CLEVER
Clean Vehicles Research

Overview of vehicle technologies
Task 1.1

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1. Introduction

In this report, the different currently available transport-based technologies and those expected in the mid and long term will be described and compared from a technical point of view. They will be compared with each other in terms of their availability on the market, any special infrastructure needed, filling and charging stations, vehicle equipment, safety aspects, driving ranges and energy consumption and emissions (well-to-wheel approach).

2. Technologies for transport

2.1 Conventional fuels: Petrol and diesel vehicles

In this case spark-ignition engines are normally used refering to internal combustion engines where the fuel-air mixture is ignited with a spark. This contrasts with compression-ignition engines, where the heat from compression alone ignites the mixture. Spark-ignition engines can be either two-stroke or four-stroke, and are commonly referred to as "gasoline engines" in America and "petrol engines" in Britain. A four-stroke spark-ignition engine is an Otto cycle engine.

Until recently, a major distinction between spark-ignition and compression-ignition engines has been where the fuel is mixed - spark-ignition engines mix fuel outside the cylinders and compression-ignition engines mix fuel inside the cylinders. However, both two-stroke and four-stroke spark-ignition engines are increasingly being designed with gasoline direct injection, eliminating this distinction between the two systems.

Small petrol vehicles consume around 7 litre per 100 km, while the average consumption of the bigger family cars equals around 9 litre per 100 km. On the other hand, small diesel vehicles consume approximately 5 litre per 100 km, whereas the consumption of diesel family cars results in an average of 7 litre per 100 km. These are theoretical values, the actual consumption could increase, depending on the driving behaviour and traffic situation (i.e. congestion traffic).

Taking into consideration the energy content of a fuel (expressed in MJ/km or kWh/km), the primary consumption level of petrol vehicles exceeds the one of similar diesel vehicles. Primary energy includes the energy consumption of the vehicle (direct energy consumption) as well as the energy necessary for the production of the fuel (indirect energy consumption).

Various technical developments of conventional vehicles have been elaborated in the last couple of years. One of the first steps, was the improved management of the ignition moment, the injected fuel quantity and the injection moment. These processes are controlled by the engine management system. Hereto, dedicated sensors are built into the newly developed engine devices to measure and control the air inlet, temperatures of cooling liquid, outside environment, driving speed, revolutions per minute and residual oxygen in the outlet gas (lambda sensor). As such, it is possible to fine-tune and control the engine behaviour depending on environmental events (e.g. cold start) or the composition of tailpipe gases, in order to optimise the process of catalysts and to reduce the overall emissions (Buning L. *et al.*, 2005).

To improve the low efficiency rate of petrol engines at reduced load (closed gas valve, increasing loading losses), various technological solutions have been developed or are in the development stage: Second generation direct ignition, full variable valve timing and valve lift, Miller cycle, downsizing, Homogeneous Charge Compression Ignition (HCCI), etc.

At present, diesel cars emit substantially more small soot particles and nitrogen oxides than similar petrol vehicles. In spite of the generally lower CO_2-emissions, the environmental impact tends to be mostly unfavourable as a result of the negative impact of soot particles on the human health. The installation of catalysts and soot filters can diminish these defects.

Catalysts process tailpipe gases and have to be seen as an after_treatment step, in order to reduce nitrogen oxide (NO_X) and carbon monoxide (CO) and hydrocarbon (HC) emissions. Other similar aftertreatment processes are the recirculation of outlet gases (Exhaust gas recirculation or EGR) and the selective catalytic reduction (SCR). The EGR process (the recirculation of outlet gases in the cylinder) results in extra heat capacity in the combustion chamber at the expense of power, whereby the combustion temperature decreases and as a result also the NO_X-emissions. SCR includes the injection of a small amount of harmless urea that decomposes in ammonia, which reacts and the further conversion with NOx into nitrogen and oxygen. More expensive models of specific car brands already apply sSoot filters are used to reduce emissions of soot particles. Starting from emission standard Euro V (2008, guideline in process), all diesel cars will probably need to be equipped with a soot filter to comply with these strict limits.

2.2 Alternative Fuels

2.2.1 LPG Vehicles

LPG (liquefied petroleum gas) mainly consists of propane (C_3H_8) and butane (C_4H_{10}) and is a by-product of the oil refinery process. At ambient conditions (approximately 1 bar), LPG is a gaseous mixture, but it can be liquefied at a pressure of 4 bar. Hence its name "*liquefied petroleum gas*".

At normal temperatures and pressures, LPG will evaporate. Because of this, LPG is supplied in pressurised steel bottles. In order to allow for thermal expansion of the contained liquid, these bottles are not filled completely; typically, they are filled to between 80% and 85% of their capacity. The ratio between the volumes of the vaporised gas and the liquefied gas varies depending on composition, pressure and temperature, but is typically around 250:1. The pressure at which LPG becomes liquid, called its vapor pressure, likewise varies depending on composition and temperature; for example, it is approximately 220 kilopascals (2.2 bar) for pure butane at 20 °C (68 °F), and approximately 2.2 megapascals (22 bar) for pure propane at 55 °C (131 °F). LPG is heavier than air, and thus will flow along floors and tend to settle in low spots, such as basements. This can cause ignition or suffocation hazards if not dealt with.

Presently, most of the LPG vehicles originate from adapted ('retrofit') petrol cars. Actually, car manufacturing companies tend to produce more LPG-dedicated vehicles, although its present share of the car market is still limited. The ratio of composing LPG compounds differs significantly depending on the originating country and the period of the year. For example, in the United Kingdom, LPG consists for 90 % out of propane, while Italy only handles LPG with 20 % of propane. Belgium has a 60/40 LPG ratio of propane/butane. Originally this lead to some problems while travelling through the European Union, but nowadays this variability in composition will not cause adverse effects on the engine.

In order to achieve the same autonomy as conventional petrol vehicles, the LPG reservoir should be 1.4 times larger than a petrol tank. This is due to the lower volumetric energy content of LPG as referred to petrol, as well as by the tank volume limitations of 80 % for safety reasons.

Small LPG vehicles, type city car, consume 9 to 10 litre LPG per 100 km. Larger LPG vehicles, type family car, on the other hand, consume about 11 tot 12 litre per 100 km. Expressed in litre per 100 km, the consumption of LPG vehicles exceeds the one of petrol cars and certainly scores higher than diesel vehicles, which is mainly caused by the previously mentioned lower energy content of LPG. The weight of LPG is around 0.54 kg/l, compared to ± 0.78 kg/l for petrol and ± 0.86 kg/l for diesel fuel. This is the reason for the higher consumption (at the pump) for an LPG engine.

However, in energy terms the mass of the fuel (kg) is used for calculations. The efficiency results of the LPG engine are comparable with the achievements of a petrol engine, and consequently slightly lower than the diesel engine. The production of LPG necessitates less energy compared to petrol (resulting in a lower indirect energetic consumption).

Taking into account the direct and indirect energy consumption, LPG vehicles generate higher CO_2 emissions than diesel vehicles but slightly lower than petrol vehicles.

In case LPG cars are adequately adjusted, all harmful emissions (NO_x, SO_2, CO, HC or hydrocarbons) are usually lower compared to the emissions of petrol cars. Nevertheless, this outcome necessitates a correct maintenance and a continuous adjustment. If not, some emissions (i.e. NO_x en HC) will increase. The emission reduction of converting a petrol vehicle to an LPG vehicle is variable and depends strongly on the quality of the installation. Only by the use of high-tech LPG installations, LPG can result in an effective reduction of these emissions.

LPG is available throughout the European Union, with a significant concentration of gas stations in the Netherlands, Belgium (about 550 filling stations), France, Italy and UK.

2.2.2 Natural gas vehicles

Natural gas is an odourless product found in nature and mainly consists of methane. The ratio of the different components depends strongly on the source location. The methane content varies between 80 and 99 %. This variation could result in engine problems, since the engine has initially not been developed to operate major changes in gas composition. Natural gas vehicles can also use biogas, generated from anaerobic fermentation of manure and/or vegetable (waste) materials.

Natural gas engines are spark ignition engines, comparable with petrol or LPG engines. The natural gas is filled into the vehicle under high pressure conditions (up to 200 bar). Besides the compression process of the natural gas, it is also possible to store it in liquid form. Then it is called ‘Liquefied Natural Gas’ (LNG), in stead of ‘Compressed Natural Gas’ (CNG). The difficulty of this technology is the fact that the liquefied natural gas has to be stored at rather low temperatures of -160 °C. Worldwide, the majority of natural gas vehicles use CNG.

As for the LPG vehicles, most of the CNG vehicles are adapted petrol cars, but presently there is a tendency to develop dedicated engines for CNG. Like this, the CNG technology can be optimized to operate natural gas as a fuel. This technology is also applied for buses and trucks (heavy duty vehicles). The heavy duty vehicles use modified diesel engines, since there are no large petrol engines available for heavy duty. The main owners of CNG vehicles in Belgium are Electrabel and MIVB/STIB. The use of natural gas for heavy duty is mainly from an environmental point of view: better air quality and less noise production in the cities (city buses run on natural gas (eg MIVB, garbage trucks (Antwerp).

The energy consumption of private cars, operating on natural gas, depends on the engine technology. ‘Bifuel’ vehicles (natural gas - petrol) cannot be easily fine-tuned for both natural gas and petrol, which creates a surplus of 10 % of energy consumption, as compared to a petrol vehicle. For vehicles with dedicated engines for natural gas, up to 80 % in energy consumption could be saved compared to petrol cars. Nevertheless, the compression of the natural gas requires an extra energy consumption of 10 to 20 % of the direct energy consumption of the natural gas car.

Taking into account the direct and indirect energy consumption, natural gas vehicles have a comparable or slightly lower emissions of CO_2 versus diesel cars and 20 % lower versus petrol cars. Since natural gas mainly contains methane, natural gas cars emit 2 to 3 times more hydrocarbons than petrol vehicles. Moreover, methane itself is a strong greenhouse gas. Nevertheless, the emissions of all other pollutants is generally lower for CNG vehicles (see section 3).

A great advantage of natural gas is the fact that it is lighter than air, which makes that it will be immediately dispersed into the atmosphere and no inflammable mixtures can be developed. In enclosed spaces this might still be possible though.

Natural gas vehicles are significantly more silent than conventional ones and the engine vibration is also less. A disadvantage of natural gas vehicles is the smaller trunk space, since they need extra space for a special gas tank, taking a part of the useful place.

The autonomy of CNG passenger cars is 200 to 250 km. To achieve equal autonomy results as conventional petrol vehicles, the CNG reservoir should be 5 times larger than a petrol tank.

There are two different methods to supply fuel into a natural gas vehicle, namely ‘quick fill’ and ‘slow fill’. A ‘quick fill’ handles a buffer storage at a pressure of about 250 bar and the filling process needs only a few minutes. In countries where CNG is applied on a large scale, public CNG filling stations are mostly equipped with a ‘quick fill’ system. In case of the ‘slow fill’ method, the reservoir is filled directly by a compressor device. This filling activity takes around 5 hours. This method is operational for natural gas buses, like the ones used by MIVB/STIB.

Currently, the number of filling stations for natural gas in Belgium is limited. The main advantage compared with other alternatives, is that, as for electricity, there is already an existing natural gas distribution network; in particular, the infrastructure for household heating can be used. The possibility of home filling stations can be easily connected to the grid, but lot of time is needed to fill and it has a high private investment cost (+- 4000 €).

In 1998, the number of natural gas vehicles in Belgium was 243, of which 202 cars and utility vehicles, 27 buses and 14 trucks. These numbers hardly changed in 2007. Worldwide, more than 4 million natural gas vehicles are driven. Argentina scores the best in this market share with an amount of 1,5 million vehicles.

2.2.3 Hydrogen

Hydrogen can be used in a combustion engine as well as in a fuel cell (see further).

The conversion of a petrol engine to hydrogen is comparable with the change of a petrol to an LPG car. For the hydrogen conversion, the ignition and injection timing (and injection duration) need to be reprogrammed. For safety reasons, the cater ventilation eventually needs to be improved and knock sensors are essential.

The hydrogen combustion engine has many important advantages compared to other fuels, such as very fast combustion (higher thermal efficiency), power controlled by the richness of the fuel-air mixture in stead of gas valve controlling (no obstruction caused by the gas valve, no loading losses and higher efficiency), higher possible compression ratio (higher theoretical efficiency). This yields a higher global efficiency of the hydrogen combustion engine compared with the petrol combustion engine (Sierens & Rosseel, 2000; Sierens & Verhelst, 2000; Verhelst, 2006; Ciatti *et al*, 2006).

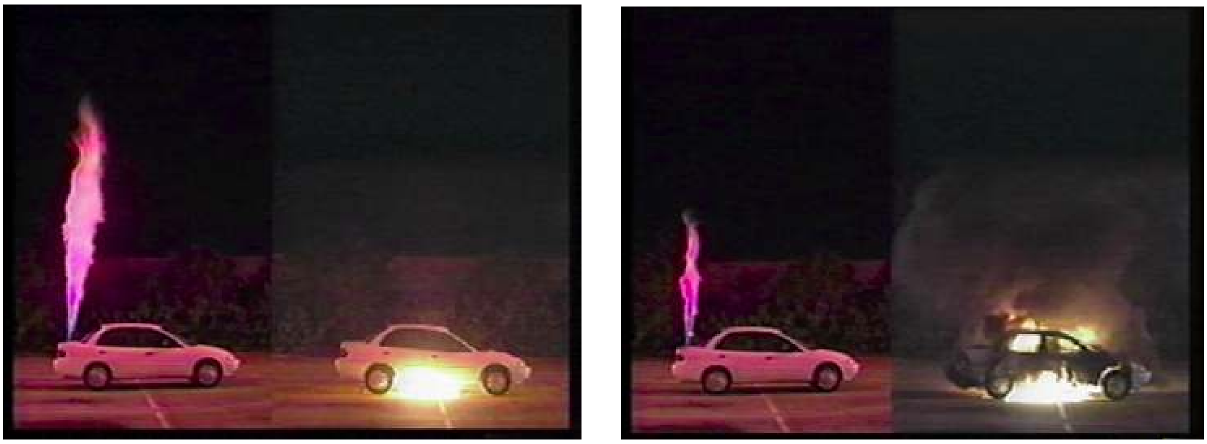
Hydrogen as such, is only in limited quantities present in nature, but the hydrogen atom is plentifully present in the water of lakes, rivers and oceans and of course also in fossil fuels as well as in fuels derived from biological processes (methanol, ethanol, biomass, ...). Four production systems are possible and mutually combinable: oxidation of gas originated from organic or fossil fuels, electrolysis of water and the direct production from biomass or from the use of bacteria. Presently, 96 % of the consumed hydrogen (mainly in the chemical industry) is produced from a fossil fuel, i.e. natural gas (CH_4).

On the one hand, the production of hydrogen gas can take place on-board of the car by converting petrol, ammonia, methanol or natural gas into hydrogen by means of a "*reformer*". The disadvantage of this "reformer method" however, is that the vehicle is not entirely emission-free. On the other hand, hydrogen can also be filled directly (in liquefied or gas phase). The liquefied storage requires lower temperatures (20 K of -253 °C) and results in losses in the storage tank. The storage under high pressure (700 bar) creates significant losses due to the compression of the gas. A mass-ratio of 5 % (ratio of the weight of the stored hydrogen versus weight of the storage tank) is feasible. An alternative solution is the storage of hydrogen in metal hydrid structures or absorption in carbon nanotubes .

Hydrogen has the image of being dangerous (as result of the Hindenburg accident and the Challenger crash event), but crash tests have proven that this fuel can be safely used in vehicles. Picture 1 shows a comparison of a fire in a car filled with hydrogen (left car) and with petrol (right car). The petrol car completely burnt out. The hydrogen car however, shows a short-lived blow-pipe flame, hardly heating the interior of the car.

Picture 1: Comparison of a fire with hydrogen (left car) and petrol (right car).

Left side: start of the ignition; right side: after one minute.



Source: Swain, 2001

In comparison with petrol, hydrogen has a higher specific energy content, namely 120 MJ/kg versus 45 MJ/kg, but it is characterized by a smaller energy density: 4,6 litre of hydrogen at 700 bar equals 1 litre of petrol.

There are also combustion engines operating on a mixture of natural gas and hydrogen. Hythane, for example is a fuel mixture of natural gas and hydrogen, usually with a hydrogen content of 20 % in volume.

In contrast to the fuel cell technology, the hydrogen combustion engine has the ability to make the shift towards a hydrogen economy more gradually. Bi-fuel (hydrogen - petrol) combustion engines have been declared operational by BMW (Rottengrubber *et al*, 2004) and Ford (Stockhausen *et al.*,2002). They will allow the hydrogen network to be built gradually and to collect the necessary experience with the handling of hydrogen. The ‘topping’ or the electricity generation of alternating wind power (otherwise not usable), will enable to gain very cheap hydrogen (Allaert *et al*, 2004).

There are many prototypes and demonstration projects e.g. GM – Opel testing the Zafira Fuel cell with Ikea in Berlin, Honda FCX being tested in the US, many other studies in the US, Japan and Germany (http://www.premia-eu.org/reports.htm).

2.2.4 Bio-fuels

As opposed to petrol and diesel, generated from mineral oil, bio-fuels are renewable fuels. They are produced from agricultural crops, wood or organic waste. Consequently, various types of bio-fuels exist. They have the advantage of being compatible to a certain extent with conventional vehicle technologies, such as petrol and diesel engines.

The European Commission has set the objective by the end of 2005 to achieve a share of 2 % bio-fuels in the global quantity of consumed transport fuels. Up to the end of 2010, this objective should reach a share of 5,75 %. On the short term, they count mainly on bio-diesel, bio-ethanol and to a lesser extent also on bio-gas and pure plant oil (PPO). On medium term, they count on production processes of the second generation. These processes originate from biomass, initially gasified and then converted to liquefied fuels. Examples of such processes are: Fisher-Tropsch bio-fuels, bio-DME (Dimethyl ether) and bio-methanol. There are two main types of second generation bio-fuels: (i) initially gasified and then converted to liquefied fuels (mainly FT-diesel) and (ii) the other is bio-ethanol from cellulosic biomas. This requires an additional production step, but is much more efficient then nowadays starting from sugar or starch crops.

Theoretically, bio-fuels are CO_2-neutral: CO_2 is taken up by plants and converted via photosynthesis in energy-rich biomass. Afterwards, this biomass will be reconverted to CO_2 by combustion in the vehicle engines. However, during the agricultural process and the processing of the plants to bio-fuels, harmful pollutants are emitted, such as greenhouse gases, so that this process cannot be called CO_2-neutral .

Bio-diesel can be made from vegetable oil, such as rapeseed, sunflower, palm or soy oil, eventually even from used alimentary oil or animal fats. In order to achieve a high fuel quality, these oils undergo a chemical reaction (esterification) with methanol. The outcome is a methylester, such as rapeseed methylester (RME). This product has characteristics comparable with those of conventional diesel oil.

Provided some small adaptations (such as adequate seals and fuel piping in suitable materials, to avoid corrosion of rubber), pure bio-diesel could be used in a conventional diesel engine. Bio-diesel is also perfectly mixable with fossil diesel fuel. All diesel engines from after 1980, could operate without any problems on mixtures containing up to 5 % bio-diesel. This ratio could even increase up to 20 or 30 %. For the time being, car manufacturers accept mixtures up to 5 % for use in the current fleet of cars. A number of car models is standard equipped with bio-diesel compatible materials and can thus run on pure bio-diesel.

Like diesel cars, bio-diesel vehicles emit more NO_x and PM than petrol cars. A diesel engine operating on pure bio-diesel, will emit a little more NO_x (about 10 %) than running on conventional diesel, whereas, the emissions of PM, CO and hydrocarbons usually decrease with 50 % using bio-diesel. A disadvantage of bio-diesel is the possible generation of smell overload ("deep-fried oil smell"), but this could be neutralized to a large extent by using an oxidation catalyst (standard equipment for new passenger cars). Most net greenhouse gas emissions are due to the agriculture phase (most N_2O emissions), the oil extraction and the esterification. Generally it is stated that bio-diesel leads to a global reduction of 40 tot 60 % in greenhouse gas emissions versus fossil diesel (IEA, 2004). Bio-diesel is biologically degraded for 98 % within a period of 21 days. This means that a leak does not result in permanent soil or water pollution.

Pure plant oil (PPO) can also be used in diesel engines, but for this purpose, the engine needs to be specifically converted (mainly for the preheating and the filtration of the fuel, also eventually for the adaptation of the injectors). Thus far, most applications have been carried out on older diesel engine models. The experience of new diesel technologies (e.g. common-rail) is rather limited. Even so, not all brands of diesel pumps are suitable. The costs for such kind of conversion lies between 2000 en 3000 Euro for passenger cars.

The advantage of pure rapeseed oil versus bio-diesel (RME) can be found in the more simplified production process (cancelling the esterification step). As a result, the fuel becomes cheaper, the production process requires less fossil energy and the greenhouse gas emissions are also lower. Regarding other harmful emissions, the effects are less unambiguous. Engine constructors react rather reluctant against the use of pure rapeseed oil (or other oils), since it could have an adverse impact on the engine operation (and as such it could potentially increase the emissions) and also because there is less control on the quality of the fuel, which may cause possible engine damage on the long term.

A third type of bio-fuel is *Bio-ethanol.* Bio-ethanol is alcohol generated by fermentation of sugar containing plants (such as sugar beet or sugar cane) or of starchy plants (such as wheat, maize or potatoes). On the long term, also celluloid materials (straw, grasses, wood) could be used for the production of ethanol.

Due to the high octane number of ethanol, it is excellent for use in spark ignition engines. Adding ethanol into petrol up to 20 % hardly results in operational problems for modern petrol cars. In case of high ethanol concentrations (such as E85 = 85 % ethanol, 15 % petrol) or use of pure ethanol, some materials in the fuel system should be adapted and the injection quantity increased, due to the lower combustion value ethanol. So-called Flexible Fuel vehicles (FFV) can operate on any mixture of petrol and ethanol. Various car constructors already developed FFV models, but these are mostly destined for the American or Brazilian market.

Currently in Europe, there are several vehicles suitable for ethanol on the market. They are so-called Flexible Fuel Vehicles (FFV): the Koenigsegg CCXR, the Peugeot 307, the Citroen C4, the Ford Focus/C-MAX FFV, the Volvo C30, S40, V50, V70 and S80 FFV and the Saab 9-3 and 9-5 FFV. Those vehicles run both on petrol and ethanol. The engine management system reacts on the fuel composition (Buning *et al*., 2005).

The production of ethanol needs a lot of energy. The exact energy amount depends on the used raw material. Even the global reduction of greenhouse gas missions is strongly dependent on the raw material and on the production process. The IEA (International Energy Agency) states that ethanol, taken into account the current generation technologies from corn or maize, is scoring globally only 30 to 40 % lower on greenhouse gas emissions in comparison with petrol. In the case that ethanol is produced from sugar containing plants, such as sugar beet and especially sugar cane, the reduction yields are higher (IEA, 2004).

Ethanol is less toxic than petrol and above all than methanol, which was mainly used in the US during the nineties. Mostly, methanol was generated from natural gas, which globally did not improve the level of greenhouse gas emissions. Moreover, methanol is more volatile than ethanol and is strongly corrosive.

In the case that ethanol is mixed in limited quantities (typically 5 %) with petrol, the volatility of the fuel increases (and consequently also the evaporation emissions). In order to solve this problem, especially in Europe ETBE (ethyl tertiary butyl ether) is introduced. *Bio-ETBE* is an octane enlarger generated from bio-ethanol and fossil iso-butylene. ETBE may be mixed up to 15 % with petrol without increasing its volatility. Provisionally, bio-ETBE is used mostly in France and Spain.

The first generation bio-fuels can be especially seen as a first step towards reducing the dominating dependence on fossil oil products in the transportation sector. In the framework of the Kyoto protocol, also their lower impact on the greenhouse effect is important. However, the ecological friendliness of first generation bio-fuels often needs to be put into perspective. The used plants require artificial fertilizer and pesticides. Moreover, agricultural and production processes require lots of energy and cause many additional emissions. In addition, more agricultural area is occupied, about one hectare is necessary to produce adequate fuel for one car operating for one year. Bio-fuels from tropical plants also need to be handled with some precaution, since they can lead to deforestation of tropical forests or jeopardizing the local food supply.

2.3 Alternative drive trains

Besides vehicles driven by a conventional drive train with combustion engine, cars with "alternative" drive trains are operational, such as battery electric vehicles, hybrid and fuel cell vehicles.

2.3.1 Battery electric vehicles

Electrically driven vehicles exist since the end of the 19th century, but have been pushed aside by the combustion engine. During the eighties and nineties, electric vehicles drew more attention again thanks to their ecologically sound characteristics. Moreover, after the oil crisis in the mid seventies, it became clear that our oil dependence becomes too high and needs to be limited. After all, electric vehicles are less dependent for their power supply on oil producing countries.

An electric vehicle is driven by an electric motor and takes its power from a rechargeable battery. Due to the characteristics of the electric motor, a gearbox device is mostly not necessary. Moreover, a part of the brake energy is recovered to load the battery again. There is even a possibility to integrate the motor into the wheels (for two-wheel and four-wheel drive). Starting from standstill, the electric motor can develop its maximum torque, resulting in a quite large acceleration power. Another fundamental difference with traditional vehicles is that the engine does not operate when the car is standing still and consequently does not consume any energy.

An important asset of electric vehicles is the absence of exhaust fumes during operation. Because of their positive impact on the environment, electric vehicles contribute considerably to the improvement of traffic and especially to a more healthy city environment. The generation of electricity can however also generate emissions. In case the consumed electricity would be generated using renewable energy sources, such as wind and solar energy or hydro-electric power stations, emissions should be negligible. Thus, the composition of the electricity generation park determines the emissions associated with these vehicles.

An electric motor has a much higher efficiency (80 to 90 %) than his thermal counterparts (10 to 40 %). Even in case the efficiency for the generation of electricity will be taken into account, as well the charging and discharging losses of the battery, an electric vehicle consumes constantly less energy. The regenerative braking and the zero-consumption at standstill result in up to 40 % more energy efficiency of electric vehicles compared to petrol vehicles (see further).

There are three types of charging infrastructures for electric vehicles, namely the “regular”, the “semi-fast” and the “fast” charging infrastructures. For the regular type a usual plug socket is used (230 V, 16 A, 3.5 kW) and a full charge lasts 5 to 8 hours. For the semi-fast type (7 kW), it takes half the time and for the fast type (20 kW and more) only some ten minutes. Besides the private plug sockets, largely present in houses and garages, also public charge stations could be used. However, relevant electric points are not yet available in our country, but require only limited adaptations or extensions of the existing electricity network.

More than 95 % of the materials of the batteries could be recycled. A network for collection and recycling of batteries is already present and runs very efficiently (Van den Bossche, 2005; Matheys. *et al.,* 2005).

The current battery electric vehicles have limited autonomy and could cover on average 80 to 120 km with a fully charged battery. Consequently, they are only very suitable for use in the city or for short distance applications. In the future, it is expected that this radius of action will increase to 300 km by using new battery technologies (such as lithium batteries).

In 2000, Belgium operated some 1053 registered electric vehicles, of which 30 passenger vehicles, 6 motorcycles, 2 buses, 78 trucks, 5 tractors and 932 special vehicles (mainly fork lift trucks).

A major financial obstacle for a market breakthrough for electric vehicles is the operating cost of the battery, since it needs to be replaced every couple of years (depending on the battery type and the number of charge-discharge cycles). It is expected that the cost of the battery will decrease, thanks to mass production and future technological developments. On the other hand, electricity is by far the cheapest energy source in comparison with diesel, petrol, LPG and bio-diesel. Given a price tag of 0,08 Euro per kWh, the electricity cost per 100 km fluctuates between 1,6 and 1,7 Euro for small and family cars. The fuel cost of diesel vehicles per 100 km is 3 to 5 times higher than what should be paid for the charging of electric vehicles (fuel costs dd. 2001).

2.3.2 Fuel cell electric vehicles

Electric vehicles could also be equipped with a fuel cell instead of a battery. To generate electricity, fuel cells use oxygen (from the air) and hydrogen (from a gas tank).

The fuel cell technology is still under development and currently, no commercial fuel cell vehicles are available. Only a few prototypes have been developed yet. Probably within 10 to 20 years, the consumer will be able to purchase such a type of vehicle.

As a result of the higher efficiency of fuel cells, combined with the electric drive train, the energy consumption of a fuel cell vehicle is lower than for conventional vehicles with a combustion engine (see further).

The current prototypes of fuel cell vehicles (FCEV) have an autonomy of around 300 km, but the aim is to increase this up to 600 km. The high production costs of fuel cells (3000 €/kW to 8000 €/kW) are partially due to the use of expensive materials, such as platinum for the separators. Switching to mass production and using cheaper materials, can lower the cost to 200 €/kW (Zegers, 2005). This price needs to be compared with the lower costs and the cancelled external costs as a result of the lower air pollution compared to conventional vehicles.

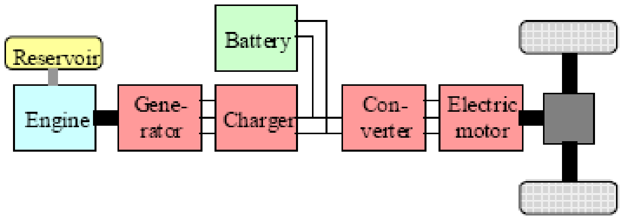
2.3.3 Hybrid vehicles

The term “hybrid vehicles” covers a compilation of vehicle technologies using two (or more) drive trains or energy sources. Often, they include a combustion and an electric engine/motor.

Two important categories can be distinguished: the *parallel hybrid* and the *series hybrid* vehicles. In the first category, the electric and the thermal motor/engine are mechanically linked and can both drive the wheels. With the second category, the wheels are only driven by an electric motor, sourcing its energy from a battery or from a generator driven by a thermal engine.

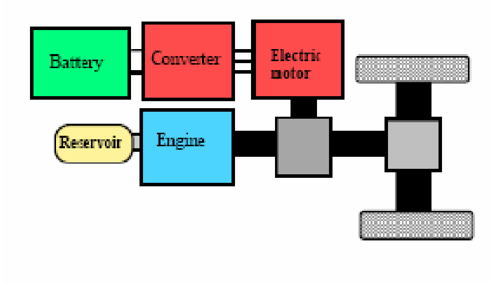
The *series hybrid* structure (see figure 2 can optimize the operation of the combustion engine by supplying the peak capacities for acceleration to the battery (e.g. Irisbus, Renault Kangoo RE). The battery can also recuperate the braking energy . In case there is no battery, when only a generator group is present, the ‘diesel-electric’ drive train is obtained, which is in fact no typical hybrid drive concept (e.g. Mercedes Cito bus). The family of *hybrid fuel cell drives* belongs to the series hybrid category. Actually, the division of the power occurs between the fuel cell and the battery (e.g. Mercedes Citaro bus).

In the *parallel hybrid* category (see figure 3, a combustion engine is assisted by an electric motor. Both engines are mechanically coupled to the wheels (e.g.Honda Civic).



Bron: Van Mierlo (2000)

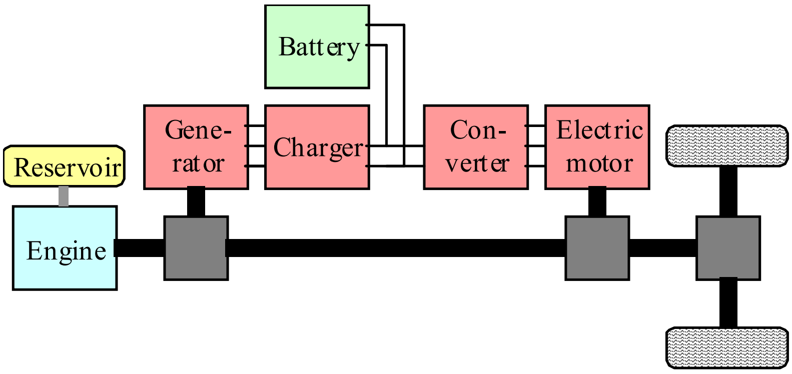
Figure 2: Series hybrid drive train



Bron: Van Mierlo (2000)

Figure 3: Parallel hybrid drive train

The combination of a series hybrid and a parallel hybrid structure ( ) is called ‘combined’ or series–parallel hybrid structure (e.g. Toyota Prius).



Source: Van Mierlo (2000)

Figure 4: Combined hybrid drive train

As such, several combinations are possible and used in practice. Obviously, these different options do not all have the same value in the field of energy efficiency, neither ecologically nor economically. The evaluation of to be considered criteria have been integrated in a computer behavioural model, within the framework of a PhD at the Vrije Universiteit Brussel (Van Mierlo, 2000).

The choice of the structure depends on the envisaged market segment. For instance, the series hybrid structure will be preferred for city buses. On the other hand, the parallel drive train is recommended for (family) cars, particularly driving on highways. The combined structure is more appropriate for mixed use (urban-rural).

The combustion engine of hybrid vehicles mostly uses petrol (passenger cars), but also fuels such as (bio)diesel, LPG, CNG, etc. are possible.

The battery of some hybrid vehicles could be charged via the electricity grid ("*Plug-in-hybrid*"), other hybrid vehicles are operational with an automatic charging device through a generator unit on board of the car.

Hybrid vehicles could strongly reduce emissions and fuel consumption because:

- The combustion engine can be stopped when no power is required (for instance in a traffic jam or standing still at traffic lights). As a result, the fuel consumption, and the associated CO_2-emissions, could be reduced with 8 to15 %.
- While braking, the braking energy can be stored and reloaded to the battery, saving energy up to 15 % for passenger cars.
- The combustion engine could be utilized within a field of activity consistent with low emissions and low fuel consumption.

That's why hybrid vehicles can consume 15 to 30 % less primary energy compared with conventional vehicles; for city traffic, the reduction can be even up to 50 % less. Some even have the possibility to drive entirely electric and consequently are capable of making locally emission-free displacements.

Presently, only a few hybrid cars are available on the Belgian market (Toyota Prius, Honda Civic IMA, Renault Kangoo Elect'Road, Lexus RX400h, Lexus GS450h). The purchase price of these vehicles is a little bit higher than the price for a conventional car of the same class. On the other hand, due to the lower fuel consumption and potential fiscal benefits, they are cheaper in use

3. Energetic comparison of vehicle technologies

Even today, little attention is paid to the fact that the energy efficiency of conventional vehicles scores less then 15% in municipal areas (80 % of the vehicles mainly move in the city). Nonetheless, this means that when starting with 50 litre fuel in an average fuel reservoir, less than 7,5 litre is fully used to drive, while the remaining 42,5 litre is converted into unused heat. Diesel motors yield the best results regarding energy efficiency, followed by petrol engines and engines using gaseous fuels (natural gas and LPG).

Moreover, fuel consumption is also defined by driving behaviour. Fuel can be saved by lowering the rotational speed of the engines (<2500 revolutions per minute (r.p.m.) for petrol and <2000 r.p.m. for diesel). Outside the built-up area, fuel saving of 25 % can be obtained by keeping the number of revolutions per minute of the engines low. The city traffic strongly depends on external factors such as traffic flux, traffic lights control, etc., through which fuel saving by driving behaviour is rather limited (about 5 %) (Van Mierlo *et al*. 2004, Van Mierlo *et al*. 2002). In order to focus on the global impact of vehicle emissions, the crucial point is the motivation of the individual driver to use a sparing driving style. Based on corporate communication (mass media, and similar), it is stated that 18% of the drivers do apply the most important elements of ecologically sound driving in practice. Referring to the Flemish fleet of cars and in case of proper driving behaviour, the potential fuel saving will be 1,8 %. (Van Mierlo *et al*., 2002).

Both, the weight of the vehicle and the power of the engines (number of kilowatt), determine the fuel consumption of the vehicle. Research studies (Van Mierlo J., 2002) stipulate that an increase in mass of the vehicle by 200 kg, will rise the fuel consumption with 8 to 13 % for lighter vehicles (< 1 ton) and with 3 to 5 % for more heavy vehicles (1.7 ton). Ecodrive (2002) also states an increase of the fuel consumption by 6.7 % for a medium-sized vehicle of 1500kg, transporting an extra load of 100 kg. In case of the same date of construction and fuel type, it appeared that the smaller the engine power, the sparing the car will be (Van Mierlo J., 2002).

The increasing safety- and comfort measures of the vehicles, but also the larger volumes of the vehicles resulted in a weight gain of almost 30 % between 1993 and 2004 (De Mol J., 2006). Also the size of the engine power increased by 51 % between 1983 en 2004 (De Mol J., 2005). Febiac (2006) outlines a mean weight increase of 24 % and an increase of the engine power by 22 % (period 1995-2005). In the same period, the official fuel consumption decreased by 15 %. Higher fuel reduction would be possible, if more smaller cars with smaller engines were constructed and purchased.

Besides, the load on the car will increase in fuel consumption due to aerodynamics. According to Vito (2002), a luggage rack on the roof of the car results in a fuel consumption increase of 7.5% at 120km per hour speed; a fully loaded luggage rack 38.7% and a ski box 16.1%. Generally, Vito (2002) states an additional fuel consumption of 10% for a ski box and 20 to 30 % for a bicycle rack on the roof of the car.

Above-mentioned analysis mainly relates to conventional vehicles. What would be the actual relation of vehicles with alternative fuels and power systems versus conventional fuels? Hereto we should use the "*Well-to-Wheel*" (WTW) approach. Table 1 shows the fuel characteristics, the direct energy consumption ("*Tank-to-Wheel*", or TTW, according to the energy consumption in the vehicle itself), the indirect energy consumption ("*Well-to-Tank*" (WTT), according to the energy consumption for the production of the fuel) and the primary (WTW) energy consumption. The vehicles from Table 1 meet EURO IV and have a engine with a cylinder volume of about 1600 cc. All vehicles were compared based on an equal driving cycle (NEDC).

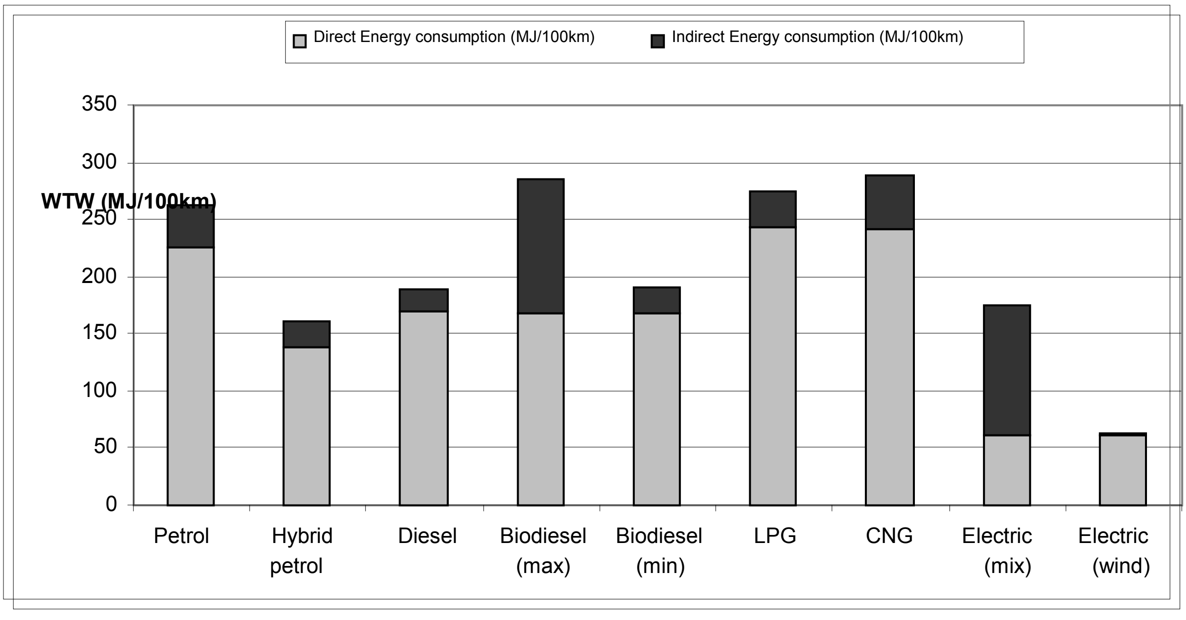
Table 1: 'Well-to-Wheel, energy consumption of passenger cars

	Consumption		Density	LHV		TTW	Energy input	WTT	WTW	
			kg/m^3	MJ/kg	kg/100km	MJ/100km	MJ/MJ	MJ/100km	MJ/km	
Petrol	7	L/100 km	755	42.715	*5.29*	*226*	0.16	*36*	2.62	100%
Hybrid petrol	4.3	L/100 km	755	42.715	*3.25*	*139*	0.16	*22*	1.61	61%
Diesel	4.6	L/100 km	850	43.274	*3.91*	*169*	0.12	*20*	1.90	72%
Biodiesel (min)	5.06	L/100 km	880	37.700	*4.45*	*168*	0.70	*118*	2.85	109%
Biodiesel (max)	5.06	L/100 km	880	37.700	*4.45*	*168*	0.14	*24*	1.91	73%
LPG	9.8	L/100 km	550	45.114	*5.39*	*243*	0.13	*32*	2.75	105%
CNG (min)	6.42	M3/100 km	717	52.367	*4.60*	*241*	0.20	*48*	2.89	110%
Electric (mixture)	0.17	kWh/km				*61*	1.87	*114*	1.76	67%
Electric (wind)	0.17	kWh/km				*61*	0.03	*2*	0.63	24%

Source: Timmermans *et al.* (2005)

Figure 5 shows these values graphically. It demonstrates the important advantage of the hybrid drive system and the influence of the production of bio-fuel and electricity on the primary energy consumption of bio-fuel vehicles, respectively battery electric vehicles. The vehicles with LPG and natural gas yield a higher energy consumption than the petrol vehicle. The diesel vehicle has a more favourable energy consumption than the petrol vehicle. The hybrid vehicle has the best score regarding energy consumption.

Figure 5: Well-to-Wheel, energy consumption of passenger vehicles, in 2005.



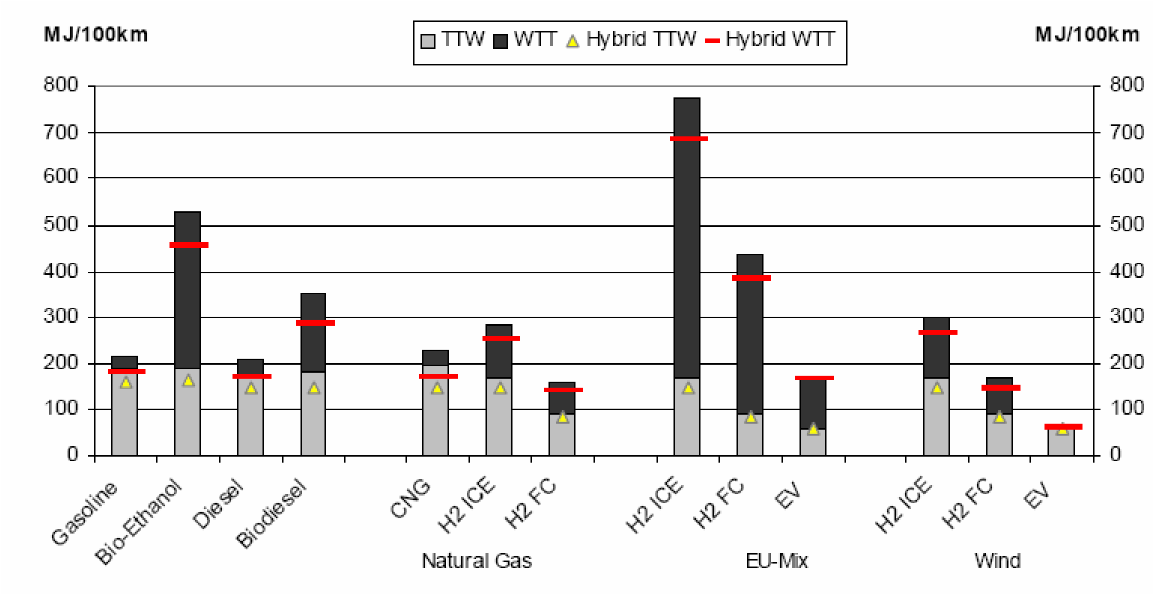
Source: based on MIRA-T (2005)

Below mentioned analysis, carried out by EUCAR (R&D network of European automobile sector), outlines a projection of the primary energy consumption up to 2010 and this for different fuels and production technologies (EUCAR, 2004). The results are shown in Figure 6. Because the different alternative and conventional vehicles could be produced with or without a hybrid drive system, the result after hybridisation is also given with a horizontal stripe.

Hydrogen can be generated from different energy sources, such as natural gas, nuclear energy, alternative energy sources (wind, hydropower, solar cells, etc.) (Brinkman N. *et al.* 2005; Choudhury R. *et al.* 2002; R. Edwards et al. 2004; Bogart S.L., 2002). Which production paths finally will be chosen for large scale production, is currently not yet clear. In most cases, electric energy will be used to produce hydrogen gas via electrolysis of water.

Alternative ways of energy supply will be discussed in function of the expected situation in 2010. For diesel and petrol an extrapolation is made to the expected technology in 2010. Comparison is made with bio ethanol and bio diesel (*RME*). To this end, diesel vehicles are provided with soot filters. In addition, attention is paid to the use of natural gas in the combustion engine *(CNG)*. Hydrogen is marked by *H2* (compressed). Distinction is made between the use of hydrogen in a combustion engine *(ICE)* or in a fuel cell *(FC)*. Hydrogen can be generated based on natural gas *(Natural gas)*, electricity according to the European mix *(EU-mix)* or electricity sourced from windmill energy *(Wind)*. The electricity could also be used directly in the battery electric vehicle (*EV*).

Figure 6: Well-to-Wheel, energy consumption of passenger vehicles, in 2010.



Source: based on EUCAR (2004)

These graphs demonstrate that the advantage of hydrogen is the lowering of the *Tank-to-Wheel* energy consumption if the fuel cell is used, but this is going to the prejudice of the *Well-to-Tank* energy, necessary for the generation of hydrogen gas. Up to 2010, the combination of hydrogen and the combustion engine shows to be no alternative for petrol and diesel, regarding energy consumption (EUCAR, 2004).

This analysis shows that almost three times more power stations should be built (for instance windmills) in case hydrogen gas is used as energy source for the fuel cell electric vehicle, than when the produced electricity would be used directly in the battery electric vehicle.

On the other hand, hydrogen gas can be seen as possible energy buffer. The electricity production of windmills is dependent on wind circumstances. However, electricity has to be generated on the moment of consumption. Therefore, power stations should be adjacent to windmills and should be switched on during the time of wind absence. Another solution is to store the electricity produced by windmills as hydrogen gas; consequently, this gas could be used in periods of less (or too much) wind. Also, one should question the economical efficiency of the use of hydrogen compared to pump stations as energy buffer, such as in Coo.

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