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Fuel cells for transport: can the promise be fulfilled? Technical requirements and demands from customers

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Abstract

The paper discusses the technical requirements and the customer demands for vehicles that have an on-board methanol reformer and fuel cells. The research concentrates on the technical developmental risks which include minimizing volume, reducing weight and, at the same time, improving efficiency and system dynamics. Fuel cell powered vehicles with methanol reformers are not only suitable for a niche market but also these vehicles will compete with conventional vehicles. The greatest hindrance will be the price of the fuel cell. A possible progressive development of the number of fuel cell powered vehicles in conjunction with a reduction in costs will be discussed in the paper. When fuel cell vehicles come to the market it is necessary that an infrastructure for the fuel methanol or hydrogen is installed. Therefore, it will only be possible to introduce fuel cell vehicles into special markets, e.g. California. Such a process will need to be subsidized by additional incentives like tax concessions. Today there are many technical risks and unsolved problems relating to production technologies, infrastructure, and costs. Nevertheless, among the alternative power units, the fuel cell seems to be the only one that might be competitive to the conventional power unit, especially relating to emissions.

Keywords: Fuel cells; Transport systems; Emissions

1. Introduction

The high standard of living in industrial countries and the resulting energy consumption leads to increasing negative effects on environmental conditions. As with energy consumption, transportation demands in the industrial and private sectors have increased to satisfy the population's needs and activities. In turn, the following negative factors have resulted: natural resources are being exhausted and emissions are polluting the environment. Therefore, the main emphasis in automobile research is to reduce both emissions and fuel consumption. Additionally, CO_2 emissions, which contribute to the greenhouse effect, increase in proportion to energy consumption. Through constant improvements to both conventional gas and diesel vehicles these negative effects can be greatly reduced.

A different challenge for the automobile industry is the proposed tough California vehicle legislation which demands 'zero-emission vehicles' (ZEV). Presently, the only vehicles that meet the ZEV standards are battery-powered electric vehicles. However, fuel cell vehicles could be an alternative to battery-powered electric vehicles. Fuel cells have the necessary development potential to become the future environmental vehicle propulsion system.

Customer's acceptance will be essential for the introduction of an alternative drive train system, like a fuel cell system. In order to accomplish this new vehicles must operate and function at least as well as conventional ones. To make fuel cell drive systems possible in the future customer demands and technical requirements must both be considered.

2. Mobility, environmental protection and resources

Mobility is a positive element of Society and the individuals therein. Mobility increases the productivity of both work and leisure time. Mobility provides more. It facilitates the arrival of goods and information to the right place at the appropriate time. In short: mobility is an essential requirement for prosperity, job security and social acceptance.

At the same time, mobility has consequences. Along with many other factors, the increased use of vehicles is burdening our environment. Since 1950, the number of vehicles on the roads has continued to increase. Fig. 1 shows an increase of 17 million vehicles per annum during this period [1]. It is commonly expected that this trend will not diminish in the next decades.

Presently, there are 500 million automobiles and almost 170 million commercial vehicles in the world. It is predicted

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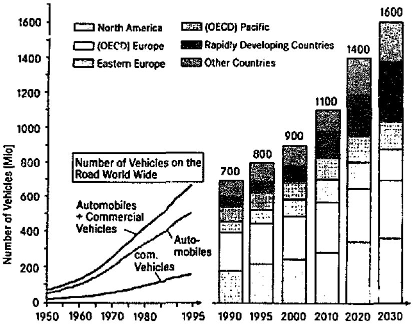


Source: AAMA World Motor Vehicle Data 1994 Edition:
European Conference of Ministers of Transport: Transport Policy and Global Warming 1993

Fig. 1. Current and predicted number of vehicles on the road, world wilde.

that in 2030 there will be approximately 1.6 billion vehicles on the roads. The causes of this increase are twofold. First, the general demand for mobility is increasing. Second, the global demand for vehicles is increasing with the rapid development of countries in Asia and Latin America. The increase in the total number of vehicles in existence worldwide has serious consequences for the supply of natural resources and for the amount of emissions polluting the environment. Through continually improving vehicles with conventional gas and diesel engines, improving traffic management systems, and developing and introducing alternative drive systems the effects of vehicles on these problems can be reduced. These solutions not only address the resource problems, local pollutants, and noise pollution, but also global emissions.

If resources are to be saved only by improving the internal-combustion engine (ICE) then virtually all road vehicles will depend on one type of energy source — petroleum-based fuels. The availability of this energy source, calculated by dividing the known reservoirs by the present annual consumption, is approximately 43 years. During the 1973–1974 energy crisis the availability was believed to be far less; this was the reason for the considerable concern and for the large increase in oil prices [1]. Fig. 2 shows the reserves of various fossil energy sources including oil, natural gas and coal. It can be seen that the estimated primary energy resources far exceeds the definite known reserve [2]. For further analysis of the supply, one must realize that it is possible to use both natural gas and synthetic fuel, converted from coal, in conventional vehicles.

For several years, increasing energy consumption and CO_2 emission has been more important than the availability of energy resources. This is because CO_2 emissions contribute to the greenhouse effect.

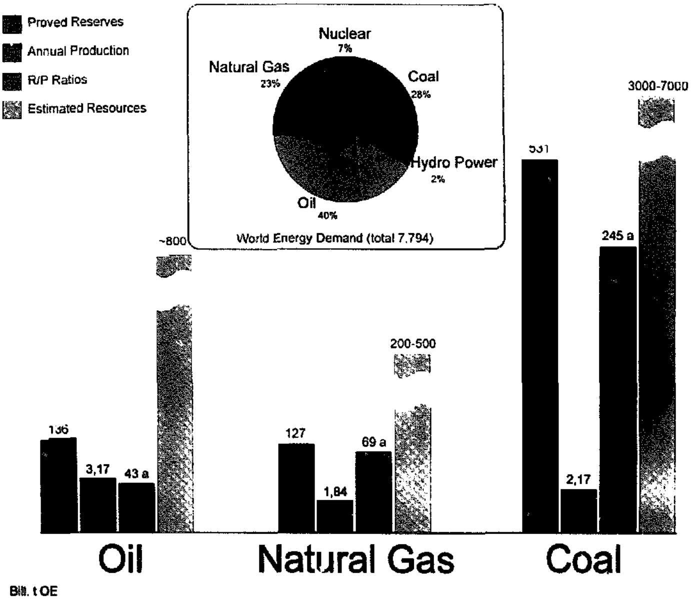
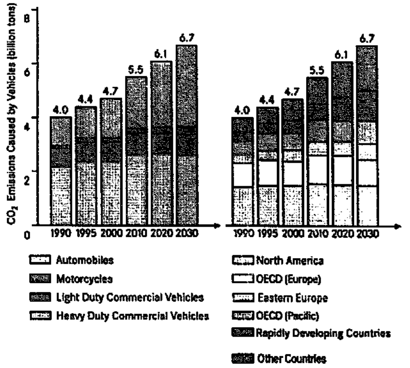


Fig. 2. World energy statistics, 1993: reserves of various fossil energy sources (source: BP, Shell, DIW).



Source: European Conference of Ministers of Transport: Transport Policy and Global Warming 1993

Fig. 3. CO_2 emissions caused by road vehicles.

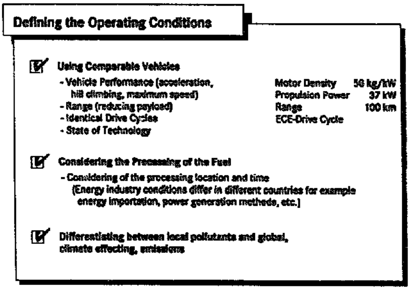
Fig. 3 shows the amount that road vehicles contribute to CO_2 emissions. It is predicted that CO_2 emissions will reach 6.7 billion tons by the year 2030. The regional division, shown on the right side of Fig. 3, indicates that there will not be any reduction in emission levels from industrialized countries and there will be an increase in levels in developing nations [1].

It is clear that the desires and needs for mobility, the need for a reduction of energy consumption and the need for lower CO_2 levels are on a collision course. The automobile industry is searching, through new and innovative techniques, for solutions that will avoid this collision.

3. Efficiency and emissions of vehicle propulsion systems

Fuel cell technology could possibly alleviate the conflict between the increasing demand for mobility and, at the same time, the desire to reduce energy consumption. In comparison to conventional engines, fuel cells have higher efficiencies, lower energy requirements and less CO_2 emissions. The following comparison between conventional and alternative propulsion systems, including the fuel production process, is presented in order to illustrate this.

In order to have an objective analysis, the operating conditions for the energy and emissions comparison must be clearly defined, as shown in Fig. 4 [2]. Vehicles with identical characteristics must be compared; for example, they must have the same acceleration and maximum velocity. The motor power density that is used is 50 kW/kg; therefore, the 1850 kg vehicles chosen have a driving power of 37 kW. In order for vehicles with alternative drive systems to meet the same range requirements as conventional ones, some of their propulsion or energy storage systems are heavier. This extra weight reduces the payload of the compared vehicles. The comparison simulation consists of 100 km driven in the pattern dictated by the ECE Drive Cycle.



Defining the Operating Conditions

☑ **Using Comparable Vehicles**
- Vehicle Performance (acceleration, hill climbing, maximum speed)
- Range (reducing payload)
- Identical Drive Cycles
- State of Technology

Motor Density	56 kg/kW
Propulsion Power	37 kW
Range	100 km
ECE-Drive Cycle	

☑ **Considering the Processing of the Fuel**
- Considering of the processing location and time (Energy industry conditions differ in different countries for example energy importation, power generation methods, etc.)

☑ **Differentiating between local pollutants and global, climate effecting, emissions**

Fig. 4. Operating conditions for an energy and emission comparison.

Since fuel cell drive trains use new advanced technologies, they require 10 to 15 years of development before they can be efficiently mass produced. Therefore, to facilitate a fair comparison, the development potential of conventional engines in the interim must also be considered. It is estimated that, in the next 10 to 15 years the gas and diesel ICEs will improve by 20 and 15%, respectively. The comparison not only includes the vehicle, but also the processing of the fuel. The differences between locally harmful pollutants and globally damaging emissions are also shown.

The different types of vehicle tested in the simulation are: gasoline (ICE), direct injection (DI)-diesel ICE, natural gas ICE, hydrogen ICE, hydrogen fuel cell, methanol fuel cell, electric vehicle with $NaNiCl_2$ batteries and electric vehicle with NiCd batteries. Various input parameters of the different drive systems are required by the simulation, for example: power density, efficiency functions, and efficiency tables.

Fig. 5 shows the mass analysis of the various types of vehicle simulated. From this figure it can be seen that alternative drive systems are much heavier than conventional ones. This is because the propulsion and storage sub-systems must be larger to meet the same driving performance.

In addition to the defined operating conditions, the comparison calculations are done including two passengers. Fig. 5 shows the energy consumption of the different vehicles. The figure not only includes the energy used in driving the vehicle, but also the energy required during fuel processing. Hence, this figure represents the energy required from the primary source through to the vehicle. The diagram shows that both electric and fuel cell vehicles require far less energy in the vehicle because of their inherently higher efficiencies than ICEs. However, Fig. 6 also shows that the energy required to produce electricity, hydrogen or methanol is greater than the energy required to produce gasoline or diesel. When comparing the combined energy requirements, the hydrogen fuel cell vehicle consumes less energy than the gasoline vehicle. The methanol fuel cell vehicle consumes

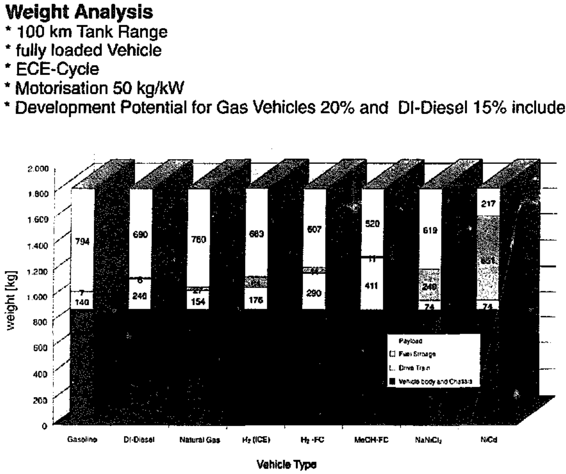


Fig. 5. Mass analysis of alternative power trains.

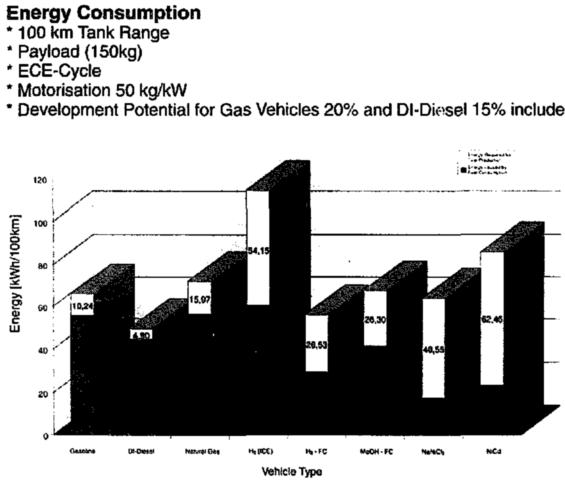


Fig. 6. Energy consumption of different vehicles.

approximately the same. However, the vehicle that uses the least amount of energy overall is the DI-diesel ICE.

In the comparison of the total CO_2 emissions, see Fig. 7, the most environmental-friendly vehicle is the hydrogen fuel cell vehicle which is slightly better than the DI-diesel ICE. The methanol fuel cell vehicle also attains approximately the same level of emissions as the DI-diesel ICE. Fuel cell drive trains are at least as good as, if not better, than ICEs when considering the total CO_2 emissions expelled during the complete energy conversion process.

The unfavorable primary process, the production of hydrogen and methanol, causes fuel cell drive trains to be only slightly better than those based on internal combustion (IC). This drawback can be counterbalanced when regenerative

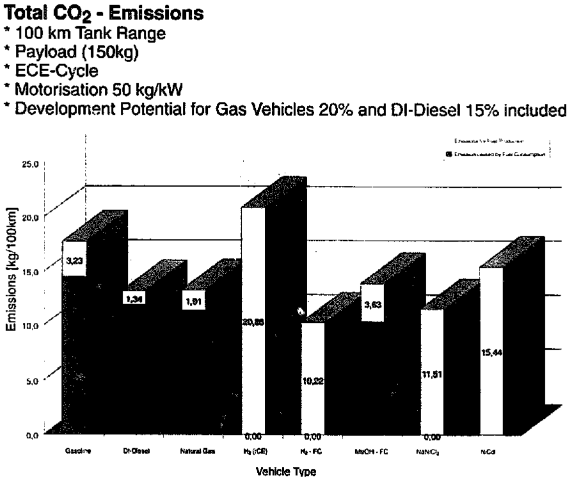


Fig. 7. Total CO_2 emissions for different vehicles.

energy processes are used to generate the methanol and hydrogen. Hence, in the future, when more favorable methods than the current natural gas based methods are used, the advantage that fuel cell power trains have over ICEs will increase.

Fuel cell propulsion systems have a major disadvantage when compared with ICEs: their power density is several times worse. Therefore, the energy efficiency advantage that fuel cells posses cannot be fully utilized. For this reason, a development goal for fuel cell systems is to improve the power density.

Without dispute, the clean emissions of fuel cell propulsion systems give them a large consumer advantage. A fuel cell system that uses hydrogen as a fuel is classified as a 'zero-emission vehicle', while a system using methanol has low CO, no NO_x and no unburned hydrocarbon emissions.

4. Fuel cell technology and fields of application

There are five different categories of fuel cell: alkaline (AFC), proton-exchange membrane (PEM-FC), phosphoric acid (PAFC), molten carbonate (MCFC) and solid oxide (SOFC). Fig. 8 shows the electrolyte used, the operating temperature range and special features for the various fuel cell types [3]. The high temperature fuel cells such as MCFCs and SOFCs are predominantly used for both the centralized and the decentralized utility power generation applications. The high operating temperatures of these fuel cells allow them to be directly used with different fuels, e.g. natural gas. PAFCs will soon be commercially available for decentralized power generation in small 200 kW units. There are also PAFC power plants in Japan capable of generating power in the MW range. This is the type of fuel cell used in the 'DOE-Bus' (US Department of Energy) in combination with a methanol reformation system [6]. Due to the limited efficiency and the long temperature-dependent warm-up time this type of fuel cell is not suitable for vehicle applications.

Low-temperature alkaline fuel cells, despite their high efficiencies, are also not suitable for vehicle applications because of their highly corrosive electrolyte, inability to handle CO_2, and the fact that they can only function with pure hydrogen and oxygen.

The other low-temperature fuel cell, the PEM-FC, has a solid electrolyte. This sulfanated fluorocarbon electrolyte

FC-Type	Electrolyte	Operating temperature [°C]	Special features
AFC	diluted potassium hydroxide solution	60 - 120	CO2 - incompatible high efficiency for pure H2/O2
PEM-FC	proton exchange membrane	20 - 120	precious metal catalyst high power density
PAFC	phosphoric acid	160 - 220	limited efficiency prototype plants with MW - power range
MCFC	molten carbonates	600 - 650	corrosion problems internal reforming possible
SOFC	solid zirconium dioxide	850 - 1000	ceramic technology required direct fuel conversion eg. methane

Fig. 8. Comparison of the electrolyte used in different fuel cells.

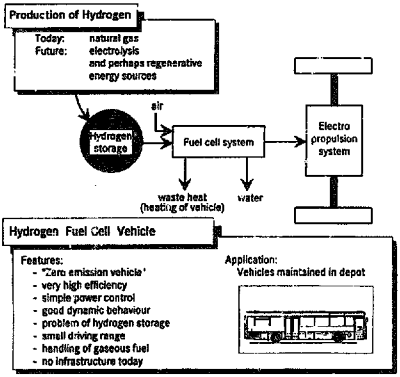


Fig. 9. Function principle with hydrogen as fuel.

proton-exchange membrane (PEM), looks similar to a sheet of transparent paper and is the key component of this type of fuel cell. The working temperature of these fuel cells is easily attainable in vehicles. This fuel cell type requires a precious metal catalyst, which has an effect on the cost. The PEM-FC has a high power density potential. In addition, these cells operate with air. It is for these reasons that PEM-FCs are best suited for vehicle applications.

An interesting possibility, perhaps for the next generation of PEM-FCs fuel cells, is the 'direct methanol fuel cell' (DMFC). This type of system functions using methanol, instead of hydrogen, directly, therefore eliminating the need for an on-board reformer. There has yet to be a stack or system that utilizes this technology. The first laboratory results have recently been collected from an individual DMFC; however, there are still many technical problems that need to be solved before such a system is viable [4].

One must consider which operating fuel, hydrogen or methanol, is most suitable for PEM-FC vehicle applications. Two positive characteristics of fuel cell vehicles using hydrogen as fuel are high efficiency and zero emissions [3]. Power control and dynamic behavior of fuel cells allow a direct coupling of current generation and electric power train without the use of any buffer batteries (Fig. 9). The problem with the application is storing hydrogen on-board the vehicle. Storing hydrogen in pressure tanks is voluminous, chemical storage in metal hydrides is too heavy and liquid storage loses one third of the original energy during liquefaction. Furthermore, the driving range is limited. The driver is unaccustomed to handling a gaseous fuel and presently, there is no infrastructure for hydrogen.

However, fuel cell vehicles, using hydrogen as a fuel, could still be the first to penetrate the market. Hydrogen fuel cell systems are not as complex or as expensive as systems with an on-board reformer. The first application of hydrogen fuel cells will be in fleet vehicles, like commuter buses or public urban vehicles.

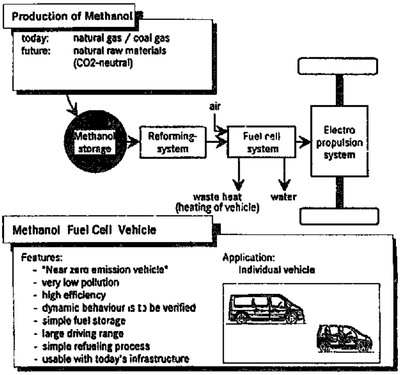


Fig. 10. Function principle with methanol as fuel.

For fuel cells to be used in personal vehicles, a liquid fuel must be used because of its inherently high energy density. A fuel that meets this requirement is methanol [3]. The principle of a fuel cell system using an on-board methanol reformer is shown in Fig. 10. Furthermore, this type of propulsion system has higher efficiency and less CO_2 emissions than the conventional ICE and most importantly, hardly any pollutants. A vehicle with a methanol fuel cell power train can be classified as a 'near zero-emission vehicle'.

The method of storing methanol on board a vehicle is simple and comparable to conventional vehicles. By using methanol, the fuel cell vehicle is able to attain the same range as IC vehicles. The customers are familiar with liquid fuels. An infrastructure for methanol is comparable to the present gasoline infrastructure. Presently, methanol is produced from natural gas. In the future, it could be possible to produce methanol from biomass. This process would have a closed CO_2 cycle.

The functionality of fuel cells in vehicles has been shown through various demonstration projects. Fig. 11 shows the best known examples: Ballard Power Systems' Bus [5], H-Power Corporation's DOE-Bus [6] and Daimler–Benz's Minivan [3].

Fig. 12 contains the important vehicle characteristics of the three prototype fuel cell vehicles. The Ballard bus uses a hydrogen-based PEM-FC system. The system provides electrical energy directly to the drive system upon demand. The DOE-Bus power train combines PAFCs and a methanol reformer. The system has approximately 50 kW of power. This low-power level requires the system to use buffer batteries for peak load conditions. However, the system's 15 to 20 min warm-up time is a major disadvantage: PEM-FC systems are able to start immediately. The fuel cell systems of both buses occupy a substantial portion of the rear of the bus. Therefore the passenger capacities of both buses are reduced.

Daimler–Benz's minivan operates with PEM-stacks from Ballard Power Systems. The complete system occupies a

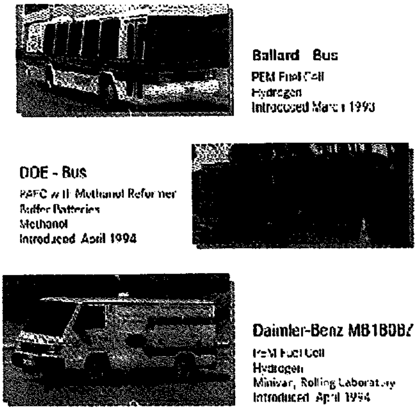


Fig. 11. Fuel cell powered vehicles.

large portion of the vehicle's rear compartment. Daimler–Benz considers this vehicle to be a rolling laboratory, from which it can gain experience in fuel cell system applications, design and controlling.

All three vehicles show that fuel cell systems occupy too much of the vehicle's capacity. For this reason fuel cell system density must be increased. The bus demonstrations have the goal of first attaining market penetration in centrally maintained fleet vehicle applications. To attain this goal, the US DOE plans to test new buses, with improved PAFC systems, in various major US cities, while Ballard's strategy is to implement Phase 2 of its fuel cell bus project. In this phase, a 40 ft fuel cell bus will be built and tested. The fuel cells in this bus [illegible] twice the power density and therefore the system only requires the same engine compartment as a conventional bus.

	Ballard- Bus Phase 1	DOE - Bus	MB180B2
Fuel Cells	PEM, MK5, Ballard	PAFC, Fuji Electric	PEM, Mk5, Ballard
Stack Configuration	3 x 8	1	2 x 6
Mass of System	2820 kg	2270 kg	840 kg
Volume of System	ca 8 m^3	?	1,3 m^3
Voltage Rang	160 - 280 VDC	120 - 140 VDC	130 - 230 VDC
Total FC Power	104 kW	50 kW	50 kW
Net FC Power	75 kW	48 kW	40 kW
Mech. Propulsion Power	ca 55 kW (Continuos)	75 kW (Continuos) 120 kW (Peak)	30 kW (Continuos)
Motor	DC - Motor	DC - Motor	AC - Motor
Transmission	3 - Speed Automatic	-	5 - Speed Standard
Methanol Reformer	-	Fa. Fuji	-
Buffer Battery	-	NiCd (Saft), 216 V, 200Ah	-
Vehicle	Cruise Bus 30'	Cruise Bus 30'	Minivan
Capacity	20	25	2
Velocity	70 km/h	90 km/h	80 km/h
Rang	165 km	240 - 320 km	130 km
Fuel	Hydrogen, 200 bar	Methanol-Water Mix.	Hydrogen, 300bar
Starting Time	immediate	15 - 20 min	immediate

Fig. 12. Comparison of fuel cell powered vehicles.

City buses are a good way for the introduction of fuel cells onto the market. However, individual vehicles, like minivans or more compact vehicles, are also a platform for fuel cell propulsion systems. For these vehicle applications, Daimler–Benz is working, in cooperation with Ballard Power Systems, on their high density stacks. These new stacks will have three to four times the power density of the present stacks.

5. Consumer and technical demands of fuel cell drive systems

In order for an alternative power train, like a fuel cell system with an on-board methanol reformer, to become popular and accepted by consumers:

(i) values of primary energy conversion and emission behavior must be better than those of the conventional ICE

(ii) legal requirements (ultra low-emission vehicles (ULEV), zero-emission vehicles (ZEV)) must be fulfilled, as well as the economical and technical demands

These demands for future vehicles and the expectations of the customers can be shown in the utilization spectrum of the vehicle. The conventional vehicle is often used for driving to work, into town and for leisure-time activities. The different necessary functions must be fulfilled in the best possible way. The consumer expects the vehicle to be multi-purpose. Customers have a high social acceptance for vehicles that are environmental-friendly. At the present time, these widespread consumer wishes cannot be fulfilled by a single type of propulsion system. There is a big contrast between small, light vehicles with a large range and local, emission-free vehicles, i.e. electric drive train vehicles.

These diverse customer wishes are shown in Fig. 13 as requirements for future power trains [7]. Energy sources must be preserved by using economical drive trains. Customers demand a cleaner, pollutant-free power train. The drive

Requirements for the Propulsion System

- economical propulsion, low fuel consumption
- clean operation, no emissions
- light weight
- small volume
- power unit must not compromise the function and use of the vehicle
- adaptable performance characteristics
- automobile-specific external parameters
- simple operation
- large operating range
- short refuelling time
- high degree of availability and reliability
- maintenance-free
- safety
- no price premium for expensive power unit technology

Fig. 13. Requirements for future power trains.

train's installation must not impair the functionality of a vehicle. It is just as inconceivable for a commuter bus to have a reduced transportation capacity as for a personal vehicle to sacrifice part of its trunk to accommodate a bulky power train.

It is important for any new drive concept that the performance of the power unit should be easily changeable and adaptable, whether for cars, for vans or for regular service buses. This requirement can no doubt be met by a modular fuel cell arrangement consisting of individual fuel cell stacks.

The parameters which are specific to automobiles make matters much more difficult. A fuel cell power unit must function perfectly both at very low temperatures (down to −30 °C) and at very high temperatures (up to +60 °C). For example, the distilled water required to moisturize the gases in PEM-FCs should not become frozen, i.e. the principle of gas moisturization must also function without cell damage using frost-protected water. Its thermal efficiency must not break down when subjected to a high ambient temperature or heavy loads. Furthermore, the power unit is subject to vibrations and knocks in a vehicle.

Since conventional vehicles set standards in terms of operability, fuel cell vehicles should not deviate from these norms. A vehicle user is already accustomed to a certain operating range on one fuel tank and fairly brief stops for refueling. The customer also expects to be able to use the vehicle at any time, therefore a pre-heating period for a fuel cell power unit could only be an acceptable compromise for centrally-maintained city buses.

Further requirements for fuel cell power units arise from the normal operating conditions of vehicles. Such operating conditions include starting the 'engine', driving off from standstill, accelerating, decelerating, normal driving operations and parking. Some of these requirements for vehicle operations may seem trivial at first glance. However, for such a complex propulsion system consisting of a methanol reformer, fuel cell and electric motor, each part of the system and its relationship with all the others must be thoroughly examined and tested with regard to these requirements. Customers know the capabilities of a conventional vehicle and this standard will also be applied to the fuel cell vehicle.

6. Cost requirements of fuel cell drive systems

Not only must all of the technical demands of fuel cell systems be fulfilled for fuel cell vehicles to reach the market, but also many other factors must be achieved. An essential factor is the cost of the system. For fuel cell systems to have a real chance in the competitive automobile market their cost must be comparable to conventional IC driven trains. Therefore, the design of the system, without compromising performance, but with mass production techniques, must reach a lower price. For this reason, it is necessary to know how, and in what quantities and price, future fuel cells will be developed. Fig. 14 shows Daimler-Benz's, along with Siemens' and General Motors', prediction for future fuel cell costs and production levels.

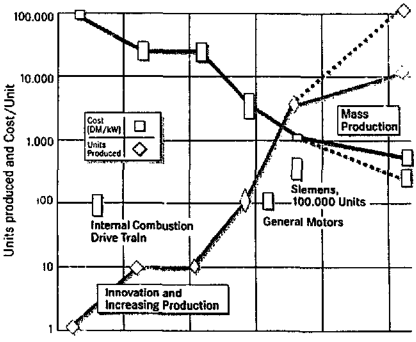
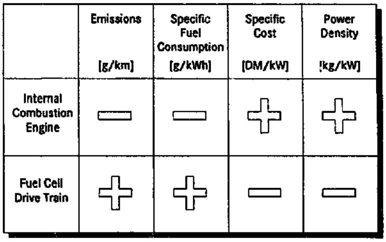


Fig. 14. Cost and unit production PEM fuel cell system.

The specific cost of PEM-FCs, during the present prototype demonstration period, is approximately 80 000 to 100 000 DM/kW. 1997–1998 will mark the beginning of a more intensive fuel cell test phase and then more automobile manufactures will start researching development techniques. Small production runs combined with improved manufacturing techniques can reduce the specific costs to approximately half the present levels. By the year 2003, when the first vehicle fleets will be operational, it is predicted that the specific costs will be reduced by a factor of ten. Between 2003 and 2005, Siemens also predicts a large increase in fuel cell production — hence, a significant improvement in specific costs. Siemens states that it should be possible to produce 100 000 units at a specific cost of 300 to 500 DM/kW. Daimler–Benz's forecasts are not so optimistic, they assume a more gradual market introduction with special and niche market applications as in California. Costs are predicted to fall in proportion to increases in unit demand. Hence, a specific cost of between 600 and 700 DM/kW is estimated for the year 2010. However, if further government regulations are implemented the unit production might be higher. In this case, Daimler–Benz predicts, with an annual production of 100 000 units in 2010, the specific fuel cell system costs will be 200 to 400 DM/kW. This value is comparable with Siemens' estimates for 2005.

One General Motors' study, based on a high unit production, states that it is possible to produce fuel cell systems with a specific cost of 100–110 DM/kW. This estimate is very optimistic and prices a fuel cell system at about the same specific cost as a conventional IC drive train. However, according to current statements from Daimler–Benz researchers, without considering possible developmental breakthroughs, in 10–15 years a fuel cell propulsion system will cost two to four times as much as a today's IC drive train [1].



	Emissions [g/km]	Specific Fuel Consumption [g/kWh]	Specific Cost [DM/kW]	Power Density [kg/kW]
Internal Combustion Engine	−	−	+	+
Fuel Cell Drive Train	+	+	−	−

Fig. 15. Comparison of important vehicle characteristics between combustion and fuel cell drive system.

7. Conclusion and future goals

Fig. 15 shows a comparison of important vehicle characteristics between combustion and fuel cell drive systems. From this figure it can be seen that conventional drive systems are superior in both cost and power density. However, IC drive trains have not reached their potential in both specific fuel consumption and emissions.

Fuel cells have an undisputed advantage concerning their emissions. They do not release any pollutants into the atmosphere. Even when one considers the primary energy conversion process of a methanol-based fuel cell system, the CO_2 emissions are still less than a conventional IC vehicle. In addition, with future fuel cell system density, the overall efficiency of the system is higher which gives fuel cell systems a specific fuel consumption advantage.

R&D to date shows that fuel cell drive trains have the potential to be the propulsion system of the future. Naturally, reducing the number and size of system components as well as increasing the power density of the fuel cell system are of paramount importance. Later, the complete system, including the on-board methanol reformer, must be optimized in the areas of efficiency and dynamics.

Although all of the technical developments of a fuel cell system must be achieved before fuel cells are introduced into the market, there are other important factors that also need to be resolved. As mentioned previously, cost is the essential factor in bringing fuel cells to the market. For fuel cells to have a chance of penetrating the market, a fuel cell power train must be comparable in cost with a conventional IC power train. For this reason, the system design must be cost-effective based on large-scale production techniques.

Even if the fuel cell vehicle is technically superior, its success still depends on the refueling infrastructure. The fuel type for fuel cell vehicles to best penetrate the market, whether it be hydrogen or methanol, is still under discussion.

Continued improvements of both the costs and the production techniques are of critical importance for the success of the fuel cell vehicle. In comparison with these obstacles, it is easier to solve the technical problems associated with fuel cell systems. Even though this is an enormous task. The fuel cell has the developmental potential, technically and environmentally, to become the power train of the future.

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