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The new generation of vehicles: market opportunities for fuel cells

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Abstract

The Partnership for a New Generation of Vehicles (PNGV), a historic US Government–auto industry partnership initiated in 1993, is pursuing three specific, interrelated goals, including the development of the next generation of vehicles capable of achieving up to three times the fuel efficiency of today's comparable vehicles. Fuel cells have been identified as one of three primary propulsion system candidates to meet this triple fuel efficiency goal, since they can dramatically increase automotive propulsion efficiency combined with very low to zero emissions. The US Government is working closely with industry and research institutions in pursuing a strategy of aggressive research and development (R&D) to accelerate the commercialization of fuel cell vehicles. The US Department of Energy has a major role in this fuel cell technology development effort. R&D activities are focused on overcoming the major technical, economic, and infrastructure-related hurdles. The high efficiency, very low emissions, and other favorable characteristics of fuel cells (such as fuel flexibility, low noise, and vibration) create significant market opportunities for fuel cells over the entire spectrum of transportation applications. While the focus of near-term markets for fuel cell vehicles will be urban areas having severe air-quality problems, long-term market prospects are encouraging since fuel cell vehicles can compete on an even ground with conventional vehicles in all key aspects, including vehicle range and refueling. This paper will discuss near- and long-term market opportunities for fuel cells in transportation and provide an update on driving regulatory developments in the USA at the federal and state level. The paper also provides an introduction to the PNGV (focusing on the role and prospects for fuel cells) and discusses the status of fuel cell vehicle development projects.

Keywords: Fuel cells; USA; Vehicles

1. Background

Meeting the rapidly growing demand for transportation services while minimizing the adverse energy and environmental impacts presents serious challenges to US planners and policy makers. The gap between the transportation sector's demand for petroleum (66% of US national demand in 1993) and domestic production is steadily growing, leading to increasing dependence on imported oil. In economic terms, petroleum imports accounted for almost 40% of the nation's merchandise trade deficit in 1993, with imports of motor vehicles and parts accounting for a further 43%. Another cause for concern is the steady growth in the number of vehicles and miles driven, which is aggravating the air quality problems in cities and increasing carbon emissions. To address these issues, a successful transition is required to clean, domestic, fuel energy resources in parallel with increased energy conversion efficiency throughout the fuel cycle. The situation clearly demands the development and deployment of new vehicle propulsion technologies and clean alternative fuels that can compete with reliable, proven, and highly developed conventional products. Fuel cells, with their high efficiency, low to zero emissions, and fuel flexible characteristics, have emerged as one of the most promising technologies to meet this challenge by potentially replacing internal combustion engines (ICEs) in all areas of ground transportation.

2. Partnership for a new generation of vehicles

2.1. Introduction

The Partnership for a New Generation of Vehicles (PNGV), announced in September 1993, is an unprecedented collaboration between the Federal Government and the US Council for Automotive Research (USCAR), which represents Chrysler, Ford and General Motors. The PNGV is aimed at strengthening US competitiveness by developing technologies for a new generation of energy-efficient and environmental-friendly vehicles. The Partnership seeks to link the research efforts of eight participating Federal Gov-

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ernment agencies and associated national laboratories with those of the US auto manufacturers in the pursuit of three specific, interrelated goals [1].

2.1.1. Goal 1: Significantly improve national competitiveness in manufacturing

This means improving the productivity of the US manufacturing base by significantly upgrading US manufacturing technology, including the adoption of agile and flexible manufacturing and the reduction of cost and lead times, while reducing the environmental impact and/or improving product quality.

2.1.2. Goal 2: Implement commercially viable innovations from ongoing research in conventional vehicles

Pursuing technology advances that can lead to near-term improvements in the fuel efficiency and reductions in the emissions of standard vehicle designs, while pursuing advances to maintain safety performance. Research will focus on technologies that reduce the demand for energy from the engine and drivetrain. Throughout the research program, the industry has pledged to apply those commercially viable technologies resulting from this research that would be expected to significantly increase vehicle fuel efficiency and improve emissions.

2.1.3. Goal 3: Develop vehicles that can achieve up to three times the fuel efficiency of comparable 1994 family sedans

Within ten years, increase vehicle fuel efficiency to up to three times that of the average 1994 Concorde/Taurus/Lumina automobiles (26.6 miles per gallon) with equivalent cost of ownership adjusted for economics.

Fig. 1 illustrates the interrelationships among the three PNGV goals: Goal 2 is near-term, Goal 3 is long-term, and Goal 1 is of a cross-cutting nature. In order to accomplish these goals, the US Government and the automotive industry are entering into various cost-shared contacts, subcontracts, cooperative research and development agreements (CRADAs), and collaborations with national laboratories, industry suppliers, universities, and others. The Partnership has identified the most promising technologies and is investigating multiple approaches with the potential to meet rigorous technical and cost requirements. The Partnership provides a unique opportunity for linking the resources and expertise found in the national laboratories, USCAR, and the eight participating Federal agencies (Department of Commerce, Department of Defense, Department of Energy, Department of the Interior, Department of Transportation, Environmental Protection Agency, National Aeronautics and Space Administration, and the National Science Foundation).

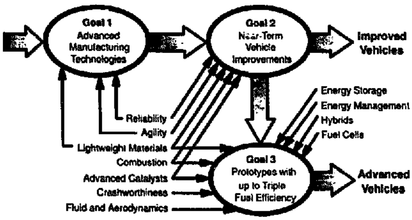

Fig. 1. Three mutually supportive, interactive goals of the PNGV.

2.2. Goal 3 strategy

This paper will focus on PNGV's Goal 3, which presents the difficult challenge of developing, by the year 2004, production prototypes of an up to 80 miles per gallon (mpg) or 34 km per liter (km/l) family sedan which will meet customers' needs for quality, performance, and utility as well as meeting safety and emission requirements. The primary approaches to improving fuel economy are to increase the thermal efficiency of the propulsion system, reduce vehicle mass, and reduce parasitic losses. On the basis of the thermal efficiencies that are technically achievable with various heat engines, it is clear that engine improvements alone cannot meet the triple fuel economy goal. A combination of engine and vehicle improvements will be needed, as illustrated in Fig. 2. The Partnership has adopted a three-prolonged approach aimed at:

- converting fuel energy more efficiently
- reducing the energy demand for the vehicle
- implementing regenerative braking to recapture energy

Technologies that can be combined to achieve the 80 mpg goal include advanced lightweight materials and structures, energy conversion systems (e.g. gas turbines, fuel cells), energy storage devices (e.g. advanced batteries, flywheels, ultracapacitors), more efficient electrical systems, and exhaust energy recovery systems. Reducing the vehicle mass through lightweight materials is critical, either with metals, such as aluminum or magnesium, or with composite materials. Dramatic improvements in propulsion system efficiency (such as is possible with fuel cells) would lessen the requirements for mass reduction. Successful development and commercialization of advanced energy storage and conversion technologies that are inherently fuel flexible will accel-

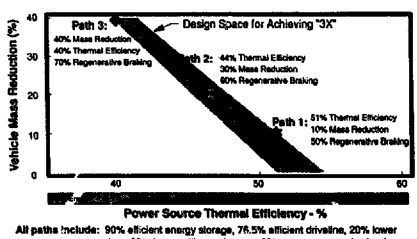

Fig. 2. Range of powertrain and vehicle improvements needed for 80 mpg goal.

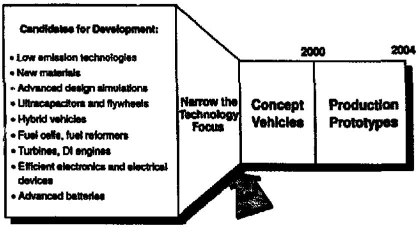

Fig. 3. Overall timetable to achieve PNGV Goal 3.

erate the use of alternative fuels (including electricity) for transportation. Reducing automotive aerodynamic drag and rolling resistance is also important, as that would lessen the magnitude of improvements required in the propulsion system and vehicle mass.

The PNGV goals (as stated earlier) are tied to an aggressive timetable (see Fig. 3) for developing a new generation of vehicles. During 1994, government and industry jointly identified technology areas in which advancements are needed to meet the PNGV goals. Within these areas, government and industry also identified various 'candidate' technologies that are to be developed concurrently. By 1997, the focus of technology development will be narrowed to only those 'candidate' technologies that have become sufficiently developed to likely meet PNGV vehicle requirements within the established timeframe. As the technology focus is narrowed, the auto partners will use these technologies in 'concept vehicles' to evaluate the engineering feasibility of incorporating these technologies into total vehicle systems. Development of these concept vehicles is expected by approximately 2000. As concept vehicle technologies become further developed through additional government and industry research and development, the auto partners will incorporate them into 'production prototype vehicles'. These production prototypes, which are expected about 2004, will demonstrate the manufacturing feasibility of the technologies, as well as their ability to meet rigorous performance criteria.

3. Role of fuel cells in PNGV

The PNGV has identified three primary propulsion system candidates to meet the 80 mpg (34 km/l) goal and is aggressively pursuing their development: 4-stroke, direct injected diesel (in stand-alone or hybrid-electric configuration), gas turbine–electric hybrid (series), and fuel cells (stand-alone or hybrid-electric configuration). Fuel cells have several advantages that make them an attractive power source for vehicle propulsion. Fuel cells can dramatically increase the efficiency of the propulsion system to as high as 50–55% from about 23% for today's conventional vehicles over the Federal Test Procedure driving cycle. As shown in Fig. 4, fuel cells have a distinct thermal efficiency advantage over competing alternatives, based on projected efficiencies over the next ten years. In addition, fuel cell systems have low noise and vibrational characteristics compared to conventional powertrains and produce extremely low or zero emissions that are significantly below current and future automobile emission standards (Fig. 5). When fueled by on-board hydrogen, fuel cell vehicles are true zero-emission vehicles.

Fuel cells also provide a considerable degree of fuel flexibility: they can operate on hydrogen, methanol, ethanol, natural gas, and higher hydrocarbon fuels, which can be derived from a variety of domestic and/or renewable resources. Because of the fuel efficiency advantage of fuel cells, the fuel economy goal of the PNGV could be met with minimal impact on the vehicle design, i.e. the high thermal efficiency will reduce the need for weight reduction of the non-propulsion components). Researchers face a stiff challenge, however, in making fuel cells affordable and practical (size, weight, reliability, serviceability, and durability) for automotive applications within the ten-year timeframe of the PNGV. Key technology challenges include cost, weight, and size reduction; fuel storage, conditioning, and delivery; membranes and electrodes with high efficiency and low loadings of metal catalyst, and thermal management of fuel cell stacks. Integration of the fuel cell, energy storage system, and electric drive and controls is a critical requirement. For automotive

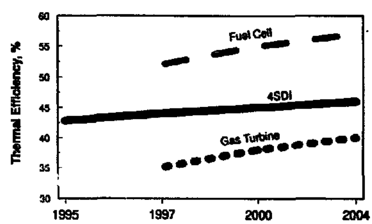

Fig. 4. Fuel cells have the thermal efficiency advantages over competing alternative propulsion candidates (4-stroke, DI diesel; gas turbine). Projected efficiency improvements to year 2004.

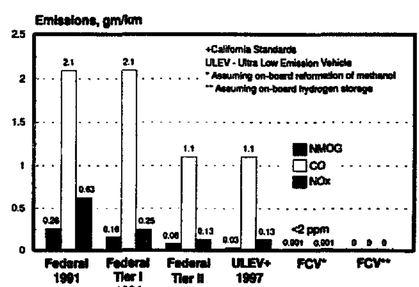

Fig. 5. Fuel cell vehicles provide very low or zero emissions.

use, proton exchange membrane fuel cell (PEMFC) technology is the most mature, but is not yet commercially ready. Direct methanol fuel cell (DMFC) technology does not require fuel reformers, but this technology has not yet attained the power density needed for automotive applications. Solid oxide fuel cell (SOFC) technology offers high power density and the ability to operate on any fuel, but the technology is not yet as mature as PEMFC technology.

4. Fuel cell program of the US Department of Energy

The US Government is working closely with industry and research institutions in pursuing a strategy of aggressive research and development (R&D) to accelerate the commercialization of fuel cell vehicles as an alternative to the internal combustion engine for US transportation. R&D activities are focused on overcoming the major technical, economic, and infrastructure-related hurdles. This growing government–industry program is supported primarily by the US Department of Energy (DOE) and, to a lesser extent, by the US Departments of Defense (DOD) and Transportation (DOT), the National Aeronautics and Space Administration (NASA), and the National Science Foundation (NSF).

The US DOE program is working toward four strategic objectives [2]:

- develop commercially viable fuel cell propulsion systems with the characteristics required for application in the light-duty vehicle market sector by the year 2004 (in support of PNGV)
- develop commercially viable fuel cell-powered propulsion systems with the characteristics required for application in the heavy-duty market sector by the year 2000
- conduct a research and development program to develop materials, components and subsystems necessary to continuously reduce costs, improve performance, and increase reliability of fuel cell systems
- analyze and assess critical technical, market, and policy issues

Consistent with the above four strategic objectives, the current DOE program activities are summarized below.

4.1. Light-duty propulsion systems

DOE is developing two approaches to PEMFC propulsion for light-duty vehicles. The 'on-board methanol reformation approach' (DOE–General Motors project) exploits the existing liquid fuel infrastructure and relies on conventional on-board liquid fuel storage techniques. This approach, however, does burden the vehicle with on-board fuel conditioning and degrades fuel cell performance. The 'direct hydrogen approach' (DOE–Ford and DOE–Chrysler projects) maximizes fuel cell performance and avoids on-board fuel conditioning. This approach, however, requires the development of on-board hydrogen storage technology and an infrastructure with new production, distribution, site storage, and dispensing systems. As referred to earlier, DOE has awarded cost-shared, competitive contracts to teams led by General Motors Corporation, Ford Research Laboratory, and Pentastar Electronics (a Chrysler company) to develop PEM fuel cell technologies for light-duty vehicles. The PEM-based system being developed by the GM team using methanol fuel and an on-board reformer is currently in Phase II of a 30-month effort which began in September 1994. Methanol reformer and fuel cell stack development will result in scale-up to a 60 kW brassboard system. Both the Ford and Pentastar teams are developing PEM-based systems using hydrogen fuel stored directly on-board the vehicle. Both companies began their 30-month contracts in July 1994. They will demonstrate a 30 to 50 kW brassboard system and evaluate hydrogen storage, safety, and infrastructural issues. Overall, the DOE Program has achieved significant progress in PEMFC technology for light-duty vehicles. Large improvements in stack power density (from 0.2 W/cm^2 in 1984 to 0.6 W/cm^2 in 1994) and efficiency (from 40 to 50%) has been achieved with substantial reduction in platinum cost per car and stack cost (from US \$12 000/kW in 1984 to US \$5000/kW in 1994). These technology improvements represent significant progress toward ambitious program goals.

4.2. Heavy-duty propulsion systems

In a joint project with the US Department of Transportation's Federal Transit Administration and the South Coast Air Quality Management District (SCAQMD) of California, DOE initiated development of a phosphoric acid fuel cell (PAFC)-powered bus in 1987 because the bus platform offered the most flexibility in packaging the fuel cell and auxiliary components then available. The first of three methanol-fueled, urban test-bed buses was delivered in April 1994 and is currently undergoing test and evaluation at Georgetown University. The 30 foot long, 25 passenger bus uses a 50 kW PAFC to supply all of the vehicles' energy needs, including wheelchair lifts and air conditioning. The second bus is being readied for demonstration operation by the Los Angeles County Mass Transit Authority. The third bus is undergoing final shakedown testing prior to delivery to the US Department of Transportation. The buses are expected to perform at a level equivalent to diesel buses but with significantly improved fuel economy and emissions. Actual test data from a 50 kW PAFC propulsion system built for a test bed bus shows fuel cell system efficiency of 41% at full load and up to 44% at part load. Carbon monoxide and nitrogen oxide emissions are less than 1/30th of the 1998 Federal heavy-duty diesel emission standards with virtually no hydrocarbon or particulate emissions. Performance is comparable to a diesel bus with half the noise level. Overall, the results of the PAFC bus program are very promising, enhancing the prospects for early commercialization of fuel cells in an urban transportation application. Cost remains a key barrier (US \$3000/kW for PAFC versus US \$100/kW for diesels). In

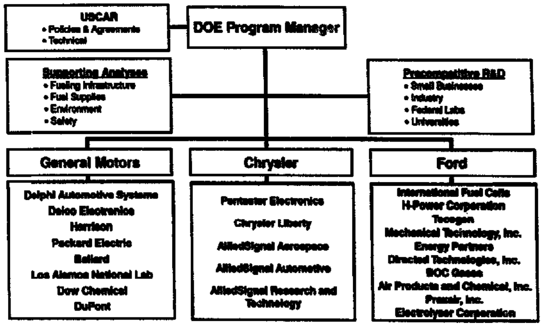

Fig. 6. National fuel cell alliance for light-duty vehicles.

1995, DOE completed a feasibility study (with SCAQMD of California) of a fuel cell propulsion system for locomotives. No further locomotive development effort is planned at this time.

4.3. Supporting R&D

In support of fuel cell system and vehicle development, DOE sponsors a range of pre-competitive R&D activities that are guided by and shared among the major system development contractors. These activities include:

- continued exploratory research of PEM and direct methanol fuel cells, focusing on higher performance, lower cost, and higher reliability, and
- development of compact, lightweight, durable, advanced fuel reformers with rapid startup and load following capability and innovative on-board hydrogen storage systems. A subscale ethanol reformer for potential fuel cell bus application was demonstrated by Arthur D. Little and a comprehensive evaluation of carbon technologies for storing hydrogen was completed. Work on high-efficiency air compressors is being initiated.

4.4. Supporting analysis and assessment

These activities help to integrate the transportation fuel cell program with major federal initiatives to improve the nation's economic productivity, international competitiveness, and environmental quality. DOE conducted an analysis of potential fuel savings and emissions reduction achievable by light-duty fuel cell vehicles [3]. Supporting studies and analyses of fueling infrastructure (e.g. production, storage, transport, and dispensing) for commercializing fuel cells are also being conducted.

4.5. Program funding

Funding for the DOE Fuel Cells in Transportation program has increased steadily from its inception in 1987 to a level of US $22.5 million in Fiscal Year 1995. Funding is projected to slightly decrease in Fiscal Year 1996. The majority of this funding is directed to fuel cell developers under independent vehicle integration teams by the Big Three US automakers. This enables the automakers to pursue different technical approaches which they believe provide the greatest payoffs. To coordinate pre-competitive R&D, a 'National Fuel Cell Alliance' of major government and auto industry stakeholders has been formed under the PNGV umbrella. Fig. 6 shows the major participants which include US automakers, fuel cell developers, subsystem and component suppliers, and the fuels industry.

5. Market opportunities for fuel cell vehicles

5.1. Near-term markets

The focus of near-term markets for fuel cell vehicles will be urban areas having severe air quality problems. Currently, a major driving force for the development of advanced propulsion technologies such as fuel cells is the increasingly stringent emission regulations facing automanufacturers in the USA and overseas. Emissions from fuel cell vehicles fueled with methanol will be substantially lower than California's Ultra Low-Emission Vehicle (ULEV) standard and the US EPA's Tier II standard (for year 2004). California's ULEV standard, for example, specifies stringent emissions levels of 0.03 g/km for non-methane hydrocarbons, 1.1. g/km for carbon monoxide, and 0.13 g/km for nitrogen oxides. When fueled by on-board hydrogen, fuel cells are true zero-emission vehicles (ZEVs), as mandated by California for 1998.

The status of California's ZEV mandate and efforts to adopt the mandate in other parts of the USA (such as the Northeast) is still uncertain and subject to ongoing government–industry negotiations and political developments. California is standing by its ZEV mandate for 1998, despite strong auto industry pressure. The state has turned down an auto industry proposal to participate in a 50-State national Low-Emission Vehicle (LEV) standard that would have scrapped the ULEV and ZEV rules. California's position is that this 50-State program would not allow it to meet Clean Air Act standards by 2010. While not wavering from clean air goals, the State is showing signs of flexibility toward changes to its ZEV mandate in order to accommodate technological realities. In a joint effort with Massachusetts, Governor Wilson of California has ordered an independent audit of battery technologies that will be on the market in 1998. The California Air Resources Board (CARB) is considering proposals for changes in the mandate to allow hybrids to qualify as ZEVs. CARB has conducted a series of workshops to study hybrids and changes to ZEV mandates. CARB has proposed to allow hybrids up to half a ZEV credit if they meet power plant emissions levels associated with recharging of electric vehicles. This could present a major challenge to hybrid vehicle designers since it is reported that hybrid vehicles would have to be 40 to 150 times cleaner than ULEV to meet California's proposed criteria for qualifying as ZEV. Adoption of such challenging emissions requirements for hybrid vehicles could create a significant market opportunity for fuel cell vehicles with their very low- or zero-emission characteristics.

In the Northeastern USA, New York and Massachusetts had previously adopted the California ZEV mandate and been subject to continuing, but unsuccessful, court challenges by the major US automakers. Massachusetts is standing by the ZEV mandate but has indicated flexibility with regard to timing. Massachusetts Governor Weld has proposed rolling back the ZEV mandate from 1998 and requiring that automakers must bring an electric vehicle to market within two years after it is shown that a marketable electric vehicle can be built at no more than 25% price penalty. The US automakers, the Northeastern states, and the US EPA are also engaged in talks on an alternative 49-State plan proposed by the automakers in exchange for rolling back or dropping ZEV mandates. This plan will start in 1997 and is aimed at reducing emissions in all 49-States (excluding California). The plan would be based on baseline LEV standards which can be met with vehicles fueled by reformulated gasoline.

In the near-term, the results of these efforts will have a significant impact on commercial prospects for advanced technology vehicles such as electric and fuel cell vehicles. Based on the adoption of ZEV mandates by California and all 11 Northeastern (and Mid-Atlantic) states of the Ozone Transport Commission region, light-duty ZEV sales are projected to rise from about 71 000 and 1998 to over 350 000 in 2003. (These estimates are based on applying ZEV mandated sales percentages of 2, 5 and 10% to new car and light truck sales.) Looking out to 2003 and beyond, these mandated sales requirements do represent a potentially significant market opportunity for fuel cells and other advanced propulsion technologies.

The current high cost of fuel cells remains a key hurdle to their commercialization. Recent US studies (primarily focused on electric vehicles in California) of the market for advanced technology vehicles provide growing understanding of consumer preferences. While a substantial fraction of consumers (especially in California) are willing to consider the purchase of 'clean' vehicles, competitive pricing is key to consumer acceptance, i.e. initial purchase price is the single most important factor for consumers. Vehicle range may not be as important as initially thought, while availability of refueling infrastructure is very important. For automotive applications, the cost of mass-produced ICEs represent a difficult target for fuel cells to achieve. As levels of fuel cell production increase, economics of scale should help to reduce the cost gap. There is considerable reason for confidence. In a February 1994 report for DOE [4], Allison Engine Company estimated costs of automotive-scale PEMFC system at ≪ US $100/kW (assuming high volume production).

Heavy-duty vehicles may represent a near-term opportunity to gain early experience with fuel cell vehicles because of the greater relative ease with which existing fuel cells can be integrated into the vehicle chassis. Heavy-duty trucks and buses also face increasingly stringent nitrogen oxides and particulate emission standards, both in California and nationally. These are posing serious challenges to diesel engine manufacturers. In fact, urban transit buses may represent an early commercial market opportunity for fuel cells. Despite a higher first cost, fuel cell-powered urban transit buses are projected to be competitive with diesel buses on a life-cycle cost basis. Not surprisingly, aggressive development and testing programs for fuel cell buses are underway in the USA, Europe and Japan.

5.2. Long-term markets

The long-term market prospects for fuel cell vehicles are indeed encouraging. Fuel cell vehicles can compete on an even ground with conventional vehicles in all key aspects, including vehicle range and refueling. The high efficiency, very low emissions, and other favorable characteristics of fuel cells (such as fuel flexibility, low noise, and vibration) create significant market opportunities for fuel cells over the entire spectrum of transportation applications. In fact, fuel cells can be applied to all areas of surface transportation that now use internal combustion engines, from heavy-duty trucks, buses, locomotives, and ships to passenger cars, light trucks, and vans.

Light-duty vehicles represent, by far, the largest segment of the transportation market and are the focus of most US Federal government R&D efforts. Light-duty vehicles are also the largest contributors to transportation petroleum use and polluting emissions in the USA. As an indicator of the size of the overall market, in North America alone, light-duty vehicle sales exceed 16 million units while sales of medium-/heavy-duty trucks and buses exceed 250 000 and 25 000 units, respectively. However, the conventional gasoline (spark ignition) engine and the heavy-duty diesel engine continue to show their versatility and ability to meet more

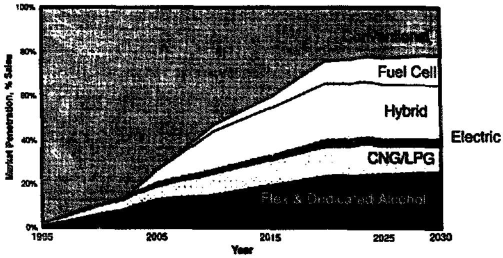

Fig. 7. Fuel cell vehicles face strong competition: market penetration estimates in light-duty vehicle market (1995–2030) [5].

stringent regulations and are expected to remain formidable competitors to other alternatives. Fuel cells also face strong competition from other 'clean' advanced candidates — alternative-fueled ICE's, heat engine — electric hybrids, and electric vehicles. Such a competitive scenario for the light-duty vehicle market is illustrated in Fig. 7. This figure presents market penetration estimates for various advanced vehicle technologies (alcohol, CNG/LPG, electrics, hybrids, fuel cell vehicles) as they displace conventional gasoline vehicles from 1995 out to year 2030. These planning estimates are from the US DOE's 'Five-Year Transportation Program Plan' [5], August 1994 and are based on analysis of consumer preferences for various vehicle attributes and on assumed success of technology R&D efforts being supported by the US DOE. No explicit 'supporting policy' changes by the government are considered. Clearly, the fuel cell faces a very competitive future in the transportation sector. Aggressive development and cost reduction efforts will be needed.

6. Summary

Successful commercialization of fuel cells in transportation will require major investments, sustained commitment, creativity, and a willingness to simultaneously pursue several technology pathways. Near-term opportunities will be created by environmental and regulatory drivers such as California's low-emission and zero-emission requirements. Heavy-duty vehicles with their controlled duty cycles are attractive near-term targets. Long-term prospects are based on achieving competitive performance and economics in the face of strong competition from conventional and other advanced technologies. Establishing advanced vehicles and alternative fuels in the market will take time, gasoline engines have the benefit of over 100 years of evolution and infrastructure development. Government support will be critical in overcoming numerous technical and institutional hurdles, given the magnitude of the investments required and the associated risks. In this overall context, the Partnership for a New Generation of Vehicles (PNGV) is quickly evolving into a unique and effective program to address these barriers through government–industry cooperation. Achievement of the stated PNGV goals will help the nation achieve a smooth transition to a clean, energy-efficient, and fuel-flexible transportation future within an accelerated timeframe. Fuel cells will play an important role in achieving PNGV goals, and many PNGV activities already directly or indirectly support the development and accelerated commercialization of fuel cells in transportation.

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