CLEAN FUELS AND ALTERNATIVE VEHICLES FOR SUSTAINABLE DEVELOPMENT IN TRANSPORTATION

ELENA TSIOLIARIDOU [a, b], GEORGE BAKOS [b], NEBOJSA NAKICENOVIC [a]
[a]Technical University of Vienna, Austria
[b]Democritus University of Thrace, Greece

Abstract
This paper discusses the prospects for using clean fuels and alternative vehicles to satisfy the sustainable development objectives which include reliable energy supply, affordable energy services and a cleaner environment for everyone. Transport energy demand is the most important driving force of increasing oil demand over the past thirty years, and accounts for almost half of the world oil consumption. Emissions from fuel combustion in conventional vehicles and the effects on air pollution are on-going concerns in both developed and developing countries. Concerns continue to grow over carbon dioxide (CO_2) emissions in the context of global warming and climate change. Clean fuels and alternative vehicles offer considerable promise to achieve major reductions in air pollutants, as well as in CO_2 emissions, and to meet other objectives of sustainable development such as reliable and affordable energy services.

1. Introduction

Transport energy use continues to rise rapidly around the world. Transport is becoming the dominant sector in terms of oil use. It has accounted for nearly all growth in oil use over the past 30 years, and this is expected to continue over the next 30 years as well. In very few countries does oil account for less than 97% of transportation fuel use. Figure I shows the share of transport energy demand of oil on a global level [I]. Secure energy supply for the countries would mean that countries are not dependent only on oil imports, especially imports from the Gulf. Secure energy supply would mean that exporters and importers have the same incentives, as so, for example, in gas supply from Russia.

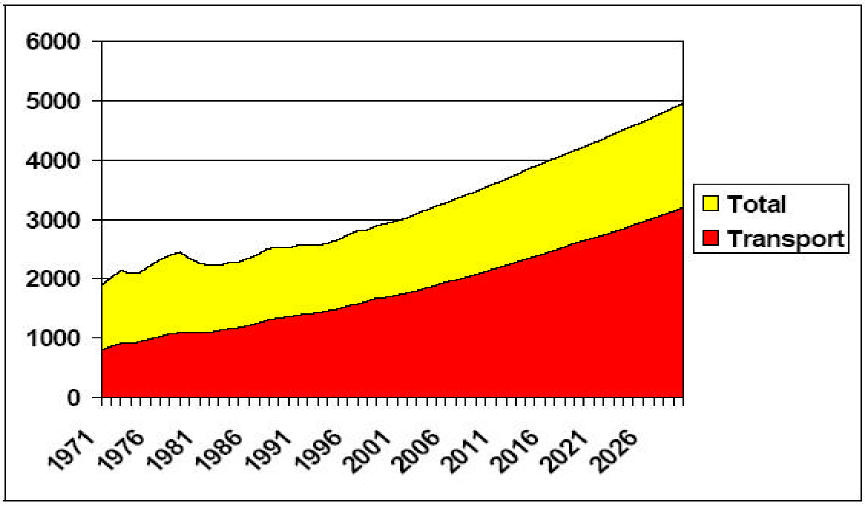


Figure I Transport & Total world energy demand, 1971-2030, in Megatons Oil Equivalent, MTOE

Road transport plays a central role in developed and developing countries, and while providing a lot of positive benefits, the operation of road vehicles can also lead to adverse environmental impacts. These include local air pollutants and GHG emissions.

The combustion of fossil fuels by conventional vehicles is one of the sources which are responsible for most smog and harmful particulates in the air. Vehicles operating on today's gasoline emit complex mixtures of compounds that lead to the formation of ground-level ozone, and many of these compounds are also toxic. A lot has been done to reduce automobile pollution, from development of innovative emission control technologies like catalytic converters, to the establishment of inspection and maintenance programs. But each year there are more cars on the road, travelling more miles, and the pollution control measures taken so far have not been sufficient to solve the ozone problem in many cities. Ozone, better known as smog, is the most widespread air pollution problem. In most OECD (Organisation for Economic Co-operation and Development) countries, emissions of nitrogen oxides (NO_x), carbon monoxide (CO) and hydrocarbon (HC) were at their highest levels in the early 1990s. Since then, air pollutants have decreased by 20-50%, despite increasing sizing of vehicles and distance travelled in these countries. Conventional fuels with the best current technologies, as well as tight standards and regulations have contributed in this reduction.

Clean fuels can contribute even more to the improvement of air quality, especially in urban areas. They have a number of inherent properties that make them cleaner than conventional gasoline or diesel. In general, these fuels emit less hydrocarbons, and the hydrocarbons they do emit are less reactive (slower to form ozone) and less toxic. In addition, they are neutral with respect to carbon emissions [II].

The use of cleaner fuels could also help slow atmospheric buildup of carbon dioxide, a "greenhouse gas" that could contribute to global warming. Greenhouse gases from human activities are responsible for anthropogenic changes in global climate [III]. They trap excess heat from the sun's infrared radiation that would otherwise escape into space, much like a greenhouse is used to trap heat. Combustion of any carbon-based fuel produces carbon dioxide. The overall impact of a given fuel on global warming depends on how the fuel is made. In general, fuels produced from biomass and from natural gas result in less carbon dioxide accumulation than fuels made from petroleum or coal.

Another major concern is the increasing levels of CO_2 emissions from the road transport sector which represent around 23% of total CO_2 emissions in OECD countries and are growing at a rate of 2% per annum in absolute values. Despite technological advances, efforts to reduce per-vehicle fuel consumption and as a consequence per vehicle emissions of GHG have been offset by market trends towards increasing power and weight of vehicles. Alternative vehicles, such as hybrid (diesel/electric), and in the longer term fuel cell vehicles appear to offer the best prospects among new technologies for surpassing CO_2 emissions performance of conventional gasoline and diesel engine motor vehicles [IV,V].

An important message of this paper is that many technologies are already available to provide near term oil savings, energy security benefits, better air quality and CO_2 reductions. Clean fuels and alternative vehicles can address the concerns of today's society, contributing to a more sustainable energy development in the transport sector.

2. Clean Fuels

A range of clean fuels is available for road transport vehicles and many have been in use for a number of years. Fuels such as biodiesel, ethanol, methanol, natural gas and propane can replace gasoline and diesel in conventional vehicles. New technology vehicles running on hydrogen and electricity are even more promising to achieve oil savings and minimise countries' dependence on oil imports.

2.1 Biofuels

Biofuels can be produced from various biomass stocks including agricultural products. One important advantage is that they can be blended with petroleum fuels and used in conventional engines. Up to date two types of green fuels from biomass have reached technical maturity and acceptation in the market: biodiesel and ethanol fuels.

2.1.1 Biodiesel

Biodiesel is a clean burning replacement fuel made from natural, renewable sources such as oil of crops including oilseed rape, sunflowers, and soybeans as well as from animal fats or recycled cooking oil. Just like petroleum diesel, it operates in compression- ignition engines. Blends up to 20% biodiesel (mixed with petroleum diesel fuels) can be used in nearly all diesel equipment and are compatible with most storage and distribution equipment. These low-level blends (B20) generally do not require any engine modifications. Higher blends, even pure biodiesel (100% or B100) can be used in many engines built since 1994 with little modification.

Biodiesel produces fewer particulate matter, carbon monoxide and sulphur dioxide emissions. The use of biodiesel decreases the solid carbon fraction of particulate matter (PM) and the sulphate fraction (it contains less than 24ppm (parts per million) sulphur), while the soluble or hydrocarbon fraction remains the same. Therefore, biodiesel works better with new technologies such as diesel oxidation catalysts (which reduce the soluble fraction of diesel particulate but not the solid carbon fraction). Net Biodiesel reduces carbon dioxide emissions by more than 75% over petroleum diesel. Using a blend of 20% reduces CO_2 emissions by 15%. Since biodiesel can replace a part of petroleum used in vehicles, it displaces imported petroleum and reduces the country dependence on it.

Biodiesel costs about 1.5 times more than No. 2 diesel fuel, so you can expect biodiesel blends to cost slightly more than standard diesel. This elevated cost may be offset by the superior lubricity of biodiesel, which reduces wear and tear on the engines [VI, VII].

2.1.2 Ethanol

Ethanol is an alcohol-based alternative fuel produced by fermenting and distilling starch crops that have been converted into simple sugars. Feedstocks for this fuel include corn, barley, and wheat. Ethanol can also be produced from "cellulosic biomass" such as trees and grasses and is called bioethanol. Ethanol can be blended with gasoline to create E85, a blend of 85% ethanol and 15% gasoline. E85 and blends with even higher concentrations of ethanol, E95, for example, qualify as alternative fuels under the Energy Policy Act of 1992 (EPAct). Vehicles that run on E85 are called flexible fuel vehicles (FFVs) and are offered by several vehicle manufacturers. Ethanol (E10) is most commonly used to increase octane and improve the emissions quality of gasoline

Ethanol reduces countries' dependence on foreign oil because it can be produced domestically. In Brazil ethanol accounts for about 30% of gasoline demand in transport sector. Reductions are not, however 1:1 on a volume basis since ethanol has a lower energy content. Reviews of "well to wheels" studies indicate that it typically takes 0,15 to 0,20 liters of petroleum fuel to produce 1 liter biofuel. Air pollution can also be reduced by using ethanol. Ethanol is low in reactivity and high in oxygen content, making it an effective tool in reducing ozone pollution. It is also a safe replacement for toxic octane enhancers in gasoline such as benzene, toluene, and xylene. Ethanol provides significant reductions in GHG emissions compared to gasoline. Figure II shows the net reductions in CO_2 equivalent emissions for both types of biofuels.

Although ethanol is more expensive to produce than gasoline, tax incentives reduce the price to a competitive level [VI], VII, VII].

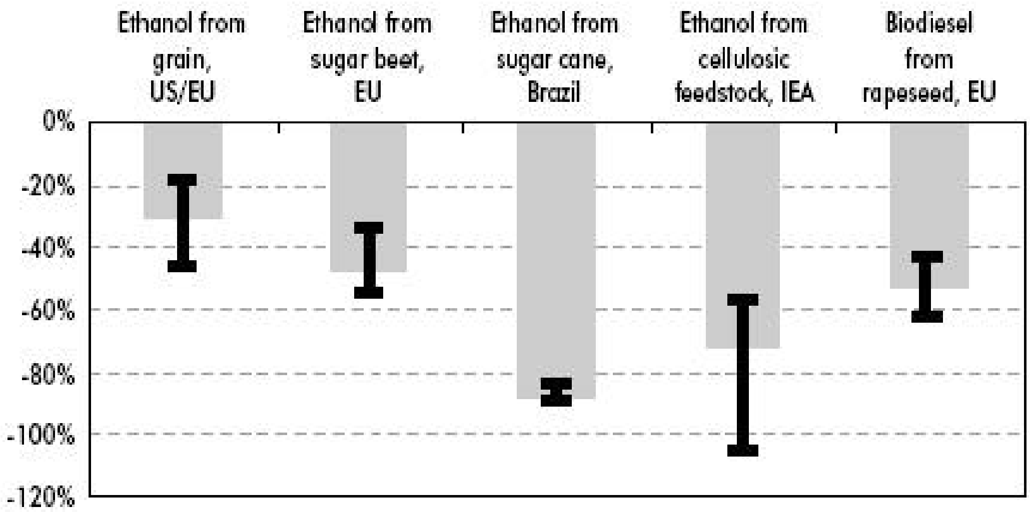


Figure II Range of Estimated Greenhouse Gas Reductions from Biofuels [V]

Note: Ethanol is compared to gasoline vehicles and biodiesel to diesel vehicles

2.2 Methanol

Methanol ("wood alcohol"), like ethanol, is a high-performance liquid fuel that emits low levels of toxic and ozone-forming compounds. It can be produced at prices comparable to gasoline from natural gas and can also be produced from coal and wood. All major auto manufacturers have produced cars that run on "M85," a blend of 85 percent methanol and 15 percent gasoline. Cars that burn pure methanol (M100) offer much greater air quality and efficiency advantages. Many auto manufacturers have developed advanced M100 prototypes. Methanol has long been the fuel of choice for race cars because of its superior performance and fire safety characteristics.

Nevertheless, methanol is no longer commonly used as a motor fuel, largely because of problems resulting from its corrosiveness, ground water contamination and its toxicity for health [VI, VII]

2.3 Compressed Natural Gas (CNG)

Natural gas is a mixture of hydrocarbons, mainly methane, and is produced either from gas wells or in conjunction with crude oil production. The interest in natural gas as an alternative fuel stems mainly from its clean burning qualities, its domestic resource base, and its commercial availability to end users. Because of the gaseous nature of this fuel, it must be stored onboard a vehicle in either a compressed gaseous state (CNG) at 204-245 atmospheres or in a liquefied state (LNG, Liquefied Natural Gas) at 1,5-10 atmospheres. Natural gas can also be blended with hydrogen, and used in fuel cell vehicles.

Natural gas engines have demonstrated more than 30% reduction of CO_2 and up to 95% reduction of CO and PM, in comparison to gasoline engines. NO_x however remain roughly the same. When CNG vehicles are compared to diesel vehicles, NO_x emissions are about 80% lower, CO reductions are up to 95%., where CO_2 emissions are equivalent or higher. Table I indicates the performance emissions of natural gas engines [VIII,IX].

CNG is currently the cheapest of all the fossil-based fuels (including propane) when fuel costs alone are considered].

Compared to:	CO_2	NOx	PM
a similar gasoline engine	↓20-30%	Roughly the same	↓95%
a similar diesel engine	↑5-10%	↓75-85%	↓95%

Table I Emission Performance of CNG engines

2.4 Liquefied Petroleum Gas (LPG)

LPG is mainly comprised of propane and it is produced either as a by-product of oil refining or from natural gas (methane) fields. LPG consists mainly of propane, propylene, butane, and butylene in various mixtures. When natural gas is produced, it contains methane and other light hydrocarbons that are separated in a gas processing plant. Because propane boils at 230°K and ethane boils at 184°K F, it is separated from methane by combining increasing pressure and decreasing temperature. The natural gas liquid components recovered during processing include ethane, propane, and butane, as well as heavier hydrocarbons. Propane and butane, along with other gases, are also produced during crude refining as by-products of the processes that rearrange or break down molecular structure to obtain more desirable petroleum compounds. LPG burns clearer than gasoline but is limited in supply. To run on LPG, existing gasoline and diesel engines needs to be converted, however, diesel is more expensive to convert. New purpose-built vehicles can also be purchased from some major manufacturers.

LPG gives comparable performance to gasoline engine vehicles on levels of pollutant emissions, and reduced CO_2 emissions. In comparison to diesel engine vehicles LPG technologies offer very good results, but produce somewhat higher levels of CO_2 emissions. With the improvement of diesel technology though, some major engine makers have decided to stop the production of LPG vehicles Table II indicates the performance emissions of LPG engines [VI, X].

An LPG car costs approximately 30% less to run than gasoline, and approximately the same as diesel.

Compared to:	CO_2	NOx	PM
a similar gasoline engine	↓10-15%	↑up to 5%	Roughly the same
a similar diesel engine	↑10-20%	↓75-85%	↓95%

Table II Emission Performance of LPG engines

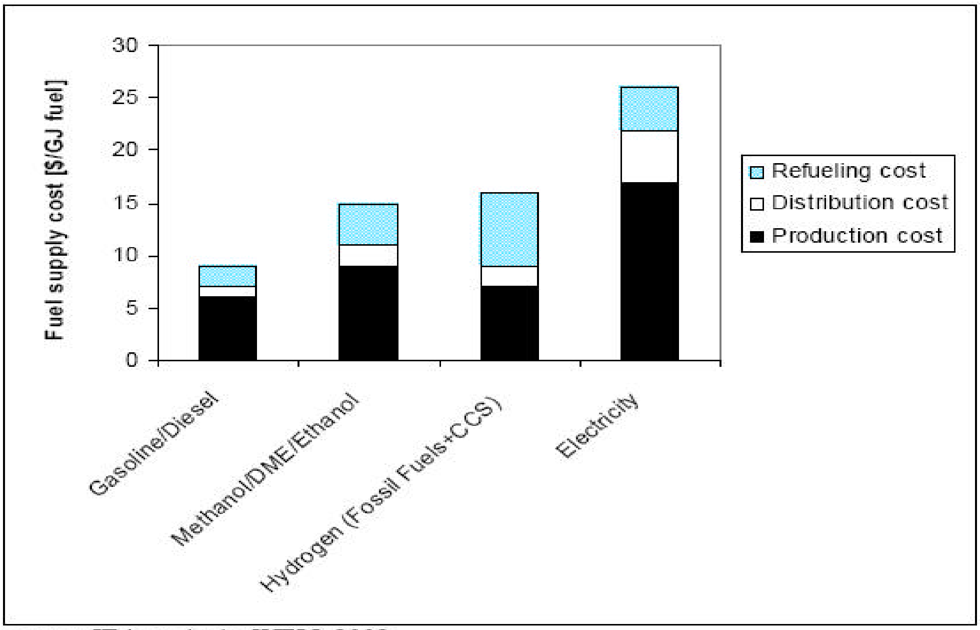
2.5 Hydrogen

Hydrogen is a simple and light fuel, in a gaseous state at atmospheric pressure and ambient temperatures. It may contain low levels of carbon monoxide and carbon dioxide, depending on the source. Today, the two most common methods used to produce hydrogen are steam reforming of natural gas and electrolysis of water. The predominant method for producing synthesis gas is steam reforming of natural gas, although other hydrocarbons can be used as feedstocks. For example, biomass and coal can be gasified and used in a steam reforming process to create hydrogen. Electrolysis uses electrical energy to split water molecules into hydrogen and oxygen. The electrical energy can come from any electricity production source including renewable fuels [VI].

Hydrogen is being explored for use in combustion engines and fuel cell electric vehicles. On a volumetric basis, the energy density of hydrogen is very low under ambient conditions. This presents greater transportation and storage hurdles than for liquid fuels. Storage systems being developed include compressed hydrogen, liquid hydrogen, and physical or chemical bonding between hydrogen and a storage material (for example, metal hydrides). Storing H_2 onboard motor vehicles is challenging because of its low volumetric energy density. With current technologies, the least costly option is compressed gas (typically 350 atmospheres), for which the storage density is less than one-tenth gasoline's. In comparison to gaseous storage, storage volumes could be reduced by half with metal hybrids, but storage system weight would increase several times and the costs would be much higher. H_2 liquefaction could reduce storage volumes to a third of those for compressed H_2 but would require consuming electricity equivalent to one third of the H_2.

Hydrogen is widely perceived to be an unsafe fuel, because it burns or detonates over a wider range of mixture with air than other fuels, and very little energy is required to ignite H_2 mixed with the minimum amount of air needed to completely burn it. Nevertheless, when used in unconfined spaces, as will be typical in transport applications, the lower limits of flammability and detonability matter most. In this regard, H_2 is comparable to or better than gasoline. An important safety issue of H_2 is leaks- prevention, detection and management, particularly in confined spaces. Areas where hydrogen is stored and dispensed have to be well ventilated.

Hydrogen production costs depend to a large degree on the hydrogen's source and the scale of production. In small volumes, produced through electrolysis (common for small-scale production today), per unit energy costs are very high. But if hydrogen is produced on a large scale, through reforming of natural gas at central plants, and then shipped or piped to retail stations, costs could eventually drop to near parity with those of gasoline (on an energy equivalent basis). Taking into account the relative efficiency advantage of fuel cell vehicles (further analysis will follow in the next paragraph), fuel costs per kilometre of travel could even be lower for hydrogen than for other fuels. Figure III indicates the estimated H_2 supply cost under high-volume production [IX, X].



source: IEA analysis, WEIO 2003

Figure III Estimated Hydrogen supply cost under high-volume production ($/GJ fuel) [I]

2.6 Fuel cells

Fuel cells are extremely efficient electro-chemical devices that use hydrogen and oxygen to produce electricity to power an electric motor. Fuel cells were devised in the 19th century and were used to provide on-board electrical energy and water for the Apollo spacecraft.

A fuel cell produces electricity directly from the reaction between hydrogen derived from a hydrogen-containing fuel or produced from the electrolysis of water) and oxygen from the air. Like an internal combustion engine in a conventional car, it turns fuel into power by causing it to release energy. In an internal combustion engine, the fuel burns in tiny explosions that push the pistons up and down. When the fuel burns, it is being oxidized. In other words, the fuel combines with oxygen and, as a result, produces energy in the form of heat and mechanical motion. In a fuel cell, the fuel is also oxidized, but the resulting energy takes the form of electricity. What's more, when powered by pure hydrogen, the only by-products of the reaction are heat and water [IX, XI].

A fuel cell power system has many components, but its heart is the fuel cell stack, which is made of many thin, flat cells layered together. (Although the term fuel cell is often used to describe the entire stack, strictly speaking, it refers only to the individual cells.) Each cell produces electricity, and the output of all the cells is combined to power the vehicle [II].

Fuel cells are currently much more expensive to produce than conventional engines. Further discussion will follow.

2.7 Electricity

Electricity is unique among the alternative fuels in that mechanical power is derived directly from it, whereas the other alternative fuels release stored chemical energy through combustion to provide mechanical power. Motive power is produced from electricity by an electric motor. Electricity used to power vehicles is commonly provided by batteries, but fuel cells are also being explored. Batteries are energy storage devices, but unlike batteries, fuel cells convert chemical energy to electricity. The electricity for recharging the batteries can come from the existing power grid, or from distributed renewable sources such as solar or wind energy [II]

Vehicles that run on electricity have no tailpipe emissions. This is the most important benefit. Detailed analysis will follow up in a paragraph about electric vehicles.

3. Alternative vehicles

With growing energy and environmental concerns surrounding today's conventional vehicles, a great deal of research is going into alternative vehicles. Four main types of alternative technology vehicles have the potential to reduce the environmental and efficiency deficits of conventional vehicles and become commercially available in the near future.

3.1 Electric vehicles

Electric vehicles are powered by rechargeable batteries. They use a battery and an electric motor to power the vehicle, and have therefore no emissions at the point of use. The battery can be made of lead-acid, nickel-metal or lithium polymer, and can be recharged at home or, in the future, in recharging stations. Electrical vehicles (EVs) have several environmental benefits, including no tailpipe emissions and lower hydrocarbon, carbon monoxide and nitrogen oxide emissions. Power plants that produce electricity do pollute, but even when power plant emissions are included, electric vehicles are 90% cleaner than the cleanest conventional vehicle. They have lower fuel and maintenance costs than gasoline-powered vehicles, although the batteries must be replaced every four to six years

But electric vehicles have also disadvantages. The driving range of today's vehicles averages 80 to 120 miles, and current batteries take about six hours to recharge. The top speed of an EV is significant lower than an equivalent gasoline or diesel car, but more than adequate for city driving. Lack of infrastructure for recharging stations and the high price of EVs (they cost about $30.000) make electric vehicles too expensive for the most markets [II, VIII].

3.2 Hybrid vehicles

Hybrid electric vehicles (HEVs) combine the internal combustion engine and fuel tank of a conventional vehicle with the battery and electric motor of an electric vehicle, to obtain the benefits of both technologies. HEVs are powered by an energy conversion unit (such as combustion engines or fuel cell) and an energy storage device (such as batteries). The energy conversion unit may be powered by gasoline, methanol, CNG, hydrogen or other alternative fuels.

Hybrid electric vehicles have several advantages over conventional ones and fewer disadvantages than electric vehicles. All hybrids use regenerative braking, which means that energy is put back into the battery when braking, which improves energy efficiency and reduces brake wear. HEVs have higher fuel economy and lower emissions than vehicles with internal combustion engine and better range and more rapid refuelling than electric cars. Hybrid technologies improve fuel efficiency and therefore provide considerable fuel savings. Hybrid technology is a promising route principally to reduce CO_2 emissions, while also reducing air pollutant emissions. HEVs offer better air pollutant performance than the best gasoline and diesel vehicles [IX, XI]

Maintenance on hybrids should be equivalent to a conventional vehicle, but sometimes specialist diagnostic equipment is required to check the battery and motor. With regular maintenance the battery of a HEV should last the life time of the car Hybrids vehicles have the same performance of that of a gasoline vehicle although acceleration and top speed may be slightly lower. Nevertheless, HEVs are still expensive and not yet fully developed, which makes them unaffordable to most markets. Several programs are in place to develop and improve their performance, and in the future many automobile manufacturers will be marketing new models [II, VIII].

3.3 Fuel cell vehicles

Fuel cells vehicles operate by combining hydrogen and oxygen gases into an electrochemical device, a cell that converts them into water and electricity without using combustion. Fuel cells vehicles operating on pure hydrogen produced from renewable or other zero-carbon-emitting sources could be considered "zero-emission" vehicle, because if the fuel is hydrogen, only water is generated. When fuelled directly by pure hydrogen, fuel cell vehicles emit only heat and water vapour. As such, they are often considered to be the ideal sustainable transport solution.

However if the fuel cell vehicle is equipped with a reformer to produce the hydrogen from gasoline, diesel or methanol, HC and CO_2 emissions are likely to be around the same as for future advanced diesel vehicles. In that case, NO_x emissions are expected to be equivalent to the emissions produced by future gasoline vehicles [VI, XI].

Fuel cell vehicles can be pure or hybrid. The hybrid design incorporates the use of a battery for peak power loading. This also enables the vehicle to use regenerative braking which can reduce fuel consumption by up to 20%.

Pure or hybrid fuel cell vehicles have many advantages over conventional ones. They have a much greater conversion efficiency and fuel economy, drastically reduce pollution emissions (including greenhouse gas emissions) and use a wide variety of fuels, promoting energy diversity. In addition they are quilter and smoother in operation, have being tested at high performance level, have long driving ranges, and have about the same operating costs as conventional automobiles [VI].

Still, there are several drawbacks to fuel cell vehicles, including the lack of infrastructure to distribute hydrogen, difficult storage of pure hydrogen and possible safety concerns. Compressed hydrogen requires large storage tanks, which means that it is difficult to store sufficient quantities on board vehicles. However, it is likely that extremely high-pressure tanks or alternative storage methods will be introduced and will go a long way to resolving this problem. Another problem is that there is currently no hydrogen infrastructure to support the refuelling of vehicles. Another option is to use hydrogen-rich liquid such as methanol or reformulated petrol. While these liquid fuels do not require as much storage space on the vehicle, they must be processed onboard to obtain the hydrogen. This not only adds to the weight, cost and complexity of the vehicles, but also leads to carbon dioxide and other emissions.

Fuel cells are currently much more expensive to produce than conventional engines. The manufacturing costs need to fall by 10-20 times to be commercially viable. An enormous amount of research is currently being devoted to fuel call vehicles. Fuel cell technology for road vehicles is a promising technology with potentially high efficiency and low emissions. However large cost reductions need to occur and fuel infrastructure issues must be resolved before fuel cell vehicles are ready for the marketplace [II, IX].

3.4 Compressed Natural Gas (CNG) vehicles

CNG vehicles are powered by an abundant inexpensive fuel composed largely of methane. Natural gas is a clean-burning fuel with lower CO_2, CO, HC and NO_x emissions than gasoline. This is party due to the lower carbon context per unit of energy in natural gas relative to other fossil fuels. In addition to its environmental benefits CNG vehicles are cheaper to maintain, requiring service less frequently than conventional vehicles as well as having a lower cost of refuelling. Converting vehicles fleets such as taxis and buses to natural gas is an important interim way to improve air quality in developing counties. Conversion costs are relatively small, although baggage space is reduced because of the need to add pressurized tanks. However, it is hard to use CNG for private vehicles because of the need to create many fuelling stations [VI, XI].

4. Comparison of technologies and further discussion

Table III gives an overall estimation (overview) of the clean fuels discussed in this paper. Comparing pollutant emissions, GHG emissions and fuel costs can only lead to the fact that each technology has advantages and disadvantages. Improving the energy efficiency of today's vehicles, conventional and alternative will also play a significant role in the transport sector in the future.

According to Table III, alternative fuels appear to have higher octane numbers compared to gasoline (and biodiesel higher cetane number compared to diesel) which represent better anti-knocking, performance of the fuels, and therefore a longer lifetime of the engine. Energy content of clean fuels can vary significant [IV, XI].

Ozone-forming emissions (CO and NO_x) can be reduced (compared to gasoline) when using ethanol or methanol. CNG and LPG engine vehicles emit less NO_x in comparison to diesel engine cars, but emissions are roughly the same or more when compared to gasoline engines automobiles. Fuel cells operating on pure hydrogen emit no nitrogen oxides. However if gasoline, diesel or methanol is used to produce H_2; NO_x emissions are equivalent to the emissions produced by future gasoline vehicle.

On a well-to-wheel basis, compared to current technology vehicles, future advanced gasoline engines could achieve a CO_2 emission reduction of about 20%. Diesel engines could achieve a more moderate 15% reduction, but the reduction could be as much as 40-50% with hybridization of the diesel engine

	Gasoline	No.2 Diesel	Biodiesel	Ethanol (E85)	Methanol (M85)	Compressed Natural Gas (CNG)	Liquefied Petroleum Gas (LPG)	Hydrogen	Electricity
Chemical Structure	C_4 to C_{12}	C_{10} to C_{20}	Methyl esters of $C_{16} – C_{18}$ fatty acids	CH_3CH_2OH	CH_3OH	CH_4	C_3H_8	H_2	N/A
Main fuel source	Crude oil	Crude oil	oil of crops, oilseed rape, sunflowers, soybeans, animal fats or recycled cooking oil.	Starch crops, corn, wheat, agricultural waste	Natural gas, coal, woody biomass	Underground reserves	A by-product of petroleum refining or natural gas processing	Natural gas, electrolysis, and other energy sources (gasoline, diesel, methanol etc)	Coal, natural gas, and other renewable sources
Octane Number	86 to 94	8 to 15	~25	100	100	120+	104	130+	N/A
Cetane number	5 to 20	40 to 55	46 to 60	N/A	N/A	N/A	N/A	N/A	N/A
Energy content per litre	30,4 – 34,8 MJ/litre	35,6 – 36,3 MJ/litre	32,6 – 33,5 MJ/litre	~22,3 MJ/litre	15,6 – 18,4 MJ/litre	9,2 – 10,6 MJ/litre at 204 atm 10,6 – 12,3 MJ/litre at 245 atm	~23,4MJ/litre	31,5 – 37,4 MJ/litre	N/A
Physical state	Liquid	Liquid	Liquid	Liquid	Liquid	Compressed Gas	Liquid	Compressed Gas or Liquid	N/A
Environmental impacts of burning fuel (in comparison to gasoline and diesel)			Reduces PM and GHG emissions compared to conventional diesel, NO_x emissions may be increased.	Reduces GHG emissions by 20-80% and ozone-forming emissions (CO and NO_x) by 25% compared to reformulated gasoline	Causes 40% reduction in ozone-forming emissions (CO and NO_x) by 25% compared to reformulated gasoline	Reduces CO_2 emissions by 25% and PM by 95%, compared to gasoline. Reduces NO_x emissions by 80% and PM by 95% compared to diesel. HC emissions may be increased	Reduces CO_2 emissions by 10-15%, NO_x emissions may be increased, compared to gasoline. Causes 80% reduction in NO_x emissions and 95% reduction in PM, compared to diesel	Zero regulated emissions for fuel cells operating on pure H_2 CO_2 and NO_x emissions equivalent to gasoline, for internal combustion engines	Zero tailpipe emissions (some amount of emissions can be contributed to power generation
Fuel costs (in comparison to gasoline and diesel)			1.5 times more than No.2 diesel	More expensive to produce than gasoline	Prices comparable to gasoline	Less fuel costs of all fossil based fuels	30% less costs than gasoline	Very high costs for small scale production	Electricity less costs than gasoline

Table III Overview of clean fuels discussed in the paper [VI]

For biofuels, GHG emissions very much depend on the source of the biomass and its production method. Taking into account the energy required to produce the corps and then to process and distribute the fuel, it maybe possible to reduce CO_2 emissions by 30-60%, compared to vehicles fuelled with gasoline or diesel.

The level of CO_2 emissions, when considered a well-to-wheel basis, depends on the way the electricity is produced. When the main source is coal or gas, there are real no benefits compared to gasoline and diesel engine vehicles. When electricity comes form nuclear or renewable sources, such as photovoltaic or hydropower, electric vehicles can be considered as zero-emission vehicles.

Fuel cells powered with gasoline, diesel or methanol do not offer any advantages in terms of CO_2 emissions. However, if hydrogen is the fuel source and is produced by renewable sources, fuel cells offer the best performance in terms of GHG emissions

Different options and technologies have been presented and discussed. Nevertheless, no one can claim that there is an optimum solution on a global level [II].

Sustainable development is place specific. Sustainable is the "development that meets the needs of the present without compromising the ability of the future generations to meet their own needs" (source: World Commission on Environment, Our Common Future, 1987). In World Energy Assessment, [IX], sustainable development is described "as a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional change are all in harmony and enhance both current and future potentials to meet human needs and aspirations". This includes reliable and affordable energy services, continuity and quality of energy supply and a clear local and global environment for everyone. Resources should be produced and used in a manner that protects and preserves the local and global environment now and in the future. If clean fuels and alternative vehicles are to move towards a more sustainable energy development, then the optimum option of clean fuels is also place specific [VIII]

Countries such as Brazil and India hold the potential for relatively large biofuels production volumes. Ethanol is the primary automotive fuel in Brazil; it is produced from sugar cane at - compared to the situation in Europe- low costs. Ethanol accounts for 30% of gasoline demand and a high percentage of vehicles run on 100% ethanol (with adapted engines). Additionally ethanol is mixed at a rate of 22% to mineral oil based gasoline.

In Europe, the situation is quite inhomogeneous. Major biofuels capacity have been set up in Germany and France, followed by Italy, Spain and Czech Republic. Biofuels in Europe may technically achieve a market potential which is small, e.g. 5-15%, compared to fossil fuels, at least in the coming 20 years. On the contrary, many national and international programmes on hydrogen and fuel cell Research and Development (R&D) are well established in Europe as well as in the United States and Japan. Fuel cell technology is a promising technology in developed countries. In addition Programs on hydrogen R&D are already being developed in China and India.

Natural gas and LPG are the most accessible alternative fuels in the United States. In California there are several CNG and LPG stations as well as electric recharging stations, making the use of these alternative vehicles more popular [I, XI].

There are, however, a number of obstacles that have prevented non-petroleum fuels from playing a larger role in the transport sector, so far. These include lack of refuelling infrastructure, high fuel or vehicle costs, as well as issues regarding consumer acceptance of other vehicle attributes, such as range and refuelling time. Development of a clearer picture of the costs, benefits and challenges involved in different clean fuels towards a near-zero GHG emissions fuel system is essential. Expansions of R&D efforts with industry to further develop key technologies, such as vehicle on-board hydrogen and electricity storage could also help people to learn more about alternative vehicles [XII].

5. Conclusions

In a near-term focus it is likely that countries will still use oil to meet most of their needs in transport sector. Oil has played and will play an important role in the economy of developed and developing countries. In order to bring about an evolution toward a more sustainable transport system, including near-zero carbon emissions and non-petroleum fuels, a long-term focus has to be considered. Nevertheless, potential near-term actions could provide substantial benefits over the next few years, particularly in light of renewed concerns for energy security and diversity of energy supply.

In order to bring about an evolution toward a more sustainable transport system, including near-zero carbon emissions and non-petroleum fuels, a long-term focus has to be considered. Nevertheless, potential near-term actions could provide substantial benefits over the next few years, particularly in light of renewed concerns for energy security and diversity of energy supply.

Clean fuels and alternative vehicles discussed in this paper can address these concerns and, at the same time, minimise environmental damage and harm to human health. Secure energy supply is an on-going concern for many countries, which currently depend on oil imports from the Gulf to meet their energy demand in transportation. Secure energy supply for the countries would mean that exporters and importers have the same incentives, as far as imports of fuels are concerned.

One of the major current environmental concerns is the increasing GHG emissions from the use of petroleum fuels, with the transport sector being a major contributor. CO_2 emissions are thought to be responsible for changes in global climate, contributing to global warming. In addition, combustion of fossil fuels by conventional vehicles is one of the sources which are responsible for most smog and harmful particulates in the air, making air pollution a serious threat for people's health.

Clean fuels and alternative vehicles offer considerable promise to achieve oil savings, as well as major reductions of air pollutants and GHG emissions. There are however obstacles that have to be removed such as lack of refuelling infrastructure, high fuel or vehicle costs and the unwillingness of people to use new technologies in their automobiles.

In order to move towards a more sustainable transport system, one should bear in mind what the goals of sustainable development are: all people should have access to modern energy services and reliable energy supply, have the ability to pay for it (affordable energy supply) and live in a clean environment. Taking into account these goals, no optimum solution (option) can be suggested on a global level. Sustainable development is place specific. It is essential that resources are produced and used in a manner that protects and preserves the local and global environment now and in the future. If that means, producing and promoting biofuels in a country, in order to achieve energy security for this country, equal opportunities for everyone to buy and use this fuel and better environmental conditions, then biofuels is the "best" local option in this country.

This however is only a simple example. On the basis of present knowledge, it is possible and essential to produce and promote clean fuels and alternative vehicle technologies that meet sustainable development objectives at reasonable costs. Key technologies needed to bring about such a sustainable future in transport sector are fuel cells operating on hydrogen, hybrid and electric vehicles. Development of infrastructure, expansion of R&D and substantial cost reductions in clean fuels or/and vehicles will be critical in speeding the early adoption of alternative vehicle technologies.

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