01

H_2 fuel cell for transport

Introduction to the transport sector

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Objectives

- The first objective of this unit is to introduce the transport sector globally, to emphasise the fact that the reflection on the future of mobility cannot be limited to the example of a region, a town or village.

- The second objective is to focus the attention of the learner on current consequences of our dependence on fossil fuels and to bring out the strong link between the transport sector and oil products.

- The third objective is to give figures measuring the impact of the transport sector on CO_2 emissions and the impact of GHG emissions on the global warming.

- The fourth objective is to show that in addition health and environmental issues led to the establishment of standards that drastically limited pollutant emissions from vehicles, forcing manufacturers to bring new technical evolutions to the current engine. Among these are new exhaust after treatment devices which are significantly expensive for the consumer and may be the source of new types of malfunctions.

- The fifth objective is to show that alternative powertrains such as hybrid electric vehicles, battery electric vehicles and Fuel Cell vehicles become more credible solutions for the automotive market.

Introduction

The transport sector is an important contributor to the European economy. According to EUROSTAT, the industry of transportation employs 10 million people and the manufacture of transport equipment employs 3.3 million people. This represents 6% of total employment in Europe.

Following the same source 13% of the budget of each family is devoted to transport in the form of services or transport of goods. This sector is very wide and varied; therefore if a car is the most popular mode of transport one must actually consider all its components namely:

- Cars (private, renting, leasing, local fleets)
- Two wheelers (50 CC to 1200 CC and even more)
- Material handling vehicles and site vehicles
- Vans and trucks for national transports (small to medium range)
- Trucks for international transports (large range)
- Buses for urban and suburban routes
- Buses and coaches for long travels
- River vessels, maritime fleet, rail transport, air transport

For some types of transport one can still specify if the use is occasional or frequent and whether journeys occur on a fixed route or not.

In parallel to this, it is clear that the technologies of motorisation have changed little until the late 80s, making this sector the largest consumer of petroleum products and the second emitter of greenhouse gases, not to mention the emissions which are the HC, NO_x, CO and fine particles.

- HC, hydrocarbons are the result of unburned fuel
- NO_x, nitrogen oxides are produced when the combustion temperature is high
- CO, carbon monoxide is the result of incomplete combustion
- Fine particles are mainly produced by diesel engines

From this period, a collective awareness relayed by public authorities has forced the sector to evolve through the application of standards, which have become increasingly restrictive, in order to limit emissions. These standards have often been associated with unfavourable tax for large emitters of CO_2 and sometimes associated with tax incentives to promote the emergence of new technologies for sustainable mobility such as electric vehicles.

The sector is therefore now facing a new challenge, which is to offer the market the most suitable engine for the end user to help avoiding additional cost related to a penalising taxation and an overload of pollution control technology. **This is therefore an opportunity for the emergence of new technologies, new skills and new jobs.**

1.1. Teaser

1.2. Impact of transport on energy issues

As a reader of this training, you are interested and involved in energy issues. You may have experience of this problem which has been influenced by your living environment: your area, your city, your habits and how fuels are taxed by your government.

You should know that this last point that affects you directly as a consumer is itself influenced by a European global policy in line with international agreements based on scientific studies. The reference topics are first greenhouse gas emissions and their impact on global warming and secondly emissions and their impact on environment and public health. The economic aspect related to fossil fuels is also an important topic.

Therefore, if we want to understand the causes of technological change in the transport sector, it is appropriate to quantify these influences on a large scale as opposed to small scale. This is the approach that we will present in this chapter.

1.2.1. Distribution of the global energy consumption

The annual world energy demand is huge. If we could express it with a quantity of oil, the result would be **12 gigatonnes (Gt)**. Note that the prefix “giga” is often used in computer science to explain the storage capacity for data. “**giga” is one billion and “tonne” is 1000 kg**.

This way of thinking has lead to the creation and use of a special unit, the Ton of Oil Equivalent per year (TOE/year). The global energy demand can therefore be expressed by 12 Gigatons of oil equivalent / year or 12 Gtoeyear.

This value of energy demand is very high and in constant increase of about 1.4% per year due to the growing consumption in some regions such as India and Southeast Asia.

The distribution of the world energy demand is illustrated in Figure 1 below.

About 80% of this energy is of fossil origin and thus non-renewable, oil alone accounts for one third of the energy consumed. Natural gas and coal are closely following with nearly the same ratio.

For completeness, we must add that the share of renewable energy, however, increased slowly by only 1.5% over the past decade.

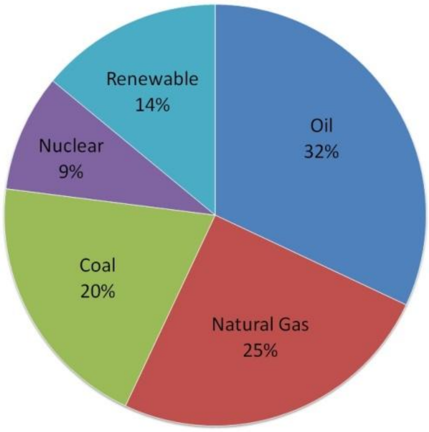


Figure 1 Share of global demand by energy type.

1.2.2. Consumption of oil products in the world

Globally, we know that about one billion cars are in circulation; in addition we must also consider trucks and other motorised vehicles. It is therefore not surprising that at this level, as in European countries, **the share of transport** in the consumption of oil products **has reached the 50% threshold**. The example of France is shown below in Figure 2.

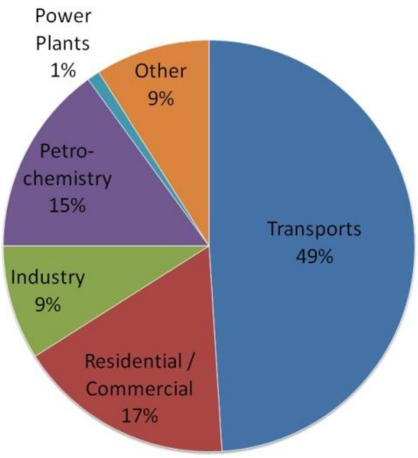


Figure 2 Consumption of oil products in France (Source, senat.fr).

A popular quote heard in many seminars is that:

"The world consumes as much oil in six weeks as it did in 1 year back in 1950"

It is therefore difficult to reduce the dependence on oil products if we do not develop alternative solutions for the transport sector. Moreover, this dependence causes three major consequences:

- Oil reserves would be limited to about a century
- Greenhouse gas emissions are estimated at 38 Gt of CO_2 per year including 32 Gt of fossil origin. Biomass and oceans capture only 25 Gt.

- The unequal distribution of resources led to geopolitical tensions

1.2.3. Price increase

All citizens are concerned by the two previous topics because the consequence of this macro-economic situation is on average a continuous price increase at the gas station. Figure 3 below illustrates that reality by showing the changes in fuel price for the consumer in Belgium, which was around a 50% rise in 10 years. This trend is found everywhere throughout Europe.

In short, you see on Figure 3 the influence of the continuous growth of energy demand and our strong dependency on oil products.

The demand therefore drives the market and the prices follow.

Figure 3 Changes in fuel prices in Belgium (Source, EDUCAM).

1.3. Impact of transport on environmental issues

1.3.1. Emissions

Internal combustion engines are becoming cleaner for mainly two reasons. First the electronic control unit (ECU) allows a precise engine mapping and secondly exhaust gas are treated or recycled.

The engine mapping of spark ignition (SI) engines consists to give to the engine the exact quantity of fuel that it needs for delivering a desired power at a given speed. Ideally the air-fuel ratio (AFR) must also be respected, for example 14.68 for gasoline. This setting point is called “stoichiometry”.
The actual injection setting is finally characterised by a parameter lambda (λ) being the ratio between the actual AFR and the stoichiometric AFR. By definition λ=1 at stoichiometry. When the quantity of fuel injected is greater the mapping setting is rich and λ<1. At the opposite when the quantity of fuel injected is smaller the mapping setting is lean and λ>1.
<u>SI engines work with λ values as close as possible to 1</u>.

The engine mapping of diesel engines is different as they work with an excess of air characterised by $1<\lambda<3$.

The post treatment of exhaust gas consists to add a particulate filter (diesel) and exhaust catalysts (SI and diesel) in the pipe.

Consequently a modern engine, whatever SI or diesel, achieves low emissions defined by the EURO standards. These concern mainly:

- The HC which are observed when the engine mapping is too rich. For SI engines the stoichiometry is the best setting but maximum power and lower temperatures are obtained for $\lambda<1$.
- The NO_x are produced when the combustion temperatures are too high. The exhaust gas recirculation (EGR) solves this issue by feeding back exhaust gas into the intake. This will reduce the oxygen content of intake air and therefore reduce the temperatures of combustion.
- Fine particles are mainly produced by diesel engines and partly removed by a specialised filter.
- CO is the result of incomplete combustion.

But these **emissions are never completely removed** and in addition some cleanup strategies have opposite effects. Consequently, the cleanup of exhaust gas always involves a compromise.

As a first example, the actual λ of a SI engine will be close to 1 but always lightly different, particularly at full load where $\lambda<1$ for temperature considerations and during transient periods.
As a second example, considering diesel engines, the increase of combustion temperatures reduces the number of fine particles but generates NO_x. At the opposite the increase of the EGR effect reduces temperatures and therefore the level of NO_x but creates fine particles.

Lastly engine manufacturers will try to respect the EU standard but without removing completely major emissions.

We know for a long time that emissions have a bad effect on health and on the environment. Table 1 below shows the major effects of emissions, most of them concern public health; NO_x emissions are also responsible of acid rains which damage forests, soil and surface water.

Table 1 Major effect of emissions.

Emissions	Effect
HC	cancer, smog
NO_x	acid rains, smog
Very fine particles	cancer, asthma, smog
CO	asphyxia

The case of diesel engines is nowadays the most sensitive because it has been proved for a short time that fine particles of hydrocarbon can cause cancer. This fact has been converted in Figure 4 into the average decrease of lifetime, expressed in months, caused by the very fine particles of a mean diameter less than 2.5 microns.

One can see that the regions with a high density of population are strongly affected, diesel engines being an important contributor to the emissions.

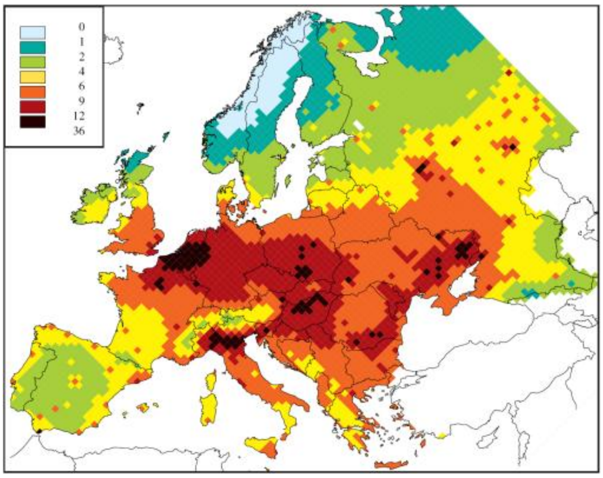


Figure 4 Influence of fine particles on health (Source, IIASA).

The only issue is to further reduce emissions. To reach this objective the car industry must continue the development of exhaust after treatment devices but it seems that the engine manufacturers have approached the limit of the technology.

Alternative powertrains are therefore being considered as the next step of the technological evolution, particularly hybrid and electric vehicles. In addition, electric powertrains could drastically reduce local emissions in large cities.

1.3.2. CO_2 Emissions

CO_2 is the natural result of the combustion of carbon. It is a greenhouse gas that is to say that once accumulated in the atmosphere; it will affect the heat balance of the earth by reflecting additional heat radiation from the surface of the planet. It is not the greenhouse effect which is the problem as this exists naturally, created by the atmosphere, clouds and renewable CO_2, which is increased through human activities.

It is now clearly proven that there is a direct link between CO_2 levels in the atmosphere and the average temperature of the planet. If we speak of an increase in temperature of only 1 degree, the consequences on some icy regions can be significant.

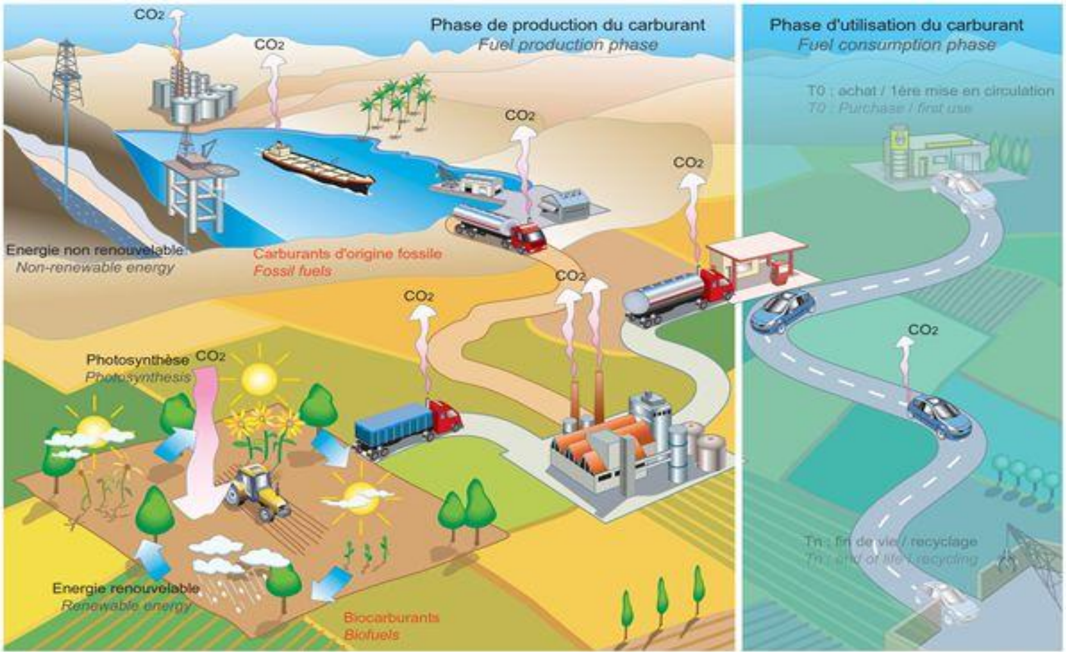


Figure 5 "Well to wheel" evaluation scheme of CO_2 emissions (Source, Renault).

It therefore becomes important to be able to legislate on CO_2 emissions of a vehicle knowing that engines will vary and that, in particular, electricity will be introduced and used with more and more power output in the powertrain. A general method is therefore needed to compare the different drivetrains.

This consideration is illustrated above in Figure 5. In the first step all CO_2 emissions from « well-to-tank » are estimated by the contributions encountered during oil extraction, transportation, refining and distribution of the fuel to retailers. In the second step we analyse the CO_2 emissions of a vehicle from the « tank-to-wheel ». Finally, if we make the sum of the two previous contributions, we get a value representing globally the emissions generated from « well-to-wheel ». The name of this method, well-to-wheel analysis, can be applied to each kind of technology and in each category for various parameters like the size of the car and the refinement of the technology.

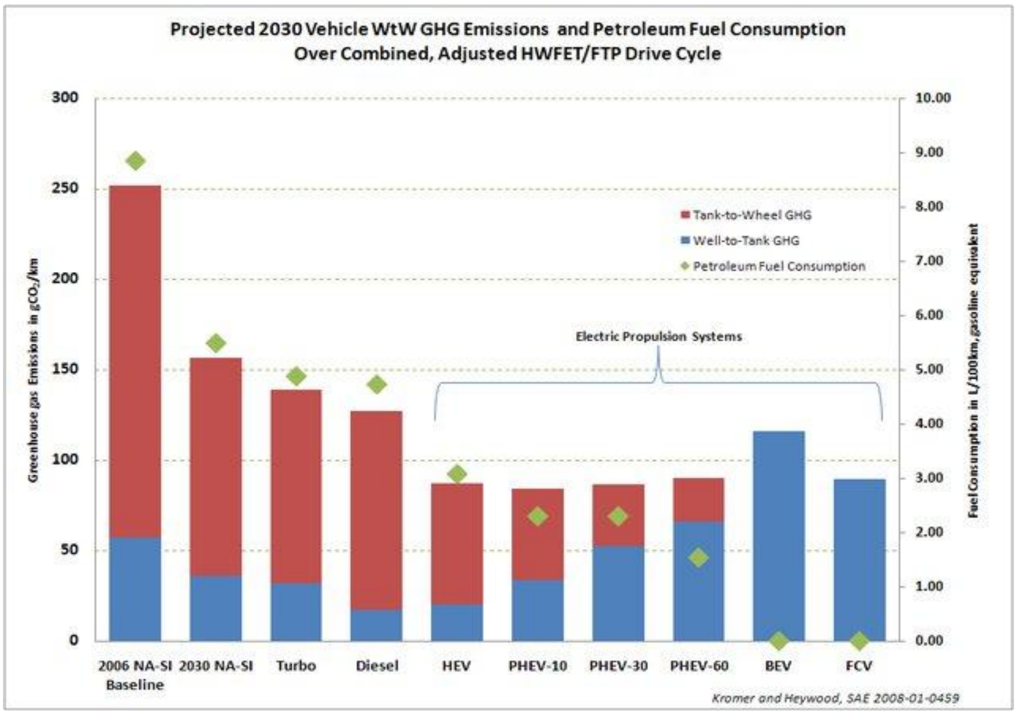


Figure 6 Comparison of CO_2 emissions of different powertrains
(Source, Kramer & Heywood, SAE 2008-01-0459).

Based on this method, according to a study by Kramer and Heywood published in SAE 2008-01-0459 and illustrated in Figure 6, it is possible to reduce CO_2 emissions by introducing and optimising the storage of electrical energy in the drivetrain. The result of a simulation extended to 2030 demonstrates that the most promising engines will be hybrid electric vehicles (HEV), battery electric vehicles (BEV) and fuel cell vehicles (FCV).

Only BEV and FCV emit no CO_2 from tank to wheel. Generally, they are distinguished by their range which is limited to 120 km for a BEV equipped with a 20 kWh battery and 500 km for a FCV using a tank containing 5-6 kg of pressurised hydrogen. In both cases, it is the end user who will make a choice based on the expected daily use.

1.4. Fuels for vehicles, properties and comparison

When considering the use of alternative fuels, it is essential to know the properties in order to evaluate the impact on the engine and therefore an informed decision can be made relating to the mechanical modifications and mapping adjustment. Table 2 below compares the conventional liquid fuels, petrol and diesel, to gaseous fuels like liquefied petroleum gas (LPG), compressed natural gas (CNG) and hydrogen gas (H_2).

Table 2 Main properties of fuels for vehicles.

Name	Diesel	Petrol	LPG	Natural gas	Hydrogen
Composition	C_8 - C_{25}	C_4 - C_{12}	C_3H_8 & C_4H_{10}	CH_4	H_2
Mean density	840 g/l liquid	750 g/l liquid	2.25 g/l gaseous	0.83 g/l gaseous	0.09 g/l gaseous
Boiling temperature	150 to 360 °C	25 to 210 °C	-42 to -1 °C	-161 °C	-253 °C
Ignition temperature	220 °C	220 to 280 °C	460 °C	595 °C	585 °C
Explosion limits	0.6 to 7% by volume	0.8 to 7% by volume	1.5 to 9.5% by volume	5 to 15% by volume	4 to 77% by volume
Calorific value	12 kWh/kg	12 kWh/kg	12.5 kWh/kg	13 kWh/kg	33 kWh/kg
Lower heating value (LHV)	44 MJ/kg	44 MJ/kg	46.3 MJ/kg	47 MJ/kg	120 MJ/kg
Point of accumulation	ground	ground	ground	dispersed	dispersed
Approximate Range with 10 litres of fuel	187 km	167 km	119 km	@ 200 bars or 20 MPa 40 km	@ 700 bars or 70 MPa 25 (42) km ( ) = FC

There are significant differences in the fuel density, calorific value or lower heating value (LHV) and the accumulation point. The fuel density gives an indication regarding storage technique. The lower heating value is the energy content of the fuel and the point of accumulation is useful to understand the safety requirements associated with the fuel.

It is more difficult to store fuel as a gas because of its low density. In this case you need a large volume for storing few kilograms. In addition, maintaining methane or hydrogen in the liquid phase under cryogenic conditions requires temperatures as low as -161 °C and -253 °C, respectively. This is why the compressed gas tank is the current trend. We typically use pressures of 200 bars for natural gas storage and up to 700 bars for hydrogen storage tanks.

The fuel accumulation point indicates that a garage must be specially adapted and well ventilated for working with CNG and H_2. In case of leakage these gases will be dispersed throughout the entire room and the only way to eliminate them is to completely and rapidly replace the ambient air with fresh air.

Finally, Table 2 provides a comparison between fuels in terms of vehicle consumption by making a cross-multiplication on the lower heating value LHV. For example, consider an average vehicle which consumes 6 litres (4.5 kg) of gasoline per 100 km, it will consume with the same combustion engine:

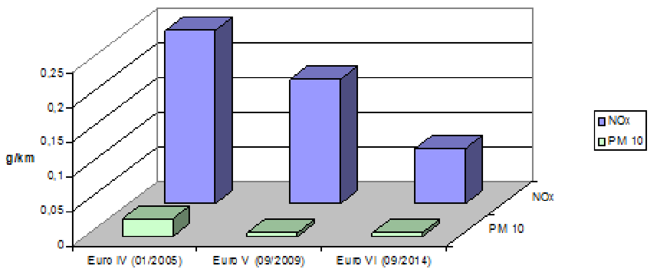
- 4.2 kg of natural gas per 100 km (result of 4.5 kg * 44/47)
- 1.65 kg of hydrogen per 100 km (result of 4.5 kg * 44/120)

Using this method we have determined the vehicle range for each type of fuel based on 10 litres. For gaseous fuels the storage pressures which are 20 MPa (200 bars) for CNG and 70 MPa (700 bars) for H_2, have been accounted for. Also, a temperature of 20 °C has been assumed. It can be seen that all liquid fuels have a range of the same magnitude and that gaseous fuels need more storage space to reach the same range, around 4 to 5 times more! This leaves room for much improvement.

Considering the difficulty of storing kilograms of hydrogen in a vehicle, high-efficiency systems such as fuel cells will further reduce the hydrogen consumption to 1 kg per 100 km. Therefore, it becomes possible to achieve a range of 500 km with 5 - 6 kg of hydrogen stored in a tank of 125 litres under 700 bars. Compared to the current range of a diesel engine, around 900 km, better FCV range is expected by the end user. R&D efforts are still delivered by car manufacturers like the cryo-compressed gas tank introduced briefly in unit 3.

1.5. Evolution of powertrains

Vehicle manufacturers are subject to strict legislation on anti-pollution standards, in particular the car industry. Their brand of vehicles must meet an average limit value of CO_2 emissions. In addition, each vehicle must emit pollutants in very small quantities, measured in g/km, as shown in Figure 7 for NO_x and fine particles. Figures 7 and 8 show that the evolution of standards over the years leaves no doubt about the continued decrease of emissions permitted.



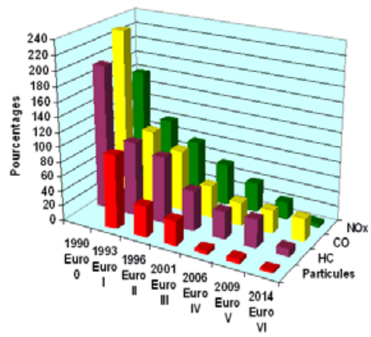


Figure 7 and 8 Evolution of standards for vehicle emissions passenger cars and light commercial vehicles, diesel (Source, Autoform & Senat.fr).

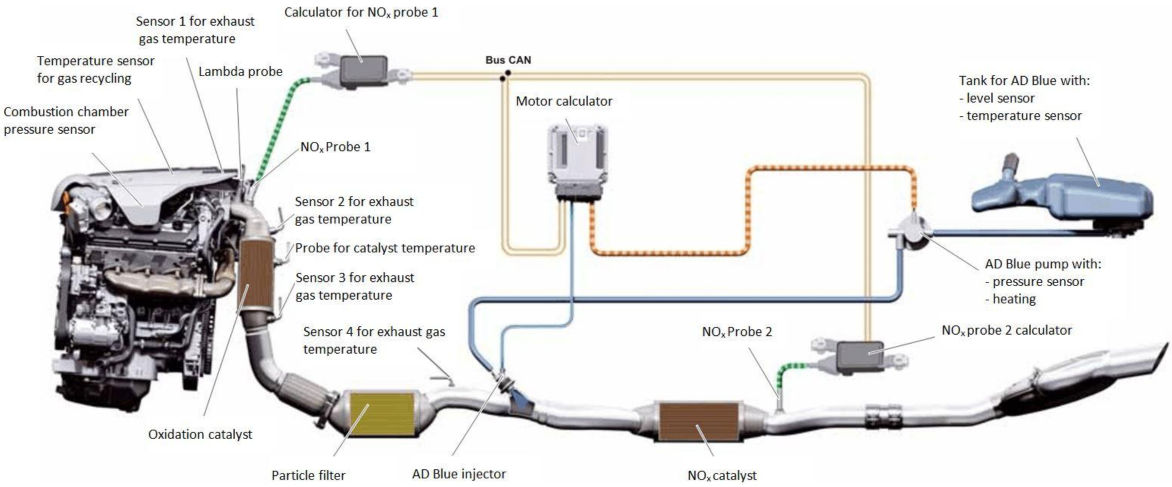


Figure 9 Post-treatment system of exhaust gas Diesel EURO 6
(Source, Audi SSP428 via EDUCAM).

This legislation requires from manufacturers to develop post-treatment systems of exhaust gas, making the current powertrain more expensive, complex and thereby increasing the risk of malfunctions. Figure 9 shows that a diesel post treatment system is comprised of two catalysts, one filter, 3 calculators or engine control unit (ECU), 1 oxygen sensor, 5 temperature sensors, 1 pressure sensor, 2 NO_x probes and 1 injection system for a special additive.

This costly development opens up the space for other solutions such as hybrid vehicles and electric vehicles. Fuel cells will naturally find its place in applications where:

1. Zero emissions are desired at the exhaust

2. Significant autonomy is desired

Summary

The world energy consumption is huge, equivalent to 12 Gt of Oil per year. Fossil fuels represent 80% of this consumption. Fortunately, the share of renewable energy slowly increases every year, reaching now 14% of the total.

Nowadays the transport sector is the largest consumer of oil products and the second emitter of CO_2 after the power generation sector. This leads to two major issues:

- Emissions and their effect on health & environment
- CO_2 emissions and their effect on the global warming

Concerning pollutant emissions, the constant evolution of EURO standards has forced the car manufacturers to introduce and develop new technologies for the exhaust gas after treatment. These sensors, ECU and catalysts are relatively costly and sensitive, which increases the risk of malfunction. Alternative solutions such as hybrid and electric motors then become more competitive regarding additional costs of the depollution technology.

Concerning CO_2 emissions, the first difficulty is to evaluate the value for different powertrains like engine, hybrid, electric and fuel cell. This is why the « **well-to-wheel** » calculation method is introduced. It evaluates all CO_2 emissions from the oil extraction process to the final user, the interest being to separate two important parts, « **well-to-tank** » and « **tank-to-wheel** ». In general, the benefits in CO_2 emission reduction will far outweigh the benefits of an increase in powertrain efficiency. Many studies predict that the best solutions for the future are based on the electrification of the powertrain, including fuel cell vehicles.

The comparison of fuel properties shows that gaseous fuels can be used, especially hydrogen thanks to its calorific value being three times greater than that of liquid fuels. However, the low density of gaseous fuels leads to a major difficulty with regards to storage. A comparison shows that the range of a CNG or H_2 vehicle is 4 to 5 times shorter than a petrol or diesel vehicle with the same tank volume. Much progress is required in this field. This is why car manufacturers continue to invest in R&D for the purpose of fuel cell improvements and to increase storage capacity.

Nevertheless, the situation of the fuel cell powertrain is quite promising. It is already considered an “electric” vehicle with an average range of 500 km that must be compared to the 120 km range of a 20 KWh battery electric vehicle.