EE-VERT

Project acronym:	**EE-VERT**
Project title:	**Energy Efficient VEhicles for Road Transport – EE-VERT**
Grant Agreement Number:	**218598**
Programme:	**Seventh Framework programme, Theme 1.1, Greening**
Contract type:	**Collaborative project**
Start date of project:	**1 January 2009**
Duration:	**36 months**

Deliverable D1.1.1: State of the art and Standards

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Dissemination level: Public
Deliverable type: Report
Work Task Number: 1.1
Version: 1.1
Due date: 31 March 2009
Actual submission date: 09 April 2009
Date of this Version 27 May 2009

EE-VERT

Consortium Members

Organisation	Abbreviation	Country
MIRA Limited	MIRA	GB
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SC Beespeed Automatizari SRL	Beespeed	RO

Document history

Planned revisions:

Version	Description	Planned date	Actual date
1.0	First version of public report	31 March 2009	09 April 2009
1.1	Editorial changes (Bob Simpkin)		27 May 2009

Summary

A state of the art survey of current technologies for conventional vehicles has been performed that aims to:

- Determine the baseline of the vehicle to be used as a reference for discussions during the future work in the EE-VERT project
- Identify areas where the potential for fuel consumption reduction in the electrical system in conventional vehicles is considered to be significant.

The areas that have been surveyed are:

- Components such as generators, converters, auxiliaries and energy storage systems
- System concepts such as start-stop and regenerative braking
- Algorithms for optimised energy supply and distribution

Also included in the report are:

- A short overview of hybrid vehicle systems
- A short survey of standards that could influence the further work of the EE-VERT project

Contents

1 Introduction

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- A short overview of hybrid vehicle systems
- A short survey of standards that could influence the further work of the EE-VERT project

The technologies of different components for a reference vehicle (State of the Art vehicle) in the EE-VERT project are defined in Table 1-1. The component technologies defined for this reference vehicle are those that are considered to be the industry standard. Industry standard is here defined as the component technology that is used in the majority of vehicles produced today. In the same manner it is listed in Table 1-2 if a certain system concept is used or not in the reference vehicle.

Components

The state of the art for selected components which are used in the majority of vehicles today are described. In some instances components and features which are under development or available on the market, but are normally not used in vehicles, are also described. In the descriptions the components general function is explained and the general characteristics are presented. For most components the energy demand is described together with possible improvements that can be achieved to reduce fuel consumption.

Table 1-1 Components and their technologies in EE-VERT reference vehicle

Component	Technology of component in reference vehicle
Generator	Claw pole generator, brushed
Starter-Generator	Not standard but used in some vehicles
Converter	Not standard but used in some vehicles
Battery	Wet lead acid, 12V passenger cars / 24V commercial vehicles
Ultracapacitor	Not standard
Starter motor	Brushed DC motor
Engine cooling fan	Brushed DC motor in passenger cars / belt driven in trucks / hydraulically driven in busses
Water pump	Mechanically driven
Oil pump	Mechanically driven
Fuel pump	Brushed DC motor
Vacuum pump	Mechanically driven
Turbo charger with VTG	Not standard (standard is turbo charger without VTG)

Power steering	Hydraulically driven
Air-condition, compressor	Mechanically driven
Air-condition, fan	Brushless DC motor in passenger cars / brushed DC motor in commercial vehicles
Air compressor	Not used in passenger cars / mechanically driven in commercial vehicles
Body loads, lights	Glow discharge lamp
Body loads, window heater	Resistive heater
Body loads, seat heater	Resistive heater
Waste heat recovery	Not standard
Pre-heater for catalysers	Not standard
Solar cells	Not standard

System

System concepts that are used in some conventional vehicles today and that might be incorporated in conventional vehicles (in some instances converting the conventional vehicles to micro hybrids) are described.

Table 1-2 System concepts and if standard or not in EE-VERT reference vehicle

System concept	System concept standard in reference vehicle?
Dual voltage (14V-42V) power nets	Not standard
Start-stop	Not standard today but will most probably be that soon
Regenerative braking	Not standard

Algorithms

Apart from components and systems this report also considers the state of the art of energy management algorithms. This type of algorithm is not routinely used in today's vehicles. Consequently the algorithms reviewed are taken from the research field. At the moment algorithms are only used "offline" (that is not in real-time) to identify a benchmark for optimal component usage, and then approximately implemented in rule based controllers. This is done mostly for hybrid vehicles to define optimal operation strategies for the electric motor/combustion engine. This report summarizes suitable algorithms for

- Peak power reduction (scheduling algorithms) and
- Globally optimizing the operation of all components (Dynamic Programming).

Their application is extended to conventional vehicles by defining and controlling the operation of all main power consumers and power sources.

Hybrids

Hybrid vehicle systems are considered in this report to ensure that the results of EE-VERT can be applied to this emerging technology.

Standards

The final section aims to identify standards relevant to the components that may be modified as part of the project. The review concentrates on the directives and standards that enable manufacturers to sell vehicles throughout the European Community. These are the Type Approval Directives for Motor Vehicles.

2 STATE OF THE ART – COMPONENTS

2.1 On-board electrical power supply

This chapter considers the state of the art for generators, starter motors and converters. Supply voltage stabilizers, supply voltage converters, charge equalizers and charge converters are the converter types that are considered in this report.

2.1.1 Generators

Description and main function

An electrical generator, Figure 2-1, is a device that converts mechanical energy to electrical energy, generally using electromagnetic induction. Automotive generators power the electrical systems on the vehicle and recharge the battery after starting. The generator is mechanically driven by the internal combustion engine through a belt at a fixed ratio. Currently vehicle generators do not use permanent magnets. They are air or water cooled.

Figure 2-1 Generator (source: Bosch)

Early motor vehicles until about the 1960s tended to use DC generators with electromechanical regulators and a 6V level. These have been replaced by generators with built-in rectifier circuits, which are less costly and lighter for equivalent output. Today the voltage level in passenger cars is 12 V for the battery operation and 14 V for the generator operation. Large commercial vehicles use 24 V (battery) and 28 V (generator) respectively to reduce the current for high power loads.

Efficiency

Figure 2-2 shows the efficiency diagram for a standard generator and the operation area on the NEDC. Typically a state-of-the-art generator has a maximum efficiency of about 60 or 65% over a wide speed range. The average efficiency of a standard generator is only about 40 or 45% during the NEDC due to the low electrical power and current demand and the efficiency characteristics. The efficiency of the system level is even less due to the efficiency of the belt and the ICE.

Potential improvements for the generator include the use of a new electric machine type based on permanent magnets offering 10% higher efficiency at every operation point, and generator operation management. The operation management will lead to generator operation in areas with higher efficiency. This can be realised by switched operation. The generator is switched on temporarily to a higher current level. The additional energy charges a storage device that is discharged while the generator is switched off. With this approach it is possible to improve the efficiency up to 70% or even 75%. But then an additional storage device and a voltage converter are necessary whose losses have to be taken into account as well. Overall an average efficiency of 65% is achievable. This is 20% more than the efficiency of a standard generator.

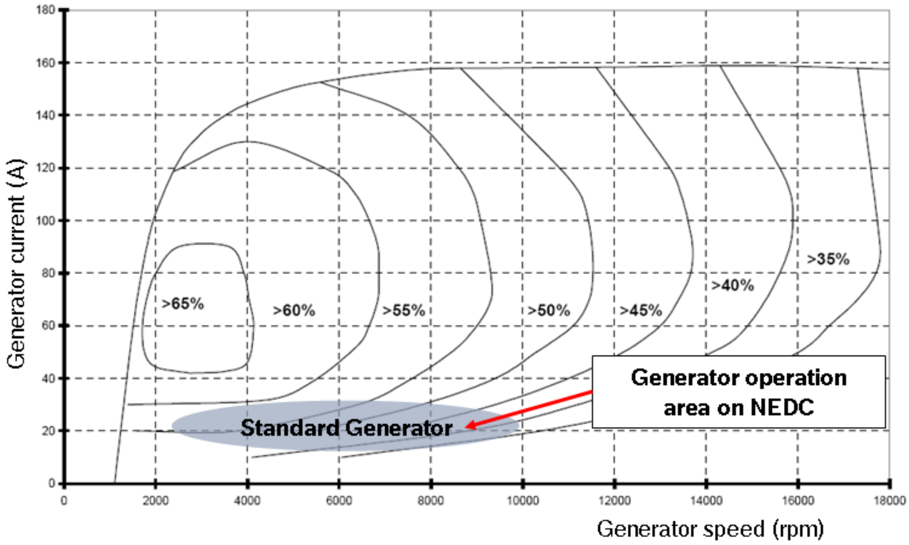


Figure 2-2 Efficiency diagram for a standard generator (source: Bosch)

Table 2-1 Typical characteristics of standard generators

	Passenger Cars			**Commercial Vehicles**
Power Class	Base	Middle	High	Very High
Voltage	14 V	14 V	14 V	28 V
Current	70 – 110 A	80 – 155 A	155 – 275 A	90 – 200 A
Power	1 - 1.5 kW	1.1 – 2.2 kW	2.1 – 3.8 kW	2.5 – 5.6 kW
Weight	4.3 – 4.5 kg	4.7 – 6.4 kg	6.6 – 8.6 kg	8 – 15 kg
Length	117 mm	131 – 139 mm	129 – 142 mm	140 – 190 mm
Diameter	125 mm	127 – 147 mm	145 – 158 mm	155 – 210 mm
Cost	<100€	<100€	<150€	<200€

Energy demand on NEDC

The CO2 reduction potential on NEDC is between 1 - 2 %, dependent upon the power net base load which relates to the vehicle class. The following estimate shows that a generator with a 20% higher average efficiency will lead to a reduction of fuel consumption by 1% under the standard NEDC conditions with the assumption of an average power net base load of 360W.

Power net base load in average:	360W electrical
Alternator efficiency increase:	20% from 360W -> 72W electrical
Fuel consumption per 100Welectrcial:	0.1 litres/100km -> 0.011 litres on the NEDC
Fuel used on NEDC:	0.759 litres -> 100%
Fuel saving on NEDC:	0.0079 litres -> 1.04%

However, the NEDC does not consider all the current vehicle energy uses. The average power net base load under real life conditions is higher. Hence, the benefit to reduce the fuel consumption with improvements of the generator could be higher under real life conditions.

Also the generator will provide additional functionalities such as brake energy recuperation by a temporarily increased generator output power. Together with the new energy storage devices this will lead to a further benefit for the reduction of fuel.

Lifetime/Reliability/Robustness/Maintenance

The typical minimum lifetime is about 250.000 km for passenger cars and 800.000 km for commercial vehicles. The reliability is high but due to brushed technology it could be improved. The component is free of maintenance. The robustness for heavy duty applications is very high.

Conclusion

A generator is necessary in every conventional vehicle. From the considerations above it is apparent that an improved generator promises a high potential for fuel reduction. Furthermore it is an enabler especially for additional functionalities such as brake energy recuperation. Hence, the generator plays a key role within the EE-VERT systems approach.

2.1.2 Starter-Generator

Description and main function

A starter-generator is a single electric machine that fulfils both functions of engine starter motor (see also chapter 2.3.1 starter motors) and electric generator (see also chapter 2.1.1 Generators). It combines the role of the starter and generator into one unit. With an adequate control a starter-generator can provide some new HEV functions that are not normally present in conventional vehicles. Typically it can provide power assist, regenerative braking and more.

Two main configurations exist. A belt driven starter-generator (BSG) is driven by the internal combustion engine through a belt. The starter function is also realised via the belt. This configuration is used in some current vehicles, like the “Smart MHD”. But the belt has only a limited ability to transmit torque from the electric machine to the engine. Hence, in another configuration, the starter-generator is integrated in the powertrain. The integrated starter-generator (ISG) is typically fitted between gearbox and ICE on the crankshaft (Figure 2-3).

Figure 2-3 Integrated starter-generator

Example with a conventional generator and 14V power net (passenger car)

Figure 2-4 shows the full alternator circuit for the example. To provide a constant output voltage for all revolution speeds the field excitation current is controlled using Pulse Width Modulation in response to the output voltage (step-down-converter principle: The current flows either over the transistor or - when the transistor is switched off- over the freewheeling diode). Permanent magnet machines are much harder to control.

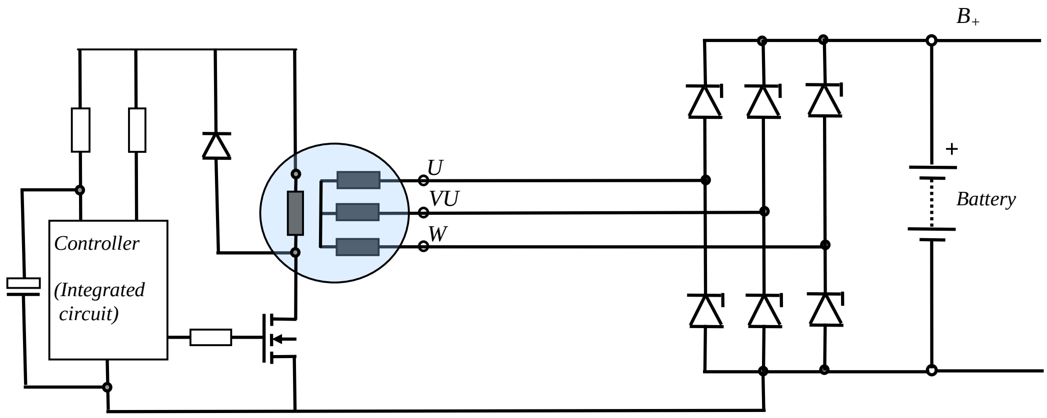


Figure 2-4 Schematics of a field excitation circuit with a wound rotor synchronous machine [1]

Conclusion

The belt has only a limited ability to transmit torque from the electric machine to the engine. Hence, the BSG has only a limited range of missions. For power assist an ISG offers more advantages. Furthermore a general challenge is the optimisation of the machine. A starter-generator can be only optimised either on the starter or the generator function. An optimisation on both functions is not feasible. Since the starter function is not of major interest for the EE-VERT approach, the ISG or BSG approach is not favoured in EE-VERT.

2.1.3 Converters

Description and main function

DC/DC-converters are devices used as power processing interfaces whenever the power net is subdivided into subnets, especially with two or more voltage levels. DC/DC-converters can be used to supply loads of one circuit by taking the energy from the other or be used as an instrument to control the energy flow by the energy management of the vehicle for example to load energy storages. Hence, DC/DC-converters are forecasted to be widely used in vehicles to supply controllable power for new applications such as regenerative braking or dual power networks.

Automotive applications with DC/DC-converters use specific topologies to work at different or overlapping input and output ranges as well as uni- or bi-directional energy transfer. The required performance and input/ output voltage ranges have a large influence on the choice of the converter's topology. Depending on the application, a distinction must be made between different types of converters:

- Supply voltage stabilizers
- Supply voltage converters
- Charge equalizers

Supply voltage stabilizers

Supply voltage stabilizers (or voltage quality modules) supply a constant output voltage for voltage-critical loads in the vehicle. Loads which react sensitively to fluctuations in voltage can thus still be operated in vehicles with a varying supply voltage.

Supply voltage stabilizers level out fluctuations in load voltage produced by fluctuations of the main power supply. Usually, they can provide constant voltage to the loads by acting as an upward converter if input voltage drops. This is a typical situation in the case of vehicles with idling switch-off of the combustion engine in start-stop operation. Figure 2-5 shows a typical battery voltage during warm engine cranking. A voltage dip appears during engine crank. In some cases, converters with upward and downward conversion capabilities are needed since voltage may both drop and increase excessively on main power supply.

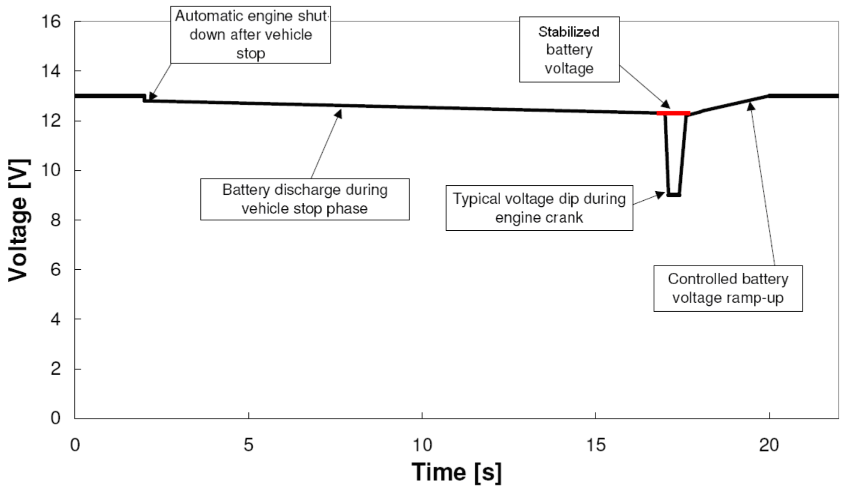


Figure 2-5 Typical battery voltage during warm engine cranking

Supply voltage stabilizers ensure the supply to the electrical and electronic subsystems, voltage-sensitive loads (for instance ECUs that may suffer memory reset if battery voltage is to low or provide consistent brightness of the. headlamps when this drop in voltage occurs. Of course, the capacity / dimensioning of the supply voltage stabilizer depend on the size of the load.

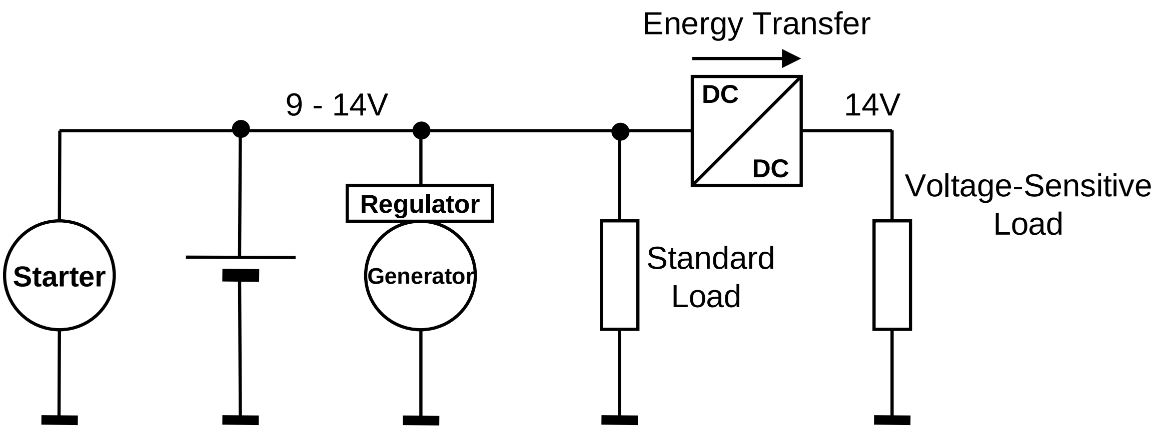


Figure 2-6 Power-net with voltage stabilising DC/DC-converter

A typical requirement is for a 12.5V ± 0,5V output voltage to be provided at a varying input voltage 6-18V and the energy transfer is uni-directional (Figure 2-6). The trend is to use converters with non-inverting topologies for step-up and step-down operation. This is a typical configuration used when input and output voltages overlap as, for instance, for uninterruptible power supply applications.
Typical requirements for these modules are:

Efficiency
85% - 92%

Power/weight ratio
600W/kg

Power
Nominal output power at 12.5V: Typical ranges from 400W to 2000W depending on vehicle characteristics and electronic loads. Maximum output power: 150% nominal power rating for a duration of 10ms

Energy demand on NEDC
Energy demand on NEDC is dependent on the power losses due to the efficiency being lower than 100%. It is assumed that excess fuel consumption is proportional to electrical load. It is estimated that 150W load consumption generate an excess fuel consumption of 0,1 L/h.

Lifetime/Reliability/Robustness/Maintenance
Calendar life: 15 years. Operational life: 10,000 hours. The DC/DC converter is designed for the vehicle’s lifetime. The reliability and robustness is high due to the solid-state technology used. The component does not require maintenance.

Supply voltage converters

Voltage converters are used in vehicles with two separate vehicle electric systems to transfer the power from a high to a low voltage level or vice-versa (Figure 2-7). They guarantee the power supply to the 12 V vehicle electric systems through a generator or a high-voltage battery or vice-versa. They are always necessary when the electrical power source in the vehicle supplies a vehicle system voltage higher than the required by the 12V-standard loads, or vice-versa.

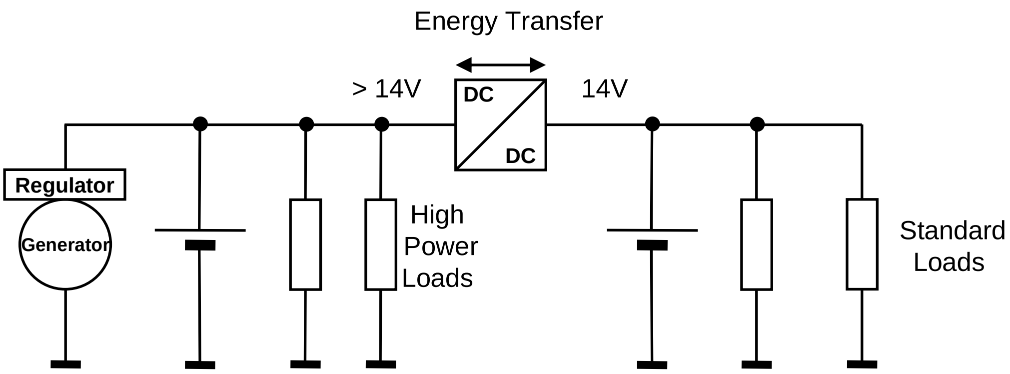


Figure 2-7 Power-net with voltage stabilising DC/DC-converter

The DC/DC converters (example in Figure 2-8) may be integrated with a control unit for vehicle electric systems or power stores to optimize system costs. Through the use of these converters, an optimum charge-state of storage elements may be reached, resulting in an increased system availability and service life of the power storages. For instance, in the case of recuperation of the braking energy, the charge converter supports power distribution within the vehicle electric system so that the start-up ability of the vehicle is always guaranteed, and free storage capacities are available for capturing electrical energy generated during braking.

Figure 2-8 DC/DC-converter (source: LEAR)

Efficiency
93% - 95%

Power:
500W – 3kW

Energy demand on NEDC
Energy demand on NEDC depends on power losses due to efficiency lower than 100%. It has been estimated that 150W load consumption generate an excess fuel consumption of 0,1 L/h.

Lifetime/Reliability/Robustness/Maintenance
Calendar life: 15 years. Operational life: 10,000 hours. The DC/DC converter is designed for the vehicle’s lifetime. The reliability and robustness is high but due to solid-state technology used. The component is free of maintenance.

Charge equalizers

Charge equalizers equalize the charge between two or more storage devices and / or batteries. In the case of the series connection of storage cells, the cyclical loads (required by some applications) cause different charge quantities in the individual cells. Charge equalization is necessary to ensure the operativeness and reliability of the storage cells. If the charge is not equalized, one of the cells will suffer higher stress (in charge or discharge) and will fail. In the case of 24V vehicle electric systems in commercial vehicles the charge equalizer increases the service-life of the 12 V lead batteries connected in series, at the same time making a 12 V vehicle electric sub-system available for selected loads.

2.1.4 Solar Panels

Description and main function

The integration of solar cells into a vehicle to generate electricity directly from sunlight is taken into consideration as the generation of electricity from fuel via a combustion engine and a generator shows relatively poor efficiency (typical values of 15% to 20%).

Solar cells use the photovoltaic effect to convert sunlight into electrical energy. The energy of photons enables electrons in a pn-semiconductor connection to be released from the atoms, thereby generating electrons (N charge) and holes (P charge). When the positive and negative charges are isolated and the circuit is closed, then electric current can flow as shown in Figure 2-9.

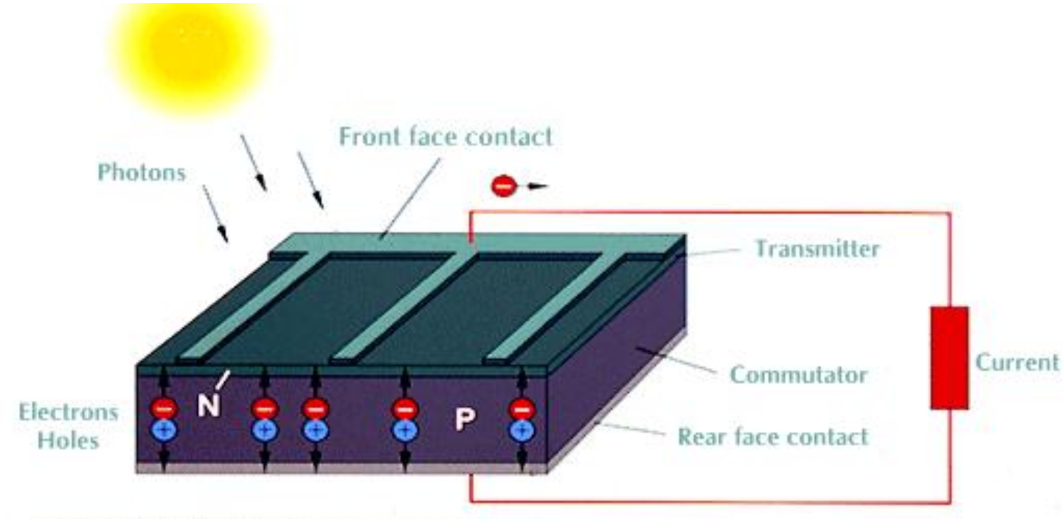


Figure 2-9 Photovoltaic effect

There are several different technologies available for solar power plants and that could be built into a vehicle. Table 2-2 gives an overview of the most common technologies for flat solar panels. CPV (concentrating photovoltaic) systems are not included, as they are only applicable for large solar power plants in high irradiation zones.

Table 2-2 Overview of solar panel technologies

Parameter	Mono-crystalline	Poly-crystalline	Thin-film Cd-Te	Thin-film silicon
Efficiency (module)	16 - 19 %	13 - 16 %	8 - 10 %	5 - 7 %
Price (€ / Wp)	2,40	2,20	1,60 - 1,80	1,60 - 1,80
Aging	<0,5%/year	<0,5%/year	0,5%/year (after pre-aging)	0,5%/year (after pre-aging)
Temperature coefficient (Power)	3,1 - 4,5% /10°C	~4,7% /10°C	~2,5% /10°C	~2,5% /10°C
Semiconductor consume	High	High	Very low	Very low

Because of the limited surface on vehicles high cell efficiencies will be essential. This is why mono-crystalline or poly-crystalline cells will be the best choice for vehicle integration.

Vehicle specific aspects:

Horizontal mounting: Horizontal (or near horizontal) mounting will be the only way of achieving acceptable cost/performance ratio of solar cell applications in vehicles. As shown in Table 2-3 for three European cities, horizontal mounting of cells results only in a 14% decrease in yield (average value for one year) compared with optimum angle mounting. Of course the low energy generation in winter time will need to be taken into account..

Cell interconnection: In order to assume the shape of the car's surface the solar cells will have different angles to the sun. As each cell performs as a current source (e.g. 0,6V; 6A for 160mm x 160mm) connecting in series will lead to current mismatch of differently radiated cells. The same problem arises, when the surface is partially shaded. Special signal conditioning circuits have to be applied to minimize the performance decrease of these effects.

Cell-Design: There are possibilities of colouring the cell surface in a certain extent to match the appearance of the car. However, only dark surfaces (black, dark-grey, dark-blue) can achieve good generating efficiencies.
The best choice in terms of elegance will be back-contacted mono-crystalline cells, showing a homogeneous dark-grey surface.

Encapsulation: the standard assembly of photovoltaic modules with crystalline cells is shown in Figure 2-10. The cells are laminated between plastic foils protecting them from air and humidity. The heat-strengthened low-iron glass (typically about 4mm of thickness) provides stability for the whole module and protects the cells from physical damage e.g. by hail. In car applications the glass surface might be replaced e.g. by acrylic glass.

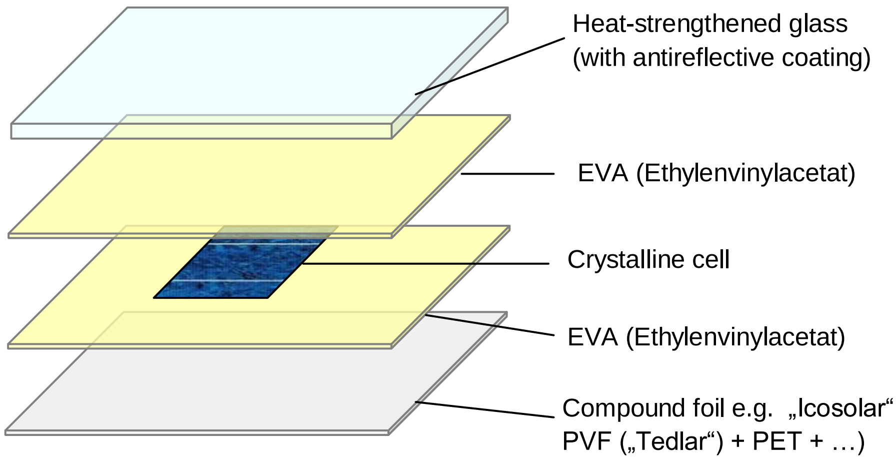


Figure 2-10 Assembly of standard solar modules (Encapsulation of crystalline cells in a lamination press with 150°C)

Table 2-3 Estimation of achievable yield for a free-standing car without shadowing: (source PVGIS)

	Optimum inclination	$H_{y,optimum}$	$H_{y,horizontal}$	E_y	$E_{december}$	E_{july}
Munich	36	1280	1110	132	3	21
Turin	38	1590	1350	167	5	24
Madrid	34	1870	1630	200	6,5	27

$H_{y,optimum}$ – Average sum of yearly global irradiation per square meter received by the modules with optimum inclination (kWh/m2)
$H_{y,horizontal}$ – Average sum of yearly global irradiation per square meter received by an horizontal mounted module (kWh/m2)
E_y – Average sum of yearly electricity production per square meter of a horizontal mounted crystalline module with 16% efficiency (kWh/m2)
$E_{december}$ – Average sum of the electricity production in December per square meter of a horizontal mounted crystalline module with 16% efficiency (kWh/m2)
E_{july} – Average sum of the electricity production in July per square meter of a horizontal mounted crystalline module with 16% efficiency (kWh/m2)

First solutions on the market
In 2008 the component supplier Webasto Solar introduced a tilt/slide sunroof with solar cells. Several OEMs (Original Equipment Manufacturers) have already integrated this solar tilt/slide sunroof into their new generation of passenger cars.

The solar cells generate electricity that powers the blower-fan while the car is parked. The continuous stream of air can reduce the temperature inside the car by up to 20°C in summer conditions. As the car's interior is not overheated when you set off, the air conditioning works much more efficiently from the very beginning of the journey and thus saves fuel. Even in winter, when the sun's rays are not so strong, a gentle stream of air efficiently dehumidifies the inside of the parked car, thereby reducing the amount of condensation on the windows.

Technical data	
Cell type	Mono-crystalline silicon
Cell size	100mm x 100mm
Cell efficiency	>16%
Number of cells	28 (4 x 7)
Maximum Power (W_p)	36,7W
Max. Output Current	3A

Figure 2-11 Solar cells integration 2008 (source: Webasto Solar)

Conclusion

The EE-VERT project will investigate how to use solar energy in an overall system approach and how to integrate the modules in the new EE-VERT system concept.

2.2 Energy storage

This chapter presents the state of the art of energy storage systems used today in automotive systems. Although, it is possible to store energy by many different means including:

- Chemically, using batteries
- Electrically, with capacitors.
- Mechanically, using flywheels
- Through pressure, using natural compressed gas, hydrogen
- Magnetically, using super conducting magnets

Energy storage systems in conventional cars use batteries only, as they are able to hold the large amounts of energy required in standard vehicles. However, research is underway to improve energy storage systems to overcome limitations of present battery systems such as high-recovery batteries or high-energy capacitors for new applications. Flywheels or superconducting magnets are not forecasted to be used in high-volume applications in a near or mid-term future. Therefore, only chemical and electrical storage are described in this chapter.

2.2.1 Batteries

Basic Concepts

Batteries are rechargeable electrochemical systems used to store energy. They deliver, in the form of electric energy, the chemical energy generated by electrochemical reactions. These reactions take place inside a cell, between two electrodes plunged into an electrolyte, when a load is connected to the cell's terminals. The reaction involves the transfer of electrons from one electrode to the other through an external electric circuit or load. The cathode is the electrode where reduction (gain of electrons) takes place. When discharging, it is the positive electrode, when charging, it becomes the negative electrode. The anode is the electrode where oxidation (loss of electrons) takes place. While discharging, it is the negative electrode, while charging it becomes the positive electrode. A battery consists of single or multiple cells, connected in series or in parallel or both depending on the desired output voltage and capacity [2].

In automotive applications, the battery is usually referred as an SLI battery, which takes its name from the basic electrical functions of starting (S), lighting (L) and ignition (I). In a vehicle propelled by an Internal Combustion Engine (ICE), the battery provides the electric power for cranking the ICE, buffers electrical energy within the vehicle electric power system during operation, provides electrical energy when the engine is off (especially for lighting), and is recharged from an alternator driven by the ICE [3]. Table 2-4 contains basic definitions related to specification and terminology related to automotive battery technology and operation.

Table 2-4 Basic definitions related to automotive battery technology and operation

Energy density	The amount of energy that can be stored in one kg of battery (Wh/kg)

Power density	The amount of power that one kg of battery can deliver on demand (W/kg).
Specific energy	The amount of energy that can be stored in one volume-unit of battery (Wh/m3)
Specific power	The amount of power that one volume-unit of battery can deliver on demand (W/m3)
Capacity (C)	The rated (nominal) capacity = the charge a battery can store, expressed in Ah or mAh, for a given total discharge time. Thus batteries are usually specified at an "hour" rate, for instance 100Ah at 20 hours, or 90Ah at 10 hours
Cold Cranking Amperes (CCA)	The amount of current a battery can provide at -18 °C (0 °F). The rating is defined as the current a lead-acid battery at that temperature can deliver for 30 seconds and maintain at least 1.2V per cell (7.2V for a 12V battery)
Columbic efficiency	As the chemical reactions cause dissipative losses, the electrical energy provided to a load is of course less than the energy consumed at the charging process. The rate of available energy in relation to the energy delivered by the charger is called columbic efficiency or cell efficiency.
Peukert Equation	The so called Peukert Equation approximates the time a battery can run a certain load is stated in Equation (1). $$T = \frac{C}{I^n} \quad (1)$$ *C:* rated Peukert capacity (at 1 amp discharge rate) of the battery, expressed in Ah. *I:* the current expressed in amps *T:* time expressed in hours *n:* the Peukert exponent, an empirically determined constant for a given battery.
Internal resistance	The internal resistance of a battery cell causes a voltage drop at high currents and reduces its effective efficiency: The internal resistance is a function of the age of the cell, the temperature and the depth of discharge. The higher the internal resistance of a battery cell the higher are the losses while charging/discharging, especially at higher currents. The slower the discharge, the more power (expressed in the Capacity C [Ah]) can be drawn out of the cell.
Cycle life	The cycle life is defined as the number of full charge - full discharge cycles a cell can perform before its capacity drops to 80% of its specified capacity.
State of Charge (SOC)	The actual available battery capacity = charge expressed as a percentage of its rated (nominal) capacity. Knowing the amount of energy left in a battery compared with the energy it had when it was fully charged gives the user an indication of how much longer a battery will continue to perform before it needs recharging. Using the analogy of a fuel tank in a car, SOC estimation is often called the "Gas Gauge" or "Fuel Gauge" function.
State of Health (SOH)	There is no absolute definition of the SOH. The SOH reflects the general condition of a battery and its ability to deliver the specified performance compared with a fresh battery. It is a subjective measure in that different people derive it from a variety of different measurable battery performance parameters which they interpret according to their own set of rules. It is an estimation rather than a measurement. Battery manufacturers do not specify the SOH because they only supply new batteries. The SOH only applies to

	batteries after they have started their ageing process either on the shelf or once they have entered service.
State of Function (SOF)	Predicted minimum voltage value at battery terminal during the next cranking procedure. It should include the aging effect (battery stratification), battery temperature, voltage drop during cranking, internal resistance and current cranking profile. The SOF prediction is used to determine the startability. This is especially relevant for stop/start systems.

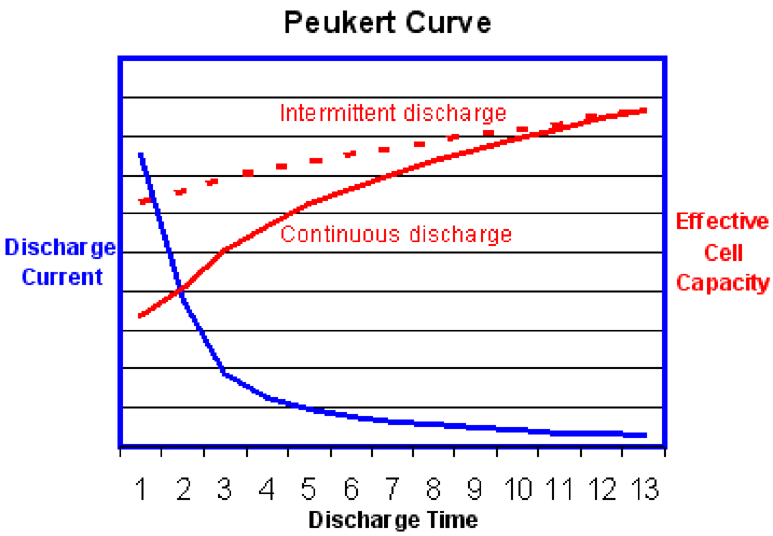


Figure 2-12 Discharge curve and effective cell capacity as function of the total time of the discharge process, according to the Peukert equation

Battery Technologies

Batteries used in automotive applications are all rechargeable (secondary batteries). Presently, more than ten different technologies have been proposed. The most common are: (i) lead–acid batteries, (ii) nickel-based batteries including nickel-cadmium (Ni-Cd) and nickel-metal hydride (NiMH), (iii) lithium-ion batteries and sodium sulphur. Table 2-5 summarizes the electrochemical aspects of these technologies while Table 2-6 summarizes the performance characteristics of these technologies [19].

Table 2-5 Technological characteristics of typical automotive batteries [19]

BATTERY	Anode	Cathode	Electrolyte	Cell voltage
Lead-acid	Pb	PbO_2	H_2SO_4	2.0 V
Nickel-cadmium	Cd	$NI(OH)_2$	KOH	1.2 V
Nickel-metal hydride	Metal hydride	$NI(OH)_2$	KOH^{α}	1.2 V
Lithium-ion	Carbon	Lithium oxide	Lithiated solution	3.6 V

Table 2-6 Performance characteristics of typical automotive batteries [19]

BATTERY	Wh/kg	W/kg	Cycles
Lead-acid	35	180	600
Nickel-cadmium	50	120	1500
Nickel-metal hydride	60	200	1000
Lithium-ion	135	430	1200

Wet batteries

Lead–acid (wet) batteries are the oldest type of rechargeable batteries and are based on chemical reactions involving lead dioxide (which forms the cathode electrode), lead (which forms the anode electrode) and sulphuric acid which acts as the electrolyte. The rated voltage of a lead–acid cell is 2 V and the typical energy density is around 30 Wh/kg with the power density around 180 W/kg [2]. Lead–acid batteries have high energy efficiencies (between 85% and 90%), are easy to install and require relatively low levels of both maintenance and investment cost. In addition, the self-discharge rates for this type of batteries are very low, around 2% of rated capacity per month (at 25 ºC) which makes them ideal for long-term storage applications.

The limiting factors for these batteries are the relatively low cycle life and the battery operational lifetime. Typical lifetimes of lead–acid batteries are between 600 and 800 charge/discharge cycles or 5–10 years of operation. The cycle life is negatively affected by the depth of discharge and temperature. Attempts to fully discharge the battery can be particularly damaging to the electrodes, thus reducing lifetime. Regarding temperature levels, although high temperatures (up to 45 ºC which is the upper limit for battery operation) may improve battery performance in terms of higher capacity, they can also reduce total battery lifetime as well as the battery energy efficiency.

AGM batteries

Valve-regulated lead–acid (VRLA) batteries can withstand higher Ah turnover than the classical wet lead-acid battery. They eliminate fluid electrolyte by absorbing and retaining the sulphuric acid electrolyte with mat separators made of glass fibre unwoven cloth. Therefore, these batteries are named AGM, from absorptive glass mat. Batteries can be closed because oxygen evolved from water decomposition during charging is reduced to water on negative plate surfaces. Battery elements are closed by a safety valve that keeps internal pressure below a certain level by releasing pressure when it rises, which is the reason for calling them “valve-regulated lead-acid batteries” (VRLA). Features of VRLA batteries are that, unlike flooded batteries, they have very low water loss, and that there are few limitations on their installation orientation.

AGM batteries give at least a three-fold increase of cycle life compared to wet lead-acid, at equal or even a higher power density. Further improvement can be expected from ongoing R&D work optimizing AGM technology for high-rate partial state-of-charge (HRPSOC) operation. This technology development has been originally devoted to 42V mild-hybrid vehicles, but it is also applied to 12V systems, e.g. for engine stop/start applications and regenerative braking [4].

Since AGM batteries are becoming very popular for use in stop & start applications, their price is falling, with a potential of long term and high volume part cost reaching 1.2–1.3 times that of a wet type. AGM batteries have a good potential to become the de facto standard for automotive applications where medium to high cycle life is required since the cost per charge throughput during battery life outperforms the wet battery technology,

Figure 2-13 Internal structure of an AGM battery (source: wikipedia)

Nickel-based batteries

The nickel-based batteries are mainly the nickel–cadmium (NiCd), the nickel–metal hydride (NiMH) and the nickel–zinc (NiZn) batteries. All three types use the same material for the positive electrode and the electrolyte which is nickel hydroxide and an aqueous solution of potassium hydroxide with some lithium hydroxide, respectively. As for the negative electrode, the NiCd type uses cadmium hydroxide, the NiMH uses a metal alloy and the NiZn uses zinc hydroxide. The rated voltage for the alkaline batteries is 1.2 V (1.65 V for the NiZn type) and typical maximum energy densities are higher than for the lead–acid batteries. NiMH batteries are currently used in all commercially available full-HEVs.

Typically, power density values are 50 Wh/kg for the NiCd, 80 Wh/kg for the NiMH and 60 Wh/kg for the NiZn. Typical operational life and cycle life of NiCd batteries is also superior to that of the lead–acid batteries. At deep discharge levels, typical lifetimes for the NiCd batteries range from 1500 cycles for the pocket plate vented type to 3000 cycles for the sinter vented type. The NiMH and NiZn have similar or lower values to those of the lead–acid batteries.

Despite the above advantages of the NiCd batteries over the lead–acid batteries, NiCd and the rest of the nickel-based batteries have several disadvantages compared to the lead–acid batteries for low voltage systems. Firstly, the energy efficiencies for the nickel batteries are lower than for the lead–acid batteries. The NiMH batteries have energy efficiencies between 65 and 70% while the NiZn have 80% efficiency. The energy efficiency of the NiCd batteries varies depending on the type of technology used during manufacture. For the vented type, the pocket plate has 60%, the sinter/PBE plate has 73%, the fibre plate 83% and the sinter plate has 73% energy efficiency. The sealed cylindrical type of NiCd batteries has 65% energy efficiency. Self-discharge rates for an advanced NiCd battery are much higher than those for a lead–acid battery, in some cases reaching more than 10% of rated capacity per month. Finally, NiCd battery may cost up to 10 times more than the lead–acid battery.

Lithium-ion batteries

The third major type of battery storage technology is the lithium-based battery storage system. Currently, lithium battery technology is typically used in mobile or laptop systems and in the near future it is envisaged to be used in hybrid or electric vehicles. Lithium technology batteries consist of two main types: lithium-ion and lithium-polymer cells. Their advantage over the NiCd and lead–acid batteries is their higher energy density and energy efficiency, their lower self discharge rate and extremely low maintenance required. Lithium ion cells, with a nominal voltage around 3.7 V, have energy densities ranging from 80 to 150 Wh/kg while for lithium-polymer cells it ranges from 100 to 150 Wh/kg. Energy efficiencies range from 90 to 100% for both these technologies. Power density for lithium-ion cells ranges from 500 to 2000 W/kg while for lithium-polymer it ranges from 50 to 250 W/kg.

For lithium-ion batteries, the self-discharge rate is very low at a maximum 5% per month and battery lifetime can reach more than 1500 cycles. However, the lifetime of a lithium-ion battery is temperature dependent, with aging taking its toll much faster at high temperatures, and can be severely shortened due to deep discharges. Furthermore, lithium-ion batteries are fragile and require a protection circuit to maintain safe operation. Built into each battery pack, the protection circuit limits the peak voltage of each cell during charge and prevents the cell voltage from dropping too low on discharge. In addition, the cell temperature is monitored to prevent temperature extremes. The maximum charge and discharge current on most packs are also limited. These precautions are necessary in order to eliminate the possibility of metallic lithium plating occurring due to overcharge.

But the main disadvantage of common lithium-ion batteries is that the **detection of its state of charge (SOC)** is difficult because of the (on the other hand favourable) flat output voltage curve. It is not relevant to know the SOC when the battery is loaded all the time (as normally is the case in conventional vehicles), but in the case of improved intelligent control it becomes important to know how long energy will last with not loading the battery at all. The easiest method is to keep track of the SOC by integrating the current along the discharge time. Other methods use sensors directly within the battery call for specific gravity measurement or impedance based (as chemicals are transforming).
Research in lithium-ion batteries is a very active file in present days. Further investigation is being done to increase the storage capacity of lithium-ion batteries. The storage capacity of lithium-ion batteries is limited by how much lithium can be held in the batteries anode, which is typically made of carbon. The greatly expanded storage capacity of nanowire batteries is reached by storing lithium in a forest of tiny silicon nanowires. silicon can hold Li better that carbon, nanotechnology prevents the battery from pulverizing (the battery swells while absorbing positively charged Li ions during charging, then shrinks during use).These batteries can hold 10 times the charge of existing lithium-ion batteries. Other than silicon also cobalt oxide can be used, which further improves the cyclic properties in a rapid charge/discharge process.

In conclusion, lithium-ion batteries are likely to become serious competitor to the NiMH technology currently used in commercially available full-HEVs. For a 12V vehicle electric system, their cost as well as the technological drawbacks will prohibit each of the above systems from completely replacing the lead–acid battery. However, if the cost of either of these technologies can be further brought down significantly, it may complement the lead–acid battery in a dual-storage system, covering the shallow-cycle power throughput requirement.

Actual usage of batteries

Today's vehicle electric power systems, with the battery as an essential component, are characterized by the increasing number and associated power demand of electrical consumers, by packaging issues, and by the limitation of the operational voltage of electronic components.

PowerNet Stability

In modern vehicles, electronic ICE controllers allow reduced idling rpm to lower emissions, while many comfort components and mechanical devices that are driven electrically require electrical power. Under poor weather conditions in a hot climate, with air conditioning, headlights and wipers on and the electrical cooling fan of the ICE in operation periodically, the alternator cannot supply sufficient current. This effect is shown in Figure 2-14. When the vehicle is in idle, the alternator is capable of providing about 70 A, while the overall current load fluctuates between 80 and 100 A. Therefore, the battery has to provide the difference. If the electrical power assisted steering is activated, battery discharge peaks reach −60 A.

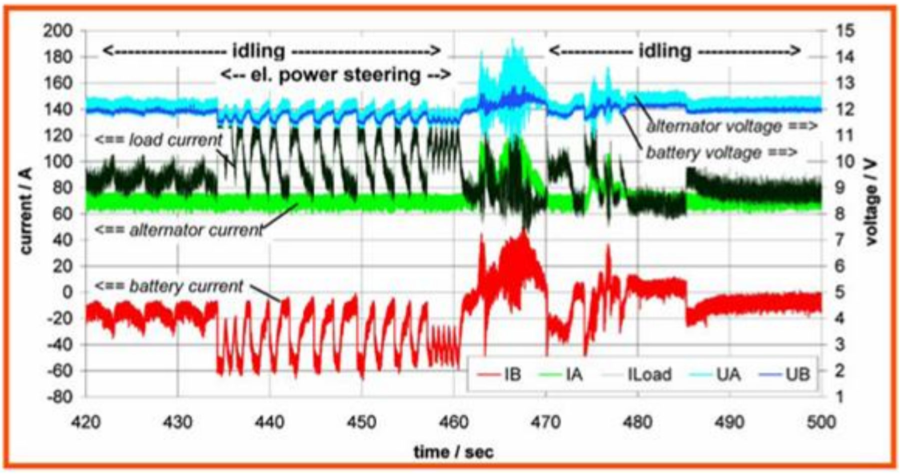


Figure 2-14 Battery voltage UB, alternator voltage UA, battery current IB, alternator current IA, and total electrical load current load over time when idling a highly equipped A-segment car (city car or small car) with many consumers on [3]

Cranking Support

Today, the cranking is an automated process controlled during the whole period by the electronic engine control unit (ECU). With many modern cars, the driver turns the ignition key (or presses the cranking button) to give only a 'cranking request' signal to the engine control unit, which manages the whole cranking event. The driver no longer has control of the flow of cranking current and the duration of the cranking procedure.

The ECU, energized by the battery, has to control fuel injection and ignition timing to optimize cranking characteristics and to minimise emissions. The ECU activates a relay, which allows the cranking current to flow to the starter motor. The ECU requires a minimum voltage for operation. If the voltage falls below this minimum value – for instance, if the short-circuit current through this motor (in stand-still position) causes the voltage to drop below the minimum level for ECU operation for a period of time longer than the capacitors in the ECU power supply can bridge – the ECU will work improperly and perform a logical re-set when the voltage level is recovered - or the relay will not be released and the starting procedure will be discontinued, i.e., cranking will not happen.

Independent of the reason for a deep voltage drop, e.g., low battery charge, low temperature, other electrical loads (headlights, etc.) activated or battery worn out, the driver will be discontent. With the old starter technology, cranking became gradually more cumbersome, which even the inexpert driver could perceive. Today, the driver expects to have a reliable warning for cranking capability, or, at least, similar information to the old technology.

2.2.2 Ultracapacitors

Ultracapacitors (also called supercapacitors) are very high surface area capacitors that use as dielectric, a molecule-thin layer of electrolyte, to separate charge. Energy is stored in the electrostatic field (i.e. static charge) rather than as a chemical state as in batteries [5]. Ultracapacitors, thus, rely on the separation of charge at an electric interface that is measured in fractions of a nanometre. The surface area is a critical feature since the opposing charges are very close, only separated by the dielectric medium. Most polymer film capacitors contain a layered arrangement with a separation distance on the micrometer scale which is volumetrically inefficient.

In ultracapacitors, the solution between the electrodes contains ions from a salt that is added to an appropriate solvent. The operating voltage is controlled by the breakdown voltages of the solvents with aqueous electrolytes (1.1V) and organic electrolytes (2.5V to 3V) [6].

The lifetime of ultracapacitors is very long and their energy efficiency is normally above 90% if they are kept within their design limits. Their power density is higher than that of batteries while their energy density is lower. However, unlike batteries, almost all of this energy is available in a reversible process. This means that ultracapacitors are able to deliver or accept high currents, but only for short periods compared with batteries.

Technologies

Depending on the material technology used for the manufacture of the electrodes, ultracapacitors are classified into three types [2]:

- Electrochemical double layer capacitors (ECDL) based on high surface area activated carbon electrodes
- Pseudocapacitors based on metal oxide or conducting polymers electrodes
- Hybrid capacitors

Figure 2-15 shows the different available technologies for each type.

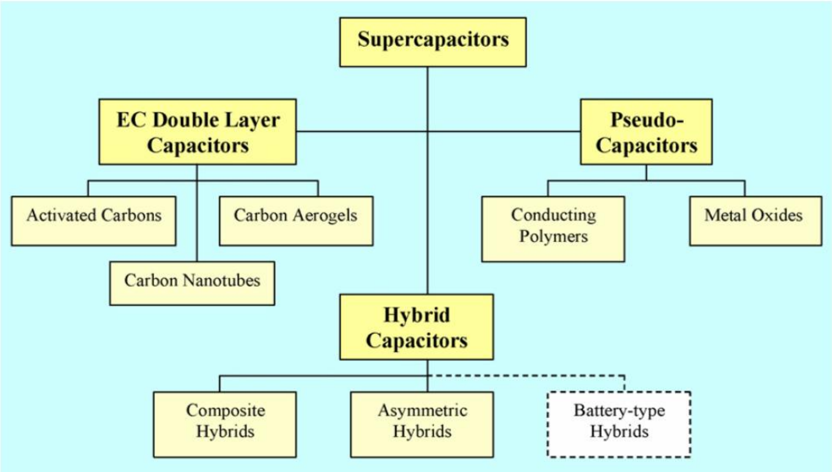


Figure 2-15 High capacitance technologies [2]

Electrochemical double layer capacitors (ECDL)

ECDL ultracapacitors are currently the least costly to manufacture and are the most common type of ultracapacitor. The first high capacity electrochemical capacitor device was developed and patented in 1957 by Howard Becker (General Electric Company) patented in 1957 (US Patent 2800616). The device was built using porous carbon electrodes. Robert Rightmire (SOHIO) introduced in 1966 a double layer capacitor utilizing porous carbon in a non-aqueous electrolyte (US Patent 3288641). In 1971, NEC produced the first commercially successful high capacitance device using the commercial name of 'supercapacitor'. They were mainly used in aerospace and military industries until, more than a decade later, ECDL were introduced in vehicular applications [7].

The internal structure of an ECDL ultracapacitor can be observed in Figure 2-16. The ECDL ultracapacitors have a double-layer construction consisting of carbon-based electrodes immersed in a liquid electrolyte (which also contains the separator). Porous active carbon is usually used as the electrode material,. Recent technological advancements have allowed carbon aerogels and carbon nanotubes to also be employed as electrode material. In particular, the use of vertically aligned, singlewall carbon nanotubes which are only several atomic diameters in width instead of the porous, amorphous carbon normally employed can significantly increase the ultracapacitor capacity and power density. This is due to the fact that the surface area of the electrodes is dramatically increased by the use of such materials.

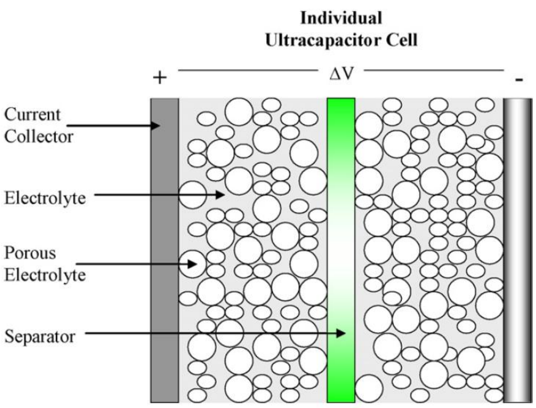


Figure 2-16 ECDL ultracapacitor structure [2]

The electrolyte is either organic or aqueous. The organic electrolytes use usually acetonitrile and allow nominal voltage of up to 3 V. Aqueous electrolytes use either acids or bases (H_2SO_4, KOH) but the nominal voltage is limited to 1 V. During charging, the electrically charged ions in the electrolyte migrate towards the electrodes of opposite polarity due to the electric field between the charged electrodes created by the applied voltage. Thus two separate charged layers are produced. Although, similar to a battery, the double-layer capacitor depends on electrostatic action. Since no chemical action is involved the effect is easily reversible with minimal degradation in deep discharge or overcharge and the typical cycle life is hundreds of thousands of cycles. Energy efficiency is very high, ranging from 85% up to 98%. The reported cycle life is more than 500,000 cycles at 100% depth of discharge.

The limiting factor in terms of lifetime may be the years of operation with reported lifetimes reaching up to 12 years. Another limiting factor is the high self-discharge rate of ultracapacitors. This rate is much higher than batteries reaching a level of 14% of nominal energy per month. Apart from a high tolerance to deep discharges, the fact that no chemical reactions are involved means that ultracapacitors can be easily charged and discharged in seconds thus being much faster than batteries. Also, no thermal heat or hazardous substances can be released during discharge.

Capacitances of 5000F have been reported with ultracapacitors and energy densities up to 5Wh/kg compared to 0.5Wh/kg of conventional capacitors. Ultracapacitors can also drain / deliver very high currents since this depends (it is directly proportional) on the surface area of the electrodes. Thus, the power density of ultracapacitors is extremely high, reaching values such as 10,000 W/kg which is a few orders of magnitude higher than the power densities achieved with batteries.

Table 2-7 shows the major manufacturers of ECDL ultracapacitors with commercially available capacity values.

Table 2-7 Main commercial ECDL ultracapacitor automotive modules

MANUFACTURER	DEVICE NAME	CAPACITY(F)	MAX. VOLTAGE (V)
Kold Ban	KAPower	1000	14.5
Maxwell	Ultracapacitor	500	16.2
		165	48.6
Ness	EDLC	57	17.5
		205	42.0
		238	52.0

Figure 2-17 Maxwell Technologies BMOD0165-48.6V Ultracapacitor

Pseudo-capacitors and hybrid capacitors

Pseudo-capacitors and hybrid capacitors are also promising technologies because they can achieve improved performances over ECDL ultracapacitors. Pseudo-capacitors use metal oxides or conducting polymers as electrode material and can achieve higher energy and power densities than ECDL ultracapacitors. Metal-oxide ultracapacitors use aqueous electrolytes and metal oxides such as ruthenium oxide (RuO2), iridium oxide and nickel oxide mainly for military applications.

These ultracapacitors are based on a high kinetics charge transfer at the electrode/electrolyte interface transforming ruthenium oxide into ruthenium hydroxide (Ru(OH)2) leading to pseudo-capacitive behaviour. However, metal-oxide ultracapacitors are still very expensive to produce and may suffer from lower efficiencies and lower voltage potential due to the need for aqueous electrolytes. Hybrid ultracapacitors can reach even higher energy and power densities than the other ultracapacitors without sacrifices in affordability or cyclic stability.

At this time both technologies are still mainly at a research and development level. Therefore, only few devices are available commercially. ESMA offers a hybrid capacitor (asymmetric design) family using a negative electrode of activated carbon material (polarizable electrode) and a positive Faradaic (non-polarizable) electrode. The positive electrode is made of nickel oxyhydroxide. A low cost aqueous KOH solution, as in alkaline batteries, is used for the electrolyte [8].

Table 2-8 Main commercial hybrid ultracapacitor automotive modules

MANUFACTURER	DEVICE NAME	CAPACITY(F)	MAX. VOLTAGE (V)
ESMA	-	8000	17.5

Figure 2-18 ESMA capacitor modules

Actual usage of ultracapacitors

Currently, the high power storage ability of ultracapacitors together with the fast discharge cycles, make them the best option for use in temporary energy storage. Furthermore, due to the low energy density, this high amount of power will only be available for a very short duration. In the cases where ultracapacitors are used to provide power for prolonged periods of time, it is at the cost of considerable added weight and bulk of the system due to their low energy density. Consequently the main applications for ultracapacitors are forecasted to be capturing and storing the energy from regenerative braking or other energy harvesting methodologies and for providing a booster charge in response to sudden power demands.

Since ultracapacitor application in the automotive industry is quite recent, United States Advanced Battery Consortium (USABC) in collaboration with the U.S. Department of Energy and National Labs developed and established standards for performance and abuse tolerance of ultracapacitors. Subsequently, potential applications in the automotive industry were identified and a consensus requirement specification was drawn as a development guide for the industry. Requirements issued are shown in Table 2-9. Three categories were identified: the 12V stop–start (TSS), 42V stop–start (FSS), and 42V transient power assist (TPA), represent increasing demands from the ultracapacitor bank, respectively [8].

Table 2-9 USABC ultracapacitor end-of-life (EOL) requirements

System attributes	12V start-stop (TSS)	42V start-stop (FSS)	42V transient power assist (TPA)
Discharge pulse	4.2kW – 2s	6kW – 2s	13kW – 2s
Regenerative pulse	N/A	8kW – 2s	
Cold cranking pulse at -30˚C	4.2kW – 7V min	8kW – 21V min	8kW – 21V min
Available energy (CP at 1kW)	15Wh	30Wh	60Wh
Recharge rate (kW)	0.4	2.4	2.6
Cycle life/equiv. road miles	750k/150k miles	750k/150k miles	750k/150k miles
Cycle life profile	UC50	UC50	UC50
Calendar life (years)	15	15	15
Energy efficiency un UC50 (%)	95	95	95
Self discharge (72h from max. V)	<4%	<4%	<4%
Maximum operating voltage (Vdc)	17	48	48
Minimum operating voltage (Vdc)	9	27	27
Operating temperature range (˚C)	-30 to +52	-30 to +52	-30 to +52
Survival temperature range (˚C)	-46 to +66	-46 to +66	-46 to +66
Maximum system weight (kg)	5	10	20
Maximum system volume (l)	4	8	16
Selling price (US$/system at 100k year^{-1})	40	80	130

USABC also developed example requirements for systems integrating a battery and ultracapacitors. For instance, they presented requirements for a SLI battery and an ultracapacitor integrated in a dual bus configuration separating loads between the battery and ultracapacitor. In this bus configuration, the loads can be divided into two groups. The low power but energy intensive loads to be supplied by the lead-acid battery, but the burst of high power low energy loads such as those of cold-cranking, and hot restarts to be provided by the ultracapacitor bank. Used in this manner, a typical specification is derived for the ultracapacitor bank as shown in Table 2-10 [8].

Table 2-10 Battery–ultracapacitor specifications

Attributes	SLI battery	Ultracapacitor bank
Discharge pulse power		6kW – 2s (3.3Wh)
Regenerative pulse power		6kW – 2s (3.3Wh)
Engine-off accessory load	0.7kW – 2min (23Wh)	
Available energy	50Wh at 700W	10Wh at 6kW
Energy efficiency on load profile		90%
Cycle life on UC 10-5	100,000 at 23Wh DOD	150,000
Cold-cranking power at -30˚C		6kW at 7V min
Calendar life (years)	5	15
Maximum operating voltage	17	17
Minimum operating voltage	8	8
Operating temperature range (˚C)	-30 to +52	-30 to +52

The **Ragone chart** in Figure 2-19 shows a performance comparison of existing technologies. It can be seen that high energy capacitors are able to deliver high power for a short time, while batteries contain much energy which is not quickly available.

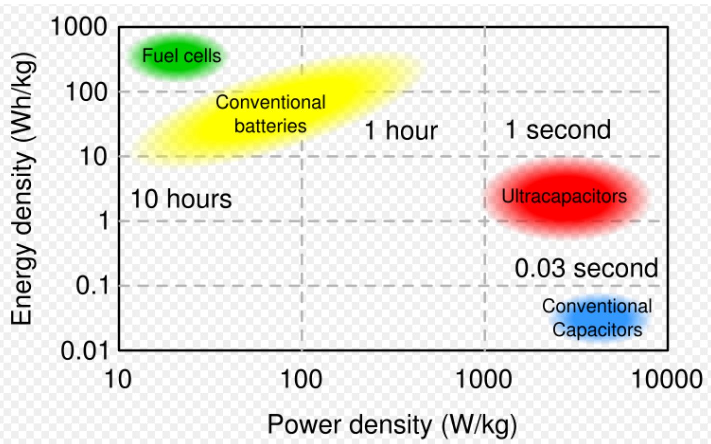


Figure 2-19 Ragone chart comparing power density and energy density of energy storage devices

It is apparent that using the combination of batteries as a long term energy storage device, with ultracapacitors that can quickly accept energy (e.g. from regenerative breaking) and act as a pulse power source, provides many advantages for the energy storage system of the future.

2.3 Auxiliaries

This chapter deals with the state of the art of the following auxiliaries: starter motors, motor fan, air-conditioning systems, water pump, oil pump, electrical fuel pump, power steering, air compressor and body loads (e.g. light, seat heater).

2.3.1 Starter motors

Description and main function

Both Otto cycle and Diesel cycle internal-combustion engines require the pistons to be moving before the ignition phase of the cycle. This means that the engine must be set in motion by an external force before it can power itself. An engine starter motor or simply "starter", Figure 2-20, is an electric motor that initiates rotational motion in an ICE before it can power itself. The modern starter motor is a permanent-magnet, a series- or series-parallel wound direct current electric motor with a solenoid switch (similar to a relay) mounted on it. When current from the starting battery is applied to the solenoid, usually through a key-operated switch, it pushes out the drive pinion on the starter driveshaft and meshes the pinion with the ring gear on the flywheel of the engine.

Figure 2-20 Electrical starter motor (source: BOSCH)

A starter motor for a start/stop system is designed for a considerably high number of starts. A start/stop system offers great benefits in economy for relatively low cost. It can considerably reduce fuel consumption and CO2 emission in urban traffic. When the vehicle comes to a standstill, the engine is automatically switched off after a couple of seconds. To continue driving, all that is needed to restart the engine is (depending on the operational concept) activation of the clutch pedal. The start/stop system can be easily integrated in any vehicle because the components are no larger than traditional ones. Table 2-11 shows the typical parameters of standard starter motors.

Table 2-11 Typical characteristics of standard starter motors

	Passenger Cars			Commercial Vehicles
Pole housing ∅	70 mm	74 mm	78 mm	78 – 109 mm
Voltage	12 V	12 V	12 V	12 or 24 V
Engine	Gasoline	Gasoline / Diesel	Diesel	Diesel
Engine capacity	Up to 5.0 l	Over 5.0l/up to 3.0l	Up to 5.0 l	Up to 13.0 l
Battery	66 / 300 Ah/A	110 / 450 Ah/A	143 / 570 Ah/A	352 / 1500 Ah/A
Power	1.1 kW	< 1.9 kW	< 2.5 kW	2.5 – 6.0 kW
Weight	2.65 – 3.25 kg	3.50 – 3.80 kg	4.10 – 4.40 kg	3.80 – 10.00 kg
Length	152 – 185 mm	168 – 200 mm	180 – 210 mm	189 – 306 mm
Diameter	125 mm	127 – 147 mm	145 – 158 mm	145 – 180 mm
Cost	< 100 €	< 100 €	< 100 €	< 200 €

Efficiency
The efficiency of a standard starter motor is about 60 %. But the efficiency of a starter is not an important parameter due to the very short time of operation.

Energy demand on NEDC
The energy demand on NEDC is negligible due to the very short time of operation. Even in start/stop systems the energy demand is not relevant under energy demand aspects.

Lifetime/Reliability/Robustness/Maintenance
Standard starter motors are designed to guarantee about 50.000 starts of the ICE while starters for start/stop systems are designed to provide about 300.000 ICE starts. The component is free of maintenance.

Conclusion
Due to the very short time of operation a starter motor has only a minor impact on the vehicle energy demand. Hence, the starter motor offers no direct potential for the reduction of the fuel consumption. But the starter motor has an indirect impact in start-stop systems where the starter motor is an important component.

2.3.2 Engine cooling fan

Description and main function
The primary function of the ICE cooling system is to transfer heat from the engine to the ambient through the coolant liquid. The cooling system performance is strongly dependent on the amount of air flow through the radiator core. At high road speeds, ram air by itself is generally sufficient to cool the engine (i.e. when the engine is mounted in the front of the vehicle). At lower road speeds, a fan is needed to provide the necessary air flow. The amount of air flow that a fan can deliver through the radiator depends on a variety of factors including the restriction of the heat exchanger cores located in front of the fan. Fan diameter and speed are two other critical factors that determine air delivery.

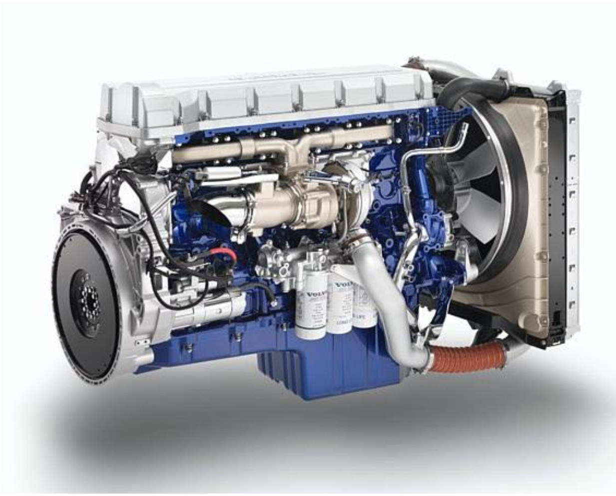


Figure 2-21 Engine with cooling fan and radiator to the right in the picture

The engine cooling fan can be of belt driven, hydraulic or electric type. The motor fan commonly used in city busses is a hydraulic fan, while the fan commonly used for trucks is belt driven. In passenger cars the engine cooling fan is generally of the electrical type. Table 2-12 lists typical characteristics of the hydraulic, belt driven and electric fans used in busses, trucks and passenger cars.

Table 2-12 Typical characteristics of a hydraulic, belt driven and electric fan

	Hydraulic fan busses	Belt driven fan trucks	Electrical fan passenger cars
Voltage	-	-	12V
Current	-	-	0 – 40A
Power	0,35[1] – 20 kW	0,2[1] – 45 kW	0,2 – 0,6kW
Weight	-kg	14kg	2,5kg
Length	120mm [2]	160mm	200mm
Diameter	750mm [2]	750mm	400-700mm
Cost	€300[3]	€150	€25-300

[1] Idling power
[2] Size of fan blade, not hydraulic pump
[3] Approximate price including blades and hydraulic system

Energy demand on NEDC

Since the energy used for the engine cooling fan is dependent on e.g. the engine load and the ambient temperature the energy consumption during a driving cycle varies a lot. For climates like northern Europe the engine cooling fan is not used much at all and the power consumption is most of the time the idling power consumption. In hot climates the average power consumption for a city bus and a distribution truck is around 8kW.

There is no specified power demand on the engine fan for passenger cars in NEDC. There is though a need for the fan to be in use in a real drive cycle which results in possible energy reduction by using a fan with better efficiency and control.

Design issues / possible improvements

For safety reasons hydraulic fans are not suited for trucks or passenger cars, this due to the fact that the engine is placed in front of the vehicle and thereby the flammable hydraulic oil is exposed in crash zones. This is not an issue in buses when the engine is placed in the rear of the vehicle, which is most common.

Even though trucks and busses only use the available power infrequently, the maximum power is in some cases needed. Consequently it can be difficult to design an electric fan for 24V, at least in the existing power network.

2.3.3 Water pump

Description and main function

Water pumps are typically used on vehicles today to provide heat transfer means for an engine during operation. The water pump circulates cooling through the engine. Water pumps are typically driven by the engine with a belt at a fixed ratio. Hence, the water pump rotates at a speed proportional to a rotation speed of the engine. Since 2004 electrical water pumps have been used in some BMW vehicles, Figure 2-22.

Figure 2-22 Electrical water pump (source: BMW)

Efficiency

Typically a mechanically or electrically driven state-of-the-art water pump has an efficiency of about 40%. The efficiency on the system level is lower than 40% due to the characteristics of the cooling circuit and the efficiency of the belts and the ICE.

Cost

<80€

Power

The mechanical power demand for a passenger car water pump is 400 - 600 W on average and at maximum 2000 W. For an electrical water pump the electrical power is 200 - 400 W at 14V.

Figure 2-23 compares two possible operational modes of the water pump. One curve shows the operational characteristic of a mechanically driven water pump while the other curve shows the operational characteristic of an electrically driven water pump which is used in some vehicles. The curve that shows the volume flow rate relates to the mechanically driven water pump. While the volume flow rate increases linearly, the power demand of the mechanically driven water pump is increases exponentially. The benefit of an electrically driven water pump is that it is adjustable on the actual cooling demand of the internal combustion engine. A volume flow rate higher than 40 l/min is not needed. Therefore the power demand does not exceed 400 W.

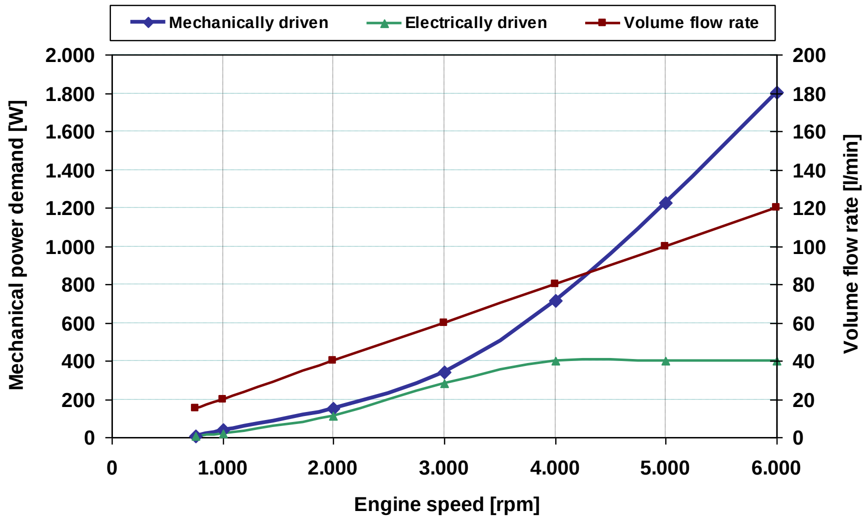


Figure 2-23 Two possible operational modes of the water pump

Energy demand on NEDC

The CO2 reduction potential on NEDC by replacing the mechanically driven water pump by an electrically driven one is low. But together with an optimised thermal management of the engine it could be 2 – 4 % because a high proportion of the CO2 emissions on NEDC results from operation of the engine at less than the optimal operating temperature.

Lifetime/Reliability/Robustness/Maintenance

A water pump is designed for the vehicle's lifetime. The reliability and robustness is high. The component is free of maintenance.

Conclusion

To replace the mechanically driven water pump with an electrically driven one could bring a benefit for the fuel consumption through optimisation of the thermal management of the engine and if the electrical energy used can be mainly generated without the internal combustion engine for example through braking energy recuperation.

2.3.4 Oil pump

Description and main function

Motor oil is a lubricant used in ICEs. Lubricating oil creates a separating film between surfaces of adjacent moving parts to minimize direct contact between them, decreasing friction, wear, and production of excessive heat, thus protecting the engine. The oil pump, Figure 2-24, powered by the vehicle engine, pumps the oil throughout the engine to the bearings, including the oil filter. The oil pump is usually of the gear type, driven by the camshaft or crankshaft, or a rotor type. Oil pressure varies quite a bit during operation, with lower temperature and higher engine speed increasing pressure to a maximum of about 4.5bar.

Figure 2-24 Engine oil pump (source: MAHLE)

Efficiency

Typically a state-of-the-art oil pump has an efficiency of about 80%. The efficiency at the system level is less due to the characteristics of the efficiency of the oil circuit, the belts and the ICE.

Cost

< 60€

Power

The mechanical power demand for a passenger car is 200 – 400 W on average and reaches a maximum of 2000 W. In Figure 2-25 it can be seen that currently oil pump operation mode produces high losses especially during cold engine operation and at higher engine speeds. The actual engine oil demand depends on the engine speed, the load, component tolerances and especially on the engine operation temperature. To maximise efficiency the oil pump should adapt the displacement to the actual oil demand.

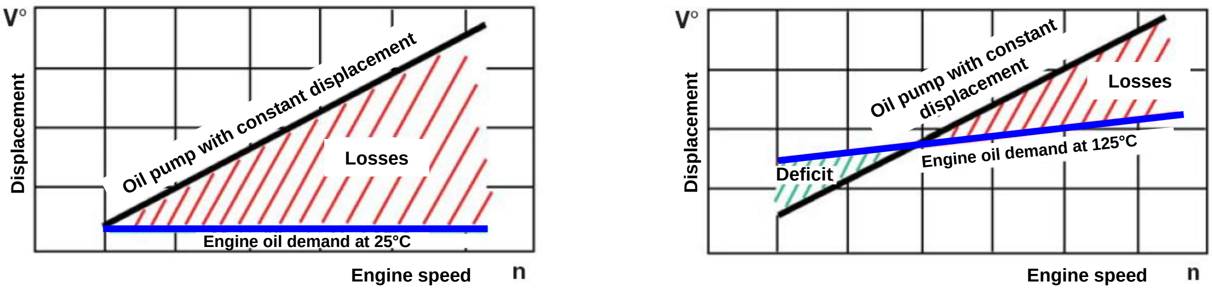


Figure 2-25 Engine oil demand and actual oil pump characteristic

Energy demand on NEDC

The CO_2 reduction potential on the NEDC is about 0.5 to 1 % by using an engine oil pump that is able to adapt its operation mode to the actual engine oil demand.

Lifetime/Reliability/Robustness/Maintenance

An oil pump is designed for the vehicle's lifetime. The reliability and robustness is high. The component is free of maintenance.

Conclusion

Replacing the mechanically driven engine oil pump with an oil pump that is able to adapt its operation mode to the actual engine oil demand can bring a notable reduction in fuel consumption, especially if the thermal management of the engine is optimised as well.

2.3.5 Fuel pump

Description and main function

An electric fuel pump, Figure 2-26 pumps the fuel from the fuel tank to the engine and delivers it under high pressure to the fuel injection system. It is usually located inside of the fuel tank. A benefit of placing the pump inside the tank is that it is less likely to start a fire. Liquid fuel will not explode and therefore submerging the pump in the tank is one of the safest places to locate it. In most cars, the fuel pump delivers a constant flow of gasoline to the engine. Fuel that is not used is returned to the tank.

Figure 2-26 Electrical fuel pumps (source: Bosch)

Efficiency

Typically a state-of-the-art electrical fuel pump has an efficiency of between 20 and 40 %.

Cost

<60 €

Power

The current demand for a passenger car is between 2 and 12 amps. Hence, the electrical power demand is between 28 and 168 W in average on a 14V system.

Energy demand on NEDC

Currently the mission profile has little influence on the electric fuel pump operation. In most cars the fuel pump delivers a constant flow of gasoline or diesel to the engine. The fuel flow is typically between 60 and 140 l/h for a passenger car. Fuel that is not used is returned to the tank via a bypass. The fuel pump is working as long as the electronic ignition system is in operation. They produce fuel pressures up to 4.5 or even 6.5 bar.

Lifetime/Reliability/Robustness/Maintenance

An electrical fuel pump is designed for the vehicle's lifetime. The reliability and robustness is high but due to brushed technology it could be improved. The component is free of maintenance.

Conclusion

There is a potential to reduce the fuel consumption by introducing a new mode of operation of the fuel pump. Currently the fuel pump is constantly working during the whole trip at a pressure level that is not needed under lower engine load conditions. An optimised operational strategy for the fuel pump is to be investigated that uses a controlled pulse-width modulated operation that is based on the real fuel pressure demand of the engine.

2.3.6 Vacuum pump

Description and main function

Both Otto and Diesel engines in passenger cars require a brake booster support. In the hydraulic brake system the human pedal brake force must be supported via a vacuum brake booster because the brake pressure must increase for braking down from high vehicle speed and/or heavy cars. The vacuum constitutes a pressure gradient to ambient air and so the brake force increases inside of the brake booster.

Diesel and Otto engines are different in brake booster:

- Engines using the Otto principle need a throttle valve to deliver the correct fuel-air ratio to operate at partial load conditions. The secondary effect is that a vacuum is generated in the inlet manifold behind the throttle that can be used for the brake booster. Newer engines with gasoline direct injection or variable valve timing do not have a throttle valve and a separate vacuum pump is fitted similar to a diesel engine.
- Diesel engines do not need of a throttle valve and only a very little (not feasible to use) inlet manifold vacuum exists. An auxiliary vacuum pump is required on diesel engines for the brake booster. The vacuum pump is directly driven by the camshaft or via a belt, Figure 2-27.

Figure 2-27 Vacuum pumps, left – mechanically driven, right – belt driven (source: WABCO)

The electric vacuum pump supports the brake booster when there is insufficient manifold pressure:

- during start-stop operation
- during heating the catalyst (fulfilling legal emission requirements)
- during strong exhaust gas recirculation
- for vehicles with automatic transmission
- for reducing of fuel consumption, compared to a mechanical vacuum pump

Figure 2-28 Electric vacuum pump

Table 2-13 Typical characteristics of vacuum pumps

	Electrical e.g. (Figure 2-28)	**Mechanical www.wabco-auto.com**
Evacuation time (p_{amb}=1000hPa) 500hPa/300hPa	5s/10s (5litre)	3s/5,5s (3,8litre)
Max. vacuum [% amb. pressure]	>85%	>85%
Power consumption [W]	150	180
Lubrication	no	yes, motor oil
Mass [g]	ca. 1100	750
Cost w/o connectors [€]	<50	<30

Efficiency
The efficiency of standard vacuum pumps is between 40 and 60 %.

Energy demand on NEDC
A demand driven electric vacuum pump (evp) can reduce the CO_2 emissions compared to a mechanical vacuum pump (mvp). The following estimate shows the benefit on the NEDC (GDI engine):

- Calculated mvp fuel consumption: 0,06 litre / 100 km
- No evp activation in NEDC necessary
- CO_2 emissions caused by mvp: 1,4 g / km (2,38 kg CO_2 per litre fuel)

Lifetime/Reliability/Robustness/Maintenance
Standard vacuum pumps are designed to run for about 250.000 km of the ICE. The component is free of maintenance.

2.3.7 Turbo Charger

Description and main function
Figure 2-29 shows that combustion engines have their best fuel economy at high loads. Whereas typical operating patterns tend to use only low loads. But in some situations, high output torque is required for accelerating the vehicle. There has been an increasing demand for higher output power in recent years, due to additional safety and convenience systems increasing the vehicle weight.

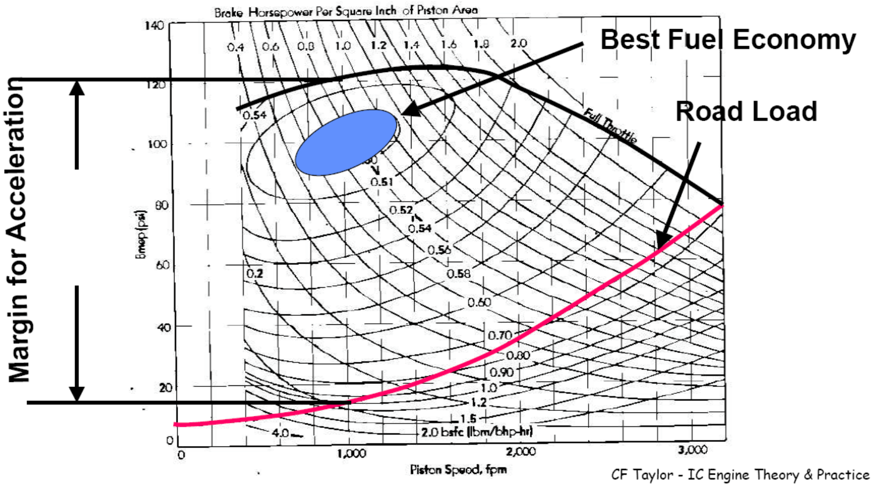


Figure 2-29 Mapping of areas of operation

Exhaust gas turbochargers are being used to increase engine power. Exhaust gas is used to drive a compressor to increase the intake air mass and the larger amount of oxygen allows more fuel to be burnt.

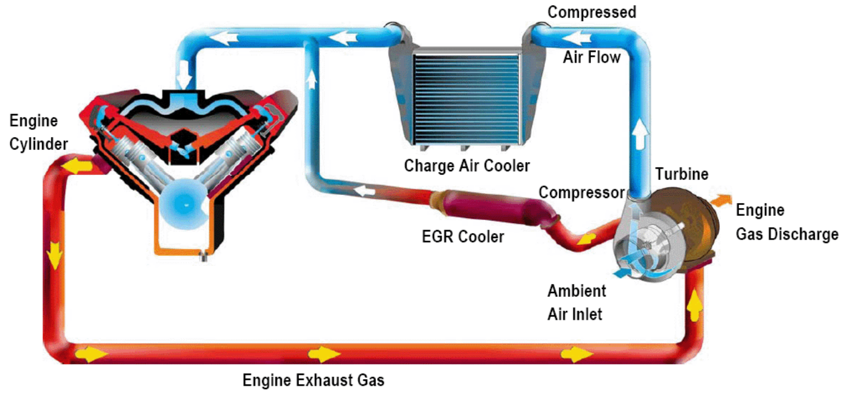


Figure 2-30 Illustration of the turbo chargers placing in system

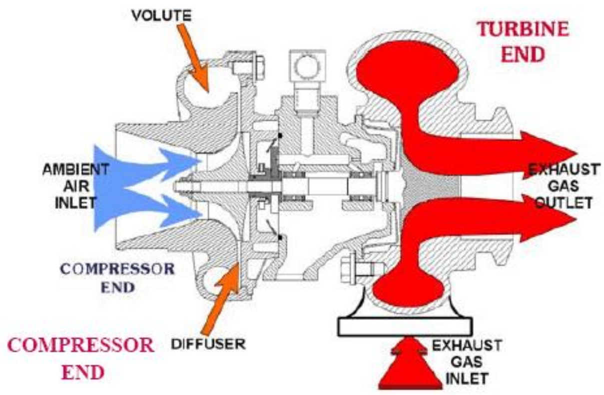


Figure 2-31 Illustration of a cross-section of a turbo charger

The benefit of using a turbocharger is to get more power out of a smaller engine. A higher efficiency is also achieved due to a reduction of thermal losses.

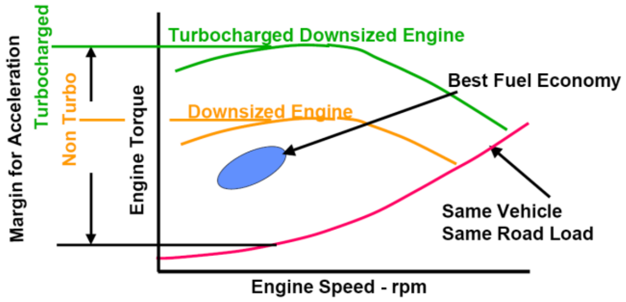


Figure 2-32 Mapping of areas of operation when downsizing and adding turbo charger

The disadvantage of the delayed turbo response due to accelerating turbo compressor can be improved by several systems:

Waste gate: The turbocharger is optimized to give a high pressure output at lower speeds and the maximum pressure is limited by a pressure controlled valve, bypassing the combustion output gas to the exhaust.

Variable turbo geometry (VTG): This system offers a more efficient method where variable vanes can be controlled to adjust the desired air pressure value. This system has the advantage of a fast response.

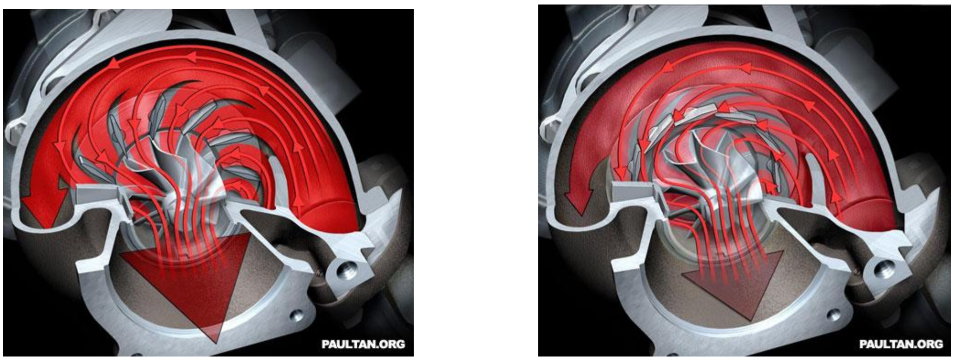


Figure 2-33 Exhaust flow when the variable vanes are fully opened (left) and almost closed (right)

An actuator is necessary to operate the VTG. First implentations used pneumatic means, often requiring an auxiliary vacuum pump.

Today electrical actuators are used, which have not been fully optimised for this application.

2.3.8 Power steering

Description and main function

Power steering is a system for reducing the steering effort on vehicles by using an external power source to assist in turning the road wheels. Most power steering systems work by using a hydraulic system to turn the vehicle's wheels. The hydraulic pressure is usually provided by a gerotor or rotary vane pump driven by the vehicle's engine. Electro-hydraulic power steering systems use the same hydraulic assist technology as standard systems, but the hydraulic pressure is provided by a pump driven by an electric motor instead of being driven directly by the engine.

Figure 2-34 Illustration of a hydraulic steering pump

Table 2-14 lists typical characteristics of the hydraulic and electro-hydraulic power steering systems used in busses. The two systems are comparable, being fitted in the same type of busses. The electro-hydraulic power steering of a passenger car is also presented in the table. Note that the power steering for passenger cars can be of both pure hydraulic or electro-hydraulic type.

Table 2-14 Typical characteristics of a hydraulic and electro-hydraulic power steering

	Hydraulic power steering Bus	**Electro-hydraulic power steering[1] Bus**	**Electro-hydraulic power steering Passenger car**
Voltage	-	28V	12V
Current	-	10 – 220A	8 – 50A
Power	0,5[2] – 10 kW	0,2[2] – 6 kW	0,1[2] – 0,5kW
Power fast lane changing	3,1kW	3,5kW	Not available
Power; dry parking	6,2kW	5,1kW	Not available
Weight	2kg[3]	12kg	1,5kg
Length	90mm	300mm	300mm
Diameter	80mm	140mm	150mm
Cost	€100	€600	€150

[1]BLDC motor with pump
[2]Idling power
[3]No pipes included

Energy demand on NEDC

There is no specified energy demand for the power steering of a bus during NEDC. During a normal city bus tour with a loaded bus, 4500kg, the average power consumption of the hydraulic power steering is approximately 1kW while the average power consumption of the electro-hydraulic power steering is approximately 400W.

The energy demand on a passenger car during NEDC is approximately 340W on average and 700W peak.

Design issues

The pure hydraulic power steering has a hydraulic pump connected to the motor. This places a severe constraint on the location of the pump resulting in long lengths of hydraulic piping through the bus. An electro-hydraulic pump offers much greater freedom in the design. It is possible to locate the pump close to the area where the hydraulic pressure is needed.

2.3.9 Air-conditioning

Description and main function

At higher outside temperatures, typically above 20°C, the air must be cooled to achieve the desired interior temperatures. The most relevant power consumers, for this project, of the air condition system are the climate compressor (consuming approximately 2kW – 5kW) and the fan (~120 W). The air conditioning system (A/C) will most likely be of high importance in future vehicle designs, as it represents the major energy consumer of all auxiliary systems (e.g. of 28% of fuel consumption during driving cycle SFTP SC03 [9]).

The purpose of this chapter is to provide the information for the specification of an air conditioning system which will serve as a common base for modelling, optimizing the operation strategy as well as for prototyping and testing. The air conditioning systems consist of a heating circuit and a cooling circuit. Components which are included in the concept of climate system are as follows:

Heating and cooling circuit are linked by:
- Shared fan and flaps
- Common control unit
- Common Sensor System

Components of Heating Circuit:
- Heater

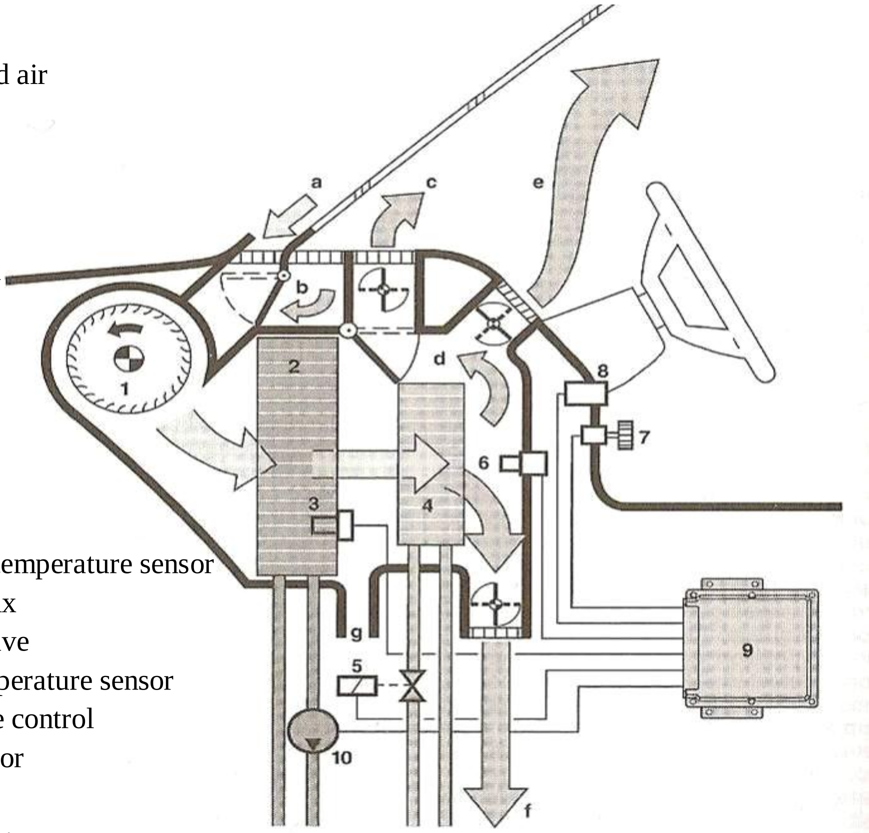
Components of Coolant Circuit:
- Compressor (presently belt driven)
- Condenser
- Evaporator
- Pressure Regulating devices

In micro-hybrids with start-stop functionality the thermal waste may not provide sufficient energy for the heater circuit, as the combustion engine will be switched off whenever possible and the electrical propulsion system will provide much less thermal waste. This is one driver for the development of fully electrical air conditioning systems.

In the future fully electrical air condition systems will probably be introduced with an efficiency, expressed through the COP (Coefficient of Performance), which is more than 50% higher than the mechanically driven compressors fitted in conventional cars.

As the primary goal is to reduce fuel consumption by optimizing the operation, it is necessary to consider transient performance analysis.

a Fresh air
b Recirculated air
c Defroster
d A/C bypass
e Ventilation
f Footwell
g Water drain



1 Fan
2 Evaporator
3 Evaporator temperature sensor
4 Heater matrix
5 Solenoid valve
6 Air exit temperature sensor
7 Temperature control
8 Interior sensor
9 Control unit
10 Compressor

Figure 2-35 Air conditioner with electronic control of coolant circuit (in contrast to air side control using flaps)

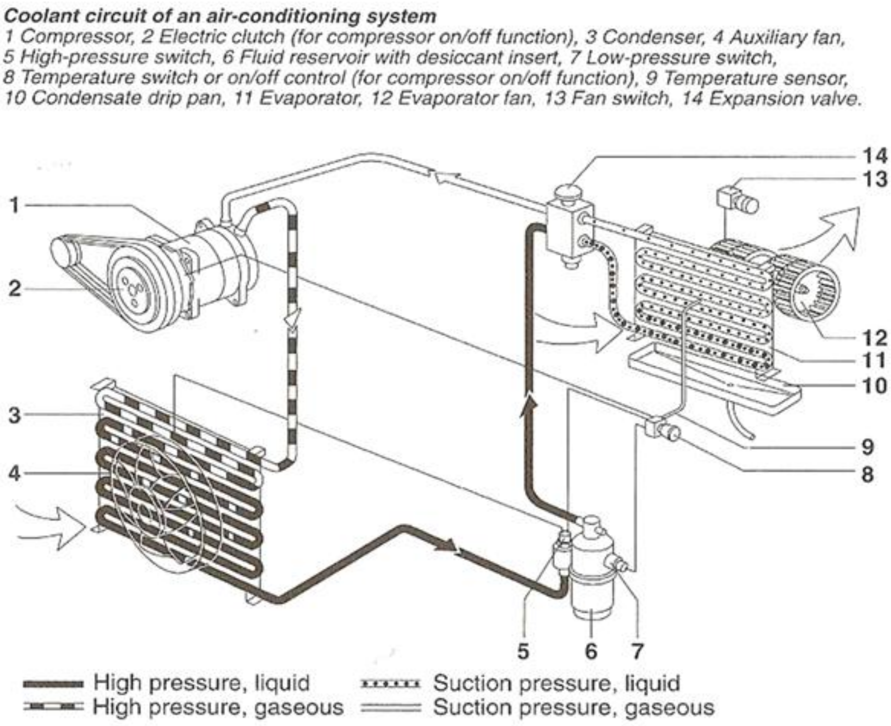


Figure 2-36 Coolant circuit of the air-conditioning system

Heater

In vehicles with liquid-cooled engines, the engine heat contained in the engine-coolant is used to warm the passenger compartment. For regulating the heater's thermal output, two design concepts are commonly used:

- Coolant-side heater control
- Air-side heater control

In the coolant-side heater control, the entire air flow is directed through the heater core, while a valve controls the heating output by regulating the flow of coolant through the unit.

In an air-side heater control, the flow of coolant through the heater is unrestricted. The heat is regulated before it reaches the cabin. A portion of the air flows through the cabin while the rest is directed around it. The two air flows are then reunited. This air-flow based control reacts faster and is less sensitive on the coolants temperature, but it needs more space.

Condenser

In the condenser the heat is dissipated to the outside air. The condenser is designed to radiate heat. As hot compressed gasses are introduced into the top of the condenser, they are cooled off. As the gas cools, it condenses and exits the bottom of the condenser as a high pressure liquid.

Evaporator

Located inside the vehicle, the evaporator serves as the heat absorption component. The evaporator provides several functions. Its primary duty is to remove heat from the inside of the vehicle. A secondary benefit is dehumidification. As warmer air travels through the aluminium fins of the cooler evaporator coil, the moisture contained in the air condenses on its surface. Dust and pollen passing through stick to its wet surfaces and drain off to the outside. On humid days you may have seen this as water dripping from the bottom of your vehicle.

Pressure Regulating Device

The thermostatic expansion valve or the orifice tube represents the point of separation between the high pressure and low pressure sections in the refrigerant circuit and is installed before the evaporator. The liquid refrigerant is injected into the evaporator through one of these devices. The evaporator temperature can be controlled via the refrigerant pressure and the flow into the evaporator.
The most common pressure regulators are:

- Orifice tube (standard version)
- Thermostatic expansion valve (TXV)
- Smart VOV (variable orifice valve)

Applied Refrigerants

Compressor-driven refrigeration units with R134a refrigerant (Tetrafluor-ethane) are in use up till now. R134a has replaced the formerly used R12 refrigerant (commonly referred to as Freon) due to its damaging effects to our ozone layer. R134a, in turn, also has been subject to use restrictions due to its contribution to climate change, having a global warming potential (GWP) of 1400 (CO_2-equivalent at a 100 years base). In the EU, it will be banned as from 2011 in all new cars. According to an SAE recommendation HFC 134a will be replaced by the new fluorochemical refrigerant $CF_3CF=CH_2$ with the trade name HFO 1234yf. Other gases like CO_2 (R744) are also used as coolants in HVAC, such as in the Toyota Prius IV.

A change from R134a to R744 has no influence on the electric drive for compressors.

Properties	1234yf	134a
Boiling Point, T_b	-29°C	-26°C
Critical Point, T_c	95°C	102°C
P_{vap}, MPa (25°C)	0.673	0.665
P_{vap}, MPa (80°C)	2.47	2.63
Liquid Density, kg/m³ (25°C)	1094	1207
Vapor Density, kg/m³ (25°C)	37.6	32.4

1234yf

$CF_3CF=CH_2$

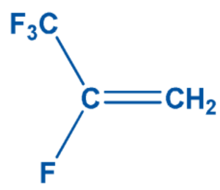


Figure 2-37 Properties of coolant HFO 1234yf

HFO 1234yf is more expensive than other refrigerants, but it shows excellent performance in terms of cooling capacity and COP-values. With its very low "100year GWP" (global warming potential) value of 4, its low toxicity and its manageable flammability (no need for a two stage coolant circuit) it is likely to be the best choice for future HVAC systems.

Selection and Design of Electrical motors for compressors and fans

Both air-conditioning compressors and blower fans can be seen as continuous electrical loads. This is why the highest possible efficiency is crucial for their performance. Permanent magnet motors are already state-of-the art for these applications.

The lower complexity of the control electronics required for permanent magnet motors of the Brush Less DC-type (BLDC), compared to three phase motors, makes them the most common choice for blower fans. The three-phase permanent magnet synchronous motor (PMSM) with sinusoidal flux distribution has been introduced as the highest efficient version from some suppliers. The PMSM-Drive (motor and converter) for a 300W fan achieves about 75% efficiency. In case of electric drives for compressors the efficiency should exceed 80%, having a typical nominal power rating in the range of 3 kW to 5 kW.

In general the efficiency of electrical drives is highly dependent on the available voltage, as the predominant losses are proportional to I^2 (current^2) so that for a given power the current is lower at a higher voltage. In this way that a higher available voltage can increase efficiency disproportionately

Climate Compressor

The compressor, as the "heart" of the coolant circuit, is a belt driven pump that is fastened to the engine via an electromagnetic clutch (in all conventional vehicles). It is responsible for compressing and transferring refrigerant gas and has an efficiency expressed through the COP (Coefficient of performance) of about 1,5 – 2.

Figure 2-38 shows the commonly used **piston compressor** (reciprocating compressor). The rotating disc with a tilted bearing surface is actuating the pistons up and down. Switching on/off the A/C system is accomplished by an electromagnetic clutch. This type of compressor is a good solution for the varying speed range of the engine, but it is not meeting future demands in terms of energy efficiency because of its high friction losses.

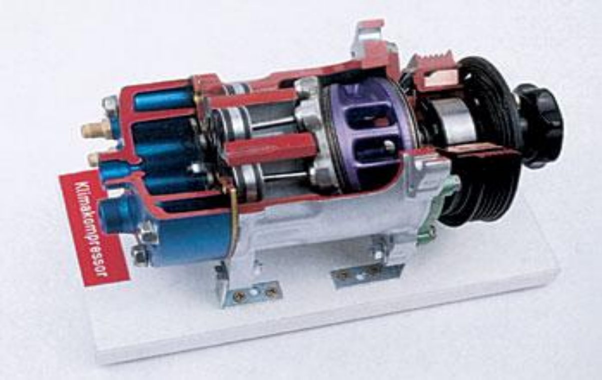


Figure 2-38 Belt-driven piston compressor

Future electrical-driven high efficiency compressors (e.g. **Scroll compressors**, SANDEN, DENSO, BOSCH in future) will replace the current belt-coupled piston compressors, offering high volumetric and energy efficiency. Scroll Compressors, Figure 2-39, feature increased reliability due to fewer moving parts, reduced sound and vibration levels due to the smooth scroll movement, and easy installation and maintenance due to a smaller footprint and less overall weight.

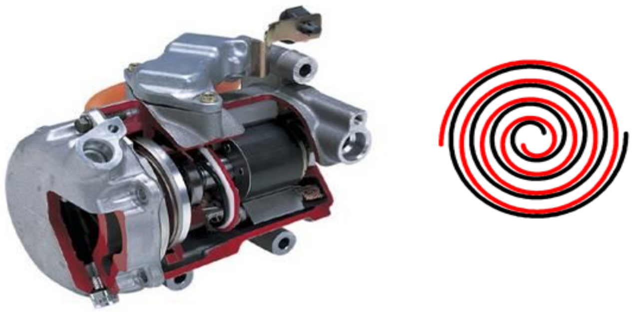


Figure 2-39 Electrically driven scroll compressor (Denso) and illustration of the working principle of a scroll pump

The latest generation of air conditioning systems for hybrid and electric vehicles consist of compact electric compressors with integrated drive electronics. A brushless DC-motor is coupled with a scroll compressor. The system acts as a heat pump for both cooling and heating.

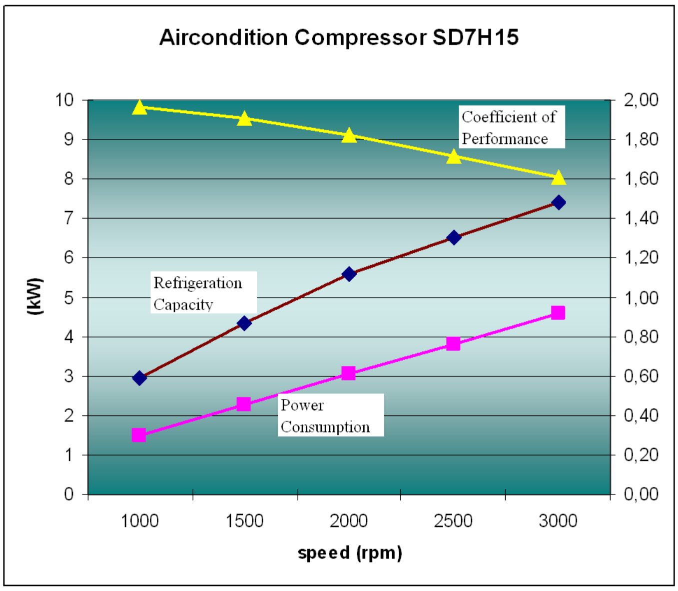


Figure 2-40 Characteristics of air condition compressor (SANDEN: SD7H15)

Table 2-15 Characteristics of climate Compressor

Coefficient of performance (COP)	1,6 -2
Weight	7kg (SD7H15)
Power consumption range	1,5 kW – 5 kW

Energy demand on NEDC

During NEDC the climate system shut off and therefore there is no energy demand on the A/C compressor.

Blower Fan

The blower fan is used for ventilating the vehicle passenger compartment. It ensures a clear view and pleasant climate inside the vehicle, which are pre-requisites for safety and driving comfort.

Figure 2-41 Blower fan with PMSM (CONTINENTAL)

Traditional electric fan:

Typically two fan speeds are possible. Full speed is obtained by direct connection, through controlled relays, to the power net supply. Reduced speed is obtained through the insertion of a series resistance between electric motor and positive supply. No energy management is applied during reduced speed and the electrical energy is wasted as heat in the resistance. Considering efficiency: electrical energy is produced from the engine via the generator. Electric motors are simple and efficiency in conversion from electric power to mechanical rotational power is about 75%.

Continuous speed fan regulation:
Fan speed can be regulated through current control electronics with a traditional electric motor. The Engine Control Unit can then deliver the correct power to cool engine water and control refrigerant pressure which minimises waste energy. With standard fan regulation there is a hysteresis around target engine water temperature, through the use of 2 levels of fan speed and as the intermediate speed is obtained through the use of series resistor connected to the electric motor, standard fan regulation is inefficient. The efficiency of the new regulator is high at around 80%-90. Overall system efficiency is improved with respect to on/off regulation with hysteresis, due to the drastic reduction of fan time operation. Brushless motors are also used for continuous fan speed control, with higher efficiency and higher cost.

Advantages

- Power consumption (emissions reduction)
- Power balance (harness, alternator downsizing)
- Noise
- Motor reliability
- Simplified architecture
- Diagnostic:
    - Rotor blocked
    - Short circuit
    - Over-load
    - Over-temperature

Disadvantages

- Additional components electronic devices
- Higher initial cost but overall system cost might be reduced

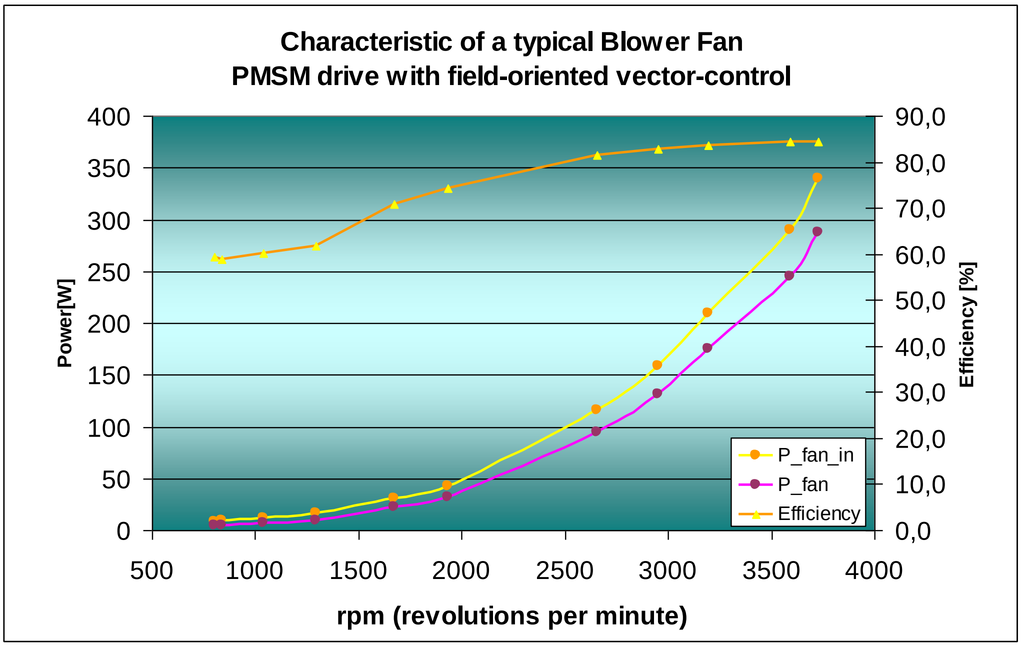


Figure 2-42: Characteristics for climate fan

Table 2-16 Characteristics of climate fans

Efficiency	60% - 85%
Volume/weight to power ratio	Not available
Power consumption range	50W-250W

Energy demand on NEDC
During NEDC, the climate system is shut off and therefore there is no energy demand on the fan.

2.3.10 Air compressor

Description and main function
Air compressors are utilized to raise the pressure of a volume of air. In trucks and busses the compressed air is used for braking, kneeling and door manoeuvrings (kneeling and door manoeuvring are not used in trucks). In today's busses a piston compressor is used, which is connected to the driving shaft.

Table 2-17 lists typical characteristics of two different air compressors; a piston compressor and an electric compressor. Since the electric compressor is constructed for 600V it can not be used in conventional busses and with the power demand on 6kW it is not realistic to produce it for a 28V system.

Table 2-17 Typical characteristics of a piston compressor and an electric screw compressor

	Piston compressor busses	Electric screw compressor busses
Voltage/Current	-	600V / 10A
Delivery of air	200 – 1000 l/min	400 l/min
Power	2 – 13 kW	6 kW
Weight	20kg	35kg
Length	240mm	660mm
Diameter	90mm	300mm
Cost	€250	€3000

The no load losses on the piston compressor are presented in Figure 2-43. The electric screw compressor can be turned of when not needed which results in no losses when there is no power demand on the compressor.

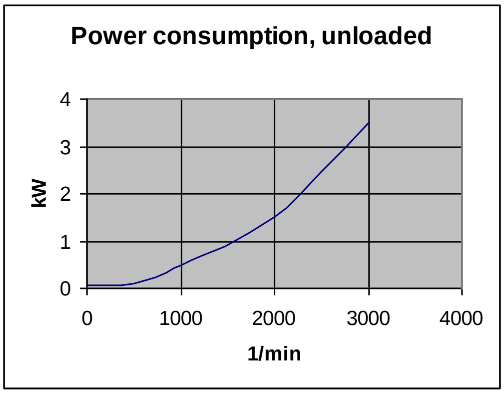


Figure 2-43 Losses when the piston compressor is unloaded

Energy demand on NEDC

The air compressor is not used in passenger cars and therefore there is no energy demand on this component in NEDC. In the standard driving cycle for trucks and busses there is a need for it to supply the system with compressed air. The average power consumption during a standard driving cycle is approximately 5kW.

Possible improvements

The air compressor is used for approximately 30-40% of the time the vehicle is in use (city driving), the rest of the time it goes unloaded which results in no load losses if it is not possible to turn off. For busses door manoeuvring is one of the loads on the air compressor; if this is changed to electrical the power outtake on the compressor can be reduced by approximately 30%.

2.3.11 Electrical Catalyst Heater

Description and main function

The aim of the catalyst heater is to reach the reaction temperature as soon as possible after cold starting. This is done using a fuel burner or heating electrically. To be efficient, electrical heaters need to supply high power, up to 3000 - 6000 W, for 6 – 15 seconds [10], [11].

Further means used to reach the reaction temperature quickly are to change the injection/ignition point, and avoid high thermal masses between the exhaust valve and the first catalyst. Modern engines use a high temperature resistant catalyst located directly behind the exhaust manifold. The manifold itself is designed as a double-walled sheet metal part with isolating air gap between the two walls. This enables modern engines to meet the newest pollution limits without electrical heating of the catalyst.

Energy demand on NEDC

None, avoided by best practice design of catalyst and exhaust manifold.

2.3.12 Body loads

Body loads are those embedded in the vehicle that are not related to the control of dynamics or powertrain but to comfort or safety aspects of driving. These include lights, windows, doors, wipers, seats and radio. The most relevant of these loads (as discussed in depth) in D1.2 are the following ones.

Lighting (Main Beam / Dipped Beam)

Typical state-of-the-art headlight lamps are glow discharge lamps (GDL) type. The main characteristic is that they emit their light through an electrical discharge in the shape of an arc. Conventional halogen lamps, in contrast, emit light from a wire filament. For a GDL lamp, an electronic ballast and harness is required to start and maintain the electrical discharge.

Also, some high end cars are being fitted withLED lamps. Although the consensus is that LEDs should be considered as the mid to long term, solution, it should not be considered as the current state-of-the-art for headlamps.

Table 2-18 Rating and power tolerance for main and dipped beams

	Rating	Power tolerance
Main beam	60 W / 12 V	Max. 73W @ 13,2V
Dipped beam	45W/12V	Max. 68W @ 13,5V

The start up current for GDL (glow discharge lamps) in worst condition is described in figure below. Worst condition at 13,5V power supply:

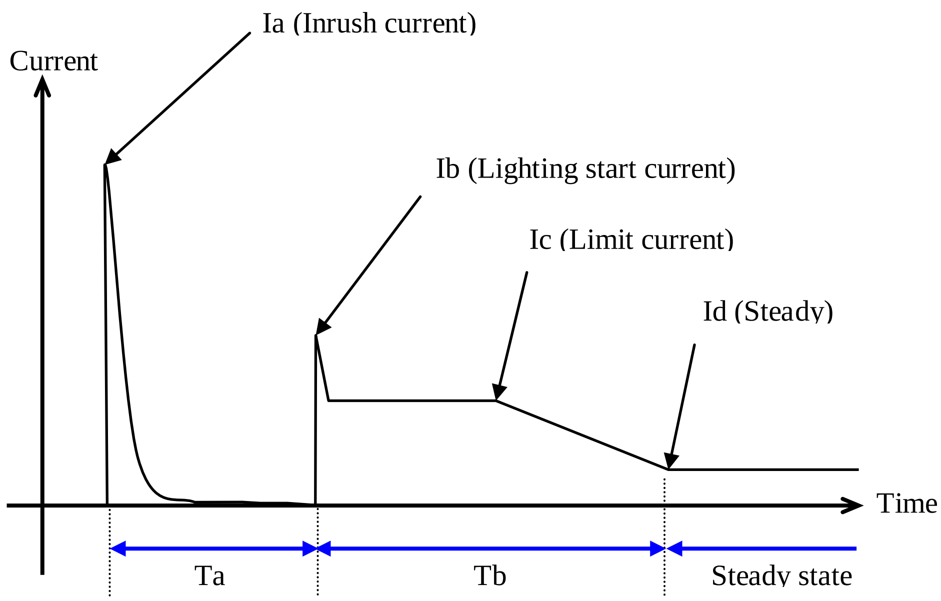


Figure 2-44 Start up current for GDL (glow discharge lamps) in worst condition (13,5V)

Table 2-19 Current peaks and time intervals presented in the figure above

Ia	Ib	Ic	Id	Ta	Tb
45.25 A	29.75 A	12.00 A	3.16 A	62.6 ms	57 s

Windshield / Rear window defroster

A defroster is a device for clearing condensation from the windshield or the rear window. It is also used for melting frost, ice, and snow that has collected on the window surface. Two versions are mainly used today:

The climate system is typically used on the front windshield or windscreen. Vents (situated on the top of dashboard) are used to blow warm air over the window surface, right above the dashboard.
Heating mode is typically used in winter. In this case, the warmth of the air lowers the relative humidity by increasing the moisture capacity of the interior air, causing evaporation.
Cooling may be used in the summer, when the humidity is very high. In this case, refrigeration causes condensation on the refrigerant pipe coils, removing water from the air. This also lowers the relative humidity and promotes drying by evaporation.
On the rear window, a defroster is used. Typically electric, it consists of an array of heating (resistive type) elements attached in very narrow strips to the window interior. These strips connect at both ends

to wider vertical bars at the sides of the window, to which electrical contacts are applied to connect it to the supply wires.

Typical power consumption of a rear window defroster / heater is 480W.

Seat heaters

Seat heaters are electrically powered, consisting of a mat (integrated under the surface of the seat, between the seat cover material and the seat cushion) with an array of heating (resistive type) elements. Different temperatures may be programmed, typically, three different ranges: high (45 to 48 ºC) medium (41-43 ºC) and low (36 to 39 ºC).

Typical power consumption of a seat heater is in the range of 50-100W.

2.3.13 Waste heat recovery

Description and main function

The combustion engines of current vehicles convert less than one third of the chemical energy supplied by gasoline or diesel into mechanical energy which can be used to propel the vehicle and overcome frictional losses and aerodynamic drag as well as drive the auxiliaries such as pumps and the alternator. The predominant part, more than two-thirds of the chemical energy, is converted into heat and will be released to the environment via the engine cooling system and the exhaust system.

The concept of waste heat recovery is to make an efficient use of the energy wasted in the form of heat in thermal engines. This heat is mainly dissipated in the exhaust device and in the cooling circuit. Many attempts have been made at trying to recover this waste heat using Rankine cycles and other principles. Possible transformations of energy are thermal-thermal (Heating, Cooling), thermal-electrical (Peltier-Effect), thermal-mechanical (Clausius-Rankine-Process, Joule-Process) and thermal-chemical (fuel up valuation). The main idea of waste heat recovery is to reduce the energy consumption and curb CO_2 emissions of vehicles by harvesting energy from the heat within the exhaust system and re-use this energy to supply components within the vehicle or to feed the powertrain of hybrid electrical vehicles. One of the recurrent ideas in this field is the use of thermoelectric devices that convert heat directly into electricity.

It has been known for some time that certain materials can generate electric power from heat and use electricity to function as heat pumps providing active cooling or heating. Such materials are said to be thermoelectric. Small pieces of thermoelectric material are connected as shown in Figure 2-45 to form a Peltier couple. One element is of p-type, the other one of n-type. They are connected in series electrically, but in parallel thermally. A multitude of couples can form a thermoelectricity module. When a heat source is applied to the hot plate, and the cold plate is maintained at a cold temperature, a voltage difference ΔV is created between the cold and hot plates, which can induce a current in an external circuit. The Peltier couple is an electric generator.

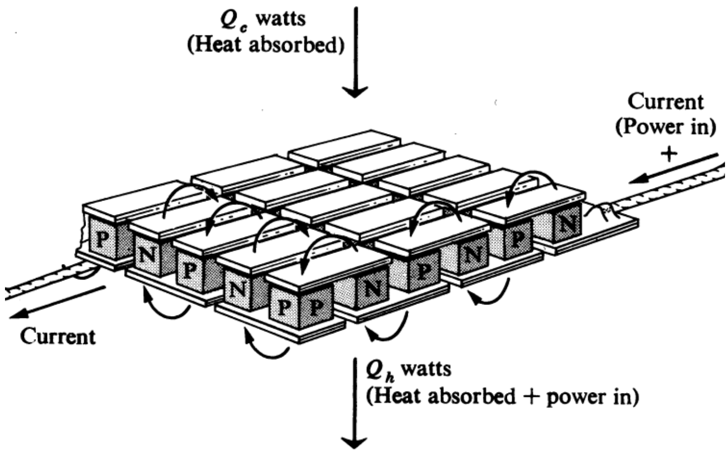


Figure 2-45 Electrical power generation from a thermoelectricity module

Efficiency

The thermoelectric device itself has an efficiency of typically about 10%. Additionally, one has to take into account the efficiency of a DC/DC-converter which will connect the thermoelectric device with the power net. The challenge is to build a high efficient DC/DC-converter with multiple inputs each working at the maximum power point of a thermoelectric module operating at comparatively low generated voltages varying over a wide range. The targeted efficiency at the optimal operating point of the converter is 95%.

Conclusion

The EE-VERT project will not investigate thermoelectric materials but how to use the energy generated in an overall system approach and how to integrate the modules in the new EE-VERT system concept.

3 STATE OF THE ART - SYSTEM

This chapter contains the state-of-the-art energy management strategies which are implemented in conventional vehicles. It treats energy management on the component level as well as on the system level. General methods for minimising energy usage are identified and summarized in order to give the reader an overview of the present state of technologies related to the efficient use of energy. It is necessary to understand present energy management strategies before improvements can be made. Improvements can be made by considering the exact demands of all electric power consumers and, where possible, suitable shift the loading in time to optimise the overall system efficiency. New approaches in current research are briefly discussed.

3.1 General approach to energy saving at system level

In order to find suitable methods for energy saving we should first examine why we presently need so much energy. Three main reasons for the high energy consumption of a vehicle are:

- Friction losses
- Drag losses (because of air resistance)
- Deceleration losses while braking, which will all increase with the speed of the car.

The first step for minimising energy usage is, generally speaking, to reduce size and weight, while increasing the efficiency of individual components. A trade-off has to be found between the benefits and the cost for new, more efficient, components.

Further these components should be embedded in an overall energy management strategy which assures intelligent control of the components at the system level. There are three potential options for further efficiency improvements:

- **Eliminating losses at standstill or cruising**
  (Strategy: engine start/stop, electrical driving)
- **Recovering braking energy**
  (Inherent for electrical traction motors)
- **Shifting the operation-point of the internal combustion engine to a more efficient area**
  (Strategy: demand oriented power distribution management for auxiliary units, boosting, Figure 3-1)

In the case of a full hybrid vehicle all three potentials can be exploited to some extent. Boosting is a method of using the electrical motor together with the combustion engine for propulsion. This allows a downsizing of the combustion engine, thus reducing engine cost and fuel consumption.

Figure 3-1 illustrates that shifting the operation point (OP 1) to more efficient areas can in principle happen by changing revolution speed (adaption of gear ratio , OP 2b). This can be achieved with manual gearbox when the energy management system provides the driver with (visual) information about the best gear selection, as engine speed has significant impact on fuel consumption). Alternatively he delivered torque can be changed through boosting or intelligent power distribution management, OP 2a.

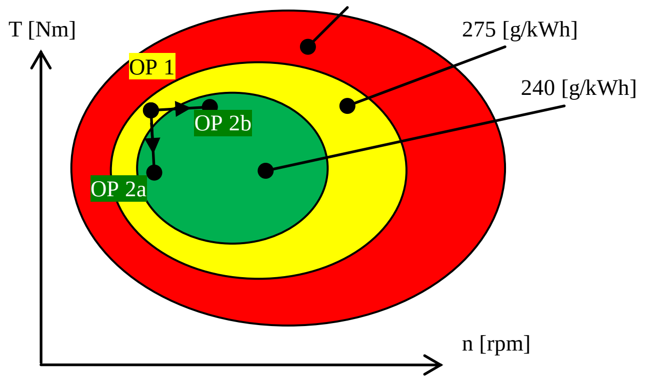


Figure 3-1 Schematic illustration of fuel efficiency of a combustion engine.

Many improvements are presently implemented to minimize the frictional losses of the car tyres, the gear ratio is being adapted to shift the operation point of the combustion engine to more efficient areas, and vehicles are being lowered in order to reduce the flow resistance. Further the idle speed of the combustion engine is lowered to reduce fuel consumption during downhill driving or at a standstill. Permanent magnet synchronous motors will commonly be chosen for various auxiliary devices, because of their high energy density and efficiency. These are important efficiency improvements, but will not be examined in more detail here as they do not affect the overall electrical system.

3.2 Energy saving strategies at system level

In a conventional vehicle with a traditional combustion engine an additional electrical motor is required to start the engine. Further a generator is included for constant production of electrical energy, regardless of the present demand. In hybrid vehicles the electrical motor is also used for propulsion. In a **Micro-Hybrid**, the classical generator and the starter-motor are combined into one electrical machine the “**Starter-Generator**” with nominal power ratings in the range of 2 to 10 kW. It is advantageous to integrate the Starter-Generator in the crankshaft to avoid the additional losses of v-belts. The Starter-Generator enables the so-called “Start-Stop” function (= switching off the combustion engine whenever the car stops). Further it enables brake energy recuperation and intelligent control of the generator function (charging the battery only during efficient engine operation) as well as boosting (additional propulsion energy for drive away and acceleration). Presently these mechanisms are implemented in some passenger cars, but they are not universally used. Communication with the central ECU gives information about the vehicles status (stop, acceleration, braking etc.), components receive their instructions via the on board bus system (today CAN, FlexRay).

Figure 3-2 gives an overview of the standard energy saving mechanisms and their usage during a virtual driving cycle of a mild hybrid vehicle. Apart from “electric only “mode and “electric power assist”, which can be applied only in hybrid vehicles, all other methods (especially “Intelligent battery charging”, “regenerative braking”) could also be applied to conventional vehicles. These mechanisms are presently used (in BMW cars) together with a gear shift indicator. A gear shift indicator does only provide the driver with (visual) information about the best gear selection. The following chapters describe the more sophisticated method of “scheduling electric power consumers” and the impacts of “regenerative braking”.

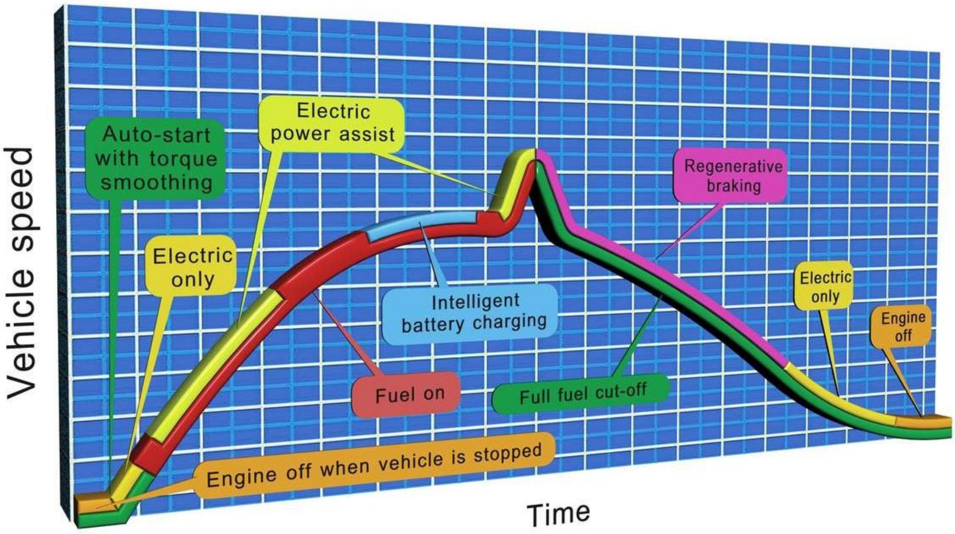


Figure 3-2 Intelligent energy management on system level [12]

3.2.1 Electrification (belt-less car)

With the continuous improvement of safety and comfort features, the number of electrical consumers (drives, actuators, heating resistors, lamps) can often reach around 100 in an upper-class vehicle. Electrically actuated devices have some basic advantages in comparison with mechanical (hydraulic) actuators:

- no power consumption, when they are not activated
- high flexibility in speed/torque (force) characteristics
- high efficiency

These advantages have lead to an extensive replacement of mechanical actuators by electrical ones. The expression "the belt less car" is a synonym for this trend, indicating the replacement of mechanically ICE-coupled drives by electrical ones. The high level of "electrification" in modern vehicles leads to a considerable demand for electrical power which may lead to average values of more than 2 kW. The high value of the total electrical load highlights the importance of the overall electrical efficiency from component level to system level. The starting point for improving efficiency is the electrical generator which may be combined with the starter to create a single electrical machine (starter-generator).

In some cases systems using mechanical-driven auxiliary coupled with a clutch and belt-drive can reach high efficiencies. However, electrical systems offer higher flexibility in speed/torque (force) characteristics and can act in a more demand oriented manner to reduce fuel consumption.

3.2.2 Dual-voltage (14V-42V) power-nets

Along with the "electrification" of auxiliaries the electrical power demand is steadily growing. The efficiency of automotive electrical machines can be increased by designing them to operate at higher voltage levels than the 14 volts systems which are currently used in passenger cars. Consequently, it would be favourable, from an efficiency point of view, if the voltage level for the generator and the heavy loads, such as the climate compressor, could be increased. Buses and trucks are currently using a 24V power net. The 14V power net would need to be retained for the control systems and low power loads. Figure 3-3 shows an example of a two level power net for passenger cars.

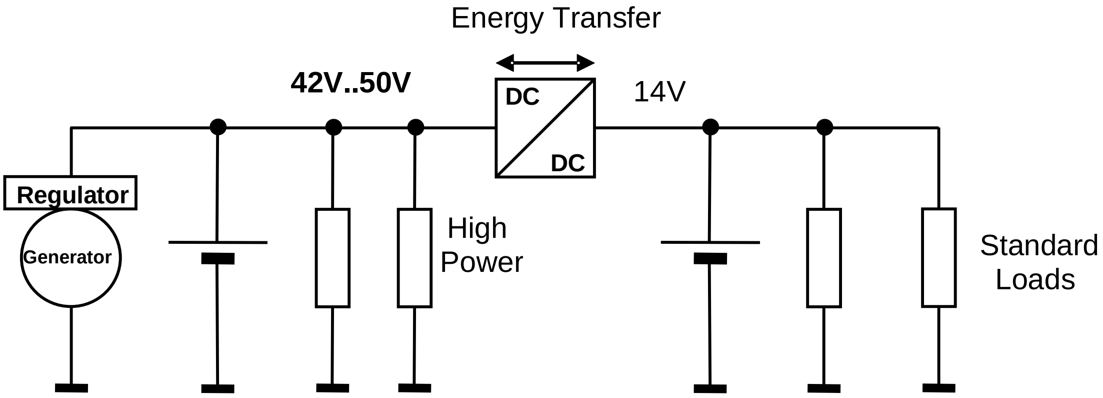


Figure 3-3 Example of a two level power net for passenger cars which would allow design of much more efficient motors/generators

For connecting the higher voltage (probably 42-50V) supply level with the 14V power net supply an additional MOSFET half bridge is needed which will act as a synchronous step-down converter when the PSM runs in generator mode and as a synchronous step-up converter respectively when the PSM runs in motor (starter) operation, as illustrated in Figure 3-4.

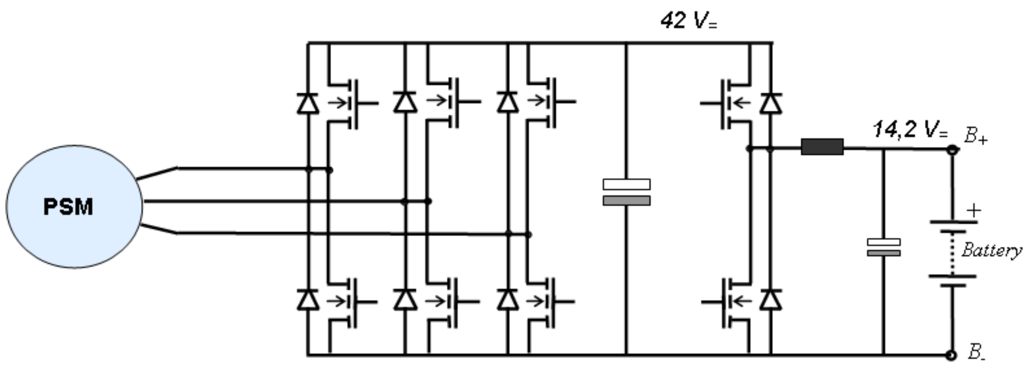


Figure 3-4 Schematics of a Starter-Generator with Permanent magnet synchronous machine and three-phase MOSFET inverter at 42V [1]

3.2.3 Scheduling electric power consumers

The challenge at system level is to use intelligent components at the right time. The basic idea behind an optimal energy management strategy is given in Figure 3-2. Further improvements can be made by shifting the loading in time in order to optimise the overall system efficiency. Electrical power consumers can be categorized into continuous, prolonged and intermittent loads. First it has to be decided which of them can occur at the same time, further loads can be augmented with priorities. With this demand oriented power control the peak electric power can be reduced and wasted energy can be minimised. Mathematical algorithms provide solutions for optimization problems, leading to minimal energy usage, thus reducing fuel consumption.

Background: how intelligent power distribution/supply management affects fuel consumption (and why energy management is a mathematical optimization problem)
Intelligent power management can use the storage capability of a battery and/or a super capacitor when the power of the alternator does not match the power of the electric loads. Now a means of determining the time has to be found to generate on board electrical energy when the cost for creation is low. The cost for creation corresponds to the fuel usage of the internal combustion engine that powers the alternator. The power flow in a conventional vehicle is given in Figure 3-5 and Figure 3-6.

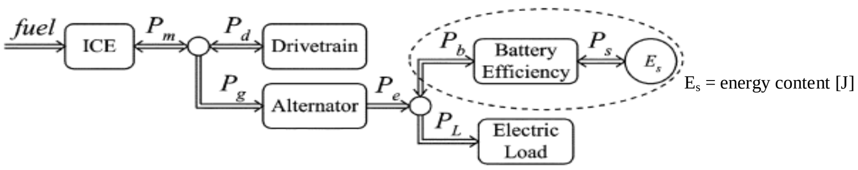


Figure 3-5 Power flow in a conventional vehicle (ICE Internal Combustion Engine)

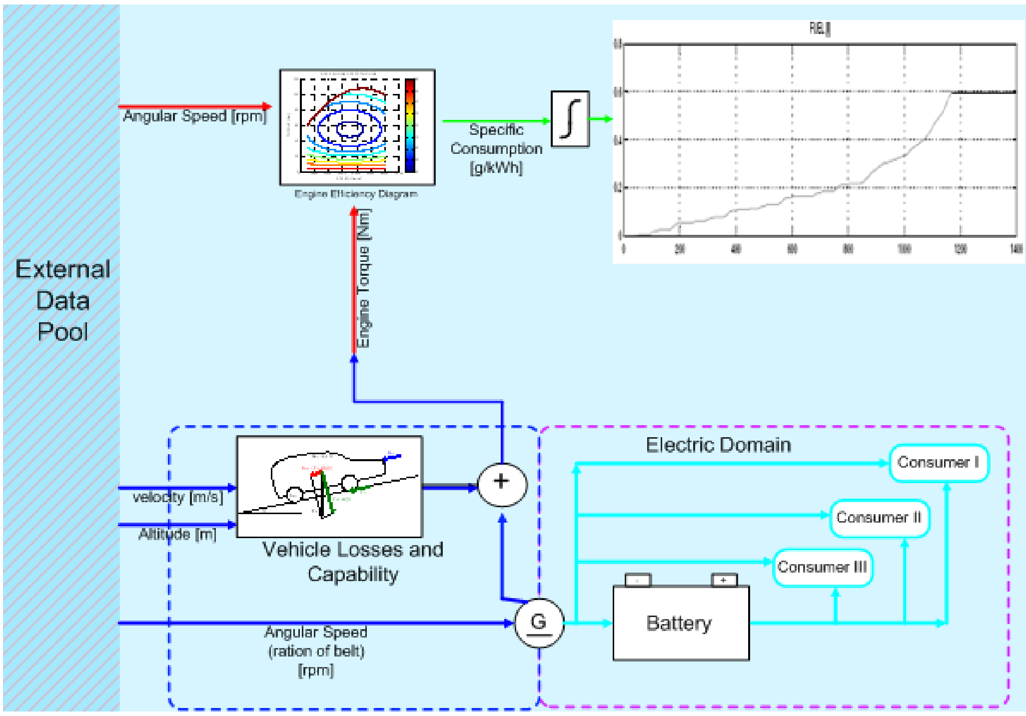


Figure 3-6 Engine torque is the result of what is required for vehicle propulsion and driving the generator

In powering the alternator the internal combustion engine has to provide additional power Pg, therefore providing additional Torque when the speed n of the vehicle is assumed to be predefined. This relation is given in Equation (2) and Figure 3-5.

The more power the generator has to provide, the greater the load on the combustion engine. The engine has to provide this torque in addition to that required for vehicle propulsion. The output of the alternator, and the related torque load on the engine, is controlled by its excitation current. Using this technique the operation point of the internal combustion engine can be shifted to more or less efficient areas of the specific fuel consumption map, thereby affecting the fuel consumption.

$$P_m[W] = P_d + P_g = 2\pi \cdot T[Nm] \cdot n[rad/s] = T \cdot \frac{2\pi}{60} n[rpm] \quad (2)$$

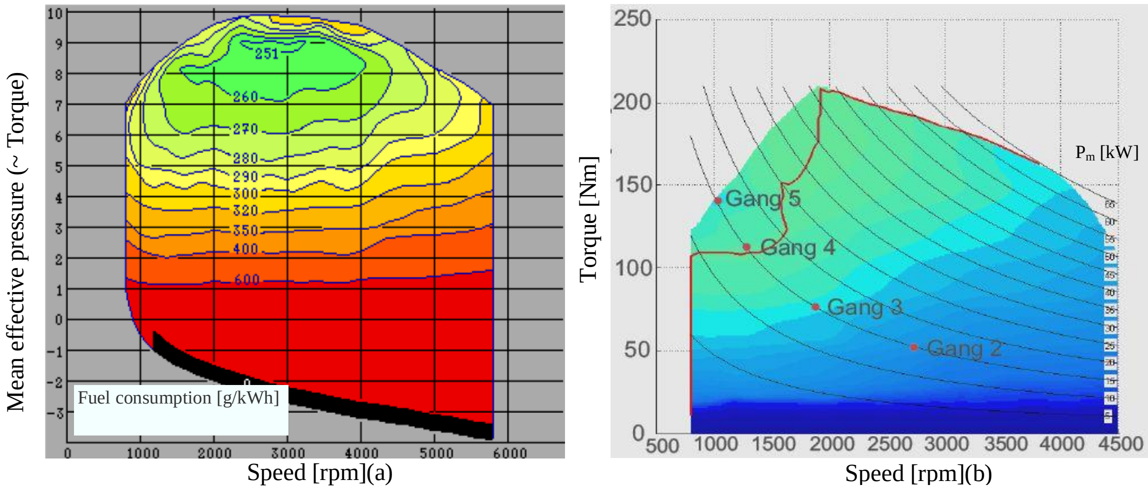


Figure 3-7 Fuel consumption [g/kWh] of example Internal Combustion Engines (Gang 2 to Gang 5 correspond to gear 2 to gear 5, revolution speed is first adapted to choose an efficient operating point of the combustion engine, if constant traction power is required. The red marking in (b), the Optimal Operation Line, connects all points of minimal fuel. The black lines in (b) connect all points of the same power Pm)

According to
Figure 3-7 the combustion engine can be shifted to more effective operating points by either changing the revolution speed or changing the produced torque. It is therefore necessary in energy management to provide the driver with information about the best gear selection.

Further intelligent control of the delivered torque (that is by scheduling electric power consumers and using the storage capacity of the battery in the electric domain) allows electrical energy to be produced when the "cost for generation" is low.

3.2.4 Start-stop

The start-stop function automatically switches off the internal combustion engine when the vehicle comes to rest, for instance, at traffic lights, in a traffic jam or at a railroad crossing. Start-stop restarts the engine automatically when the driver wishes to move off.

Figure 3-8 illustrates the procedure of start-stop in combination with a manual gear shift as implemented by BMW [14]. The start-stop is only activated if the driver stops the car, engages the neutral gear and releases the clutch. After checking the power consumption of electrical loads and the state of charge of the battery, start-stop will switch off the engine automatically and display the current state of the engine in the instrument panel.

During the standby period, the systems in use draw electrical energy from the battery. Furthermore, the engine restart after each automatic stop also results in a significantly increased number of high-rate load events compared with a standard vehicle. Together these activities place a greater workload on the battery.

The amount of fuel saved by stop-start equates to the stop time when the normally the engine would be idling time. The automatic restart decreases this fuel saving potential by temporarily increased consumption. This effect can be minimised by setting a minimum engine-off time period of 5s. Under these conditions, a maximum potential for fuel savings of 3.5% in the New European Driving Cycle (NEDC) has been reported [13].

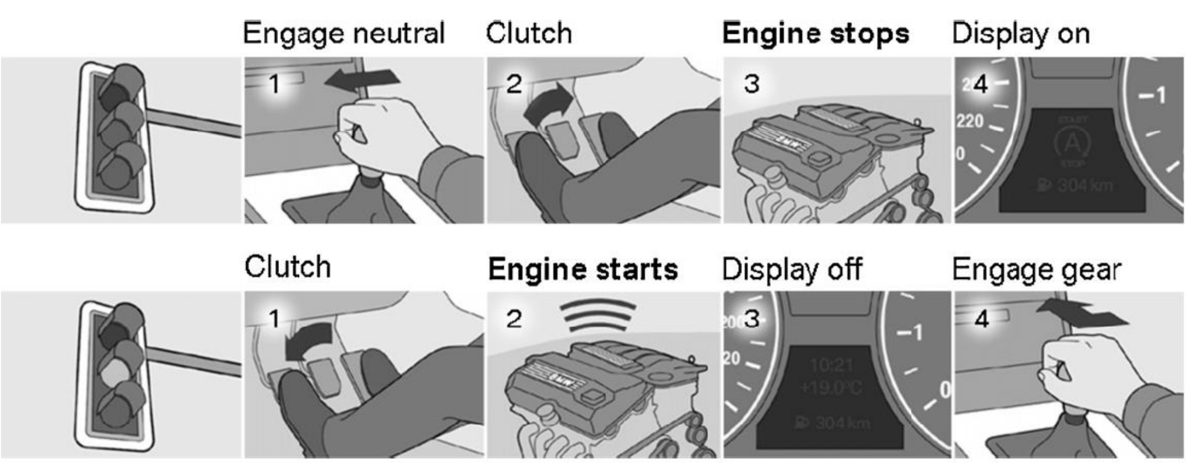


Figure 3-8 Sequences of an automatic engine stop and start with start-stop functionality. The driver induces automatic engine stops and starts by properly handling the gear shift and the clutch [14]

3.2.5 Regenerative braking

Regenerative braking is an ideal technology to use the kinetic energy of the car to charge the battery when the vehicle needs to be slowed down. The benefit is great, but limited as well. Losses reduce the amount of energy that can be recuperated during deceleration. The expression “effective energy” or “effective power” considers three major parts in case of a moving vehicle:

- friction losses
- air resistance losses (drag losses)
- braking losses (deceleration losses)

To define braking losses as a term of the effective power is not completely correct, as we know that new hybrid vehicles are able to recover some energy during deceleration. Figure 3-9 show the energy budget of a vehicle.

In addition the idle speed of the combustion engine can be lowered to reduce fuel consumption during downhill driving or standstill. A smart battery controller is necessary for improving the efficiency of brake energy recuperation. At the moment energy storage systems are limited by the charge rate and the cycle life of the battery (see chapter 2.2).

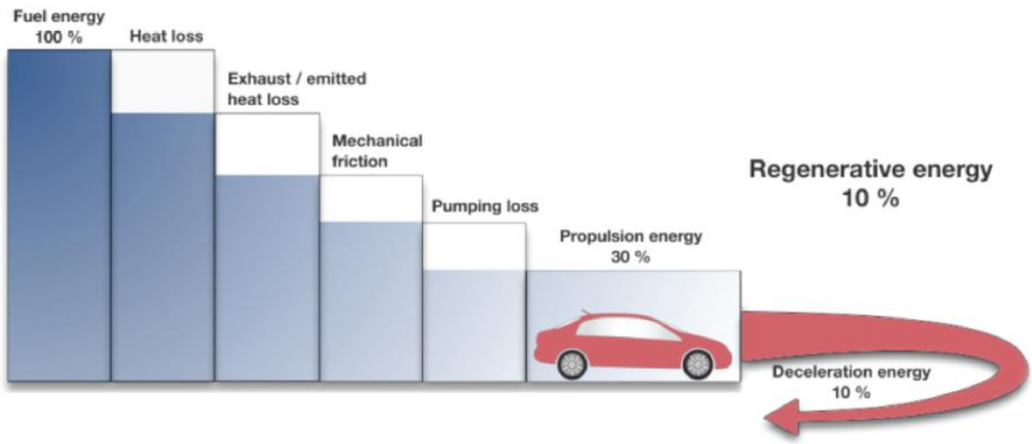


Figure 3-9: Vehicle energy budget (Source: A3PS Conference 2008)

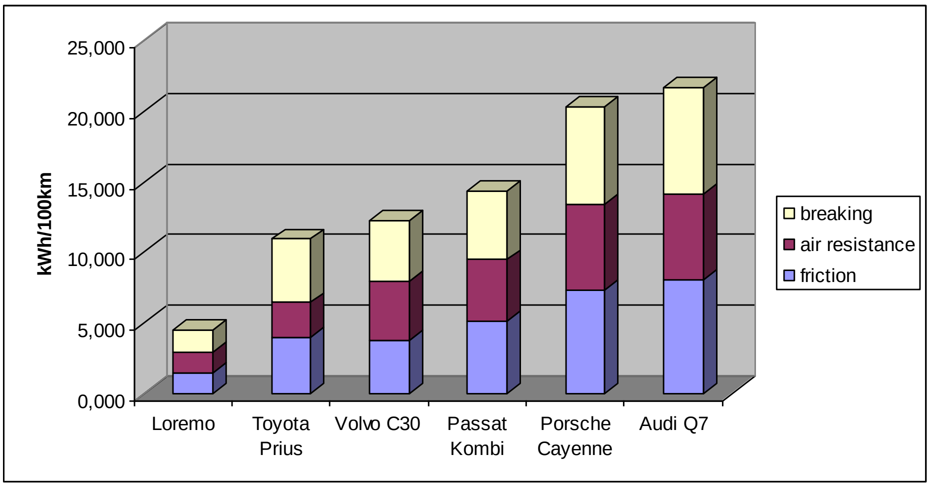


Figure 3-10 Comparison of necessary effective energy for different cars (NEDC) [1]

Figure 3-10 compares the necessary effective energy needed for this cycle by particular cars (at a base of 100km, which correlates to 9 repetitive NEDCs), and demonstrates the considerable differences, primarily as a result of different size (cross-sectional area) and weight of vehicles.

3.2.6 Other developments

Other methods have also been proposed for further energy saving mechanisms and their usage during a virtual driving condition

Travolution

Travolution is a new traffic concept that allows vehicles to communicate with traffic lights, in order to smooth traffic flow and reduce congestion and, in consequence, reduce unnecessary stop/drive-away cycles which cause more fuel consumption. Audi has deployed a first prototype using 46 smart traffic lights installed in Audi's home town of Ingolstadt which communicate with specially equipped Audi A5s and A6s. The cars interpret the information from the lights and display an ideal speed to the driver which leads to smooth driving through green lights as opposed to hitting the reds. The lights also interpret traffic density and adjust timing to reduce waiting times at the lights thereby minimising the amount of fuel-sapping "stop-start" traffic.

Figure 3-11 AUDI Travolution concept [15]

Power from home electricity household

The cost of electricity produced in a conventional vehicle has been estimated at about 0,8€ per kWh (depending on fuel prices and efficiencies), compared to about 15ct/kWh available from the home electricity outlet.

Household electricity is presently used in very cold regions to perform pre-heating of the vehicle before start. This reduces exhaust emissions by avoiding cold-starts. Investigations should be done in this field (and by simulation in EE-VERT) to compare the cost (either monetary or expressed through emissions or expressed through the use of fossil fuels) of the energy for pre-heating generated on board, with the cost when taken from the home electricity household.

The use of plug-in technologies in vehicles requires more effective energy storage systems such as Li-Ion batteries or ultracapacitors.

4 STATE OF THE ART – ALGORITHMS FOR OPTIMIZED ENERGY SUPPLY AND DISTRIBUTION

This chapter concerns algorithmic methods for solving optimization problems and explains their application in the field of vehicular energy management. In the state-of-the-art passenger car electrical power is generated with little knowledge of the actual loads.

Vehicular energy management corresponds to an overall and computationally intensive optimization problem of control, storage and distributed loads. Algorithms are needed, which are suitable for solving optimization problems accurately and set a benchmark for the best achievable solution.

Today's research work concentrates mostly on hybrid vehicles and "For convenience, the electric loads are modelled as one lumped power consumer". The challenge is to go one step further, applying existing solutions to vehicles with a conventional power train, but to consider the electric consumers in more detail. This should result in the generation of on board electric energy only when it is required and when the cost of generation is low.

In order to find out when this cost for generation is low, it is necessary to take into account the efficiencies of the engine, storage elements and loads under certain boundary conditions, as well as the driving cycle. The best example is the on board battery system. The battery's state of charge (SOC) has a significant affect on its efficiency and the number of charge cycles are limited. This makes the problem an overall and complex mathematical optimization problem in which production, storage and distribution of electric energy are rescheduled to more efficient moments. The degrees-of-freedom in this case are the power from the alternator and the power to electric loads. The storage capacity offers freedom to schedule the power request over time.

Online and offline strategies

The strategies, which determine the usage of all components in real-time while the vehicle is on road, using data about the current vehicle status, are so-called online strategies. A simple example is a controller, which decides on component usage by only considering the batteries SOC. For example if the SOC is low and deceleration is detected then brake energy recuperation is initiated accordingly.

Computations to find a global optimum have to include all the information about the future driving cycle. Such computations normally take between 4 minutes and 10-20 hours, depending on computational power and complexity of the modelling. Global optima can, therefore, not be found in real-time and have to be done offline. Global optimization algorithms are used offline to develop the best possible component usage strategy. This strategy is presently translated into several rules for rule based controllers *(If…(SOC, load demand, operating point etc.) ... then…)*, which will implement the strategy online.

Modelling the vehicle components

In order to implement any global optimization algorithm it is necessary to model the flow of electrical energy, this requires a mathematical model of each component (mechanical and electrical) that describes its behaviour.

There are two ways of modelling; first "**dynamic modelling**" shall be explained. Dynamic modelling is based on a forward directive, in which the vehicle speed is computed according to the drivers input (that is the position of the gas pedal). Each component has to be represented by its differential equation, using the original physical quantities as inputs, resulting in a system of differential equations. This physical modelling of the components dynamics guarantees a realistic behaviour in simulations and reacts very well to different types of drivers.

In the case of designing an energy management strategy it is not important to know the exact reaction (that is for example fuel consumption) of a system to driver inputs.

A more goal-oriented way is to choose a modelling technique based on a backward directive, which takes a known (optimal) system output and determines the states which were necessary to get there. This leads to the second possible way of modelling, which is "**quasi-static modelling**". In this case only the components static behaviour has to be taken into account (degree of efficiency, losses etc., and not all components will be equally complex). It is sufficient to look for a representation based on formulas according to their properties, rather than using complex differential equations. In any case it is important to coordinate and to match all of the models.

4.1 Algorithms for optimized control

Basically algorithms for optimisation problems can be classified into two basic methods: The first are heuristic methods. Heuristics rely on experimental data and require some kind of learning stage to find a solution, which is quite close to the real optimal solution. In contrast to heuristics there are analytic methods, which rely on characteristic behaviour of components and on their operating maps.

Both methods require mathematical models to represent the components, which are related to vehicular energy management. What follows is a brief description of what most suits heuristic or analytic methods, and how applicable algorithms lead to an optimal energy management strategy.

4.1.1 Heuristic methods

Heuristic methods employ experimentation and trial-and-error techniques and are used to rapidly come to a solution that is close to the optimal solution. The most important are Fuzzy-Logic and Neuronal Networks.

Fuzzy Logic deals with the concept of partial truth. The degree of truth can range between 0 and 1 and is not restricted to 0 meaning false, and 1 meaning true. The membership to any set cannot be only true or false, but is expressed through a membership function. As an example: In conventional logic the requested power for an electrical load could either be provided by the battery, or directly by the alternator. With fuzzy logic it is possible that the battery would provide for example 75% of the requested load and the alternator produces only 25%.

The difficulty in using Fuzzy Logic for energy management problems is firstly the definition of suitable membership functions, and secondly there has to be an adequate number of membership functions to give good results.

An artificial **Neuronal Network** is an interconnected group of nodes. The input nodes correspond to the sensing elements (Inputs). The output is determined by weighting the inputs and their interactions. In order to find the correct weights for the inputs a learning stage is necessary. For teaching the correct outputs, known inputs are given and the weights are adapted. An adequately taught network is capable of providing almost optimal outputs to unknown inputs.

In the case of energy management it would be necessary to provide the optimal component usage first to teach the network correctly. As the optimal energy management structure is not known in advance neuronal networks are not useful in this stage. If the optimal energy management strategy could be established for several standard driving cycles a neuronal network would be helpful to implement these techniques to non-standard cycles. This approach is not examined in existing research work, but could be investigated in EE-VERT.

Heuristic methods such as neuronal networks and fuzzy logic are advantageous in applications in which the system interactions are not all known or are difficult to describe. As this is not the case in vehicular energy management problems analytic methods are more suitable.

4.1.2 Analytic methods

Analytic methods use a “cost function”, which describes the system output with respect to the parameter that is to be optimized. This can be fuel consumption, emissions, battery life and so on. More dimensional cost functions are generally possible (e.g. reduction of fuel consumption AND emissions) but the determination of a suitable cost function gets more and more difficult. The contributing components have to be modelled. These methods lead to excellent results when accurate system models are used.

Key words for analytic methods to solve optimization problems are **Linear Programming, Quadratic Programming, Optimal Control** and especially **Dynamic Programming**. These techniques assume that the future driving cycle is entirely known. Further, **Model Predictive Control** allows results on the prediction of the vehicle load in the near future. **Stochastic Dynamic Programming** provides additional laws for augmenting the cost function with probabilities. Stochastic dynamic programming might be useful to apply to any variable cycle based on results from standard drive cycles.

The required calculations put a high demand on computational resources and preclude an on-line implementation. Nevertheless, their result can be used as a benchmark for the performance of other strategies, or to derive rules for a rule-based strategy.

Related problems in mathematics are the **Knap-Sack** problem, the **Shortest Path** problem and the **Travelling Salesman** problem. These problems will not be discussed in more detail, as there is much literature available [16] and [17]. These references are useful sources if further information is required concerning the development of a dynamic programming graph, the required computation time and possible limitations.

Dynamic Programming for vehicular energy management

Dynamic Programming (DP) relies on finding the optimal path through a graph, reusing optimal substructures. In this chapter the dynamic programming algorithm by Bellmann/Dijekstra will be adapted with respect to its application in energy management problems. This is done because other methods mentioned above (Linear Programming, Quadratic Programming) rely on this general strategy and provide simplifications for online implementation or stochastic improvements of the basic dynamic programming algorithm. A detailed explanation of the general DP algorithm will not be given as there is much literature available to this topic.

Adaptation of the DP graph

The energy management problem can be represented by a graph, consisting of nodes/vertices and edges. The edges contain the costs to reach a node; the nodes represent the state of the system/vehicle. It is now possible to determine the shortest path through the graph that reaches all the nodes (this is the Travelling Salesman Problem) but the energy management requires to determine the shortest path from a start node to the end node (which requires to determine the shortest path from start to all the nodes).

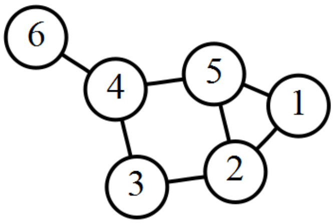


Figure 4-1 Example of an omnidirectional graph with 6 vertices and 7 edges

Layout and outer form of the graph have to be changed such that the data representation corresponds to the problem of energy management:

- The nodes shall represent all possible states which the vehicle inherits during the complete drive cycle.
- Weight applied to edges: the weight will depend on the parameter which has to be optimized.

First the general omnidirectional **graph,** Figure 4-1, must be transferred into a directed graph, as the driving cycle for which energy management is required is a time directed process. As the graph has only a limited number of nodes it is further necessary to identify a feasible number of discrete states, each corresponding to a real reproducible vehicle status. Finding the optimal path through the graph means finding the optimal sequence of states that the vehicle is in. This results in a directed graph (in contrast to the general omnidirectional graph), divided into time discrete states, each stage contains more or less nodes, depending on possible vehicle states. An example is given in Figure 4-2.

Figure 4-2 shows an example of a graph for DP which is applicable for energy management solutions. The vehicle status is represented by the batteries SOC (therefore marked in Figure 3-5) – this is an example only and has to be adapted if other parameters are significant to derive a suitable energy management strategy. In this example the SOC was used to derive a strategy for a parallel hybrid vehicle. The result of DP, therefore, is the charge/discharge cycle of the battery during the whole drive cycle, which immediately reflects the usage of the electric motor for propulsion or as generator – the optimal energy management strategy is found. The quantization of the nodes for each time step is a result of the maximal possible charge/discharge energy in the time interval. The time interval is chosen to be one second, as modern navigation systems update the information about driving cycle and velocity each second.

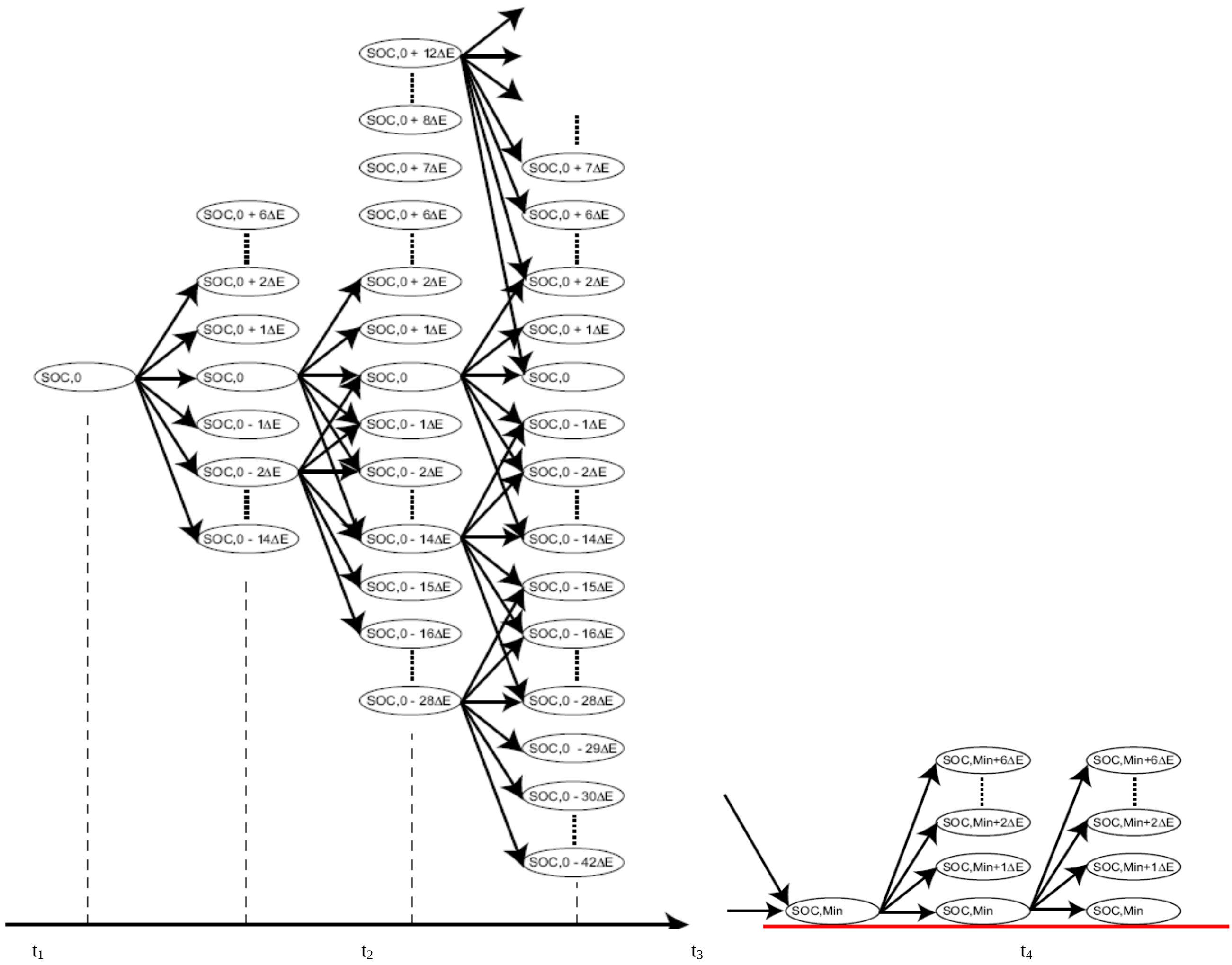


Figure 4-2 Example of a directed graph for developing an energy management strategy using DP

After the generation of a suitable graph the determination of the **weight** to describe the node transitions will be done. For each time interval Δt the drive cycle provides information of the vehicles velocity as well as the elevation profile of the cycle. With that information the necessary power for propulsion has to be computed (using the models). This power will be used to determine the necessary fuel consumption for each edge, which means for each possibility of component usage.

4.1.3 Prediction of future events

If the whole drive cycle is known it gets possible to adapt the graph in such a way, that each node receives a former transition, whose change in SOC should correspond exactly to either the demanded or the maximum recoverable amount of energy. This leads to optimal results when the altitude of the driving cycle is included in the computation. Then it is possible to shift the SOC of the battery in order to recuperate the maximum possible potential energy, as the overall energy balance is known. Present online strategies are not capable of solving such problems because of limited computational resources.

4.2 Model Predictive Control

Model Predictive Control (MPC) is an approach originating in control engineering that uses time discrete dynamic models. It is an iterative method that relies on the solution of Euler-Lagrange equations, not giving optimal, but in practice very good results.

Current system states are being measured, future system states are being computed (using the models of the system) and because of this prediction suitable inputs for the next time instance will be chosen. This allows the *prediction of optimal inputs*, at the same time taking into consideration valid boundary conditions and system state restrictions. Because of the inherent feedback MPC is a closed-loop-control technique, in contrast to DP, which is an optimal open-loop-control technique. This allows external influences to be considered, but at the same time requires much processing power. For the proper application of MPC the relevant system dynamics have to be slow enough that an optimization in every time instance is possible.

4.3 Scheduling Algorithms

Additionally to the above methods scheduling algorithms used for operating systems concepts and real time concepts (*Round Robin, Priority Pre-emption* and so on) should be examined. These could be useful to schedule electric power consumers when the available electric power is limited. So far no reference has been found in published research to the application of scheduling algorithms for energy management. However, this possibility should be considered further.

5 Hybrid Vehicle Systems

In this document a hybrid electric vehicle (HEV) contains one or more electric motors combined with either a petrol or diesel internal combustion engine (ICE) together with an electric storage system (e.g. battery or ultra capacitor). Hydraulic or flywheel hybrids and pure electric vehicles are excluded.

5.1 Configuration of Hybrid Vehicles

Hybrid systems are often classified into Parallel, Serial and Combined hybrid vehicles as described in the EE-VERT Glossary [18]. Parallel hybrid systems are used for passenger cars (e.g. HONDA Civic INA) as well as for commercial vehicles (e.g. MB Sprinter Hybrid, FUSO Canter). Serial systems are usually used for military (e.g. Propulse from Oshkosh) and commercial vehicles (e.g. city busses from FUSO, Orion and MAN). Power-split hybrids are usually passenger cars (e.g. TOYOTA Prius, LEXUS LS600h).

Another commonly used classification of hybrid vehicles is into Micro, Mild and Full Hybrid, also explained in the EE-VERT Glossary [18]. In this case the power range, mainly influenced by the size of the three main components (ICE, electric motor and battery system) and the required functionality of the vehicle (operating distance for pure electric mode, boost operation, etc.) are the main parameters.

5.1.1 Additional or Modified Equipment

The hybrid configuration, along with the functional specification, given by the application and consequently selected by the designer will have a major effect on the required characteristics of the main and auxiliary equipment.

A HEV will probably have the following equipment that may be additional to a conventional vehicle:

- Electric motor and inverter
- High voltage generator and inverter (motor and generator may be a single electrical machine)
- Secondary energy storage (battery or ultra capacitor)
- DC/DC converter
- Hybrid control unit

Although the prime purpose of the listed equipment is related to the high voltage electric traction system they all require support from the low voltage system either as a direct electric feed or for electrically powered water or air cooling.

Some of the auxiliary units must be modified to operate with electric power as the ICE is switched off during EV driving:

- Electrically powered steering (EPS or EHPS)
- Vacuum pump for braking assistance (passenger car)
- Air compressor for brake system (commercial vehicle)

- Water pump for cooling motor, inverter and DC/DC converter
- Water pump and possibly AC compressor for cooling the battery pack
- Actuator to operate clutch and automatic transmission - depending on hybrid topology (e.g. electrical oil pump)

During pure electric vehicle mode, brake energy recuperation by electric generator and stop/start operation the listed auxiliaries are required to be fully functional. The designer can decide whether the larger loads are placed on the high voltage system, otherwise these systems will draw electrical power from the low voltage system.

Additionally the comfort and infotainment systems may also be activated and draw electrical power from the low voltage system. An intelligent power management can decide or control what equipment is available during different operation modes.

5.2 Energy Management as applied to hybrid vehicles

5.2.1 Energy Management as Mathematical Optimization

The mathematical subjects for modelling the vehicle components and energy management optimization have been described in Chapter 4. These terms can be used for hybrid electrical vehicles as well as for conventional vehicles. The major deviation between a hybrid vehicle and conventional vehicle is the size of the battery for recuperation and the potential of electric traction and boost operation for hybrid vehicles.

5.2.2 Hybrid Control Strategy

To operate a HEV in an optimized mode a proper control algorithm is required which is typically located in a so-called hybrid control unit (HCU). The task of such an algorithm is to interpret the driver request and to determine how to operate the power paths of ICE and electric motor in the most optimal way. The main objective of the optimization is the reduction of the overall energy use and consequently the reduction of the fuel consumption of the ICE. The theoretical optimum is usually constrained by drivability requirements and characteristics of the components.

The following properties or requirements influence the control strategy:

- Driving safety
- Driving comfort
- Component protection
- Durability
- Fuel consumption

To provide a consistent and reproducible response to a driver request the following operation modes are available e.g. for a parallel hybrid vehicle:

- Pure ICE mode
- Pure electric mode
- Regenerative braking
- Load point shifting of ICE
- Boost operation

Classification of Control Strategies

Several possibilities for the classification of control strategies are shown in Chapter 4. The heuristic controller represents the state of the art in most prototypes and mass-production hybrids. Other similar approaches regarding control strategies have been investigated for parallel hybrid vehicles, series hybrids and combined hybrids in various publications [19], [20], [21].

Heuristic Control Strategy (Example)

A typical heuristic approach, sometimes called "electric assist" strategy is based on the torque demand and on the vehicle speed [19]:

- below a certain vehicle speed only the electric motor is used
- above this speed and below the maximum engine torque only the engine is used
- above the engine maximum torque the electric motor is used to assist the engine
- if the battery SOC is too high, only the electric motor is used
- if the battery SOC is too low, the engine is forced to deliver additional torque to recharge the battery
- at negative torque (braking) the electric drive operates as a generator and charges the battery

The main advantage of heuristic controllers is that they are intuitive to understand and rather easy to implement. The disadvantage is that they are strongly dependent on the choice of the design thresholds (speed threshold in the above example) which may vary with the driving conditions and therefore limit the robustness of the system.

6 Standards Applicable to EE-VERT

The aim of this section is to identify standards relevant to the components that may be modified as part of the project. In Europe, two systems of type approval are used. One is based around EC Directives and provides for the approval of whole vehicles, vehicle systems, and separate components. The other is based around UNECE (United Nations) Regulations and provides for approval of vehicle systems and separate components, but not whole vehicles.

Type approval is the confirmation that production samples of a design will meet specified performance standards. The specification of the product is recorded and only that specification is approved.

A review of the standards generally available indicates that European directives such as the Council Directive 70/156/EEC of 6 February 1970 relating to the type-approval of motor vehicles and their trailers are concerned, primarily, with safety and not with the functional specification of components. There are references to specific components such as directive 76/761/EEC for headlamps and all electrical devices need to satisfy the electromagnetic compatibility directive, 72/245/EEC. The European directives are supported by the UNECE regulations. There are also directives, not specifically for the automotive market, that may be relevant e.g. directive 2006/66/EC for Batteries and Accumulators.

There are several international organisations including ISO and IEC that produce standards. SAE have several component specific standards covering 12V batteries, starter motors and HVAC blowers. Generally, it appears that the functional performance of components is driven by the vehicle manufacturers.

This review concentrates on the directives and standards that enable manufacturers to sell vehicles throughout the European Community. These are the Type Approval Directives for Motor Vehicles.

6.1 European Type Approval of Motor Vehicles Directive

Within the European Union (EU) EU Directives are developed and adopted by a qualified majority in a co-decision procedure by the Council of the EU and the European Parliament (EP). The EU Directives are binding, i.e. they are applicable on a mandatory basis by all the EU Member States.

Motor vehicles are covered by the Type Approval of Motor Vehicles Directive 70/156/EEC [22]. The separate directives listed in Annex IV of 70/156/EEC are tabulated in Table 6-1. Directives potentially relevant to EE-VERT are indicated. It should be noted the scope of type approval is being extended from cars to other classes of vehicle. The text of European Directives can be found on the Europa website [23].

6.1.1 Sound levels

Directive 70/157/EEC specifies the maximum levels of sound that can be emitted from vehicles.

6.1.2 Emissions

Tail-pipe emissions for new vehicles are specified in the Directive 70/220/EEC and its subsequent amendments. Emissions are tested over the NEDC (ECE 15 + EUDC) chassis dynamometer procedure that will be used to determine the CO_2 level achieved when improvements developed within EE-VERT are applied to specific demonstrator vehicles.

6.1.3 Steering Effort

Directive 70/311/EEC defines the maximum steering effort that the driver is allowed to exert. It includes the use of "Special equipment" by which additional or independent power is produced. Additional or independent power may be produced by any mechanical, hydraulic, pneumatic or electrical system, or by any combination of these (for example by an oil pump, air pump or battery).

6.1.4 Braking

Directive 71/320/EEC is the European Directive relating to braking systems for cars and commercial vehicles. It requires braking performance tests and the brake system is checked against the design specification. A thorough static examination is conducted to ensure that the system is soundly engineered and will continue to work effectively for the life of the vehicle. Dynamic tests are conducted to ensure that stopping distances are met in the laden and un-laden conditions. A fade test is also conducted and the performance of the braking system is checked while the brakes are still hot. The performance of the parking brake and secondary braking system are also determined. For vehicles fitted with ABS there are a number of other tests that are also performed, assessing the braking efficiency and stability when the system is invoked

The directive requires the electronic control units to comply with directive 95/54/EC. Where electronic systems are involved in controlling the braking system operation the system is also subject to an assessment to ensure it functions correctly in all operating modes. Within the directive ‘Brake’ means the part in which the forces opposing the movement of the vehicle develop. It may be a friction brake (when the forces are generated by the friction between two parts of the vehicle moving relatively to one another); an electrical brake (when the forces are generated by electromagnetic action between two parts of the vehicle moving relatively to but not in contact with one another); a fluid brake (when the forces are generated by the action of a fluid situated between two parts of the vehicle moving relatively to one another); or an engine brake (when the forces are derived from a controlled increase in the braking action of the engine transmitted to the wheels).

6.1.5 Suppression (EMC)

72/245/EC is a European Commission type approval “e”marking directive that requires an Approval Authority or their appointed Technical Service to witness tests to demonstrate compliance with the technical annexes. The basis of the directive is protection of radio and television broadcast reception from radio frequency disturbances radiated by road vehicle internal combustion engine spark ignition systems.

95/54/EC is an amendment to 72/245/EC that increased requirements to include the immunity of safety related electronically controlled road vehicle functions to radiated electromagnetic disturbances and specifies a limit for the maximum permissible level of radiated narrowband radio frequency emissions from vehicles, trailers and their components. It came fully into force in October 2002. Automotive components can be approved for fitting to any model vehicle or a specific vehicle model. 2004/104/EC is a further amendment to 72/245/EC to adapt to further technical progress in that it identifies additional EMC requirements to be met by road vehicles, trailers, components and aftermarket fit equipment by harmonising the technical annexes with ISO and CISPR test methods. New vehicle types must comply from 1st July 2006 and existing vehicle types by 1st January 2009.

Spare parts are exempt if they are marked as a spare part, identical to the original type approved part and from the original manufacturer. Refurbished parts are not spare parts and need no type approval. Equipment which is not permanently fixed to the vehicle (it can be removed without tools) is exempt if it does not use the vehicle power supply. Equipment which is not permanently fixed to the vehicle, and which is powered using the vehicle power supply, nevertheless is exempt if it is connected to the vehicle by means of a separate "interface" unit that is approved to 2004/104/EC [24].

6.1.6 Anti-theft and Immobiliser

Directive 95/56/EC amends directive 74/61/EEC to provide essential security protection requirements for vehicles whereby manufacturers must fit a "device to prevent unauthorised use". Directive 95/56/EC has a number of detailed requirements to achieve the necessary combination of vehicle safety and reliability as well as security when an immobiliser or alarm is fitted.

6.1.7 Protective Steering

This Directive applies to the behaviour of the steering mechanism of motor vehicles of category M1, and vehicles of category N1 with a maximum permissible mass less than 1 500 kilograms, with regard to the protection of the driver in a frontal collision.

6.1.8 Installation of lighting and light signalling devices

The technical requirements are essentially those set out in paragraphs 2, 5 and 6 of UNECE Regulation No 48.

6.1.9 Side, Rear, Stop and Daytime running lights

The technical requirements for the end-outline marker lamps, front position (side) lamps rear position (side) lamps and stop lamps for motor vehicles and their trailers are those set out in paragraphs 1 and 5 to 8 and Annexes 1, 4 and 5 of UN-ECE Regulation No 7 and for daytime running lamps for motor vehicles the technical requirements are those set out in paragraphs 2 and 6 to 11 and Annexes 3 and 4 of UN-ECE Regulation No 87.

6.1.10 Direction Indicators

The technical requirements are set out in paragraphs 1 and 5 to 8 and Annexes 1, 4 and 5 of UN-ECE Regulation No 6

6.1.11 Headlamps

The technical requirements for headlamps depend on the type of device:

- For those emitting an asymmetrical passing beam or a driving beam or both and equipped with filament lamps of categories R2 and/or HS1 are those set out in paragraphs 1 and 5 to 8 and Annexes 3, 4 and 6 to 8 of UN-ECE Regulation No 1.
- For ‘sealed-beam’ headlamps emitting an asymmetrical passing beam or a driving beam or both are those set out in paragraphs 2, 6 to 8 and 11 and Annexes 3, 4 and 5 to 7 of UN-ECE Regulation No. 5.
- For headlamps emitting an asymmetrical passing beam or a driving beam or both and equipped with halogen filament lamps of categories H1, H2, H3, HB3, HB4, H7 and/or H8 are those set out in paragraphs 1, 5, 6, 8 and 9 and Annexes 2, and 4 to 7 of UN-ECE Regulation No 8.

- For headlamps emitting an asymmetrical passing beam or a driving beam or both and equipped with halogen filament lamps of category H4 are those set out in paragraphs 1, 5, 6, 8 and 9 and Annexes 3 to 7 of UN-ECE Regulation No 20.

6.1.12 Front fog lamps

The technical requirements for front fog lamps set out in paragraphs 1 and, 5 to 8 and Annexes 3 to 7 of UN-ECE Regulation No 19.

6.1.13 Rear fog lamps

The technical requirements are those set out in paragraphs 1, 5 to 9 and Annex 3 of UN-ECE Regulation No 38.

6.1.14 Reversing lamps

The technical requirements are those set out in paragraphs 1, 5 to 8 and Annexes 3 and 4 of UN-ECE Regulation No 23.

6.1.15 Parking lamps

The technical requirements are those set out in paragraphs 2, 6 to 9 and Annexes 3 to 5 of UN-ECE Regulation No 77.

6.1.16 Identification of controls

The scope of Directive 78/316 includes the identification of manual controls, tell-tales and indicators. Annex II contains a list of mandatory symbols which must be used when fitted whilst Annex III lists items for which, when fitted, identification is optional, and the appropriate symbols to use. The symbols are taken from ISO2575.

6.1.17 Defrost/Demist

Directive 78/317/EEC states that every vehicle shall be equipped with a system for removing frost and ice from the glazed surfaces of the windscreen. The windscreen defrosting system shall be effective enough to ensure adequate visibility through the windscreen in cold weather. The directive includes a detailed test procedure with minimum requirements. It includes a requirement that the voltage at the terminals of the demisting device may be not more than 20 % above the nominal rating of the system.

6.1.18 Wash/Wipe

Every vehicle must be equipped with at least one automatic windscreen-wiper system, i.e. a system which when the vehicle's engine is running is able to function without any action by the driver other than that needed for starting and stopping the windscreen wiper. The Test procedure for an electric windscreen-wiper system includes the following conditions that must be met:

- The battery must be fully charged;
- The engine must be running at 30% of the speed at which it develops maximum power;
- The dipped-beam headlamps must be switched on;
- The heating and/or ventilation systems, if fitted, must be operating at maximum electrical consumption;
- The defrosting and demisting systems, if fitted, must be operating at maximum electrical consumption.

6.1.19 Heating Systems

Under Directive 2001/56 all vehicles within categories M and N must be fitted with a heater for the passenger compartment. It also applies to all vehicles in categories M, N and O where a heating system is fitted. There are five classes of heater:

1. Engine waste heat –transfer medium water
2. Engine waste heat – transfer medium air
3. Engine waste heat – transfer medium oil
4. Gaseous fuel heater
5. Liquid fuel heater

It is likely that for operation all classes will require electrical power.

6.1.20 Speed Limiters

The purpose of this Directive is to limit to a specified value the maximum road speed of goods vehicles of categories N2 and N3 and of passenger-carrying vehicles of categories M2 and M3. This is achieved by a speed limitation device or an on-board speed limitation system whose primary function is to control the fuel feed to the engine.

6.1.21 Buses and Coaches

The Directive relates to special provisions for vehicles used for the carriage of passengers comprising more than eight seats in addition to the driver's seat. It includes specific requirements including the sizing of electrical cables and the securing of batteries.

6.1.22 Recyclability

Directive 2005/64/EC contains the requirement that a minimum of 85% of the mass of a vehicle and its parts be re-usable or recyclable, and that at least 95% of their mass be re-usable or recoverable. This is to maximise the environmental benefits intended by the ‘End-of-Life Vehicles’ (ELV) Directive 2000/53/EC.

Table 6-1 Requirements for Vehicle EC Type Approval

EE-VERT	Number	Subject	Directive	Applicability									
				M1	M2	M3	N1	N2	N3	O1	O2	O3	O4
				Cars	8+1 seats	Buses	Goods to 3.5t	Goods 3.5 to 12t	Goods >12t	Trailers			
✓	1	Sound levels	70/157/EEC	X	X	X	X	X	X				
✓	2	Emissions	70/220/EEC	X	X	X	X	X	X				
	3	Fuel tanks/Rear protective devices	70/221/EEC	X5	X5	X5	X5	X5	X5	X	X	X	X
	4	Rear registration plate space	70/222/EEC	X	X	X	X	X	X	X	X	X	X
✓	5	Steering effort	70/311/EEC	X	X	X	X	X	X	X	X	X	X
	6	Door latches and hinges	70/387/EEC	X			X	X	X				
	7	Audible warning	70/388/EEC	X	X	X	X	X	X				
	8	Rear visibility	71/127/EEC	X	X	X	X	X	X				
✓	9	Braking	71/320/EEC	X	X	X	X	X	X	X	X	X	X
✓	10	Suppression (radio)	72/245/EEC	X	X	X	X	X	X	X	X	X	X
	11	Diesel smoke	72/306/EEC	X	X	X	X	X	X				
	12	Interior fittings	74/60/EEC	X									
✓	13	Anti-theft and immobiliser	74/61/EEC	X	X	X	X	X	X				
✓	14	Protective steering	74/297/EEC	X			X						
	15	Seat strength	74/408/EEC	X	X	X	X	X	X				
	16	Exterior projections	74/483/EEC	X									
	17	Speedometer and reverse gear	75/443/EEC	X	X	X	X	X	X				
	18	Plates (statutory)	76/114/EEC	X	X	X	X	X	X	X	X	X	X
	19	Seat belt anchorages	76/115/EEC	X	X	X	X	X	X				
✓	20	Installation of lighting and light signalling devices	76/756/EEC	X	X	X	X	X	X	X	X	X	X
	21	Retro reflectors	76/757/EEC	X	X	X	X	X	X	X	X	X	X
✓	22	End-outline, front-position (side), rear- position (side), stop, side marker, daytime running lamps	76/758/EEC	X	X	X	X	X	X	X	X	X	X
✓	23	Direction indicators	76/759/EEC	X	X	X	X	X	X	X	X	X	X
	24	Rear registration plate lamps	76/760/EEC	X	X	X	X	X	X	X	X	X	X
✓	25	Headlamps (including bulbs)	76/761/EEC	X	X	X	X	X	X				

EE-VERT	Number	Subject	Directive	M1	M2	M3	N1	N2	N3	O1	O2	O3	O4
✓	26	Front fog lamps	76/762/EEC	X	X	X	X	X	X				
	27	Towing hooks	77/389/EEC	X	X	X	X	X	X				
✓	28	Rear fog lamps	77/538/EEC	X	X	X	X	X	X	X	X	X	X
✓	29	Reversing lamps	77/539/EEC	X	X	X	X	X	X	X	X	X	X
✓	30	Parking lamps	77/540/EEC	X	X	X	X	X	X				
	31	Seat belts	77/541/EEC	X	X	X	X	X	X				
	32	Forward vision	77/649/EEC	X									
✓	33	Identification of controls	78/316/EEC	X	X	X	X	X	X				
✓	34	Defrost/Demist	78/317/EEC	X	1	1	1	1	1				
✓	35	Wash/Wipe	78/318/EEC	X	2	2	2	2	2				
✓	36	Heating systems	2001/56/EEC	X	X	X	X	X	X	X	X	X	X
	37	Wheel guards	78/549/EEC	X									
	38	Head restraints	78/932/EEC	X									
	39	CO2 emissions/fuel consumption	80/1268/EEC	X			X						
	40	Engine power	80/1269/EEC	X	X	X	X	X	X				
	41	Diesel emissions	88/77/EEC	X	X	X	X	X	X				
	42	Lateral protection	89/297/EEC					X	X			X	X
	43	Spray-suppression systems	91/226/EEC					X	X			X	X
	44	Masses and dimensions (cars)	92/21/EEC	X									
	45	Safety glass	92/22/EEC	X	X	X	X	X	X	X	X	X	X
	46	Tyres	92/23/EEC	X	X	X	X	X	X	X	X	X	X
✓	47	Speed limiters	92/24/EEC			X		X	X				
	48	Masses and dimensions (other than vehicles referred to in Item 44)	97/27/EC		X	X	X	X	X	X	X	X	X
	49	External projections of cabs	92/114/EEC				X	X	X				
	50	Couplings	94/20/EC	X3	X3	X3	X3	X3	3	X	X	X	X
	51	Flammability	95/28/EC			X							
✓	52	Buses and coaches	2001/85/EC		X	X							
	53	Frontal impact	96/79/EC	X									
	54	Side impact	96/27/EC	X			X						
	56	Vehicles intended for the transport of dangerous goods	98/91/EC				X4	X4	X4	X	X4	X4	X4
	57	Front underrun protection	2000/40/EC					X	X				

EE-VERT	Number	Subject	Directive	M1	M2	M3	N1	N2	N3	O1	O2	O3	O4
	58	Pedestrian protection	2003/102/EC	X6			X6,7						
✓	59	Recyclability	2005/64/EC	X			X						
	60	Frontal protection	2005/66/EC	X9			X						

Notes

1	Vehicles of this category shall be fitted with an adequate windscreen defrosting and demisting device.
2	Vehicles of this category shall be fitted with adequate windscreen washing and wiping devices.
3	The requirements of Directive 94/20/EC are only applicable for vehicles equipped with couplings.
4	The requirements of Directive 98/91/EC are only applicable when the manufacturer applies for the EC type-approval of a vehicle intended for the transport of dangerous goods.
5	In case of LPG or CNG vehicles, pending the adoption of the relevant amendments to Directive 70/221/EEC in order to include LPG and CNG tanks, a vehicle approved according to UN/ECE Regulation 67-01 or 110 is required.
6	Not exceeding 2.5 t maximum mass.
7	Derived from M1 Category vehicles.
9	Not exceeding 3.5 t total permissible mass.

6.2 UNECE Regulations

Since 1958 the United Nations' Economic Commission for Europe (UNECE) has been developing vehicle regulations, initially at the regional level, but since 1998, on a global scale. Administered by the World Forum for Harmonization of Vehicle Regulations (WP.29), the existing 127 Regulations are constantly being updated to increase vehicles' safety and environmental performance. Almost 50 countries have become Contracting Parties. The World Forum for Harmonization of Vehicle Regulations and the European Commission are currently working on the harmonization between UNECE Regulations and EU Directives. Currently, some of the EU Directives are technically equivalent to UNECE Regulations or the Technical Requirements refer to the requirements of the corresponding UNECE Regulation. Table 6-2 lists the UNECE regulations that apply to specific EU directives. The full text of each regulation can be found on the UNECE website [25].

Table 6-2 UNECE Regulations applicable to Specific EU Directives

Heading No.	Description	Directive	Latest amendment	UNECE Regulation
1	Sound Levels	70/157/EEC	EC 2007/34	51.02
2	Emissions	70/220/EEC	EC 2003/76	83.05
3	Fuel Tank	70/221/EEC	EC 2006/20	34.02
4	Rear registration plate space	70/222/EEC	70/222/EEC	N/A
5	Steering Equipment	70/311/EEC	EC 1999/7	79.01
6	Door Latches and hinges	70/387/EEC	EC 2001/31	11.03
7	Audible Warning	70/388/EEC	70/388/EEC	28.00
8	Indirect vision devices	2003/97/EC	EC 2005/27	46.02
9	Braking	71/320/EEC	EC 2002/78	13.10
10	Radio Interference Suppression	72/245/EEC	EC 2006/28	10.02
11	Diesel Smoke	72/306/EEC	EC 2005/21	24.03
12	Interior Fittings	74/60/EEC	EC 2000/4	21.01
13	Antitheft	74/61/EEC	EC 95/56	18.03 and 97.01
14	Protective Steering	74/297/EEC	EC 91/662	12.03
15	Seat Strength	74/408/EEC	EC 2005/39	17.07
16	Exterior Projections	74/483/EEC	EC 2007/15	26.03
17	Speedometer and Reverse Gear	75/443/EEC	EC 97/39	39.00
18	Statutory Plates	76/114/EEC	EC 78/507	N/A
19	Safety Belt Anchorage	76/115/EEC	EC 2005/41	14.06
20	Lighting Installation	76/756/EEC	EC 2007/35	48.03
21	Reflex Reflectors	76/757/EEC	EC 97/29	3.02
22	Side, Rear and Stop lamps	76/758/EEC	EC 97/30	7.02 and 87.01
23	Direction indicator lamps	76/759/EEC	EC 1999/15	6.01
24	Rear Registration Plate	76/760/EEC	EC 97/31	4.00
25	Headlamps (including bulbs)	76/761/EEC	EC 1999/17	8.05 and 20.03
26	Front fog lamps	76/762/EEC	EC 1999/18	19.02
27	Towing Hooks	77/389/EEC	EC 96/64	
28	Rear fog lamps	77/538/EEC	EC 1999/14	38.00
29	Reversing Lamps	77/539/EEC	EC 97/32	23.00

30	Parking Lamps	77/540/EEC	EC 1999/16	77.00
31	Safety Belts	77/541/EEC	EC 2005/40	16.04
32	Forward Vision	77/649/EEC	EC 90/630	N/A
33	Identification of Controls	78/316/EEC	EC 94/53	N/A
34	Defrost / Demist	78/317/EEC	78/317/EEC	N/A
35	Wash / Wipe.	78/318/EEC	EC 94/68	N/A
36	Heating systems	2001/56/EEC	EC 2006/119	N/A
37	Wheel Guards	78/549/EEC	EC 94/78	N/A
38	Head restraints	78/932/EEC	78/932/EEC	25.04
39	Fuel Consumption	80/1268/EEC	EC 2004/3	84.00
40	Engine Power	80/1269/EEC	EC1999/99	101.00
41	Diesel Emissions	88/77/EEC	2006/81/EC	49.00
44	Masses and Dimensions	92/21/EEC	EC 95/48	N/A
45	Safety glazing	92/22/EEC	EC 2001/92	43.00
46	Tyre Installation	92/23/EEC	EC 2005/11	N/A
50	Mechanical Couplings	94/20/EEC	94/20/EEC	55.00
53	Frontal impact	96/79/EC	EC 1999/98	94.01
54	Side impact	96/27/EC	96/27/EC	95.02
58	Pedestrian Protection	2003/102/EEC	2003/102/EEC	
	Warning Triangles			27.03
	Tyres			30.02
	Temporary Spare wheels			64.00
	Whole Vehicle Type Approval (Framework Directive)	70/156/EEC	2007/37	N/A
	Frontal Protection Systems	2005/66/EEC	2005/66/EEC	

6.3 Other European Directives

6.3.1 The Low Voltage Directive 2006/95/EC

The Low Voltage Directive (LVD) 2006/95/EC [26] seeks to ensure that electrical equipment within certain voltage limits provides a high level of protection for European citizens and enjoys a Single Market in the European Union. The Directive covers electrical equipment designed for use with a voltage rating of between 50 and 1000 V for alternating current and between 75 and 1500 V for direct current. It should be noted that these voltage ratings refer to the voltage of the electrical input or output, not to voltages that may appear inside the equipment. This Directive should be considered when electric and plug-in hybrids are recharged from the domestic electricity supply.

6.3.2 Batteries and Accumulators 2006/66/EC

This Directive aims to minimise the negative impact of batteries and accumulators and waste batteries and accumulators on the environment, thereby contributing to the protection, preservation and improvement of the quality of the environment. It also contains measures to harmonise requirements concerning the heavy metal content and the labelling of batteries and accumulators [27].

6.4 Other Standards

The International Standards Organisation (ISO) and The Society of Automotive Engineers (SAE) in America develop standards that may also be relevant.

6.4.1 SAE J2801 Comprehensive Life Test for 12 V Automotive Storage Batteries

Date Published: April 2007

This SAE Standard applies to 12 V, flooded and absorptive glass mat lead acid automotive storage batteries of 180 minutes or less reserve capacity and cold crank capacity greater than 200amperes. This life test is considered to be comprehensive in terms of battery manufacturing technology; applicable to lead-acid batteries containing wrought or cast positive grid manufacturing technology and providing a reasonable correlation for hot climate applications. This document is intended as a guide toward standard practice, but may be subject to change to keep pace with experience and technical advances [28].

6.4.2 SAE J544 Electric Starting Motor Test Procedure

Date Published: August 1996

This SAE Recommended Practice provides a standard procedure for testing the output performance and plotting the performance curve of electric starting motors, and a graphical method of determining engine cranking speed [29] .

6.4.3 SAE USCAR6 Standard for D.C. Brush Motor - HVAC Blowers

Date Published: February 1999

This standard sets for the performance and durability requirements for 12-volt, D.C. brush-type electric motors used for automobile heating, ventilation, and air conditioning (HVAC) blowers and outlines production validation and continuing conformance testing [30].

6.4.4 J2185 Life Test for Heavy-Duty Storage Batteries

Date Published: September 1997

This SAE Recommended Practice applies to 12 V storage batteries which operate in a voltage regulated charging system. It simulates heavy-duty applications by subjecting the battery to deeper discharge and charge cycles than those encountered in starting a vehicle. The deeper discharge and charge cycles in service may come from a combination of the following conditions:

a. Frequent occurrences of total electrical load exceeding the alternator output.

b. Frequent occurrences of battery system supplying the electrical loads when the engine is not operating.

c. Frequent occurrences of prolonged vehicle storage combined with high vehicle key-off loads.

Batteries will be classified into two types for this life test. Type 1 applies to batteries with reserve capacity of 200 min or less. Type 2 applies to batteries with reserve capacity greater than 200 min. ("C" value for Type 1 equals 25.0; "C" value for Type 2 equals 50.0.) [31].

6.4.5 ISO 16750 Road vehicles - Environmental conditions and electrical testing for electrical and electronic equipment

This is an ISO standard which provides guidance regarding environmental conditions commonly encountered by electrical and electronic systems installed in automobiles [32].

ISO 16750 has five parts:

- ISO 16750-1: General
- ISO 16750-2: Electrical loads
- ISO 16750-3: Mechanical loads
- ISO 16750-4: Climatic loads
- ISO 16750-5: Chemical loads

6.4.6 ISO 8854:1988 Road vehicles -- Alternators with regulators -- Test methods and general requirements

This standard specifies test methods and general requirements for the determination of the electrical characteristic data of alternators for road vehicles. It applies to alternators, cooled according to the manufacturer's instructions, mounted on internal combustion engines [33].

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