Engines/Motor Fuels: Possible Long-Term Trends

All energy forecasts for the period between now and 2030 agree: oil should continue to represent 40% share of the world energy balance and oil demand should grow sharply (+60%), driven by the developing countries. In an environment marked by rising world oil consumption, the oil and automobile industries face a major challenge: how to limit the increase in the CO_2 emissions due to road transport by implementing innovative technical solutions with respect to engine technologies and energy sources.

In the next 30 years, energy demand is expected to grow fastest in the transport sector as well as in the power generation, which presently relies nearly exclusively on petroleum products. Sooner or later, this dependence on oil will raise basic questions: Are oil reserves being replaced at a rate that will ensure an adequate supply? Is it possible to develop the means of reducing the greenhouse gas emissions generated by transport activity? Between now and 2030, we may well see the emergence of industrially viable alternative solutions that are able to curb the inexorable increase in CO_2 emissions and provide a transition period in the “post-petroleum” age.

It is Imperative to Fight Local and Global Pollution

Since the 1970s, the oil and automobile industries in Europe have tackled the problem of decreasing localized pollutants: carbon monoxide (CO), volatile organic compounds including unburned hydrocarbons (VOCs, HC), nitrogen oxides (NOx), particulate matter (PM) and ozone (which causes most of the pollution peaks that occur in summer). This was part of an overall approach in response to requirements and regulations implemented by public authorities both in Europe and in the United States. This ongoing process, which has spread to a number of developing countries, should help substantially reduce tailpipe emissions.

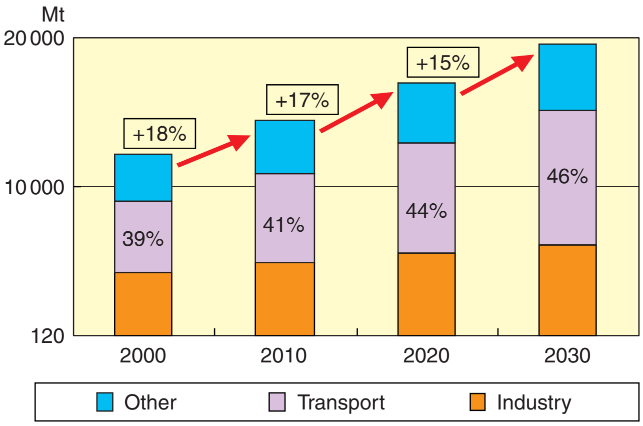
In the last 30 years, local polluting emissions from new vehicles have dropped by a factor of between 10 and 100. Among the noteworthy technology advances making this possible, the following deserve special mention:

- Lead-free gasoline has come into general use, with a lower benzene content.
- Key engine parameters are controlled electronically, and injection and combustion systems have been improved.
- Starting in the 1990s, the catalytic converter was systematically applied to vehicles with gasoline spark ignition engines; its efficiency is expected to increase.
- The sulfur content in motor fuels has been steadily reduced and will be again in 2005 (to 50 ppm) and 2008 (to 10 ppm).

In fact, European regulators are continuing their efforts to reduce the level of polluting emissions, especially nitrogen oxides, ozone and particulate matter. This policy is getting results, even if the automobile replacement rate and increased traffic can partially conceal the impact. This being said, there has not been a similar downtrend in CO_2 emissions, which will now be the main focus of actions taken by the public authorities.

According to the IEA base scenario, which includes trends but does not postulate a resolute policy in this area, world CO_2 emissions in the energy sector should rise from 23 Gt in 2000 to 27 Gt in 2010 and 38 Gt by 2030. Two sectors are expected to be primarily responsible for this increase of nearly 65% over the period 2000-2030: electricity production and transport. Looking at the world CO_2 emissions breakdown, sector by sector, one sees that the share of transport is expected to rise from 40% in 2000 to 45% by 2030.

Fig. 1 World CO_2 emissions by sector (Mt)



Source: IEA 2002 *IFP / Economics Department / 2003*

Engines/Motor Fuels: Possible Long-Term Trends

Now, these scenarios are intended to stimulate thinking about possible future outcomes more than to predict the future. Even so, it is clear that action must be taken.

Technology advances will be necessary to reduce energy consumption and greenhouse gas emissions, although societal changes (transport modes, urban planning, etc.) will also be of decisive importance. **Today, the answer does not lie in any single technology, but in a number of possible solutions** that need to be examined and perhaps used in combination to respond to the problem of greenhouse gases.

In the road transport sector, for instance, efforts to develop engines and motor fuels are interdependent.

Many Possible Responses: From the Motor Fuels of Today…

Petroleum motor fuels represent 98% of the energy consumed by road transport worldwide; the figure for aircraft, not including spacecraft, is 100%. Many improvements have been made and planned. In addition, new specifications may be implemented by 2020 to meet air quality targets in the European Union or to regulate new modes of combustion in spark ignition and diesel engines (e.g. CAI and HCCI).

Another way to reduce automobile CO_2 emissions is to turn to so-called “alternative” energies. Some have been in use for years, initially to reduce pollution or oil dependence (in Brazil, for example). Nevertheless, the motor fuels based on natural gas, liquefied petroleum gas and biofuels only represent about 20 million toe, which is less than 2% of the total energy used in the world transport sector. In late 2003, the European Commission proposed penetration targets to have replacement fuels represent 23% of motor fuel demand by 2020 (natural gas 10%, biofuels 8% and hydrogen 5%). These goals seem to be very ambitious from today's vantage point.

It is not very realistic to expect LPG motor fuel to come into generalized use in the automobile fleet, owing to difficulties of local/regional availability or distribution infrastructure. Yet the volumes that could be developed worldwide for transport applications could be fairly large in the future.

Similarly, the use of NGV in the transport sector only represents a very small share of total consumption of this primary energy source (mainly used for energy production and heating) and of the world automobile fleet. The need for high-pressure storage and relatively heavy infrastructure inhibits large-scale development. It has the most potential for use in fleets of captive vehicles that make many short trips in town centers. Research is currently exploring the possibilities of a “home distribution” system that would allow vehicle owners to refuel at home. Using an optimized natural gas engine, it might be possible to reduce CO_2 emissions by 5 to 10% compared to diesel engine.

The two biofuels selected for industrial development are vegetable oil methyl esters (VOME) and ethanol. Their cost is a major obstacle to more generalized use, even if, from the environmental standpoint, the balance sheet is fairly positive, especially with respect to CO_2 emissions.

- Up to a concentration of 5%, VOME is distributed at the pump in a manner that is transparent for the user. Today, some French refineries blend it into motor fuels for sale in proportions varying from 2-5%.
- Ethanol was mainly used after the oil shocks of 1973 and 1979 as a replacement for premium in Brazil and, to a lesser extent, in the United States. In Europe, ethanol is generally not used directly in motor fuels, due to problems related to storage and its impact on volatility. Its ether form is preferred (ETBE, produced from isobutylene and ethanol).

Nevertheless, the volumes consumed in Europe remain low, less than 0.4% of the gasoline and diesel fuel consumed in the European Union. One prerequisite for development will continue to be large public subsidies.

…to the Motor Fuels of Tomorrow

Today, liquid motor fuels (gasoline and/or diesel fuel) are only produced from petroleum. In the medium term, however, it may be possible to produce them from natural gas, coal and biomass.

GTL (gas to liquids) technologies based on the Fischer-Tropsch synthesis method offer new avenues for the valorization of natural gas that yield petroleum products of very good quality. Many operators are interested in these technologies. The cost of this type of installation has dropped substantially in recent years. In the early 1990s, this type of project cost over $50,000 bbl/day, but now the estimated cost is between $20,000 and $35,000 bbl/day. Process performance has made considerable advances, while projects have become significantly larger (from 12,000 bbl/day in the early 1990s to 30,000-75,000 bbl/day today), which has brought costs down.

In the same vein, the CTL (Coal to Liquids) technology is more costly, but technically feasible. This solution is attractive to countries with large coal reserves. World coal reserves represent over 200 years of production at the current rate and are located in countries like China and India, which will be consuming increasing quantities of energy in the years to come. A recent IFP study shows that, given a coal price of

$30/ton, the CTL solution can compete with conventional pathways provided that the price per barrel remains higher than $35-40 a barrel for a substantial length of time. It should be pointed out that not much research has been done in this area in the last 20 years.

Although these two pathways could help reduce the proportion of oil in the transport energy breakdown, large-scale production is not an option unless the problem of their high CO_2 emissions is solved. One possibility would be to capture and sequester these emissions in suitable geological formations.

Biomass (Biomass To Liquids or BTL) is the last alternative for the production of liquid motor fuels comparable to petroleum-based products. Initially, raw stock is collected and converted to "synthesis gas" then to liquid form using the Fischer-Tropsch process, to obtain diesel fuel. Expressed in euros per ton diesel equivalent, its cost is very high, on the order of €700-800/toe. This pathway is still at the R&D and demonstration stage, notably within the framework of European projects.

Hydrogen can be considered for possible long-term motor fuel applications. The present-day hydrogen consumption breakdown shows that 99% is used as an industrial gas: 50% to produce ammonia, 37% for refining, 8% for methanol synthesis and 4% to produce other special chemicals. Only 1% of world volume is valorized for energy purposes, in the space sector. As for the energy source, fossil fuels are the most frequently used. The technology most commonly used to produce hydrogen in large quantities and at the lowest possible cost is the steam reforming of natural gas. The transformation of biomass is an attractive alternative that still needs a large amount of R&D. Finally, despite very high costs and mediocre energy efficiency, the electrolysis of water represents the principal technology for the production of hydrogen that is not based on fossil fuels; any real "environmental" benefit depends directly on the mode of electricity production used. Furthermore, the creation of a supply chain (shipment by pipe, intermediate storage, onboard storage) implies major difficulties including technical problems and very high extra costs.

However, one cannot measure the real environmental benefits of a motor fuel without integrating conversion system efficiency, from spark ignition engine to electric motor.

As Conventional Engines Continue to Progress…

The bulk of GHG reduction must be obtained by focusing on vehicle propulsion systems. One approach is to make vehicles lighter, but its effectiveness will be limited by expectations in terms of passenger comfort and safety requirements.

In recent years, the development and generalization of the high-pressure direct injection engine has led to a significant decrease in per-vehicle consumption, especially for diesel vehicles.

Thanks to progress in direct injection and to its combustion concept, the diesel engine consumes about 30% less motor fuel and emits about 30% less CO_2 than its gasoline counterpart. This performance, in conjunction with increasing diesel engine penetration of the automobile fleet, has enabled European automakers to meet their CO_2 emissions reduction commitments up until now.

The real challenge facing the diesel engine will be to ensure compliance with future NOx and particulate matter emissions standards. This will require more efficient injection systems and probably the installation of aftertreatment systems: a selective catalyst reduction system or a NOx trap and particle filters, possibly with an optimized combination or even a single system ("four way" catalysis).

For the spark ignition engine, the challenge will be to reduce its CO_2 emissions, thereby enhancing energy efficiency. Direct injection is an interesting possibility that could save 10 to 15%, but it is not compatible with the three-way catalytic converter and would require the installation of an after-treatment system, such as a NOx trap.

Another approach is to downsize the engine while maintaining performance, especially torque at low and high speeds, with the systematic use of turbocharging; this could yield reductions of about 5 to 10%. If this approach were combined with direct injection and variable distribution, gains of about 25 to 30% could be achieved.

Technology advances and ICE research now underway hold out the promise of consumption gains ranging from 10 to 30, over the present ICE, depending on the solution.

Progress can be hindered by the need to control emissions, especially NOx emissions. To deal with this constraint, new modes of combustion are being studied at the European level including HCCI (Homogeneous Combustion Compression Ignition) for the diesel engine and CAI (Controlled Auto Ignition) for the gasoline engine. These two modes yield reductions for all pollutants of over 90%.

In internal combustion engine technology, the hybrid vehicle is the next development expected. This would ensure continuity with the existing ICE. As far as motor fuel distribution infrastructure is concerned, no particular modifications or major trend shifts would be necessary. It also offers good opportunities to reduce vehicle energy consumption and CO_2 emissions. Alternative hybrid vehicle

Engines/Motor Fuels: Possible Long-Term Trends

solutions (gasoline or diesel) could lead to consumption gains of 10 to 40% over the current conventional engine, depending on the technology. In the late 1990s, Toyota was the first to add a gasoline hybrid vehicle to its product range; today, the second version of the Toyota Prius is making its debut. Honda and Nissan are also coming out with a hybrid vehicle. The American automobile manufacturer General Motors plans to commercialize hybrid versions of its "gas guzzlers" (4×4s and SUVs). As for the Europeans, they are not very interested in this type of application at present, because of the commercial and technological success of the diesel engine.

Pending Long-Term Technology Breakthroughs

Looking to the long term, the electric motor could give rise to two types of breakthrough solution: vehicles powered by batteries or some other electricity storage system, or fuel cells to generate onboard electricity.

Due to their intrinsic advantages, electric vehicles attracted a great deal of interest in the past, when the general public was becoming aware of the problems represented by localized pollution. The electric motor emits no pollutants, makes very little noise and is pleasant for city driving. On the other hand, this pathway presents a series of difficulties: the battery takes too long to recharge, motor performance is limited and the range is much too short (100 to 200 km under real conditions). This is mainly due to continued inadequate performance by onboard storage batteries. Although new technologies (nickel-cadmium, nickel-metal hydride or lithium-ion batteries) have been implemented, the ratio of their specific energies (in Wh/kg) to those of liquid motor fuels is still 1 to 100. The conventional vehicle continues to easily outperform the "all electric" vehicle. More, the latter has strong rivals in the hybrid vehicle and fuel cell alternatives.

The future of hydrogen in the transport sector is very closely tied to that of the fuel cell (FC). Hydrogen obtains excellent efficiency in terms of CO_2, but there are few advantages to using it in a conventional engine as far as energy consumption and the emission of pollutants like nitrogen oxides are concerned. One advantage is that the vehicle costs less.

The only emissions given off by vehicles equipped with onboard hydrogen fuel cells consist of water vapor. At first glance, this seems to solve the problem of GHG emissions; it seems to be a "zero emissions" vehicle, an alternative to battery-powered vehicles.

But the development of the FC pathway runs into major difficulties in each case examined (onboard hydrogen storage or onboard hydrogen production). These obstacles include:

– The centralized production solution implies production infrastructure, a distribution system and onboard hydrogen storage technologies. The CO_2 balance is completely dependent on the mode of hydrogen production and/or the development of CO_2 capture/sequestration technology.

– As for onboard solutions, work still needs to be done to develop hydrogen production technologies compatible with vehicle operating constraints (start-up, transient operation, etc.), and to select the best liquid fuel (methanol, ethanol, naphtha, etc.). When hydrogen is produced on board, the CO_2 balance is not necessarily significantly better than for the other solutions. Apparently, General Motors has decided to drop this option from its R&D program and the US Department of Energy is expected to announce its position in 2004.

Finally, a major obstacle to fuel cell development is its relatively high cost. The cost of fuel cells manufactured today (of the PEM or low-temperature type) is over €3,000/kW versus €30 to 50/kW for conventional series internal combustion engines. The ICE outperforms the fuel cell even postulating the production of several hundreds of thousands of FC units, in which case the cost of FC production (not including the electric motor and storage system) would still be between €100 and 200/kW(1), i.e. three to four times more than a conventional engine, even if, in a few study scenarios, the cost range is €50 to 100/kW.

Nevertheless, the fuel cell represents a long-term option: future technological advances could improve performance and bring costs down.

Two Decision-Making Criteria: Environmental and Economic Balance Sheets

A comparison of all of these pathways should include the greenhouse effect balance sheet (the balance sheets for energy in MJ/100 km and for CO_2 emissions in grams of CO_2 equivalent per km) and the economic cost.

A recently published study on conventional/alternative motor fuel pathways was carried out jointly by the European carmakers (EUCAR), the European Commission (JRC ISPRA) and the oil companies (CONCAWE). Entitled "Well-to-wheels analysis of future automotive fuels and powertrains in the European context", it used the diesel fuel/direct injection engine combination as the reference.

Principal results are listing in Table 1.

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(1) Source: DOE and DTI, "DFMA Cost Estimates of Fuel-Cell/Reformer Systems at Low/Medium/High Production Rates", Brian D. James, Greg D. Ariff, Reed C. Kuhn, Future Car Congress 2002, June 4, 2002.

Engines/Motor Fuels: Possible Long-Term Trends

Table 1
"Well to wheel" CO_2 emissions balance sheet for conventional and alternative automotive fuels

Energy	**Origin**	**Engine**	**Energy MJ/100 km**	**g CO_2 eq./km**	**g CO_2/relative km**
Diesel 2002	Petroleum	D/ID*	212	164	1.00
Gasoline 2002	Petroleum	SI*	255	196	1.20
Hybrid Diesel 2010	Petroleum	D/ID + PT	171	131	0.80
Hybrid gasoline 2010	Petroleum	AC/ID	186	141	0.86
Diesel FT 2010	Natural gas	D*/ID + PT	216	164	1.00
Diesel FT 2010	Wood	D*/ID + PT	393	20	0.12
CNG 2002	Natural gas	SI*	256	152	0.93
CNG 2010		SI*	216	127	0.77
Ethanol 2010	Sugar beet	SI*/ID	529	97	0.59
VOME 2010	Oleagineous	D*/ID + PT	382	90	0.55
Compressed H_2	Nuclear	FC*	566	7	0.04
Compressed H_2	Natural gas (EU mix)	FC*	173	98	0.60
Liquid H_2	Natural gas (EU mix)	FC*	221	135	0.82
Liquid H_2	EU Electricity	FC*	491	222	1.35

* SI: spark ignition – D: Diesel – FC: fuel cell – PT: particulate trap.

Source: "Well to wheel analysis of future automotive fuels and powertrains in the European context", EUCAR, JRC, CONCAWE, November 2003.

When considering a "hybrid" option for each of these energy sources, the gains in terms of CO_2 emissions compared to conventional engines ranged from 10% for hydrogen to 25-30% for conventional (gasoline, diesel fuel) or alternative (natural gas, biofuels) solutions.

In addition to environmental considerations, alternative solutions must be costed to assess their economic performance. The production and distribution costs indicated in Table 2 are from the European study just mentioned. Production costs depend on the mode of production and the cost of the primary energy used. Distribution costs tend to represent differences related to the physical state of the motor fuel (liquid or gas) and operating conditions (toxicity, safety, et cetera). When computing costs, the initial investment in the vehicle is not included.

As an illustration, the additional cost for a CNG vehicles compared with to a gasoline one is expected to amount down to 1200-2000 € (2003 Report of the Alternative Fuel Contact Group to the European Commission). For PEM fuel cell, the magnitude of cost are much more important: the extra cost to the only platinium on the membrane (20 €/kW) accounts for two-third of a gasoline engine cost (30 €/kW). Globaly the best estimations give for the long term FC production cost (including mass production effect and

Table 2
Cost per km of the different motor fuels

	Consumption (MJ/100 km)	**Cost of motor fuel (€/GJ HT)**	**Cost (€/100 km)**
ICE* + gasoline 2002	224	8	1.8
ICE* + diesel fuel 2002	183	8	1.5
ICE* hybrid + diesel fuel 2010	148	8	1.2
ICE* + GNC 2010	193	7.5	1.4
FC + compressed H_2 ex-gas	84	25	2.1
FC + compressed H_2 ex-coal	84	32	2.7
FC + compressed H_2 ex-biomass	84	37	3.1
FC + compressed H_2 ex-electricity France	84	42	3.5
ICE* + VOME 2002	183	12	2.2
ICE* + ethanol 2002	224	21	4.7
Diesel FT ex-wood 2002	183	20	3.7

* ICE: internal combustion engine.

Source: IFP

technology breakthrough) about 100-200 €/kW (for more then 3000 €/kW today), than conduct to a extra cost of 5000-10 000 € per vehicle (excluding hydrogen storage and electric engine specific costs).

This analysis shows that, for hydrogen fuel cell options versus conventional ones, the extra cost per 100 km varies from 15% to over 100%, even postulating that the cost of the FC is equivalent to that of the ICE, a very favorable assumption.

Costing three times more than conventional motor fuels, ethanol is penalized by its energy content, about one-third lower than that of gasoline. Biofuels can only be competitive if a tax exemption program is implemented; they are also indirectly subsidized by the EC Common Agriculture Policy (CAP). Finally, the CO_2 balance sheet for the production of synthesis motor fuels from biomass is very good, but the cost per 100 km is about the same as for the ethanol pathway.

In this European study, a scenario in which alternative solutions achieved a penetration rate of 5% in Europe has been tested. Expressed in euros per ton of CO_2 emissions prevented, the cost was: €200/t for the hybrid solutions, €300/t for the biofuels, €600/t for onboard hydrogen storage and €5,000/t for onboard hydrogen production. As we can see, alternative solutions must progress a great deal to have a chance of being competitive.

The Future is Open to Many Possible Solutions

Moving into the 21st century, the road transport sector must face a major challenge for the next fifty years: how to limit the uptrend in CO_2 emissions by 2030. In the short term, the advantage of using biofuels is that they have the fastest impact on GHG emissions. Hybrid solutions also seem to present a good environmental/cost trade-off. In the long run, the competition is open between the engine-powered vehicle, with all possible technical improvements, and an electric vehicle equipped with improved batteries or a hydrogen fuel cell system for onboard storage.

As far as the greenhouse effect is concerned, technology is not the only possible response. Societal and behavioral changes will also be called for, e.g. in reorganizing the transport sector. Among other things, this will entail the promotion of the rail system and land use planning.

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