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Fuel cells for road transportation purposes — yes or no?

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Abstract

The issues surrounding the application of fuel cells for road transportation are evaluated. The advantages and disadvantages of the candidate fuel-cell systems and the various fuels are discussed, together with the issue of whether the fuel should be converted directly in the fuel cell or should be first converted to hydrogen on-board the vehicle. Developments in competing vehicles technologies, namely, internal-combustion-engined vehicles (ICEVs), pure-battery vehicles (EVs) and ICE–battery hybrid vehicles (HEVs) are reviewed. Finally, the impact of the introduction of fuel-cell vehicles (FCVs) on industry, and in particular on the oil and automotive industries, is examined. For FCVs to compete successfully with conventional ICEVs, it is concluded that direct-conversion fuel cells — using probably hydrogen, but possibly methanol — are the only realistic contenders for road transportation applications. © 2001 Elsevier Science B.V. All rights reserved.

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1. More efficient, cleaner road transportation

The possibility of replacing the internal combustion engine (ICE) used in road vehicles with more efficient, low emission, alternative power sources has been considered since the 1960s. From that time, it has been widely advocated that the fuel cell is the power source which is best capable of emulating the ICE. This view is still strongly supported today.

The fuel cell was invented in 1839 by Sir William Grove [1] and by the turn of the 19th century, renowned scientists such as Wilhelm Ostwald were predicting the replacement of heat engines by fuel cells because of the latter's much higher efficiency compared with the Carnot-cycle limitation of heat engines [2]. As we now know, however, this prediction was never realised and the ICE vehicle (ICEV) running on cheap petroleum-based fuel dominated the road transportation sector during the whole of the 20th century.

There have been periodic 'renaissances' of fuel-cell technology for both road transportation and stationary applications during the 20th century, especially in the 1950s and 1960s when concern over the deterioration of urban air quality in industrialised countries made the clean emissions of fuel cells an attractive proposition. In the 1970s, a perceived shortage of oil (the so-called 'energy crisis') promoted the highly efficient fuel cell as a likely replacement for the ICE in road transportation. Unfortunately, in all three of those decades, the extremely high cost of the fuel-cell system compared with that of the ICE ruled out any likelihood of realistic competition from vehicles powered by fuel cells.

During the 1990s and up to the present, grave concern has arisen over the global sustainability of road transportation in terms of the adverse environmental impacts of the ICE and the continuity of petroleum supplies. As a consequence, there has been another resurgence of interest in the application of fuel cells in road vehicles, particularly in cars and buses. This time, however, there appear to be better prospects for commercial success. In celebration of the 100th volume of the *Journal of Power Sources* — an international forum on the science and technology of electrochemical energy systems — we review these prospects and offer an opinion on whether the fuel cell, after so many failed promises, will triumph over the ICE.

2. History of fuel cells and their use in road transportation

Following Grove's invention, the fuel cell continued to be a topic of scientific interest throughout the remainder of the 19th century. Regrettably, the research was performed in the absence of any true understanding of the kinetic limitations of electrochemical processes that cause the electrical output of the device to be less than ideal. For example, the fact that

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the presence of electrocatalysts improves the performance of the fuel cells was not recognised until early in the 20th century. Thus, the thermal path for power generation was chosen rather than the electrochemical path, and so it has remained up to the present day.

Sporadic work took place on fuel cells up until the 1930s, but there was no development of properly engineered and practical power units. The seminal step forward was provided by F.T. Bacon in the UK who pioneered the use of an engineering approach to the design and construction of fuel-cell stacks. His efforts led to Pratt and Whitney — now United Technologies Corporation (UTC) — producing 'alkaline fuel-cell' (AFC) technology for the US NASA space programme in the early 1960s. Bacon-type alkaline cells delivered power for all the life-support systems on-board the Apollo spacecraft, which took the first man to the moon. Fuel cells were also employed in the earlier US Gemini series of earth-orbiting missions and were of the ion-exchange membrane type (using Nafion® polymer electrolyte) developed by General Electric. Today, this design is generically known as the 'proton exchange membrane fuel cell' (PEMFC). (Note, other acronyms such as 'solid polymer electrolyte' (SPE) have been used to signify this type of cell, but the term PEMFC is the most preferred.) As a result of the success of the US space programme (where the high costs of fuel cells could be accepted), research into fuel cells intensified world-wide in the 1960s and 1970s. Some of the companies involved during that period were: Engelhard Corporation, General Electric, General Motors, Union Carbide, UTC and Westinghouse in the USA; Energy Conversion and Shell Research Limited in the UK; AEG Telefunken, Siemens and Varta, in Germany; Exxon/Alsthom in France.

Virtually, every possible type of fuel cell was investigated, both 'direct' and 'indirect' systems, and a wide range of fuels were used. Direct systems are those where the fuel, e.g. hydrogen or methanol, is directly converted in the fuel cell. Indirect systems are those where the fuel, e.g. gasoline, is first processed to hydrogen in a fuel processor prior to conversion in the fuel cell. During the 1960s and 1970s, Shell in the UK and Exxon/Alsthom in France attempted to develop direct, liquid-fuelled, units for road transportation. The principles of such technology were demonstrated by Shell [3] in a DAF 44 passenger car which was powered by a fuel cell that operated on hydrazine. The 'direct methanol fuel cell' (DMFC) attracted much attention because methanol, being a liquid, was considered to be the fuel which was most compatible with the conventional infrastructure of road transportation. Unfortunately, the direct electrochemical conversion of methanol requires very efficient electrocatalysts, and although considerable progress was made, the commercial performance target for these materials was unattainable at acceptable cost. (For a detailed review of DMFCs, see [4].) This is still the situation today for DMFC-powered vehicles. There were other vehicles powered by fuel cells in Europe and the USA, notably the Austin A40 demonstrated by Kordesch [5] which employed a direct hydrogen AFC. Despite these efforts, however, no commercially viable systems emerged.

Thus, during the 1970s and early 1980s, most companies either abandoned or scaled back their fuel-cell programmes. An exception to this was UTC which was pursuing the development of a system, principally for stationary applications, that operated at medium temperature (200°C) and used a phosphoric acid electrolyte. This effort has continued up to the present day, through International Fuel Cells (IFC), a subsidiary of UTC. It is now possible to purchase a 250 kW unit, a so-called 'PC25 unit'. In fact, throughout the world, there is a multimegawatt-installed capacity of PC25 fuel cells, even though the cost of the individual unit is still significantly higher than that of an equivalent, conventional power source. Recently, the 'phosphoric acid fuel cell' (PAFC) has also been considered as a power source for buses, e.g. the Georgetown University bus [6]. A number of other successful trials with fuel-cell powered buses have been carried out world-wide in major cities, most notably by DaimlerChrysler with the *Nebus* which uses PEMFC technology.

The renewed interest in fuel cells for road transportation during the 1990s has been stimulated by the efforts of Ballard Power Corporation, a Canadian company based in Vancouver, who have revived the PEMFC, which, as mentioned above, was originally introduced by General Electric. From published data [7], Ballard appear to have made dramatic progress in improving the performance of PEMFCs which use hydrogen as a fuel. In recent years, the company has formed a number of alliances with automobile manufacturers, in particular DaimlerChrysler and Ford, and also with both chemical and oil companies. The IFC organisation has also turned its attention to fuel cells for road transportation, and is working with PEM-based systems but, unlike Ballard, has developed technology which operates at ambient pressure. It should be understood that a number of factors may limit the acceptability of PEMFCs. Specifically, charge transfer is by way of hydronium ions for which the incoming fuel (hydrogen or methanol) must be humidified. If humidification fails and the whole cell dries out, then catastrophic failure results due to loss of electrolytic conductivity. Further, if any heavy metal ions, such as iron, are present in the added water, they may replace hydrogen ions in the membrane and again degrade its electrolytic conductivity. The use of an aqueous electrolyte can avoid such problems.

As a result of the above activities, the automobile manufacturers, the fuel-supply industry and the fuel-cell industry are, for the first time, working together on the advancement of fuel cells for road transportation. For example, General Motors, Toyota and Exxon are collaborating on the choice of suitable fuels. These companies have reached a unanimous conclusion that pure hydrogen is the ultimate fuel, but argue that a hydrocarbon fuel which is compatible with both the ICE and fuel cells is necessary to bridge the gap between now and the establishment of a widespread infrastructure for the supply and production of hydrogen (the move towards the so-called 'hydrogen economy'). Since 1994, several prototype vehicles powered by fuel cells have been demonstrated by DaimlerChrysler (the *Necar* series), Ford (the *P2000*), Opel/General Motors (the *Zafira*), Toyota (the *RAV4L*), and others. These vehicles have provided a useful comparison of the performance of fuel cells which operate with different fuels in either the direct or the indirect conversion mode. The cost of these vehicles remains substantially higher than that of ICE counterparts, notwithstanding the added capital expense of introducing a new refuelling infrastructure.

Alkaline fuel cells have also received a new lease of life following the acquisition of Elenco, a Benelux-based company which has specialised in such technology, by ZEVCO. Though the alkaline system is the simplest of the various fuel-cell technologies, it has been the 'poor relation' of PEMFC systems given the bandwagon for PEMFCs created by Ballard's work. ZEVCO — now known as ZeTech — has advanced the alkaline approach significantly. A 'black-cab' taxi powered by a ZeTech AFC–battery (lead–acid) system is now in service on the streets of London, and the Westminster Council is using another, similarly powered, ZeTech vehicle in the upkeep of London's parks. More recently, ZeTech has ventured into fuel cells for marine applications. Alkaline technology, apart from its inherent simplicity, offers the benefit of using cheap, non-noble metal electrocatalysts.

In summary, despite substantial renewed activity in the development of fuel cells for road transportation applications, the barriers to commercial success are still similar to those encountered in earlier years. There do, however, appear to be much greater environmental and legislative driving forces for cleaner transportation than at any time in the past. Furthermore, an increasing acceptance of hydrogen as a fuel is being shown by oil companies, car manufacturers, government bodies, and other authorities.

3. Environmental forces and the future of road transportation

In the last two decades of the 20th century, there has been growing concern about pollution in major cities, and in particular about the large contribution made by road transportation sources to this problem. Additionally, there have been parallel concerns about the emissions of carbon dioxide, from both transportation and stationary power sources, and their influence on climate change (global warming') via the 'greenhouse effect'. Whilst the true extent and consequences of global warming are still fiercely debated, it is generally agreed that action needs to be taken to curb emissions of carbon dioxide. Taken together, these environmental problems argue the case for the development and introduction of fuel-cell vehicles (FCVs). Obviously, the fuel cell will, depending on system type, produce zero or almost zero tailpipe emissions of regulated pollutants such as NO_x, CO, SO_x and hydrocarbons and, by virtue of its high efficiency, will emit significantly lower amounts of CO_2 than the ICE.

When comparing the efficiencies and the emissions of different power sources in road transportation applications, it should be remembered that the only meaningful data are those where the full 'well-to-wheels' process is considered, namely, extraction of resource (natural gas, coal, or oil), fuel production, transportation and local distribution, refuelling, any further on-board processing of fuel, engine or fuel-stack efficiency together with any other losses prior to delivery of power to the wheels. In this respect, no vehicle can be considered to be truly zero emission, even when powered by fuels which operate on pure hydrogen. Recently, there have been numerous calculations of well-to-wheels efficiencies and emissions of ICEs and FCVs. In most cases, it has emerged that FCVs are significantly better than conventional vehicles on both counts. The most efficient and cleanest system is the direct, pure-hydrogen fuelled FCV [8] which can operate at an efficiency about twice that of the ICEV and with nearly 50% less greenhouse gas emissions.

Government legislation on ICE emissions and fuel quality during the 1980s and 1990s, and of course the introduction of the catalytic converter, have substantially improved the air quality in cities through reduction in regulated pollutants, but there has not been a similar reduction in emissions of carbon dioxide. In the European Union, legislation on engines and fuel quality that is based on detailed studies in two Auto/Oil Programmes — a collaboration between the car manufacturers, the oil industry, and the European Commission — will lead to all European major cities attaining designated standards for air quality by the year 2010 (note, again carbon dioxide is not a regulated pollutant). Despite this initiative, there is still great pressure from environmentalists and the car industry for even cleaner fuels — for instance, there is a call for sulfur levels in diesel and gasoline to be reduced to a few parts per million. This could, however, result in an increase in the emissions of carbon dioxide because of the extra energy required to produce such clean fuels. Nonetheless, it is expected that such aspirational demand for cleaner engines and fuels will continue to be made since both environmental and health–safety considerations are based to a significant extent on perceptions and emotions. There are also concerns that standards for air quality are derived from modelling studies which may not take account of localised pollution in cities, e.g. in narrow congested streets (so-called 'street canyons').

Similar legislation on engine emissions and fuel quality has been enacted in the USA. In certain States, such as California, it is exceptionally severe. In many respects, what California legislates today will inevitably spill over to the rest of the USA and to Europe in due course. In the early 1990s, California introduced the so-called 'zero-emission vehicles (ZEV) mandate' which called for 2% of all new vehicles offered for sale in the State in model years 1998–2000 to be ZEVs. This percentage was to increase to 5% in 2001 and 2002, and 10% in 2003. Initially, it was intended that such vehicles would be battery-powered electric vehicles (EVs). This produced great protests from the car manufacturers, but did lead to the introduction of some 2000 EVs in California, e.g. the Ford *Ranger*, the Honda *EV Plus*, the General Motors *EV*1, and the Toyota *RAV4*. Such vehicles did not attract much interest other than from EV aficionados. In 1996, the regulations were relaxed to allow additional time for the technology to develop. The requirement for 10% ZEVs in model year 2003 and beyond was maintained, but the sales requirements for 1998–2002 were eliminated. A further revision, in 1998, provided additional flexibility in the ZEV programme by allowing other types of vehicle to be used to meet the legislative requirements. Under the 1998 amendments, the manufacturers must have 4% of their sales in model year 2003 classified as 'full ZEVs'. The remaining 6% of sales can be made up of extremely clean, advanced-technology vehicles, which are referred to as 'partial ZEVs' (i.e. near-zero emitting vehicles). This partial-allowance approach towards satisfying the ZEV requirement is intended to promote continued development of battery-powered electric and zero-emitting FCVs, while encouraging the development of other vehicles which have the potential for producing extremely low emissions. FCVs powered by hydrogen would be considered to be ZEVs, but FCVs which have on-board conversion of fossil fuels to hydrogen could, at best, qualify as partial ZEVs.

Also in California, during 1999, the California Fuel Cells Partnership (CFPC) was set up to address FCV testing between the years 2000 and 2003, to resolve fuel infrastructure issues, and to evaluate technology for using gasoline as a source of hydrogen to power the vehicles. Originally, this partnership was made up of the California Air Resources Board (CARB), the Californian Environmental Protection Agency (CEPA), the California Energy Commission, Shell, Texaco, ARCO, DaimlerChrysler, and Ford. Since then, several other car manufacturers, fuel-cell companies (e.g. Ballard and IFC) and oil companies have become involved. In November 2000, the CFPC opened its Sacramento Centre which is equipped with hydrogen-refuelling facilities.

In summary, it is by no means certain that the solution to global environmental problems will be provided by fuel-cell transportation technology. Nevertheless, there can be no doubt that FCVs are real contenders as power sources for future road transportation. Improvements to gasoline and diesel ICEVs will also continue apace and will present real challenges to the fuel cell. In the next section, we examine the various types of fuel cell that are available for road transportation applications.

4. Fuel cells for road vehicles — the candidates and their advantages/disadvantages

Six types of fuel cell are currently being developed for both stationary and road transportation applications, namely, the phosphoric acid fuel cell (PAFC), the alkaline fuel cell (AFC), the molten carbonate fuel cell (MCFC), the solid oxide fuel cell (SOFC), the polymer electrolyte membrane fuel cell (PEMFC), and the direct methanol fuel cell (DMFC). A summary of some of the operational characteristics of these systems is given in Table 1. The PAFC, MCFC and SOFC technologies are almost exclusively being developed for stationary applications such as load-levelling, domestic and commercial power generation, and stand-by power. As mentioned above, however, some work has been carried out on the PAFC as a power source for buses. Meanwhile, BMW are investigating the use of the SOFC as a power source for auxiliary equipment in cars, buses and trucks, e.g. heating, air-conditioning, and electrically-operated services when the vehicle is not in motion (i.e. key-off loads).

Table 1
Operational characteristics of fuel cells

Fuel-cell technology	Temperature (°C)	Efficiency (%HHV)[a]	Start-up time (h)[b]
PAFC	200	36–45	1–4
AFC	<100	>50 (direct)	<0.1
MCFC	650	43–55	5–10
SOFC (planar)	1000	43–55	–
PEMFC	<100	32–45 (indirect), >50 (direct H_2)	<0.1
DMFC	<100	–	<0.1

[a] HHV: higher heating value, i.e. the total heat released including the latent heat of vapourisation of the water formed by the oxidation process.

[b] For fuel-stack only, i.e. does not include response time for a fuel processor, if present.

The PEMFC has received particular attention for vehicle applications because of its smaller size and rapid start-up time. The simplest and most practical PEMFC systems for powering a car are those where the fuel is converted directly to electricity, e.g. direct-hydrogen or direct-methanol PEMFCs. Because of the lack of a supply infrastructure and a safe and efficient storage system for hydrogen, the main approach has been to 'fit the fuel cell to the fuel' and to use a readily available liquid fuel such as gasoline, or perhaps methanol (see Sections 5.1 and 5.3). The problem with this approach is that a 'mini-refinery' has to be contained under the hood of the vehicle in order to convert the fuel, via a number of catalytic processes, to almost pure hydrogen for feeding to the fuel cell. Moreover, the hydrogen must contain no sulfur and only a few parts per million of carbon monoxide, otherwise the catalytic electrodes of the fuel cell will become poisoned. This technology has a number of other disadvantages such as the production of some emissions (i.e. not zero-emitting), a reduction in the overall efficiency of the system, and a substantial increase in complexity. In fact, the only advantage is the use of a familiar fuel. Even then, the gasoline used would have to contain zero sulfur, and thus would have to be contained and distributed by a means which is different to that used to fuel

ICEVs. There are also concerns over the method and total time for start-up of such an indirect system, as well as the driveability of the vehicle. Driveability is basically the response of the vehicle to the touch on the accelerator and the ability to drive off smoothly from rest. With an indirect fuel cell, the transient response of the fuel processor will have to be sufficiently rapid to provide good vehicle driveability. In many respects, an indirect system compromises many of the laudable properties of the fuel cell simply to accommodate a familiar fuel.

The simplest and best fuel-cell systems for powering vehicles are those in which the fuel is converted directly in the fuel cell without the need for any pre-processing. There are four contenders, namely, the direct hydrogen PEMFC, the direct hydrogen AFC, the direct methanol PEMFC, and the direct hydrogen or methanol fuel cell with a liquid acid electrolyte.

Taking the DMFC first, since it is furthest from commercialisation, there remain many technical difficulties to be overcome; these have been discussed in detail in a recent review [4]. In brief, the DMFC suffers from poisoning of the platinum-based electrocatalyst by unconverted methanol residues and this results in a decline in cell performance. To solve this problem, a much more effective co-catalyst or promoter has to be found to combine with the platinum. Thirty years ago, finely-divided platinum–ruthenium alloys supported on carbon materials were the best catalysts for methanol electro-oxidation. This catalyst system still remains the most effective, though some improvement in activity has been claimed [3]. A comparison with the performance in the 1970s is difficult, however, since the earlier studies on the catalyst were carried out in sulfuric acid electrolyte rather than in PEM electrolyte. With the latter electrolyte, there is also the problem of methanol crossing over to the air electrode; the methanol is transferred in solution by the highly hydrated hydronium ions in the PEM electrolyte. Such cross-over decreases system efficiency, through loss of fuel into the air stream, and causes poisoning of the air electrode. It has been found that methanol cross-over is more manageable with a circulating liquid sulfuric acid electrolyte and a suitable microporous membrane than with a solid PEM electrolyte. In contrast to the PEM situation, charge transfer in sulfuric acid appears to proceed via 'proton hopping' and the tortuous passage through the microporous membrane restricts the transfer of methanol. Indirect proof of this mechanism has been provided by studies on hydrazine fuel cells [3]. When using a similar liquid electrolyte membrane system, stoichiometric electrochemical conversion of hydrazine was obtained, i.e. no fuel reached the air electrode. In summary, both liquid acid and PEM types of DMFC remain much further from commercialisation than all the direct hydrogen systems.

The direct hydrogen PEMFC is attractive and excellent results have been achieved with the Ballard-type systems which operate at high pressures, and with the IFC systems which function at near ambient pressure. Nonetheless, although no definitive cost data have been published, the total system remains far too expensive to compete with the ICE. Given the progress that is being made, however, there are good prospects for PEMFC systems to become less expensive. The direct hydrogen AFC has not received much attention, at least not until the recent work of ZeTech (see Section 2). There is no doubt that the AFC offers the benefits of simplicity and cheapness since there is more flexibility in the choice of materials compared with an acid system. Base-metal catalysts can be used for both hydrogen and air electrodes, as opposed to expensive platinum catalysts in PEMFCs, as well as a variety of low-cost metallic conductors. ZeTech has certainly been very active in the advancement of AFCs and has established small assembly lines for their manufacture. Some of the ZeTech systems are now in operation.

The two main obstacles to introducing vehicles powered by either PEMFCs or AFCs are the acceptability of hydrogen as a fuel and the lack of a suitable storage medium for hydrogen on-board the vehicle (see Section 5.4). With respect to the former, there is some concern over safety when using hydrogen, and there is no infrastructure for transporting and distributing the gas in large quantities. Indeed, there exists strong vested interests against installing a hydrogen infrastructure. According to the oil industry, such an enterprise would cost hundreds of billions of dollars, and thus it would be preferable to use gasoline as the fuel, albeit converted to hydrogen on-board the vehicle. Nevertheless, BP, Shell and Texaco are all committed to providing a hydrogen infrastructure where there is a demand. Storing hydrogen on-board vehicles is the second major technical challenge. To provide an acceptable driving range, storage of compressed hydrogen in tanks would require pressures in excess of 34 MPa. Tanks also impose weight and volume penalties. Storage of hydrogen as a cryogenic liquid, which requires a temperature of -253°C, involves energy consumption in the liquefaction process. Storage in metal hydrides has been proposed, but this would again add extra weight to the vehicle and restrict its driving range. Other approaches will be discussed in Section 5.4.

Consideration is also being given to the development of hybrid designs of FCVs. The basic strategy is to improve vehicle efficiency through the use of a storage device, such as a battery or an ultracapacitor, for 'load-levelling' so that it is no longer necessary to size the fuel cell for maximum power demand. Instead, the fuel cell operates at essentially constant power output and any excess output is fed to the storage device. The latter provides the surge power for acceleration and hill-climbing, and captures the high power produced by regenerative braking of the vehicle. Some manufacturers (mainly automotive) who have produced prototype FCVs over the past 6 years are listed in Table 2. Clearly, most of these companies are favouring the fuel-cell-battery hybrid. At present, the choice of battery lies between the nickel-metal-hydride and the lithium-ion systems.

Table 2
Some car manufacturers undertaking the development of FCVs[a]

Company	System type	Fuel cell	Fuel
DaimlerChrysler	Straight fuel cell	Direct	Hydrogen
	Fuel-cell–battery hybrid	Indirect	Methanol
Ford	Straight fuel cell	Direct/indirect	Hydrogen/methanol
General Motors	Fuel-cell–battery hybrid	Direct/indirect	Hydrogen/methanol
Honda	Fuel-cell–ultracapacitor hybrid	Direct/indirect	Hydrogen/methanol
Mazda	Fuel-cell–ultracapacitor hybrid	Direct	Hydrogen
Nissan	Fuel-cell–battery hybrid	Indirect	Methanol
Renault	Fuel-cell–battery hybrid	Direct	Hydrogen
Toyota	Fuel-cell–battery hybrid	Direct/indirect	Hydrogen/methanol
Volkswagen	Straight fuel cell	Direct	Hydrogen
	Fuel-cell–battery hybrid	Indirect	Methanol
ZeTech	Fuel-cell–battery hybrid	Direct	Hydrogen

[a] All vehicles use PEMFCs, with the exception of the ZeTech vehicle which has an AFC. The information has been obtained from recent press releases issued by the various companies.

In summary, it would appear that the decision on which fuel cell will be the power source in a FCV rests on whether the fuel cell is made to operate with conventional fuels, or with a fuel that manifests the best attributes of the fuel cell.

5. Candidate fuels for FCVs

There are a number of issues surrounding the choice of fuel to be used in a fuel cell. This is well-illustrated by the following statements from those most closely concerned with the development of FCVs.

- "It is the fuelling infrastructure which is the critical issue affecting the choice of fuel." — a Vice President in the oil industry.
- "The transition to hydrogen infrastructure is the big issue, the advantages of hydrogen are clear, but how as an industry do we get there?" — a Chief Executive Officer in the car industry.
- "Reformer technology is critical to the fuel cell industry; only with a liquid fuel do we have a chance to enter the market." — a car industry representative.

Possible fuels for FCVs, namely, gasoline/diesel, natural gas, ammonia, methanol and hydrogen, are discussed in the following sections.

5.1. Gasoline/diesel, natural gas

Gasoline and diesel cannot be converted directly in the fuel cells which are being considered for road transportation applications, i.e. those systems which operate at low-to-medium temperature. Nevertheless, because these two fuels obviously would present no difficulties in terms of a supply infrastructure and storage on-board FCVs, they are seriously being considered for fuel cells. As mentioned in Section 4, the idea is to use a mini-refinery under the hood of the car to convert the liquid hydrocarbon to hydrogen. The carbon monoxide by-product is then removed and the purified hydrogen is fed to the fuel cell. There are still doubts about the viability of this approach from the point of view of overall system efficiency and reduced emissions. Although both of these performance aspects are expected to surpass those for the best ICE, the improvements would be much smaller than those for an FCV running directly on pure hydrogen. Major issues include: start-up time; dynamic range (i.e. the ability to go from low to high power outputs without too much loss of efficiency); response time; capacity factor (i.e. the ability to provide high peak output); weight; system complexity and maintenance; temperature extremes; resistance to shock and vibration. These are being addressed by General Motors who has recently claimed [9] to have reduced the start-up time of its fuel processor to about 1 min, and to have improved the resistance to vibration. It has been generally asserted that one of the main advantages of FCVs is a much reduced need for maintenance, but this is difficult to accept for FCVs with mini-refineries under the hood. Finally, the gasoline has to contain no sulfur or additives to avoid possible poisoning of the fuel-processor catalysts and the fuel-cell electrocatalysts. In many respects, the new fuel would resemble a sulfur-free naphtha and would need to be segregated from the gasoline used for ICEVs.

Natural gas must also be processed on-board the FCV, and there is the added complication of it not being a liquid at normal temperatures and pressures. This fuel does, however, offer certain advantages, namely: it is relatively cheap compared with all the other fuels (including gasoline); there are massive reserves of over 500 billion tonnes; there exists more of an infrastructure than for hydrogen — at present, more than one-million conventional vehicles are operating world-wide on compressed natural gas. As with hydrogen, there is the storage problem which will restrict the driving range of vehicles. It should be noted that a developed infrastructure for natural gas could pave the way for a similar facility for hydrogen.

5.2. Ammonia

Although ammonia was seriously considered as a fuel for fuel cells in the 1950s–1970s, it receives little attention today. Indeed, ammonia has always been unfavourably regarded as a mass-market fuel because of its pungent smell. Nevertheless, ammonia is capable of being used directly in a fuel cell, albeit with very low electrochemical activity. If ammonia were to be converted to hydrogen on-board the vehicle, i.e. in a manner analogous to that described above for gasoline, then it would have some significant advantages. For example, it can be catalytically cracked to hydrogen and nitrogen, and thus the vehicle would be zero emitting. Additionally, there is no production of carbon monoxide and, hence, no need for hydrogen purification. Thus, the on-board processing system would be much simpler than that for gasoline. Other relevant features of ammonia are as follows:

- world production >130 million tonnes;
- manufactured from methane, steam and air;
- stored and transported as liquid at about 1 MPa by means of an existing infrastructure;
- safe handling procedures have been developed;
- vapour pressure versus temperature characteristics are identical to those of propane;
- readily cracked into nitrogen and hydrogen;
- FCVs running on ammonia would, in principle, be zero emitting.

Clearly, ammonia has many attributes. Furthermore, it can be used in conjunction with an alkaline electrolyte in a fuel cell. This would reduce costs. In fact, ammonia is the only fuel that can be used with a simple fuel processor and an alkaline electrolyte. Thus, ammonia may warrant more detailed examination than hitherto for indirect fuel-cell systems.

5.3. Methanol

Methanol is a strong candidate fuel for FCVs; its advantages and disadvantages are listed in Table 3. Methanol would be converted on-board to hydrogen via a steam reformer. Clean-up of the hydrogen would be required, but the overall processing system would be simpler than for either gasoline or diesel. Additionally, methanol can be converted directly to carbon dioxide in a fuel cell which uses an acid electrolyte, and whilst this is very difficult at present, there are firm views that DMFCs might eventually prove viable for FCVs. Certainly, if the DMFCV became practical, there could, by that time, be much greater familiarity with methanol as a fuel.

Table 3
Advantages and disadvantages of methanol as a fuel

Advantages	Disadvantages
Relatively easy to convert to hydrogen on-board vehicle	Lack of a dedicated infrastructure Corrosive
Liquid at normal temperatures, can be handled by present gasoline distribution infrastructure	Toxic Burns with non-luminous flame Miscible with water
Abundant supplies	Cost
Potential for direct conversion	
Renewable resource	
Biodegradable	

Compared with gasoline, methanol has some advantages in terms of safety, namely, lower volatility, a higher lower-flammability limit, lower heat of combustion, and less hazardous (i.e. less combustible) by-products. The issue of a lack of fuel infrastructure for methanol is an interesting one. Back in the 1970s, when Shell and Exxon were researching the DMFC, one of the reasons for choosing methanol was that it was perceived then as being compatible with the existing fuel infrastructure — it can be stored and poured like gasoline. Today, this view is no longer held by the oil industry. Estimates of the cost of creating a methanol fuel infrastructure vary depending on who is giving the estimate. For instance, the cost of installing methanol capacity at 50% of the service stations in Western Europe has been estimated by the American Methanol Institute (AMI) as US$ 3.04 billion, but by an oil company (Shell) as twice this cost. There is some experience of introducing methanol distribution networks — for example, a number of methanol service stations have existed in California for many years, and the cost of their installation must be well established. In Brazil, an infrastructure for ethanol has been established, presumably by the oil industry. Thus, the lack of an infrastructure does not seem to be a major impediment to the use of methanol in FCVs.

The supply of methanol would appear to pose few problems. The AMI has identified a production capacity of 11.4 billion gallons per year with a utilisation rate of 80%; in other words, there is significant undercapacity. The undercapacity is likely to increase as methyl tertiary butyl ether (MTBE), which is made from methanol, is phased out as an additive for gasoline. This additive is already banned in California, where it represented 6% of the global demand for methanol, and some European countries are considering similar action. Trillions of cubic feet of natural gas are flared annually and, according to the AMI, conversion of just 10% of this gas to methanol would fuel nearly 10 million FCVs [10]. Finally, methanol can also be made from coal or a variety of renewable feedstocks (biomass) such as wood, municipal waste, and sewage. The present cost of methanol is estimated [11] to be greater than that of gasoline, namely, 9.0–14.2 US$/GJ compared with 6.4–7.4 US$/GJ. Of course, the actual cost of methanol to the customer will be greatly influenced by the tax treatment of the fuel. Methanol has half the calorific value of gasoline, and at present, gasoline is taxed on a volumetric basis rather than on an energy-content basis.

The health, safety and environment (HSE) issues of methanol as a fuel must also be considered. Methanol is a human poison by ingestion, about 2–6 teaspoonfuls are potentially lethal. Sub-lethal doses can cause blindness. When gasoline is ingested, automatic vomiting occurs and this restricts the dose of gasoline that can be taken orally. If methanol were to be used, then some sort of additive, such as a bitterant or an odourant, would be required at the ppm level. Likewise, if it were deemed essential for methanol to burn with a flame, then luminosity additives would also have to be incorporated in the fuel. It must be remembered that such additives must be compatible with both the catalysts of the fuel processor (indirect system) and the electrocatalysts of the fuel cell.

In summary, the greatest obstacles to the use of methanol in FCVs are the unfamiliarity with methanol compared with gasoline, vested interests (e.g. AMI versus oil companies), politics, and consumers' perceptions of the health and safety issues. There is also a 'why bother?' feeling if hydrogen is to be the ultimate fuel.

5.4. Hydrogen

In terms of fuel-cell performance, pure hydrogen is the ideal fuel. Also, it can be converted easily in either acid or alkali electrolyte. The advantages and disadvantages of hydrogen are summarised in Table 4. As far as advantages are concerned, the easy conversion of hydrogen has already been highlighted (Section 4). In addition, however, a fuel cell operating on pure hydrogen has a very good load response and is zero emitting (the only product is water). There are of course emissions associated with the production and distribution of the hydrogen itself, but even if these are taken into account, a direct hydrogen FCV is likely to be much cleaner and more efficient than the best gasoline or diesel ICE counterpart.

One of the principal reasons for the perception that hydrogen is unsafe is the belief that the Hindenburg airship disaster in 1937 was caused by a hydrogen fire, in spite of the fact that the Hindenburg blazed with a bright flame, which would not be expected with such a fire. The research of Addison Bain [12] has recently provided convincing evidence that the disaster had more to do with the flammability of the fabric chosen for the airship's envelope than with the fact that it was filled with hydrogen. In the first-half of the 20th century, more than 50% of the gas in the pipeline networks of the Western World was hydrogen, and today the gas is produced and used in refineries around the world. Thus, safety risks tend to be over-exaggerated.

Table 4
Advantages and disadvantages of hydrogen as a fuel for FCVs

Advantages	Disadvantages
Simplest fuel cell system	Perceived as unsafe (Hindenburg syndrome)
Good load response	High cost
Zero-emitting system	Range/refuelling issues
	No existing infrastructure
	No effective on-board storage

In terms of cost, there can be no doubt that hydrogen is substantially more expensive than either gasoline or methanol. On an energy-content basis, it has been estimated that hydrogen is two to six times more expensive than gasoline [11]. Many uncertainties surround the cost of hydrogen, however, since there is no experience to date of the retail production and the sale of large quantities of hydrogen. There are a number of options for the production and the distribution of hydrogen, e.g. remote production and retail distribution, local production and storage at a retail site, on-board production via processing of hydrocarbons or methanol. The HSE, cost/benefit and, very importantly, the FCV performance aspects of each option must be carefully assessed.

Whilst large-scale remote production is economically favourable, there is currently little requirement for an increase in hydrogen capacity which is already more than sufficient for existing demands. Pipeline infrastructure is very limited and the costs of construction are high. Moreover, there is the additional expense of storing hydrogen on-board the vehicle as either a compressed gas or a cryogenic liquid. The cost of creating a hydrogen infrastructure has been estimated at 300 billion dollars for the USA alone [13].

Hydrogen could be produced locally at service stations by reforming natural gas, and thus could make use of the existing infrastructure. Equally, production by water electrolysis using the electricity network is a possibility and is particularly attractive in countries with large supplies of cheap nuclear or hydroelectric power. Local generation of hydrogen would involve high capital cost, and concerns have been expressed over the safety, reliability and maintenance of the proposed hydrogen plants. The voicing of such concerns is surprising given that one of the alternative proposals is to produce hydrogen under the hoods of millions of cars!

The third alternative is to produce hydrogen by processing methanol or gasoline on-board the FCV. Studies by Thomas et al. [14] have shown, however, that this approach would be more expensive, on a cost-per-vehicle basis, than utilising existing natural-gas pipelines or electricity grids to produce hydrogen when and where it is needed to accommodate a growing FCV market. Moreover, the demands placed on an on-board fuel processor compared with those placed on a large stationary unit at a service station are much greater in terms of properties such as warm-up time, dynamic range, response time, and capacity factor.

Perhaps the single most important challenge facing the development of commercial hydrogen-fuelled FCVs is the need for an effective and safe system for on-board storage of hydrogen. Possible storage methods are: hydrogen, ammonia, methanol, compressed gas, cryogenic liquid, metal or metal-alloy hydride, carbon absorption (nanotubes/nanofibres).

Storage on-board as hydrocarbons, ammonia and methanol has been discussed in Sections 5.1–5.3. In the case of compressed hydrogen, the low volumetric density of hydrogen (10–20 times less than gasoline) will restrict vehicle range. Although progress is being made towards lighter and less-expensive storage tanks, substantial improvements are still required. James et al. [15] have reported that the Ford Motor Company has used hydrogen in a tank at 34 MPa (5000 psi) which gave a range of 600 km and could be integrated into a five-passenger sedan with no encroachment on the passenger and the luggage compartments. IMPCO in the USA are working on various technologies for compressed hydrogen storage and have a goal of 8.5 wt.% storage at 34 MPa. A consortium of IMPCO, the Lawrence Livermore Laboratory, Thiokol Propulsion and the Alcoa Industrial Component Group has recently achieved [16] compressed storage of hydrogen to a level as high as 11.3 wt.%, and has concluded that the technology is simple, cost-effective, durable and safe for vehicle use.

Liquid hydrogen has a volumetric density which is about 25% that of gasoline. A high consumption of energy is associated with the cryogenic process, super-insulated storage vessels are required, and boil-off losses occur. In addition, special systems are needed for the storage and dispensing of the fuel.

Although metal-hydride fuel tanks have been successfully incorporated into prototype FCVs, notably the Toyota *RAV4L*, this form of hydrogen storage introduces significant weight and cost penalties compared with the use of compressed gas. In addition, a complex heat-exchanger system is required to manage the release and supply of heat during refuelling and operation, respectively.

Perhaps the most exciting possibility for the on-board storage of hydrogen is the use of carbon nanostructures. The concept was reported in 1995. The most controversial work has been that of Baker and Rodriguez at North-Eastern University in Boston [17]. It was claimed that up to 67 wt.% of hydrogen could be stored at a pressure of 12 MPa. This amount of hydrogen would give a FCV a range of about 8000 km on a single full tank! Such high levels of storage have not been confirmed by other groups, though sufficiently high uptakes of up to 12 wt.% have been achieved [17]. Theoretical and modelling studies have predicted carbon nanostructures to store between 4 and 14 wt.% hydrogen [17]. The upper value would provide FCVs with a more than adequate driving range.

Whatever, if any, technology emerges as the accepted storage technology for hydrogen, much work will have to be done before an appropriate hydrogen infrastructure emerges. This process would be assisted by data on the following: the fuel-handling requirements for compressed gas, cryogenic liquid and any other form of stored hydrogen; the safety aspects of the chosen storage system; global harmonisation and standardisation on all matters concerned with the production, distribution and retailing of hydrogen fuel. It is encouraging to note that projects in the USA and Europe have been initiated to address these issues.

6. Alternatives to FCVs

The principal competitors of FCVs are pure-battery EVs, heat-engine (e.g. gasoline or diesel)–battery hybrid vehicles (HEVs), and advanced conventional ICE-powered vehicles (ICEVs).

Pure-battery electric vehicles have a long history. In fact, at the turn of the 19th century, the world land speed record was held by such a vehicle. By the first decade of the 20th century, 35% of all vehicles registered in the USA were EVs, and there were 10,000 EVs operating in London. Networks of charging points for such vehicles were established in major US cities, and many drivers preferred EVs to their hand-crank started and smelly ICE counterparts. In 1912, the self-starter made its first appearance in an ICEV and, in 1913, Henry Ford implemented the first assembly-line production of gasoline cars. The heyday of the EV was over! Within a decade, the EV industry and its infrastructure had disappeared. From then until now, the use of EVs has been restricted to niche applications where the limited range and the long refuelling times of the vehicles are not a practical inconvenience — a classic example of such an application is the doorstep delivery of milk in the UK by the ‘milk float’. Whereas history has shown that the self-starter greatly assisted the introduction of ICEVs, it is expected that the development of a means for the effective, safe and inexpensive on-board storage of hydrogen will similarly facilitate the commercial realisation of FCVs.

The energy crises in the 1970s saw a revival of interest in EVs and great efforts were made to develop lead–acid, nickel–zinc, sodium–sulfur, zinc–air, zinc–halogen and several other battery systems for motive-power applications [18]. The age-old battery problems of excessive weight, low specific energy, inadequate reliability, long recharging time, limited service life and high cost were the principal reasons for the failure of EVs to succeed. Despite the fact that the major proportion of people’s daily use of cars amounted to less than 50 km, insufficient interest in EVs was generated to create a viable market. Moreover, the image of the EV was not helped by the launch in the 1980s of the Sinclair C5 ‘vehicle’ — a battery-powered one-seater with pedal-power back-up. The zero emissions legislation introduced in California in the 1990s (see Section 3) again boosted interest in the EV, since this was the only technology which could fulfil the mandated requirement. Of course, the legislators conveniently ignored the fact that, with EVs, the emissions are simply switched from the vehicle tailpipe to the central power generator. A wide variety of EVs were introduced by the major car manufacturers, but none of these proved to be a commercial proposition for the same reasons as before — very limited range, long refuelling times and, inevitably, high cost. Today, the battery-powered EV does not appear to pose any threat to the supremacy of the ICEV, except for specialised applications. From these experiences, FCV developers should conclude that the customer will only change to a new technology if it is significantly better than that which it seeks to replace.

Considerable interest is also being shown in heat-engine–battery hybrids, of which there are two basic types: the ‘series HEV’ and the ‘parallel HEV’. In the series configuration, the output of a heat engine is converted to electrical energy through a generator which, either separately or jointly with a battery, powers a single drive-train. In one typical version, the series HEV would have a battery which is sufficiently large to meet the daily range and peak-power requirements for city driving, and a small heat engine, e.g. an ICE, which is used to generate electricity purely as a ‘range extender’ for out-of-town driving. The battery is said to operate in the ‘dual-power mode’. The series HEV is essentially an electric vehicle with an EV-sized battery and a small auxiliary engine.

By contrast, the parallel HEV has two distinct drive-trains such that the vehicle can be driven mechanically by a heat engine, or electrically by a battery–electric-motor, or by both. The heat engine is larger than that in a series HEV (but smaller than that in a conventional automobile) and is sized for steady highway driving. The independent battery system provides auxiliary power for acceleration and hill-climbing, accepts regenerative-braking energy, and restarts the engine in city traffic. In such duty, the battery has to furnish and absorb high, short bursts of current and is said to operate in the ‘power-assist mode’. The parallel HEV corresponds to a conventional automobile with a smaller engine and a larger battery.

It can be seen that the basic principle of the HEV (either configuration) is that the electric drive cuts in and the ICE switches off when the latter would otherwise have to operate inefficiently, e.g. at traffic lights or at low part-loads. In this way, the batteries are kept charged by the ICE and the total emissions of the vehicle are reduced compared with the pure ICE version. Thus, the HEV combines the best aspects of both power sources. The Toyota *Prius* and Honda *Insight* — both parallel designs of HEV which use nickel-metal–hydride batteries — have attracted the most attention. Indeed, Toyota’s managing director of electric-drive vehicle programmes is convinced that the HEV will be the core vehicle technology of the future. Some 50,000 units of the *Prius* have been sold, mostly in Japan. On a well-to-wheels efficiency basis, Toyota claim [19] that the vehicle has an efficiency of 25%, i.e. 4% better than a pure-battery EV and 13% better than a conventional ICE. It is probable that if, or when, fuel-cell technology for vehicles becomes commercial, it will assume the role of the ICE in current hybrid vehicles.

Finally, turning to the third technology which is competing with FCVs, namely, vehicles powered by heat engines, it is safe to say that here the industry is not exactly standing still. Over the last 10 years or so, remarkable improvements in the emissions performance of such vehicles have been made and are expected to continue. Thus, the FCV is competing against a moving target. For instance, there were 350 million vehicles on the road world-wide in 1995 and these produced about 250 million tonnes of pollutants (excluding carbon dioxide). By year 2010, it is estimated [20] that there will be about 700 million vehicles which will produce around 20 million tonnes of pollutants, i.e. about one-tenth of the pollution from twice as many vehicles. Beyond that date, it is still likely that such vehicles will continue to get cleaner. It has also been predicted [20] that heat-engine vehicles with zero emissions (apart from carbon dioxide) will be on the roads in year 2015. Some of the developments that can be expected are: exhaust gas recovery (EGR) tolerant engines and lean NO_x trap/catalysts for gasoline vehicles; particulate traps, active de-NO_x catalysts and plasma after-treatment for diesel vehicles. Such developments will also impact on fuel requirements, e.g. reductions in sulfur levels to less than 30 ppm, different additives, and improved cetane numbers for diesel [21].

Thus, in summary, the main competition to FCVs will come from ICE–battery hybrid vehicles and improved gasoline or diesel ICEVs. The FCV will have to surpass the performance of future versions of these types of vehicle, not that of today’s models.

7. Impact of competitive FCVs on automotive, energy and other industries

The industries principally affected by the advent of successful commercial FCVs would undoubtedly be the automotive and oil industries, though the impact on industry in general would be widespread. The FCV poses a threat to the traditional business of such industries, yet at the same time should present opportunities for new products and markets. Of course, it should be recognised that the replacement of a technology such as the ICEV would not occur overnight — the time taken to turn over the car parc (car population) varies from country to country and it takes many years to turn over the world car parc. The main impact on the car industry will occur in the servicing, maintenance and replacement parts sector. At present, this business is very profitable. FCVs based on the simplest and the most effective technology of the direct, pure-hydrogen, fuel cell should require much less servicing and maintenance than conventional ICEVs. The fuel-cell ‘engine’ should have a very long lifetime as there are no moving parts in the fuel-cell stacks, and thus there is less likelihood of the wearing out of parts. Auxiliary pumps and blowers, too, should have long lives. Some effect on employment within the automotive industry is also expected as it will be necessary to train personnel to carry out what servicing is required with electrochemical engines and electric-drive systems. Should PEMFCs prove to be the winning technology, knowledge of materials such as polymers would be an obvious pre-requisite.

In the event that a fuel-cell system is chosen that uses a liquid fuel such as hydrocarbons, methanol or ammonia, the situation is somewhat different since there is little long-term experience of the maintenance requirements of FCVs which incorporate mini-refineries. For example, there is no existing information on the service intervals for such vehicles. Given the exacting conditions under which such mini-refineries must operate, it could be argued that the maintenance and servicing requirements of such FCVs could be more demanding than those for conventional vehicles. Again, new skills will have to be developed by the mechanics who will perform this work. Likewise, the call for the periodic replacement of parts in such FCVs has not yet been established. Undoubtedly, the impact of FCVs on the automotive industry is likely to be substantial.

The oil industry will also be affected by the introduction of FCVs, and probably to a greater extent than the automotive industry. Once the fuel is established, actions will be required for its production, distribution and retail at service stations. There would be challenges even if hydrocarbons are chosen, since these would be quite different from present hydrocarbon fuels. The new fuel would not contain any sulfur and, therefore, would probably be manufactured by a gas-to-liquid process. Moreover, the fuel would have to be distributed and stored separately from that used for conventional vehicles. Methanol would also demand its own distribution and storage system with protection against corrosion and the ingress of water. Life-cycle analyses on the HSE aspects of the widespread use of methanol in vehicles would have to be undertaken. To achieve this task, helpful information can be gleaned from the experience gained in California from using methanol as a vehicle fuel, and in Brazil with ethanol. It is appropriate that, as mentioned in Section 5.3, joint automotive and oil industry studies are being conducted in Europe and the USA on the implications of introducing fuel infrastructures other than those for conventional gasoline and diesel.

An FCV has no moving parts and as such would require no crankcase lubrication. Crankcase lubricants, which represent 85% of an automobile's lubricant requirements, are a large and profitable part of the oil industry's business. The world demand for lubricants in year 2000 was 40 million tonnes and this was shared between commercial vehicles (38%), passenger cars (23%), and industrial applications (39%). Some consultants to the oil industry have estimated that by year 2015, the demand for crankcase lubricants will decline by 30% if certain projections of FCV numbers have materialised by that year. It is not all bad news for lubricants, however, since there will be new demands created by the growing FCV industry in the industrial lubricant sector. For example, the manufacture of components for the fuel-cell stacks will require lubricants for metal and plastic cutting, demoulding and forming. Electric motors will have to be produced and if these are to be copper-wound, there will be an enormous growth in the demand for copper-drawing oils. Overall, a marked change would occur in the present balance of the demand between the various lubricant sectors. Although the extent of this change is difficult to quantify, the advent of commercial FCVs in large numbers would clearly have a dramatic effect on the lubricant business of the oil industry.

Crankcase lubricants usually contain up to 20 wt.% of performance-enhancing chemical additives. Again, these are very profitable items for their manufacturers who are usually chemical companies or subsidiaries of oil companies. It is therefore somewhat surprising that the renaissance in fuel cells for road transportation applications has not stimulated much interest from additive manufacturers. Quite apart from lubricants, performance-enhancing additives have found increasing use in fuels such as gasoline and diesel to decrease engine emissions, to improve the lubrication properties of diesel fuels, and to act as colourants. It is unlikely that there will be a major demand for such additives in the fuels required by FCVs. This would be particularly true if gasoline, processed on-board to hydrogen were to be the fuel. If methanol is chosen, then there could be the requirement for additives such as odourants, bitterants and flame luminosity additives (see Section 5.3), but only in very small amounts to avoid the possible poisoning of fuel-processing catalysts and cell electrocatalysts. Overall, FCVs would clearly cause some change in the traditional business of the chemical additives industry.

The production of electric-drive systems for FCVs will obviously influence activity in the electric and electronic components industry. There will be a greater demand for large electric motors, for the supply of the various components that go into these motors, and for electronically-operated control systems. The components used to manufacture fuel-cell stacks, such as membranes, separators, electrode assemblies and noble-metal catalysts, will also create opportunities within the relevant industries.

The methanol industry could be strongly affected by the introduction of FCVs. This is obviously highly dependent on the acceptability of methanol as a fuel for widespread use in vehicles. As already mentioned in Section 5.3, there are significant difficulties associated with the toxicity of methanol, and these should not be underestimated. The banning of MTBE as a gasoline additive because of environmental problems is a good indication of the extent of this challenge. The methanol industry, which had significant overcapacity before the banning of MTBE, has been quick to see the opportunity for increasing the demand for methanol should it become the fuel of choice for FCVs. The AMI, through conference presentations and its website, has vigorously promoted the benefits of methanol as the best fuel for FCVs. Methanex, the world's largest producer of methanol, has become closely involved with the development of fuel cells for both vehicle and stationary applications. The company has formed alliances with a number of players in the fuel-cell and energy businesses.

In summary, a switch to FCVs, whilst undoubtedly presenting significant threats to traditional business across a number of industries, also offers many opportunities for new markets and products and, of course, employment.

8. How can FCVs become competitive?

Any new technology which aspires to compete with an existing technology will only succeed if it matches, or preferably exceeds, the state-of-art at the same, or preferably lower, cost. These conditions have been well demonstrated by the repeated failure of EVs to gain market acceptance. The downfall of the EV has been its fundamental inability to match the ICEV in terms of driving range, refuelling time, and cost. New technologies become successful through customer acceptance, not through legislation. A salutary example has been the General Motors *EV*1. This vehicle was introduced in California in response to the ZEV mandate but did not achieve commercial success. On the other hand, information on electric drives, customer response to electric vehicles, etc. that is gained from failures such as the *EV*1 will no doubt be used by companies engaged in the development of FCVs.

Some characteristics of FCVs compared with ICEVs are listed in Table 5. The comparison is made for a FCV in which fuel is converted directly to electricity, e.g. a direct hydrogen or a direct methanol system. The advantages in the areas of emissions, efficiency, driveability and maintenance are not so clear-cut for FCVs which operate on hydrogen produced on-board. There is little experience of how such vehicles might perform in practice. For instance, a complex mini-refinery under the hood of a car may require more maintenance than an ICE. Likewise, the time for start-up may prove unacceptable. Indeed, it is fairly certain that a battery will be required to power the vehicle at start-up, i.e. a hybrid system. Finally, the driveability of such FCVs is difficult to predict with any good degree of accuracy.

The concept of an FCV which employs an on-board fuel processor is an example of matching the fuel cell to the existing fuel infrastructure, rather than the fuel infrastructure to the fuel cell. In our opinion, such an approach endangers the acceptability of FCVs in general. With the ongoing advancements in gasoline and diesel engines, the performance improvements offered by indirectly-fuelled FCVs may in fact become marginal and will, in all probability, be much less than those obtainable with directly-fuelled FCVs. It is therefore unlikely that FCVs with fuel processors will be able to replace conventional, improved ICEVs. For passenger cars and heavy vehicles, the FCV directly fuelled with hydrogen or methanol offers the best chance of supplanting conventional vehicles. With hydrogen as the fuel, the major challenge is to find a cheap, safe technology for on-board storage. With methanol, it is necessary to devise much more effective catalysts for the electro-oxidation reaction.

Table 5
Rating of FCVs vs. ICEVs

Vehicle characteristic	FCV performance vs. ICEV
Emissions	Much better (zero?)
Noise/smoothness	Better
Energy efficiency	Better/much better
Power:weight ratio	Worse
Driveability	Better
Range/refuelling	Similar
Running cost	Better
Maintenance	Better
First cost	Worse

9. Conclusions

The title of this paper poses the question: ‘‘Fuel cells for road transportation purposes — yes or no?’’ and it is incumbent upon us to provide an answer. We have examined all of the issues which surround the advancement of FCVs, together with the competition from conventional ICEV and new HEV technologies. We have reached two conclusions.

Our answer to the question is ‘no’ if the FCV will require an on-board fuel processor. This judgement is based on the conclusion that it will not be possible for such a FCV to exceed the performance of future ICEVs in terms of emissions, efficiency, driveability, maintenance, and first-cost.

Our answer is ‘yes’ if the FCV is powered by a directly-fuelled fuel cell, since there is then every prospect that the performance will exceed that of the ICEV in all respects except first-cost. Given the recent rate of progress in fuel-cell technology, however, we expect a significant reduction in the cost of directly-fuelled fuel cells.

For direct-hydrogen FCVs, the main task is to develop a cost-effective, reliable and safe method of storing sufficient hydrogen on-board the vehicle. To this end, there have been encouraging advances in the storage of hydrogen as a high-pressure gas, or in metal hydrides or carbon nanofibres. Even now with buses, where there is more room for storage of hydrogen as a compressed gas, there are good prospects that commercial fuel-cell-powered versions will be on the roads within the next two to three years. Such vehicles are centrally refuelled and, therefore, hydrogen-distribution infrastructure is not a difficult issue.

For direct-methanol FCVs, a breakthrough is required in catalysis. Since electrocatalysis is very similar to conventional heterogeneous catalysis, we suggest that greater application of the world-wide expertise in noble-metal hetero-geneous catalysis could be of great assistance in addressing the direct methanol conversion issue and in improving the performance of the air electrode. Thus, fuel-cell developers should exploit more the talent of the heterogeneous catalysis community. If the catalysis problem can indeed be overcome, then a cost-effective approach would be to use a sulfuric acid electrolyte solution. For direct-methanol PEM systems to achieve acceptable performance, improved membranes must be developed.

We do not accept that the costs of installing either hydrogen or methanol infrastructures for FCVs will be an unsolvable problem. For FCVs to enter the road transportation sector, it is necessary to improve the performance and lower the cost of the fuel-cell system itself.

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