further reduce the overall energy consumption [6] by only operating when required e.g. electrical vacuum pump or electrical water pump (EWP). An EWP enables the engine cooling water temperature to be increased from about 94-98C° to about 100-102C°. This is expected to increase the efficiency of the ICE by 2% leading to an additional reduction of fuel consumption.

4. System simulation to get best specifications

A simulation software "platform" has been developed using Matlab/Simulink which models the project reference car, an Alfa Romeo 159 jtdm as a physical model. This simulation model is based on models specifically developed for each of the new components mentioned and realistic models for the other elements in the vehicle. The aim is to compare fuel consumption in the actual car with the consumption in the “modified” car with new components and electrified auxiliaries. A further aim is the development of the system management strategy. Fig. 5 shows the structure of the simulation software.

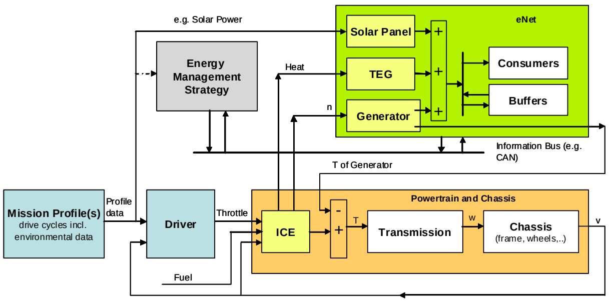


Fig. 5. Structure of the simulation software

The reference mission profile of a passenger car was defined through the following activities:

- Collecting information from existing standards and state of the art real use cycle;
- Collecting information from the ARTEMIS project [8], [9];
- Experimental activity on a vehicle for setting up an acquisition system;
- Experimental driving cycles in urban, rural and highway scenarios;
- Analysis of recorded data;
- Boundary condition definition through analysis of recorded data;
- Database of recorded missions available for future data integration.

The link between the mission profile and the operational mode of components has been investigated, particularly the impact of the EE-VERT real-life mission profile on generator, water pump, engine oil pump and the fuel pump. A statistical analysis of the mission profile has been done and possible improvements of the mentioned components were suggested. Furthermore a first working simulation (using a driver model) of the vehicle fuel consumption has been created. The simulation is capable of testing various mission profiles.

As an example fig. 6 shows the simulated maximum power diagram for the generator on the mission profile real-life cycle. It was used to identify and to define the optimal power performance of the generator.

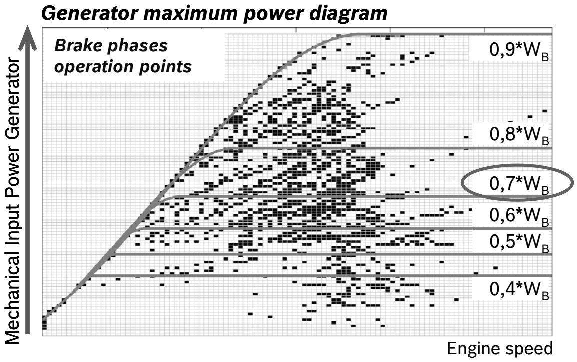


Fig. 6. Identification of the optimal power performance of the new generator [5]

The brake phases operation points show the available maximum recuperation energy for each braking phase [5]. The simulation study analysed that an electric machine with around 10kW is required to recuperate around 70% of the available braking energy (WB) during the whole cycle. It was analysed that this leads to an attractive cost-benefit ratio for the new generator.

5. Electric generator performance for the scope

The generator concept that was developed within this project is based on a claw pole machine with integrated permanent magnets for flux influence [fig. 7]. Main characteristics of this concept are an increased efficiency during standard operation and a boost power capability of up to 8-11kW during the braking phase of the vehicle.

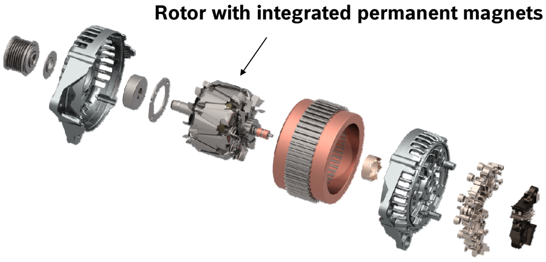


Fig. 7. Exploded view of the generator prototype

Due to the promising characteristics from the simulation analysis a generator prototype was assembled during this project. This prototype was tested on a generator test bench. Fig. 8 presents the measured maximum power characteristic of this generator prototype with extended recuperation capability: output current (IG), torque (MD) and efficiency (eta). The red graph shows that the maximum generator current is up to 270A while the voltage is about 40V. Consequently the available power during recuperation is up to 11kW with this prototype. The efficiency is about 80% in the low range of speed while in the high range of speed the efficiency is still around 70%. Important is that the dimensions of the generator were only slightly increased in comparison to a standard generator.

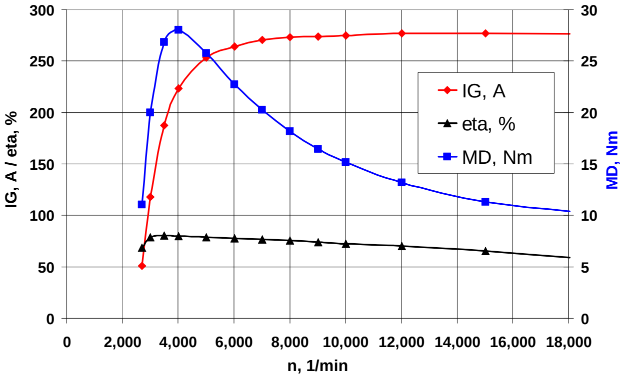


Fig. 8. Maximum power characteristic of the recuperation generator at 40V

6. Li-Ion battery description, some test results and performance

The main results from the storage analysis were to use a Li-Ion battery operating at 40V (nominal) with a capacity of 64Ah for the main solution. With a target maximum recuperation power of 8kW the storage device has to be able to tolerate a charging current of up to 200A. The proposed 40V Li-Ion battery from MIRA is based on 8Ah lithium iron phosphate cells from LiFeBatt with 12 cells in series giving a nominal voltage of 39.6V (3.3V/cell) and 8 cells in parallel to accept a maximum charge rate of 200A (25A/cell). This results in a maximum charge power of 8.8kW and a 64Ah capacity. The maximum charging voltage is 3.65V/cell, giving a maximum battery charging voltage of 43.8V.

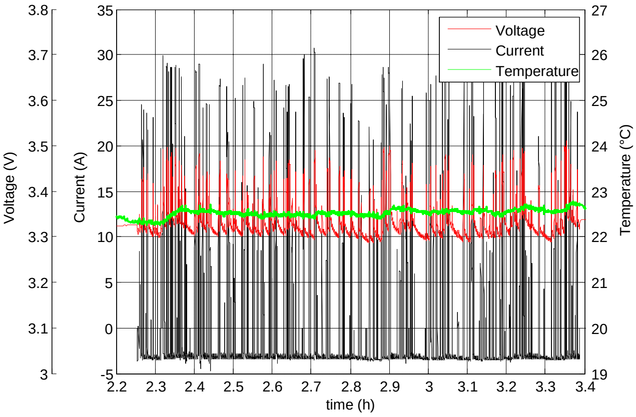


Fig. 9. Dynamic real life battery test (real-life profile)

Especially considered were the real-life characteristics. Within the PhD of Mr. Heuer two types of cells were tested: LiFeBatt cells and A123System cells. The cells run through several test like charge/discharge acceptance, SOC vs. voltage test or a dynamic real-life test. This dynamic real-life test is used to show the ability of the cells to work on real-life conditions. The main focus was the temperature behaviour of those cells as it's shown in fig. 9.

Fig. 9 shows that the change of temperature was only 1K at a constant ambient temperature. Both cell types passed this test. The data for this test was simulated with a whole battery pack. The resulting current and voltage was scaled down for the single cell testing. The limit was the maximum charge current because in this way the battery got the maximum applicable load.

7. DC-DC converter configuration, design and preliminary tests

One of the main components of the EE-VERT approach is a DC/DC converter with multiple inputs for interfacing between the two voltage levels and the different power generation sources (Multiple-Input Power Electronic Converter - MIPEC). Regarding design and implementation, the MIPEC is being built in two boards: one for control / supervision using a last-generation automotive PowerPC microcontroller and another one for power (with drivers, power modules and protections). Frequency of the converter is 100kHz. The system includes High-speed CAN-bus and LIN-bus for communication and a limp home mode for safety.

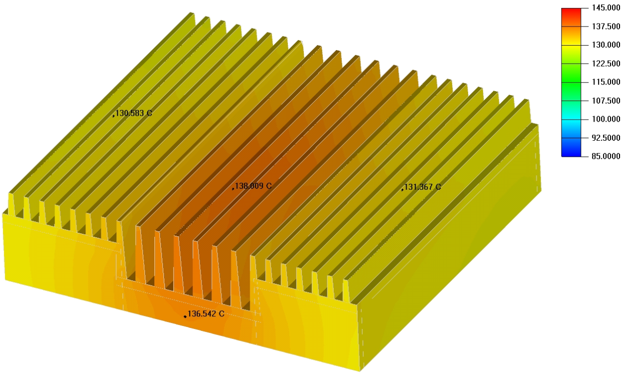


Fig. 10. Thermal simulation of the MIPEC cooling case

Thermal simulations are shown in fig. 10 and 11.

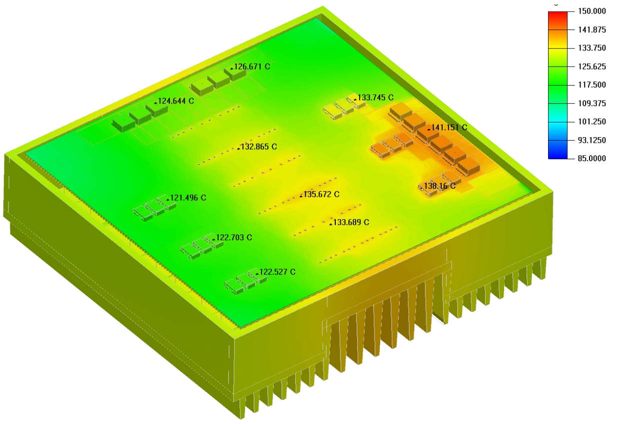


Fig. 11. Thermal simulation of the MIPEC power board

The preliminary mechanical design is shown in fig. 12. The system includes high-power input / output connectors for high-voltage (40V) and low-voltage power net able to support up to 1.5kW and medium power input / output connectors (700W) for the thermo-electric and photovoltaic generators. Anyway, the system is designed to limit the power transfer between inputs and output (low voltage power net at 14V) to a 1kW maximum.

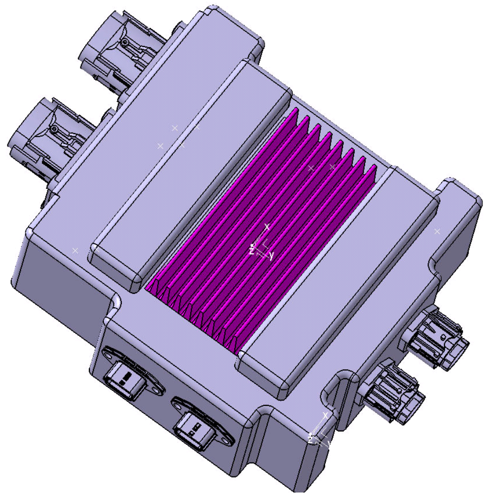
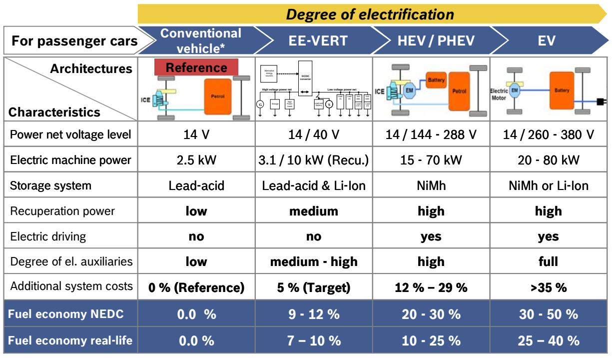


Fig. 12. MIPEC preliminary mechanical design

8. Cost-benefit comparison of modern powertrain concepts

To guarantee a marketable solution with a rapid launch and a fast market penetration EE-VERT is aiming to achieve an attractive cost-benefit ratio for the solution.

In the EE-VERT project a first cost estimation was done to calculate the additional system costs of the EE-VERT approach from a vehicle manufacturer point of view. Furthermore a first cost-benefit analysis was undertaken by a comparison of the EE-VERT costs and benefits with other powertrain concepts.



	Degree of electrification			
For passenger cars	Conventional vehicle*	EE-VERT	HEV / PHEV	EV
Architectures / Characteristics	Reference ICE Petrol	Alternative energy sources DC/DC converter High voltage power net Low voltage power net G Storage High Power Loads Lead acid Battery S	ICE EM Battery Petrol	Electric Motor EM Battery
Power net voltage level	14 V	14 / 40 V	14 / 144 - 288 V	14 / 260 - 380 V
Electric machine power	2.5 kW	3.1 / 10 kW (Recu.)	15 - 70 kW	20 - 80 kW
Storage system	Lead-acid	Lead-acid & Li-Ion	NiMh	NiMh or Li-Ion
Recuperation power	**low**	**medium**	**high**	**high**
Electric driving	**no**	**no**	**yes**	**yes**
Degree of el. auxiliaries	**low**	**medium - high**	**high**	**full**
Additional system costs	**0 % (Reference)**	**5 % (Target)**	**12 % – 29 %**	**>35 %**
Fuel economy NEDC	**0.0 %**	**9 - 12 %**	**20 - 30 %**	**30 - 50 %**
Fuel economy real-life	**0.0 %**	**7 – 10 %**	**10 - 25 %**	**25 – 40 %**

Fig. 13. Cost-benefit comparison of electrified powertrain concepts

Fig. 13 summarises the cost-benefit comparison of electrified powertrain concepts including the EE-VERT concept. The achievable benefit of the EE-VERT approach on real-life cycle is between 7 and 10%. The total benefit on NEDC is estimated between 9 and 12%.

The cost-benefit comparison of current powertrain concepts shows that the EE-VERT concept has a very attractive cost-benefit ratio. HEVs and EVs have high additional system costs. Fig. 13 considers at the moment only additional system costs for the vehicle manufacturer. It is based on [4]. The total cost of ownership is not yet included.

The solution of the EE-VERT project is a highly attractive solution and has the potential to bridge the gap between conventional vehicles and HEVs and EVs respectively by delivering a fast market launch and therefore an important impact to reduce the CO_2 emissions in Europe.

9. Assembling of a demonstrator vehicle

Currently the project is concerned with assembling a demonstrator vehicle that will validate the improved and developed components (fig. 14). All these components which will be integrated in the demo car will be improved in comparison to the start of the art especially in terms of energy efficiency. They will be managed by the overall system management of the EE-VERT approach.

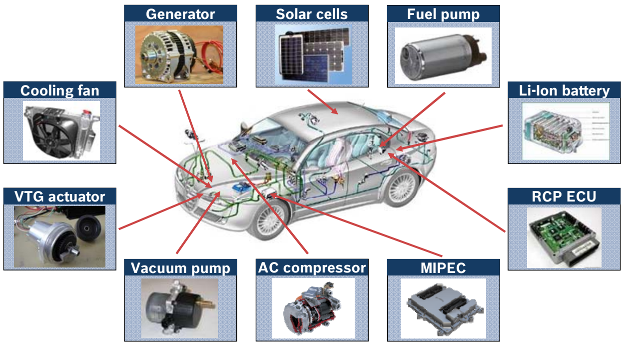


Fig. 14. EE-VERT components for the demonstrator vehicle AR159jtdm

The basic fuel consumption for the AR159 jtdm on NEDC is 5.9l diesel per 100km. Consequently a reduction in fuel consumption of 1% is equal to 1.57g CO_2/km (1l diesel leads to 26.6g CO_2/km). 0.07l diesel per 100km is necessary to generate an electrical power of 100W. The basic electrical power net load was assumed to be 350W on real-life and NEDC.

The car is being equipped with a data acquisition system able to monitor all the energetic flow on the vehicle from the combustion engine to final consumers. The overall system management will be realised with a rapid prototyping system (RCP ECU) which is also already installed in the demo car.

10. Conclusion

This paper has presented the EE-VERT concept and activities which are undertaken to realise energy efficiency and CO_2 reduction for conventional vehicles. This project is aiming to make a significant contribution to reducing CO_2 emissions of conventional vehicles in road transport service.

Central to the EE-VERT approach is the deployment of an overall energy management strategy in combination with the electrification of auxiliaries driven by recovered energy, along with an optimisation of the auxiliary systems. Furthermore, the concept provides additional convenience and functional benefits which increase the acceptance for necessary system changes and costs. Main additional benefits are:

- Air conditioning for several minutes during engine stop-phase;
- High voltage stability for the whole power net during engine cranking;
- Higher engine start availability;
- Possibility to supply high power loads on a higher voltage level;
- Two power sub-nets for the supply of safety relevant loads.

Technologies such as those to be developed in the EE-VERT project are a key part of achieving the required CO_2 reduction targets. As the volumes of road vehicles in service and the CO_2 they produce are significantly greater than other surface transport means, EE-VERT presents an opportunity to make a substantial impact at the European level.

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