European
Science and
Technology
Observatory

TRENDS IN VEHICLE AND FUEL TECHNOLOGIES

OVERVIEW OF CURRENT RESEARCH ACTIVITIES

Contact person at JRC-IPTS:
Panayotis Christidis

Operating agent / editor:
Luc Pelkmans (VITO)

Study participants:
Ina De Vlieger (VITO)
Robin Cowan, Staffan Hultén (MERIT)
Ana Morato (OPTI)
Gotzon Azkárate, Rafael Estevan (OPTI - INASMET)

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Institute for Prospective Technological Studies

About the JRC-IPTS

The **Joint Research Centre** (JRC) is a Directorate General of the European Commission, staffed with approximately 2,100 people, coming in the vast majority from the 15 Member States of the European Union. The Brussels Support Services (including the office of the Director General and the Science Strategy Directorate) and seven Institutes located in five different countries compose the main organisational structure of the JRC (http//:www.jrc.org). The Institute for Prospective Technological Studies (IPTS) is one of the seven Institutes making up the JRC. The mission of the JRC is to provide customer-driven scientific and technical support for the conception, implementation and monitoring of EU policies.

The Institute for Prospective Technological Studies (IPTS) is one of the seven Institutes making up the JRC. It was established in Seville, Spain, in September 1994.

The **mission of the IPTS** is to provide prospective techno-economic analyses in support of the European policy-making process. IPTS' prime objectives are to monitor and analyse science and technology developments, their cross-sectoral impact, and their inter-relationship with the socio-economic context and their implications for future policy development. IPTS operates international networks, pools the expertise of high level advisors, and presents information in a timely and synthetic fashion to policy makers (http//:www.jrc.es).

The **IPTS is a unique public advisory body**, independent from special national or commercial interests, closely associated with the EU policy-making process. In fact, most of the work undertaken by the IPTS is in response to direct requests from (or takes the form of long-term policy support on behalf of) the European Commission Directorate Generals, or European Parliament Committees. The IPTS also does work for Member States' governmental, academic or industrial organisations, though this represents a minor share of its total activities.

Although particular emphasis is placed on **key Science and Technology fields**, especially those that have a driving role and even the potential to reshape our society, important efforts are devoted to improving the understanding of the complex interactions between technology, economy and society. Indeed, the impact of technology on society and, conversely, the way technological development is driven by societal changes, are **highly relevant themes within the European decision-making context**.

The **inter-disciplinary prospective approach** adopted by the Institute is intended to provide European decision-makers with a deeper understanding of the emerging science and technology issues, and it complements the activities undertaken by other institutes of the Joint Research Centre.

The IPTS **approach** is to collect information about technological developments and their application in Europe and the world, analyse this information and transmit it in an accessible form to European decision-makers. This is implemented in the following **sectors of activity**:

- Technologies for Sustainable Development
- Life Sciences / Information and Communication Technologies
- Technology, Employment, Competitiveness and Society
- Futures project

In order to implement its mission, the Institute develops appropriate contacts, awareness and skills to anticipate and follow the agenda of the policy decision-makers. **IPTS Staff** is a mix of highly experienced engineers, scientists (life-, social- material- etc.) and economists. Cross-disciplinary experience is a necessary asset. The IPTS success is also based on its **networking capabilities and the quality of its networks** as enabling sources of relevant information. In fact, in addition to its own resources, the IPTS makes use of external Advisory Groups and operates a number of formal or informal networks. The most important is a Network of European Institutes (*the European Science and Technology Observatory*) working in similar areas. These networking activities enable the IPTS to draw on a large pool of available expertise, while allowing a continuous process of external peer-review of the in-house activities.

About ESTO

The European Science and Technology Observatory (ESTO) is a network of organisations operating as a virtual institute under the European Commission's – Joint Research Centre's (JRC's) Institute for Prospective Technological Studies (IPTS) - leadership and funding. The European Commission JRC-IPTS formally constituted, following a brief pilot period, the European Science and Technology Observatory (ESTO) in 1997. After a call for tender, the second formal contract for ESTO started on May 1st 2001 for a period of 5 years.

Today, **ESTO is presently composed of a core of twenty European institutions**, all with experience in the field of scientific and technological foresight, forecasting or assessment at the national level. These nineteen organisations have a formal obligation towards the IPTS and are the nucleus of a far larger network. Membership is being continuously reviewed and expanded with a view to match the evolving needs of the IPTS and to incorporate new competent organisations from both inside and outside of the EU. This includes the objective to broaden the operation of the ESTO network to include relevant partners from EU Candidate Countries. In line with the objective of supporting the JRC-IPTS work, ESTO **aims** at detecting, at an early stage, scientific or technological breakthroughs, trends and events of potential socio-economic importance, which may require action at a European decision-making level.

The ESTO **core-competence** therefore resides in prospective analysis and advice on S&T changes relevant to EU society, economy and policy.

The **main customers** for these activities is the JRC-IPTS, and through it, the European policy-makers, in particular within the European Commission and Parliament. ESTO also recognises and addresses the role of a much wider community, such as policy-making circles in the Member States and decision-makers in both non-governmental organisations and industry.

ESTO members, therefore, **share the responsibility** of supplying the IPTS with up-to-date and high quality scientific and technological information drawn from all over the world, facilitated by the network's broad presence and linkages, including access to relevant knowledge within the JRC' Institutes.

Currently, ESTO is engaged in the following **main activities:**

- A series of **Specific Studies**, These studies, usually consist in comparing the situation, practices and/or experiences in various member states, and can be of a different nature a) *Anticipation/Prospective analysis*, intended to act as a trigger for in-depth studies of European foresight nature, aiming at the identification and description of trends rather than static situations; b) *Direct support of policies in preparation* (ex-ante analysis); and c) *Direct support of policies in action* (ex-post analysis, anticipating future developments).
- Implementation of **Fast-Track** actions to provide quick responses to specific S&T assessment queries. On the other hand, they can precede or complement the above mentioned Specific Studies.
- To produce input to **Monitoring Prospective S&T Activities** that serves as a basis of experience and information for all other tasks.
- ESTO develops a "**Alert/Early Warning**" function by means of Technology Watch/Thematic Platforms activities. These actions are putting ESTO and JRC-IPTS in the position to be able to provide rapid responses to specific requests from European decision-makers.
- Support the production of **"The IPTS Report"**, a monthly journal targeted at European policy-makers and containing articles on science and technology developments, either not yet on the policy-makers' agenda, but likely to emerge there sooner or later.

For more information: http//:www.jrc.es   Contacts: esto-secretary@jrc.es

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prepared by:

LUC PELKMANS (VITO)
STAFFAN HULTÉN, ROBIN COWAN (MERIT)
GOTZON AZKÁRATE (OPTI-INASMET)
PANAYOTIS CHRISTIDIS (JRC-IPTS)

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Editor: Luc Pelkmans (VITO), Panayotis Christidis (JRC-IPTS)

Authors: Luc Pelkmans (VITO)
Staffan Hultén, Robin Cowan (MERIT)
Gotzon Azkárate (OPTI-INASMET)
Panayotis Christidis (JRC-IPTS)

Collaborators:
Ina De Vlieger (VITO)
Rafael Estevan (OPTI-INASMET)
Ana Morato (OPTI)
Hector Hernandez, Ignacio Hidalgo, Antonio Soria (JRC-IPTS)

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CONTACTS

JRC-IPTS
Edf. Expo WTC – C/. Inca Garcilaso, s/n
E-41092 Sevilla, Spain
Tel. +34 95 4488 493 ; Fax. +34 95 4488 279
Panayotis Christidis (panayotis.christidis@jrc.es)
Hector Hernandez (hector.hernandez@jrc.es)

VITO (Operating agent)
Boeretang 200, B-2400 Mol, Belgium
Tel. +32 14 33.58.30 ; Fax. +32 14 32.11.85
Luc Pelkmans (luc.pelkmans@vito.be)
Ina De Vlieger (ina.devlieger@vito.be)

EXECUTIVE SUMMARY

This report covers the second work package of the ESTO study “Trends in Vehicle and Fuel Technologies”. While in the first work package a review was given of trends in the past, the focus in work package two is on recent and on-going research activities concerning vehicle and fuel technologies, mainly for passenger cars.

Most manufacturers still spend most of their efforts in improving conventional gasoline or diesel technology. Their main goal is to comply with future emission limits and to improve fuel economy. Apart from more and more electronic controls in the vehicle, the main developments that can be expected in the area of conventional combustion engines are variable valve actuation and cylinder deactivation, gasoline direct injection and lean burn control, emission after-treatment for lean burn gasoline and diesel engines, auto-ignition, HCCI, etc. In addition to these developments, research is also focusing on new engine fuels, hybrid vehicles and fuel cell vehicles. Interest seems to have been lost in battery electric vehicles.

Hybrid vehicles entered the market several years ago with the introduction of the Toyota Prius and the Honda Insight. More models have followed and other car manufacturers are also considering offering hybrid vehicle models. “Mild hybrids” in particular are gaining interest. These are not so different from conventional vehicles, but have an integrated starter-generator replacing the IC engine’s flywheel and taking over the function of the alternator and the starter. This improves both performance and fuel economy since the IC engine can be downsized, engine turn-off and restart is facilitated, and energy can be recaptured with regenerative braking.

The number of prototype fuel cell vehicles increases day by day, and Honda, Toyota and DaimlerChrysler have recently started limited leasing programmes to gain real-world experience with their fuel-cell cars. Because the cost is still very high and technical improvements are still needed, the vehicles will only be leased to selected private sectors, institutional organisations, research facilities and technology-related companies. These first cars are fuelled with hydrogen, which limits their use since there are only a few hydrogen refuelling facilities at present. Some fuel cell vehicle prototypes have on-board chemical factories called reformers that extract hydrogen from methanol, gasoline or other hydrocarbon fuel. This seriously facilitates the infrastructure and storage issues related to the use of hydrogen gas although, unfortunately, a reformer adds more weight and technical complexity to a car.

There are still a great number of structural obstacles to the diffusion of fuel-cell technology. The choice of the fuel with reference to various primary energy sources, the development of new infrastructures required to produce and distribute the new fuels, the learning time of the new fuel-cell technologies (fuel storage, on-board reforming, membrane electrodes assembly, etc.) including the definition of new standards related to safety and to other relevant homologation issues, the engineering optimisation (reduction of volume and weight, efficient auxiliaries), cost reduction, all require a long development time-frame (15-25 years). This means that a major breakthrough of fuel cells into the market will probably not happen before 2020. In the meantime, demonstration programmes are expected to be followed by the growth of niche markets, mainly supported by public administrations sensitive to environmental issues where motivations could help in overcoming the economic and infrastructure obstacles.

The report also highlights the differences between stationary and mobile applications of fuel cells. From an environmental point of view, the two types of fuel cell applications should be addressed in different ways, depending on their uses and the required power outputs, considering at the same time the differing state of progress in research and development. The shift to a hydrogen economy does not necessarily mean that a common technology development path will be followed, nor that there would be synergies between the markets for power generation and transport applications.

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ACRONYMS

Fuels and chemical substances

CFC	Chloro-Fluoro carbons	LNG	Liquefied Natural Gas
CGH_2	Compressed Gaseous Hydrogen	LPG	Liquefied Petroleum Gas
CH_4	Methane	M85	85% Methanol, 15% Gasoline
CHF	Clean Hydrocarbon Fuel	MTBE	Methyl Tertiary Butyl Ether
CNG	Compressed Natural Gas	N_2O	Dinitrogen Oxide
CO	Carbon Monoxide	NG	Natural Gas
CO_2	Carbon Dioxide	NiMH	Nickel Metal Hydride
DME	Dimethyl Ether	NMHC	Non-methane Hydrocarbons
E85	85% Ethanol, 15% Gasoline	NMOG	Non-Methane Organic Gases
E95	95% Ethanol, 5% Gasoline	NO_x	Nitrogen Oxides
ETBE	Ethyl Tertiary Butyl Ether	PM	Particulate Matter
FAME	Fatty Acid Methyl Ester	RFG	Reformulated Gasoline
GHG	Greenhouse Gases	RME	Rapeseed Methyl Ester
GTL	Gas-to-Liquid	SOF	Soluble Organic Fraction
H_2	Hydrogen	SO_x	Sulphur Oxides
HC	hydrocarbons	TBA	Tertiary Butyl Alcohol
HCHO	Formaldehyde	VOC	Volatile Organic Compounds
LH_2	Liquefied Hydrogen		

Technical terms

4WD	4 wheel drive	LDV	Light Duty Vehicle
A/F	Air to Fuel ratio	LEV	Low Emission Vehicle
ABS	Anti-lock Braking System	MCFC	Molten Carbonate Fuel Cell
AFC	Alkaline fuel cell	MDPV	Medium Duty Passenger Vehicle
APU	Auxiliary Power Unit	MDT	Medium Duty Truck
BEV	Battery Electric Vehicle	MIL	Malfunction Indicator Light
CAFE	Corporate average fuel economy	MPI	Multi Port Injection
CAGR	Corporate Average Growth Rate	MTA	Manual Transmission
CAN	Controller Area Network	MY	Model Year
Cd	Drag Coefficient	NA	Naturally aspired
CI	Compression Ignition	NEDC	New European Driving Cycle
CIDI	Compression Ignition Direct Injection	NGV	Natural gas vehicle
CR	Compression Ratio	OBD	On-Board Diagnostics
CRT	Continuously Regenerating Trap	OEM	Original Equipment Manufacturer
CVT	Continuously Variable Transmission	PAFC	Phosphoric Acid fuel cell
DFI	Digital Fuel Injection	PCU	Power Control unit
DI	Direct injection	PCV	Positive Crankcase Ventilation
DISI	Direct injection spark ignition	PEM-FC	Polymer Exchange Membrane Fuel Cell
DMFC	Direct methanol fuel cell	PFI	Port fuel injection
DPF	Diesel Particulate Filter	POX	Partial Oxidation
ECE	Urban Driving Cycle (EU)	P-ZEV	Partial Zero Emission Vehicle
ECU	Engine (electronic) Control Unit	RVP	Reid Vapour Pressure

EDC	Electronic Diesel control	SA	Starter Alternator
EFI	Electronic Fuel Injection	SCR	Selective catalytic reduction
EGR	Exhaust gas recirculation	SI	Spark ignition
EUDC	Extra-Urban Driving Cycle (EU)	SOFC	Solid Oxide Fuel cell
EV	Electric Vehicle	SR	Steam Reforming
FC	Fuel Cell	SULEV	Super Ultra Low Emission Vehicle
FCV	Fuel Cell Vehicle	SUV	Sport Utility Vehicle
FFV	Flexible Fuel Vehicle	TBI	Throttle Body Injection
FPFC	Fuel Processed (reformer) fuel cell	TC	Turbo charged
FSI	Fuel Stratified Injection	TD	Turbo diesel
FT	Fisher-Tropsch Processed	TDI	Turbocharged Direct Injection
FTP	Federal Test Procedure (US)	TLEV	Transitional Low Emission Vehicle
GDI	Gasoline Direct Injection	TTW	Tank-to-wheel
GVW	Gross Vehicle Weight	TWC	Three Way Catalyst
HCCI	Homogeneous Charge Compression Ignition	ULEV	Ultra Low Emission Vehicle
HEV	Hybrid Electric Vehicle	ULSAB	Ultra Light Steel Auto Body
HSDI	High Speed Direct Injection	ULSAC	Ultra Light Steel Auto Closure
HVAC	Heating, Ventilation and Air-Conditioning	ULSAS	Ultra Light Steel Auto Suspension
ICE	Internal Combustion Engine	VMT	Vehicle Miles Travelled
IDI	Indirect injection	VVA	Variable Valve Actuation
IMA	Integrated Motor Assist	VVT	Variable Valve Timing
ISAD	Integrated Starter Assist Damper	WTT	Well-to-tank
ISG	Integrated Starter Generator	WTW	Well-to-wheel
LAN	Local Area Network	ZEV	Zero Emission Vehicle

Organisations and workgroups

AAA	Association Auxiliaires de l'Automobile
ABI	Austrian Biofuels Institute
ACEA	European Automobile Manufacturers Association
AECC	Association for Emissions Control by Catalyst
AFDC	Alternative Fuels Data Centre (US)
AMAA	American Automobile Manufacturers' Association
AMI	American Methanol Institute
APME	Association of Plastics Manufacturers in Europe
CAA	Clean Air Act
CAAA	Clean Air Act Amendment
CARB	California Air Resources Board
CEC	California Energy Commission
DOE	United States Department of Energy
DOT	United States Department of Transportation
EAA	European Aluminium Association
EIA	United States Energy Information Administration
EPA	United States Environmental Protection Agency
EU	European Union
EU15	15 member states of the European Union
IANGV	International Association for Natural Gas Vehicles
IEA	International Energy Agency

INEE	Instituto Nacionàl de Efficiéncia Energética (Brazil)
IPCC	Intergovernmental Panel on Climate Change
JAMA	Japan Automobile Manufacturers Association
MEET	Methodologies for Estimating Air Pollutant Emissions from Transport
NAEI	National Atmospheric Emissions Inventory (UK)
NAVC	Northeast Advanced Vehicle Consortium
NLEV	National Low Emission Vehicle Program (US)
OTT	Office of Transportation Technologies (US DOE)
PNGV	Partnership for a New Generation of Vehicles
SAE	Society of Automotive Engineers
SMMT	Society of Motor Manufacturers and Traders
UFOP	Union zur Förderung von Öl- und Proteinpflanzen (Germany)

INTRODUCTION

In recent years there has been considerable growth in road transport, and this trend is set to continue for the foreseeable future. Today's transport is based almost exclusively on the consumption of petroleum products such as gasoline and diesel, and is responsible for producing more than 20% of overall anthropogenic CO_2 emissions. The contribution of transport to greenhouse gas levels will continue to grow as demand for cars worldwide remains high and the potential for reducing CO_2 emissions from conventional vehicles reaches its limits.

The achievement of sustainable mobility represents a major challenge for policymakers and vehicle technologies for individual mobility are recognised as having the potential to make a significant contribution. In particular, they could provide continued personal freedom with reduced energy consumption and improved environmental performance.

In recent decades vehicles have undergone several changes towards more environmentally friendly transport. Some of these changes are a matter of technology developments and cost optimisation, but many were driven by government interventions such as emission legislation. There are several technical options for future vehicles, all getting cleaner because of the will to comply with stricter emission levels. In particular, developments towards fuel cell vehicles seem attractive for the long term, at a time when fossil resources are slowly but surely diminishing.

The objective of the ESTO study is to review the past trends and anticipate future developments in vehicle and fuel technologies, in relation mainly to passenger transport. The overall study provides an overview of the trends in the main families of conventional and alternative technologies and fuels, covering the evolution of their main technical characteristics, fuel economy, user costs (variable and fixed) and environmental impacts.

The technologies covered include internal combustion engines both on conventional fuels (gasoline or diesel) and on alternative fuels (LPG, natural gas, hydrogen, alcohols, biodiesel, DME and synthetic fuels), electric vehicles, hybrid vehicles and fuel cells. Extra attention has been given to alternatives that can provide hydrogen for fuel cells.

The time-scale of the study covers the last 20 years for the past trends and extends to 2020 in its anticipation of possible developments. The study covers worldwide developments, with particular emphasis on the potential of introduction of new technologies in Europe, North America and Japan.

1 MAIN DEVELOPMENTS IN RESEARCH ACTIVITIES, PILOT APPLICATIONS AND FIELD TRIALS

by Luc Pelkmans (VITO) & Gotzon Azkarate (INASMET)

Review of the main developments in research activities, pilot applications and field trials of emerging vehicle and fuel technologies.

1.1 Conventional drive trains: Spark ignition engines

1.1.1 Introduction

R. Bernard, FIAT Research Centre*:* "The 4-valve per cylinder head design with sequential PFI injection, combined with the 3-way catalyst is the top technology today adopted world-wide in passenger car gasoline engines. For the near future the R&D effort is aimed to further develop this technology with focus on fuel economy improvement." [Bernard, 2001]

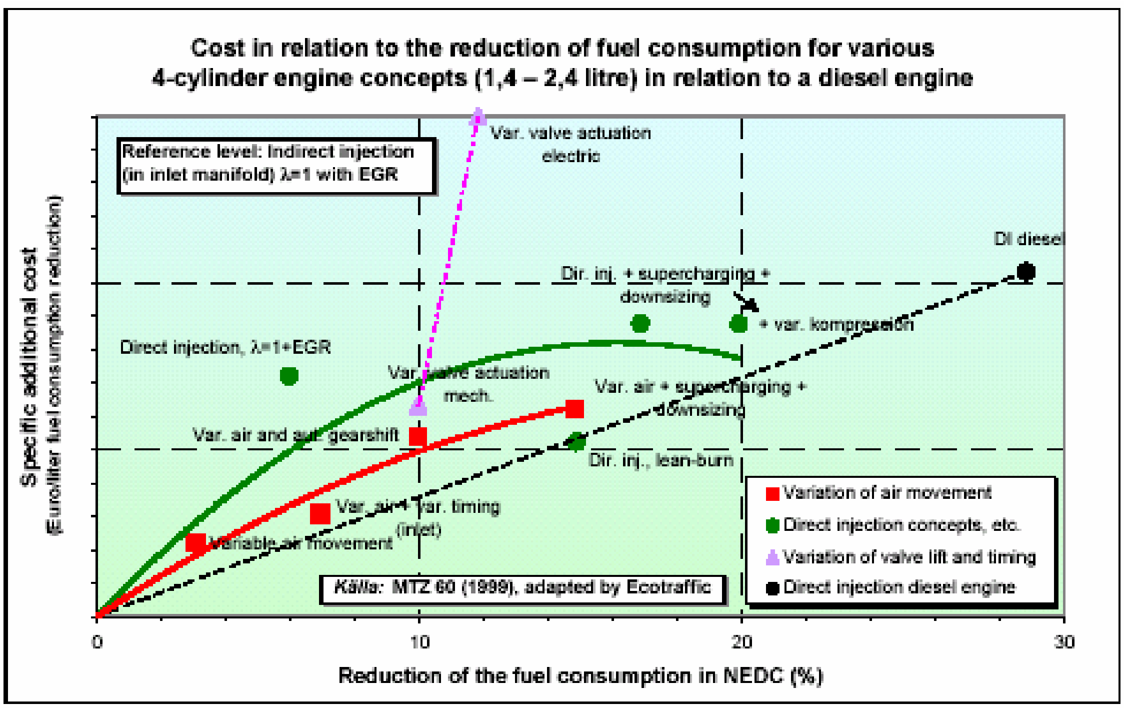
Spark-ignition engine trends [Automobile Engineering, January 2002]

In the face of growing competition from diesels and alternative power sources, some of the latest prototype and production gasoline-fuelled engines show how continued engineering development is meeting demands for more power, reduced fuel consumption and emissions, and more efficient packaging.
The main target for advanced spark-ignition engine development is improvement in fuel economy, thus a reduction in CO_2 emissions. This goal can be achieved thermodynamically by operating at higher loads or with reduced gas exchange and heat losses at part load. Technical solutions include supercharging and turbocharging, fully variable-valve timing, and direct injection.
One strategy for substantially improving fuel economy is to **downsize engine** displacement while retaining the shape of the torque curve. This initiative can be achieved by pressure boosting (up to 250 kPa) at low loads and by lowering the compression ratio at high loads. Technologies needed for this concept are a **high-efficiency mechanical supercharger** that would provide high levels of immediately available torque. A **variable-compression-ratio** device would enable reduced knock-free compression at full load, while retaining highly efficient compression at part load.
Charge exchange losses could be avoided with **fully variable-valve timing**. Devices are under development that could provide variability using electromagnets. Employment of this technology would allow valve timing to be infinitely adjustable to vary inlet-air and residual-gas masses, avoiding throttle losses at part load and reducing NO_x formation. In addition, full freedom for cylinder management would be ensured. Prototype tests confirm fuel savings of 15%, reaching 20% if **cylinder cut-out** in multi-cylinder engines is adopted.

New **high-pressure injection systems** and progress in **de-NO_x catalysts** have resulted in the first mass-produced gasoline engines from Mitsubishi Motors Corp., Toyota Motor Corp. and Volkswagen AG that offer fuel economy advantages of 10%-15% For best fuel economy, these engines operate at part load with extremely lean air/fuel ratios (lambda). To stabilise the combustion process and avoid soot formation at part load, the mixture formation has to be supported by a controlled charge-air motion. At full load, the mixture becomes homogenous to deliver maximum power output.
New **multihole injector designs** will no longer operate by wall-or air-guided charging, but will instead enable a spray-guided combustion process similar to that of a diesel engine. Since the stratified charge process would operate with excess air, a deNO_x catalyst system and the subsequent availability of sulphur-free fuel will be required for this technology.

The following figure is derived from an Ecotraffic study in 2001 and shows the cost of these various engine improvements compared to the fuel consumption reduction.

Figure 1.1-1: Engine improvements for fuel consumption reduction – relation between cost and reduction potential



Source: Ahlvik & Brandberg, 2001

1.1.2 New technology prototypes and production engines

Spark-ignition engine trends [Automobile Engineering, January 2002]

2002 **Honda** Acura RSX with the first US application of Honda's latest "intelligent" valve-control system (i-VTEC), adding variable timing control (VTC), which continuously adjusts camshaft phase, to Honda's variable-valve timing and lift electronic control (VTEC). The result is impressive power, fuel economy and low exhaust emissions.

Porsche AG adds forced induction via turbocharging to its VarioCam Plus variable-valve timing technology in its "ultimate" sports cars – the GT2.

The new **BMW** 316ti Compact was the first of many BMWs to feature the company's patented Valvetronic engine-management system, which infinitely adjusts intake-valve lift and makes the car's 1.8L 4-cylinder engine the first production gasoline unit in the world to do *without a throttle butterfly*. BMW says the system helps to reduce fuel consumption under normal operating conditions by at least 10% and reduces exhaust emissions accordingly – regardless of fuel quality. BMW believes the introduction of Valvetronic is as significant as the transition from the carburettor to fuel injection, from two to four valve technology, and from mechanical to electronic engine management. BMW will fit Valvetronic technology to all of its eight and 12 cylinder engines within the next two years.
The reduction in fuel consumption provided by the throttle-free load management is roughly 10% in the EU-cycle and at least 10% under normal driving conditions. Valvetronic offers at least the same improvement in fuel economy as direct injection without some of its compromises, especially in emissions, adds the company. Lean-burn direct-injection drawbacks include the additional technology required for exhaust after-treatment and the limited availability of low-sulphur fuel. Beyond the new V8s and I4, Valvetronic technology will be supplemented by gasoline direct injection for the upcoming 760Li's 12 cylinder powerplant. Unlike gasoline direct-injection engines incorporating lean-burn technology and a deNO_x catalytic converter, BMW's Valvetronic + DI concept uses lambda-1 emissions technology.

Ford's DISI (direct-injection spark-ignition) technology is developed for testing in a 52kW 1.1 L inline three-cylinder Ford Fiesta. DISI technology uses stratified charging to overcome the lean ignition limitation of the air/fuel mixture. In a direct-injection engine, the injection nozzle is located inside the combustion chamber rather than in the induction system. A relatively small, precisely shaped A/F mixture around the spark plug results just before ignition. Only the area directly around the spark plug contains the concentrated or stratified A/F mixture; the rest of the combustion chamber contains air or recirculated exhaust gas. The charge stratification allows Ford's new DISI engine to burn total cylinder mixtures with a much higher concentration of air than conventional lean-burn engines; the A/F ration can be as high as 60:1 (lambda~5). The "cushion" of gas around the combustion chamber means that less heat has to be evacuated, improving the thermal efficiency of the engine. The DISI's charge stratification process works best at low and medium loads in the lower half of the engine-speed range - where traditional gasoline engines are least efficient. The major fuel-consumption reduction potential of 21% is realised in the urban driving cycle because the DISI engine operates in a stratified-lean mode most of the time. Another factor contributing to the improved fuel economy of Ford's DISI is an increase in compression ratio from a conventional 10:1 to about 11.7:1, without the need for premium fuel, because direct injection reduces the tendency for engine knock. The higher compression ratio increases efficiency by about 2%.

The **Opel** Signum concept car unveiled at the Frankfurt Motor Show featured a new General Motors V8 concept engine called XV8. The all-aluminium 4.3L XV8 uses a three-valves-per-cylinder combustion chamber configuration to support optimisation of its air-assisted direct fuel-injection system. "Displacement on Demand" technology allows the XV8 to shut down half of its cylinders in certain situations to significantly reduce fuel consumption without adversely affecting performance.

1.1.3 Optimisation of classical throttled engine

The future development of SI engines will be determined by a considerable reduction of pollutant emission and specific fuel consumption. On the opposite side, a relatively high torque, respectively high power level remains a basic condition of acceptance. The optimisation way between both sides shows different stages of complexity.
The consequent *optimisation* of the classical, throttled SI engine with external mixture formation – concerning mass reduction, accurate function optimisation, exhaust gas recirculation, intake flow tuning and camshaft angle variation – allows a decrease of the specific fuel consumption in the range of 15 %, respectively an emission of pollutants under the future limitation levels.

1.1.4 Gasoline direct injection

The gasoline Direct Injection technology offers in principle many advantages in comparison with traditional PFI systems:

- Higher volumetric efficiency
- Elimination of the wall-wetting phenomenon
- Better control of the air-to-fuel ratio in transient operations and warm-up conditions
- Charge stratification if an ultra-lean combustion system has to be developed.

Applying the stoichiometric DI concept to today's four-valve engines, a fuel economy improvement of about 6% can be achieved without major modifications of the combustion system, thanks to the combined effect of increased compression ratio and improved A/F control. Part of this fuel economy improvement can be obtained with the use of longer transmission ratio, allowed by the higher low-speed torque. With this approach the future European emission standards could be easily satisfied with well-assessed after-treatment technologies.

The development and application of the gasoline ultralean DI concept is, of course, very attractive for its theoretical potential of fuel consumption reduction higher than 10%. In this case, however, the injection system has to meet much more severe requirements concerning fuel atomisation and long-term operation stability; moreover, a $DeNO_x$ catalyst with very high efficiency must be available and fuels with a sulphur content practically equal to zero must be used in order to satisfy the Euro 4 emission standards of the year 2005. In any case, the specific A/F variation to allow the NO_x reduction process and above all the necessity to regenerate often the catalyst result in a significant penalty for fuel economy. For this reason the widespread use of this technology in the European passenger-car market is still in doubt.

1.1.5 Advanced cooling system

Another technology that could offer a lower, but significant contribution to the improvement of fuel economy of the gasoline engines is the "Advanced Cooling System", based on the use of an electric water pump and a flow-controlling valve, both controlled by the engine control unit. In this way engine efficiency could be improved by controlling the heat transfer between the coolant and the engine structure and maintaining the coolant temperature as close as possible to the optimal values in any engine operating point. Moreover, smart management of the heat transfer could give further advantages in terms of thermal comfort for the car passengers. The potential maximum fuel consumption reduction achievable on a gasoline engine in the NEDC cycle is of the order of 3%; this benefit could be even higher in the real vehicle use, especially in urban and winter use, where the warm-up phase is more important.

1.1.6 Variable valve control

The strategic potential of **Variable Valve Actuation** technologies for engine performance and fuel economy improvement is widely recognised. Furthermore, the use of VVA systems to deactivate some of the cylinders and in such a way as to increase engine efficiency in partial load conditions is another means of increasing the fuel economy of large displacement gasoline engines.

Fully electronically controlled VVA systems have been envisaged in recent years by several car manufacturers and suppliers, and are capable of fully exploiting the variable timing, duration and lift potential through a complete and highly flexible electronic control of the valves opening and closing laws. Apart from systems based on the variation of the valve motion through sophisticated mechanical systems (one of these was recently launched on the market by BMW), two are the main actuation technologies presently under investigation, namely the electro-magnetic technology and the electrohydraulic one. These systems allow:

- Maximisation of the trapping efficiency over the entire engine speed range (torque optimisation)
- Operation of the engine unthrottled (pumping loss minimisation)
- Dynamic control cylinder-by-cylinder and stroke-by-stroke, of the inlet air or charge (driveability improvement)
- Selective deactivation of any valve in any cylinder (combustion optimisation and engine modularity).

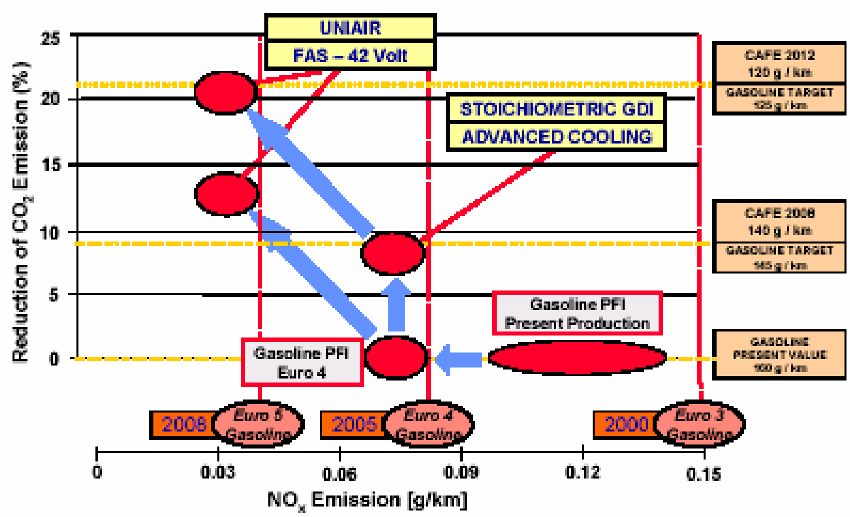
The electro-hydraulic approach, followed by Fiat (UNIAIR system), has the potential to achieve all the functional advantages expected from the VVA concept. The robustness of this technology and its intrinsic fail-safe characteristics are fundamental prerequisites for the development of a reliable and mass producible automotive system. Moreover, the system is applicable on both gasoline and diesel engines; in diesel, other systems cannot be used due to the very short distance between the piston top and the cylinder head.

Table 1.1-1: The Advantages of the FIAT UNIAIR System

Spark-Ignited Engine (Intake valves – Throttle elimination)	Diesel Engine (Intake and exhaust valves)
- Engine performance (Torque – Power) increase between 10 and 15% - Vehicle fuel economy increases between 10% and 15% - Emission reduction through specific engine valve management strategies - Increased vehicle driveability ("programmable" via software)	- Improved engine cold-start performance (low-end torque-turbo lag reduction) - Emission reduction (internal EGR – variable swirl) - Further fuel economy increase

Source: Bernard, 2001

Figure 1.1-2: Gasoline powertrain technology road map

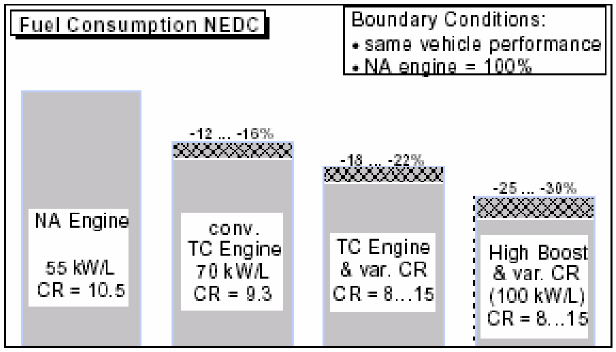


Source: Bernard & Rinolfi, 2001

1.1.7 Engine downsizing and variable compression ratio

Downsizing concepts allowing a displacement reduction through an increase in volumetric efficiency have already been realised in production vehicles. Here, the advantages in fuel consumption are obtained through friction reduction and shifting of the operating point. The adjustment of the compression ratio is a compromise, however, since due to engine knock sensitivity high power calls for a low compression ratio, whereas for part load a high compression ratio is beneficial. Frequently, a relatively high compression ratio is chosen during the design which yields advantages in the cycle fuel consumption. These advantages, however, can often only be partially exploited during actual driving; e.g. in the case of a high percentage of highway driving. Only the combination of supercharging and variable compression can make use of the full potential of downsizing: Reductions in fuel consumption of up to 30% can be achieved.

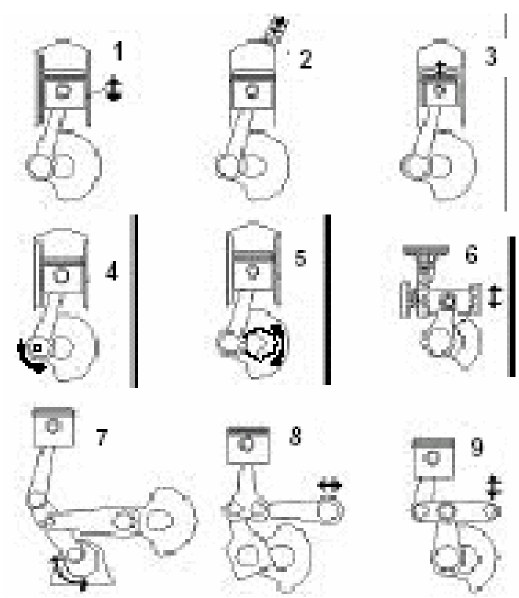
Figure 1.1-3: Fuel consumption benefits by variable compression ratio (CR)



Source: Pischinger, 2001

Patent literature offers many possibilities for realisation of a variable compression ratio. shows the variations graphically.

Figure 1.1-4: Design concepts - state-of-the-art



1: Shift of cylinder block
2: Combustion chamber shaping
3: Piston shaping
4: Excentric conrod bearing
5: Excentric crankshaft bearing
6: Force transmission via rack and pinion gear
7-9: Additional conrod mounting point

Source: Pischinger, 2001

Table 1.1-2: Comparison of known concepts of variable compression ratio

Concept	Combustion - chamber geometry	force requirement adjusting unit	additional forces of inertia	controllability	costs
movable cylinder head,-barrel	+	-	++	o	--
variable combustion-chamber volumeauxiliary piston	–	++	++	++	o
piston with adjustable compression height	+	++ (self reg.)	-	-	o
eccentric conrod bearing	+	o	o	o	o
crankshaft positioning	+	++	++	+	o
two-piece pivoted conrod CCE-principle	+	-	--	+	-

excellent	++
good	+
satisfactory	o
disadvan-tageous	-
insufficient	--

Source: Pischinger, 2001

Important players in this area mentioned in the literature are FEV (Germany) and Saab (Sweden).

Saab Variable Compression Ratio engine [SAAB, 2000]

At the 2000 Geneva Motor Show, Saab Automobile AB unveiled the Saab Variable Compression (SVC) engine. The engine is comprised of a cylinder head with integrated cylinders, which is known as the monohead, and a lower portion consisting of the engine block, crankshaft and pistons. The compression ratio is varied by adjusting the slope of the upper part of the engine in relation to the lower part by up to four degrees. This alters the volume of the combustion chamber and changes the compression ratio.

The energy in the fuel is better utilized when the compression ratio is as high as possible. However, if the compression ratio is too high, the fuel will pre-ignite and cause "knocking," which could damage the engine. Due to its variable compression ratio, the SVC engine can be run at the optimum compression ratio of 14:1 at low load in order to maximise the use of the energy in the fuel. The compression ratio can then be lowered to 8:1 at high load to enable the engine performance to be increased by supercharging without causing engine "knock."

The SVC engine concept reduces fuel consumption by up to 30 per cent when compared with a larger conventional naturally aspirated engine of similar power output. It also provides the tremendous output of 150 horsepower per litre of engine displacement.

1.2 Conventional drive trains: diesel engines

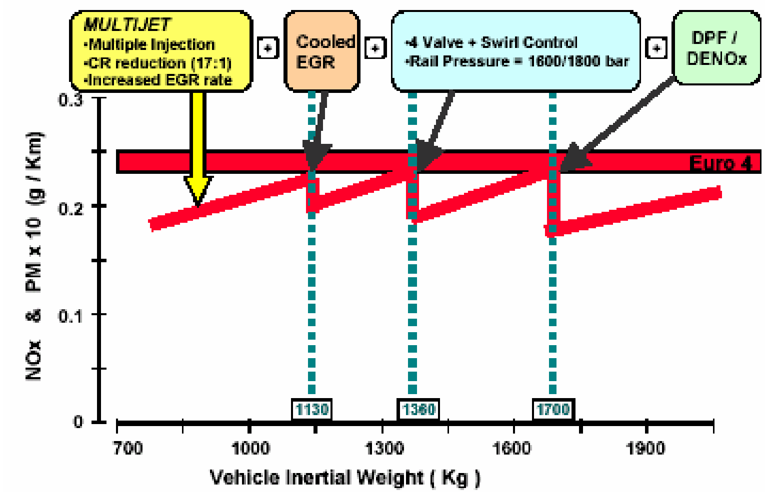
1.2.1 Technologies for the diesel powertrain

Modern High Speed DI Diesel engines are today capable of reaching levels of performance and refinement unbelievable just a few years ago: this is mainly due to the availability of very advanced fuel-injection technologies.
Over the last three years High Speed DI Diesel engines have gained a great market penetration in Europe, both in passenger cars (over 35% for new registrations) and on Sport Utility Vehicles (SUV) (almost 100% for new registrations). Thanks to the high efficiency of DI Diesel combustion, these engines show an average advantage of about 30% (in terms of fuel consumption) in comparison with gasoline engines. This means a reduction of more than 20% in terms of CO_2 emission and a substantial fuel cost-saving for the customer, given the lower price of diesel oil in most European countries.

The technological evolution of diesel engines in the near future will be driven by environmental requests for much lower emission levels which, by the end of this decade, could approach those for gasoline engines. The fulfilment of these future emission standards will allow the diesel powertrain market share to continue increasing, so helping car manufacturers meet the CAFE demand from the European Union.
The second-generation Common Rail technology, apart from the increase of the maximum injection pressure, will also be based on the use of **Multiple Injections**. This concept will allow splitting of the present main injection into two or more smaller injections, enabling control of the injection-phase duration independent of injection pressure: this means better control of the combustion process and, in the end, lower emissions, especially in terms of soot and NO_x.

Considering the Euro 4 emission standards, various technologies must be utilised as a function of the vehicle inertial weight (see Figure 1.3). The Multijet (Multiple Injection) system allows these limits to be met on small-medium size cars with conventional EGR and after-treatment systems. On heavier cars, swirl control and higher pressure levels for the fuel injection must be used; on high-segment cars, the use of specific after-treatment devices, such as the PM trap or high efficiency $DeNO_x$ catalyst, will become mandatory. Even if the PM trap is not needed for low inertia vehicles, its adoption could be foreseen in order to accomplish socio-political expectations in respect of fine-particle elimination.

Figure 1.2-1: Diesel technologies to meet Euro 4 emission standards



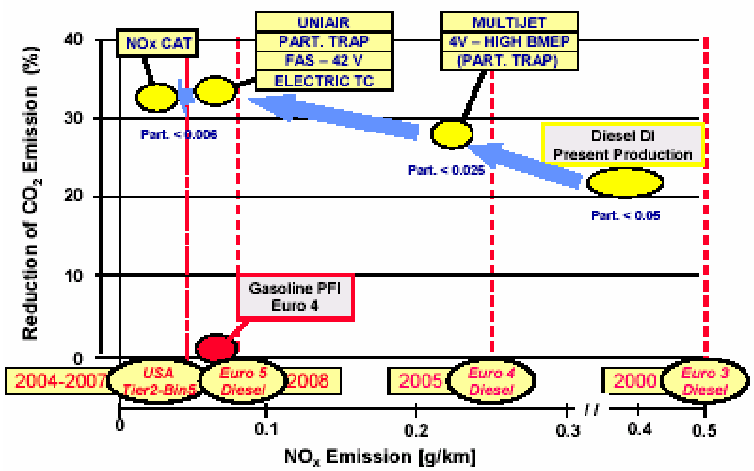
Source: Bernard & Rinolfi, 2001

When the PM trap is considered by way of example, the main problem to solve is the cyclic regeneration of the trap, i.e. burning the particulate trapped in the filter, without the use of complex and expensive systems for increasing the exhaust gas temperature (e.g. the addition of some additives in the fuel). Moreover, the oxidation of some hydrocarbons in the catalyst upstream of the trap could help to increase the gas temperature at the trap inlet. In order to help the trap regeneration process with minor modifications of the engine hardware, the key-idea is to use injection strategies based on fuel after and post injection in specific engine operating points. In such a way a gas temperature above 600°C, necessary to regenerate the particulate filter, can be achieved in all the engine points corresponding to the emission driving cycle, without incurring a heavy penalty in fuel consumption.

Considering the transition to the stricter Euro 5 emission standards, the need to use PM trap and $DeNO_x$ catalyst technologies will continue to increase. In view of this, a new diesel combustion approach is needed not only to manage the regeneration of these after-treatment devices, but also to reduce the engine-out emission levels; in fact it is quite impossible to rely only on after-treatment technology as this would mean a conversion efficiency for NO_x approaching 80% to 90%.
The formation of NO_x and PM are mainly defined by combustion temperature and equivalence ratio; new combustion process such as the **HCCI** or, in any case, a Low Temperature Combustion process, could allow achievement of this target by controlling at the same time the equivalence ratio through the EGR recirculation.

Beside the use of the Multiple Injection technology for the control of the combustion process, new technologies could be used to control in addition, stroke by stroke, the air and EGR quantity in the cylinder. The VVA actuation technology mentioned previously could help to solve this problem.

Figure 1.2-2: Diesel powertrain technology road map



Source: Bernard & Rinolfi, 2001

The use of a new high-efficiency electric machine, such as the **Flywheel Alternator Starter** or **Electrical Assisted Turbocharger**, could help to reduce the peak levels of pollutant emission in transient conditions, allowing a lower transient increase of the engine torque by the addition of an electric “boost” (and “clean”) torque.

1.2.2 DeNO$_x$ after-treatment systems

The Future of Clean Diesel [*Auto Emissions*, Special Report, Autumn 1999]

Nitrogen oxides present the most daunting ongoing challenge to the pursuit of lowering diesel emissions. Traditional three-way catalysts do not respond to the lean air-fuel mixture that makes diesel so efficient. Several technologies, however, are being introduced or are in development which address the NO$_x$ issue in lean-burn engines. Exhaust Gas Recirculation (EGR) reduces NO$_x$ 40% on average but even this is not enough to satisfy upcoming regulation. So what is the answer?

1.2.2.1 Selective Catalytic Reduction

One of the promising alternatives appears to be Selective Catalytic Reduction (SCR). SCR technologies use ammonia in the form of urea to supplement the catalytic reaction – in essence, giving nitrogen oxides the "extra" molecules needed to convert to harmless nitrogen and water.. SCR does not require special fuel, owing to its high sulphur tolerance, and can be a good candidate for retrofitting in heavy duty applications, since it does not necessarily require interaction with the engine controller. The technology has demonstrated a 70% to 90% NO$_x$ reduction in both the North American FTP cycle, and the New European Driving Cycle. And this demonstration has come not just in research labs, but through wide use in the later stages of development. In terms of efficiency and sulphur tolerance, SCR is a very promising technology.
At the same time, SCR is not without its drawbacks. SCR produces relatively high N_2O emissions compared to a conventional diesel engine. The urea form of ammonia it uses is not dispensed at every gas station, and would need to be: an immense undertaking in

terms of capital investment and infrastructure development. And with urea use will come other demands within the automobile, such as an OBD system to monitor use, and precise control to avoid ammonia slip. Despite all these factors, SCR remains highly regarded as a NO_x solution, at least in the heavy-duty sector.

1.2.2.2 NO_x Adsorber Catalysts

NO_x "traps" adsorb nitrogen oxides during lean cycles, and regenerate during periodic heat (and/or rich) spikes. To be effective, however, they require low-sulphur fuel to insure the durability of the catalyst materials – in gasoline applications, a maximum of 30 ppm for a 70% reduction, and 10 ppm for the peak 90% reduction which comes with heavier loading. Engine cycles must be adjusted so that periodic rich excursions will regenerate the filter, burning off NO_x at 650º Celsius without producing significant amounts of smoke. For lean-burn gasoline engines, the NO_x adsorber catalyst is currently the most promising emissions control technology, and some direct injection gasoline vehicles are already using these catalysts.

In addition to their high efficiency, NO_x adsorbers also have a number of other benefits, most deriving from their design simplicity. A relatively passive technology (other than requiring periodic rich excursions), NO_x adsorbers or traps require no storage tanks or infrastructure costs. They are compact and efficient over the long life of the trap. And best of all, they are an extension of proven current technologies. Their regeneration, however, is dependent on highly sophisticated control strategies. If these are in place, and if the fuel sulphur issues in both Europe and the USA are resolved in favour of very low-sulphur fuel, NO_x adsorbers may be the most promising route to NO_x reduction.

1.2.2.3 Non-Thermal Plasma

One deNO_x technology that many observers find promising is still in an experimental stage: non-thermal plasma. In this system, exhaust gases pass through a very intense field of charged particles. As a result, NO_x and other particles dissociate and ionise into far more reactive particles, which can then be easily catalysed downstream.
Plasma technologies promise a reduction of up to 80%, but so far this has been demonstrated only in laboratory environments – a far cry from the rigours of the road. Systems currently being tested are still too large and energy-consuming for practical use.

1.2.3 Particulate traps

***Auto Emissions*, Special Report: The Future of Clean Diesel (Autumn 1999)**

Of even greater concern than NO_x to many health researchers, is particulate matter (PM), the signature black soot many people still associate with diesel emissions. PM became a major emissions control issue in 1998, when the California Air Resources Board (CARB) declared PM a toxic air contaminant. CARB is considered to be in the worldwide vanguard of emissions regulation, and it became plain that the winds of change were blowing PM into the dustbin of history.

Cleaning up most PM is a relatively simple matter, mechanically speaking. With the use of diesel particulate filters (DPFs), up to 99% of total particles by number can be trapped. At the same time, DPFs capture only 70% to 90% of particles by weight, due to an odd paradox: after having their tarry outer coating or soluble organic fraction (SOF) broken down by the heat of filter regeneration, the resulting gases reform as aerosols that show up as large particles coming out of the tailpipe.
Most health specialists concerned about PM in ambient air are not as concerned with these larger particles, however. The bigger a particle, the less likely it is to be deposited deep into the lungs where it can do the most damage. Furthermore, most observers feel that with additional engine improvements, the Soluble Organic Fraction (SOF) can be minimised.

Still, new Tier 2 regulations emerging from the Environmental Protection Agency make it clear only very low levels of PM will be allowed in emissions from diesel passenger cars, light and heavy duty trucks. And while DPFs are compact, offer little in the way of back pressure, and represent a proven and inexpensive solution, many emissions engineers are concerned with developing reliable systems that burn off soot and regenerate themselves repeatedly over the life of the vehicle.

Great strides have been made in this direction with the development of "common rail" engines featuring highly flexible combustion processes which allow for multiple injections to spike temperature as needed to regenerate the filter. As yet, however, regeneration often remains far less simple and efficient than emissions engineers would like. To address the problem, several different solutions have emerged.

1.2.3.1 The Continuously Regenerating Trap (CRT)

The CRT uses excess NO_x to eliminate PM: NO is oxidised to NO_2, which, in turn, oxidises soot into carbon dioxide and nitrogen. The CRT system, however, requires a minimum NO_x to PM ratio of 8:1 (which is generally available over most of the operating range) to work. The CRT can reduce PM by approximately 90% under optimal conditions – one of which is low-sulphur fuel (50 ppm or lower).

1.2.3.2 Catalysed Soot Filters

These filters use a reactive catalyst to facilitate oxidation. At temperatures under 350°C, they also can yield a 75% reduction in PM, and like the CRT are a passive method easily adapted to retrofitted engines.

1.2.3.3 Catalysed Fuel Additives

Another school of thought involves putting catalysts directly into fuel. This answer is relatively inexpensive in terms of fuel-cost penalty, often adding up to only one or two cents a gallon, and offers 75+% efficiency (when used with filters). Some technologies utilise a system in which an additive is commingled into fuel from a supplementary reservoir next to the main fuel tank. The additive allows the particulate to burn (in a filter) at a lower temperature which common rail engine technology can easily reach through sophisticated combustion control.

It should be noted that with all these technologies, the conversion efficiency for particles by mass is very much dependent on engine tuning. The smaller the SOF, the greater the efficiency. Active engine tuning, both "common rail" and otherwise, can go a long way toward addressing PM problems in both light- and heavy-duty vehicles.

1.2.4 Homogenous Charge Compression Ignition (HCCI)

The Homogeneous Charge Compression Ignition (HCCI) engine is often described as a hybrid between the spark-ignition engine and the diesel engine. A premixed charge is used, as in the SI engine. The charge is compressed to auto ignition as in a diesel engine. The advantages are high efficiency and low emissions of soot and NO_x, while the drawbacks are high emissions of hydrocarbons and CO, and difficulties in controlling the engine.

The Ford motor company has an active research programme in HCCI combustion. Researchers are using optical diagnostics in single-cylinder engines to explore viable HCCI operating regimes and to investigate methods of combustion control. In addition, chemical kinetic and cycle simulation models are being applied in order to understand better the fundamentals of the HCCI process and to explore methods of implementing HCCI technology.

GM, at a research level, is evaluating the potential for incorporating HCCI combustion into engine systems. This work includes assessing the strengths and weaknesses of HCCI operation relative to other advanced concepts, assessing how best to integrate HCCI combustion into a viable powertrain, and the development of appropriate modelling tools. Work is focused on fuels, combustion control, combustion modelling, and mode transitioning between HCCI and traditional SI or CI combustion. GM is also supporting HCCI work at university level.

Cummins has been researching HCCI for almost 15 years. Industrial engines run in-house using HCCI combustion of natural gas have achieved remarkable emission and efficiency results. Cummins has found, however, that it is quite challenging to control the combustion phasing over a real-world operating envelope, including variations in ambient conditions, fuel quality variation, speed and load. Because the new diesel emission targets are beyond the capability of conventional diesel engines, Cummins is investigating all options, including HCCI, as part of its design palette and future engine strategy.

Table 1.2-1: Summary of recent HCCI R&D activities (1998−2000)

Categories	Total Publications	Publications by Region	
Fundamental understanding and benefit demonstration	33	Japan	20
		U.S.	8
		Europe	5
Gasoline HCCI Control	8	Japan	4
		Europe	4
Diesel HCCI Control	3	Japan	3
Alternative Fuel HCCI Control	6	Japan	4
		Europe	2
Load Extension	5	Japan	3
		Europe	2
Catalysts for HC and CO Emissions Control	2	Japan	1
		Europe	1
Mixture Preparation for Diesel	9	Japan	9
Nissan MK	10	Japan	
New ACE	12	Japan	
Lund Institute of Technology	11	Europe	
Keio University	8	Japan	
Lawrence Livermore National Laboratory	5	U.S.	

Source: US DOE, 2001

Advantages of HCCI [Linna, 2000]:

- High thermal efficiency (some studies have reported over 50%) associated with unthrottled, ultra-lean operation:
  - *Increased ratio of specific heats during expansion stroke*
  - *Lower dissociation losses*
  - *Reduced cooling losses*
- Very low NO_x emissions (<10ppm, some studies have suggested that less than 1ppm may be attainable) resulting from ultra-lean operation ($\lambda > 2$)
- Next to zero emissions of particulate matter thanks to pre-mixed homogeneous charge operation
- Compatible with fuels ranging from natural gas to diesel.

"If the control issues are successfully addressed, HCCI could combine fuel economies comparable with the best diesel engines, with exhaust emissions comparable with the best spark-ignition engines."

Challenges:

- Combustion phasing is hard to control over a range of load, resulting in problems with misfire and knock

- Very rapid combustion results in high pressure rise rates provoking audible noise
- High peak pressures
- The combustion of highly dilute mixtures in these engines results in relatively low power density (unless supercharged)
- In addition, lean-burn exhaust composition is incompatible with the current state of the art NO_x reduction catalyst technology. Consequently, reaching very low levels of NO_x emissions hinges on achieving stable controllable operation at ultra-lean conditions ($\lambda > 2$).

Load control options to regulate the system output at any given speed include:

- Engine equivalence ratio
- Charge pressure (density) via variation of boost on the fly
- Charge temperature (density) via intake heat exchanger bypass
- Variable effective compression ratio via inlet valve timing
- Variable geometric compression ratio
- On-board Cetane / Octane modification by fuel reforming

Findings of experimental work by Arthur D. Little:

- HCCI is operating with a high thermal efficiency on par with diesel (>40 %)
- NO_x emissions are emitted at ultra-low levels (~ 10 ppm) compared to 600-3000 ppm for diesel engines
- HCCI engines must be kept within a very narrow window of operation, which calls for advanced and precise control.
- High levels of HC and CO indicate that an oxidation catalyst will be necessary.

1.3 Hybrid vehicles

The gasoline/diesel-battery hybrid vehicle is a development born out of the limitations of battery technology. Battery-powered electric vehicles are heavy, due to the weight of the battery pack, and have severe range limitations. Even the most advanced batteries have a range of about 100 miles in real-world conditions, much less than consumers demand from a vehicle.
On the hybrid vehicle, a small gasoline or diesel engine is provided to give extra range. There are a variety of designs, but all have the common feature of allowing a battery pack to be recharged during operation. Moreover, they allow the gasoline engine to be optimised to control emissions to very low levels. For example, Toyota's hybrid battery-gasoline vehicle will reduce emissions of NO_x and VOCs significantly. Mileage per gallon may double if vehicle weight penalties are not too high, resulting in CO_2 emission reductions of up to 50%.

1.3.1 Engine assist systems

In 1997 the 'German Industry Innovation Award' was given to the tyre company Continental for the development of the ISAD engine assist system (Integrated Starter Alternator Damper). Honda, Citroen and Ford have developed similar systems, respectively named 'Honda Integrated Motor Assist' (IMA), 'Dynalto' and 'Ford Low Storage Requirement hybrid' (LSR). But many other vehicle manufacturers (for instance BMW, Renault) are also carrying out research and development on ISAD-like systems. These integrated starter-generator systems replace the IC engine's flywheel, taking over the function of the alternator and the starter in a conventional engine configuration, and improve both performance and fuel economy.
These systems make it possible to:

- Turn off the engine when no propulsion power is needed, yet restart it on demand
- Downsize the combustion engine, improving its efficiency
- Recapture energy with regenerative braking
- Make it easy to upgrade the on board voltage level to 36 / 42 V.

Fuel economy can be improved considerably without sacrificing performance. In order to reduce battery weight and to downsize the drivetrain the batteries used are relatively compact and therefore pure electric, locally emission-free driving is not possible with these hybrids. Because these hybrid powertrains are so compact, however, it is possible to incorporate them in existing models, which greatly simplifies series production.

Although one can discuss whether such vehicles are to be regarded formally as HEVs or not, they are constructed at least with all lessons in mind that have been learned from HEV developments over the past decades. Moreover, they combine essential HEV components and thinking with conventional vehicle technology in a way that makes these engine-assist systems relatively cheap to produce and easy to introduce.

Some examples of vehicles with engine-assist systems will therefore be discussed in the next chapter on hybrid vehicles.

Various manufacturers in Japan, Europe and the USA have developed engine-assist systems.

1.3.1.1 42V vehicle powernet

Because of the high increase of electric consumption in new car models, the electric supply has reached values that come close to the limits of current 12/14 V powernets. The shift to higher voltages allows currently mechanically driven auxiliaries such as hydraulic power steering, air-conditioning pumps and water and fuel pumps to be replaced by electrically driven components. Catalyst heating, active stabilisation and electromechanic brakes, steering control, active valve control are also to be expected in the very near future, increasing the demand on the vehicle powernet to between 1 and 3.4 kW [“Das 42-Volt-Bordnetz kommt”, 30 August 2002].
Apart from the introduction of higher voltage, this also brings the need for new electric power components, new generators, battery concepts and new integrated control strategies.
Generally there is agreement to triple the voltage level in new car models (apart from emerging technologies such as electric, hybrid and fuel cell vehicles, which bring the need for higher voltages) in the near future from 12 / 14 V level on board to 36 / 42 V. This way the need for extra safety measures, which are needed when increasing the 50V level, are also avoided.
The higher voltage also paves the way for the use of engine-assist systems.

1.3.1.2 Technical background of engine-assist systems

With the ISAD system, the conventional starter and alternator of the combustion engine are replaced by one compact electrical device, placed between the engine and the clutch and gearbox. Besides its role in assisting the engine, the ISAD system provides the vehicles on-board electric system with a high level of efficiently produced electric power (by enlarging both the current and voltage level), which offers a big potential advantage for the application of more electrical auxiliaries and on-board devices, a trend foreseen for the future. In this way, the use of ISAD systems has great synergy with the trend to upgrade the present 12 / 14 V level on board to 36 / 42 V. This higher voltage level allows currently mechanically driven auxiliaries such as hydraulic power steering, air-conditioning pumps and water and fuel pumps to be replaced by electrically driven components.
With help of the electrical machine it is also possible to apply an additional torque to the crankshaft of the combustion engine. This load moment can offset for the most part the alternating torque generated by the gas and inertia forces. In this process, the power exchange occurs between the crankshaft and the intermediate circuit capacitor, leading to a reduction in non-uniform rotation and resulting in a stabilisation of the drivetrain overall.

Benefits on fuel economy and emission reduction

The benefits brought by various aspects of the engine-assist system for performance, fuel efficiency and emissions are summarised in Table 1.3-1.

Table 1.3-1: Benefits of engine-assist systems

	Performance improvement	Fuel economy improvement	Reduction of emissions
"Instant" restart (<0.3 sec) allowing engine shutdown at zero vehicle speed		X	X
Higher efficiency and power than conventional alternator		X	X
IC Engine assist	X		
Regenerative breaking		X	X
Engine vibration dumping	X		
Driveline damping	X		

Engine shutdown when the vehicle stops and restart when the accelerator pedal is actuated, will lower fuel consumption and will reduce exhaust emissions. In urban start-stop driving conditions this can improve fuel efficiency by more than 10%, according to ISAD Electronic Systems GmbH.

Surveys carried out on actual vehicle use highlight the fact that a conventional car uses on average 10% to 15% of its maximum power during city driving. Maximum power is only used during acceleration or hill climbing. Most of the time the ICE is operating below its optimum working point, which reduces overall efficiency. But by downsizing the engine and adding an engine-assist system the smaller ICE will work closer to its "sweet spot" while the vehicle's acceleration remains the same (until the battery is discharged). Furthermore, regenerative braking becomes possible via the integrated starter alternator damper.

Compactness

Because the engine assist system replaces the flywheel it can be placed in the existing transmission bell housing. Thus the engine-assist systems have minimal impact on engine bay packaging, making it possible to convert existing models into hybrids without extensive modifications. The engine-assist systems do not need a big battery pack because the vehicles in which they are fitted are not designed to operate in zero-emissions mode. For these reasons engine-assist hybrids are probably the easiest hybrid-electric vehicles to put into mass production.

1.3.2 Prototype hybrid vehicles in the past decade

IEA-HEV database (status 2001):

Table 1.3-2: Selection of LD hybrid passenger cars from IEA-HEV database

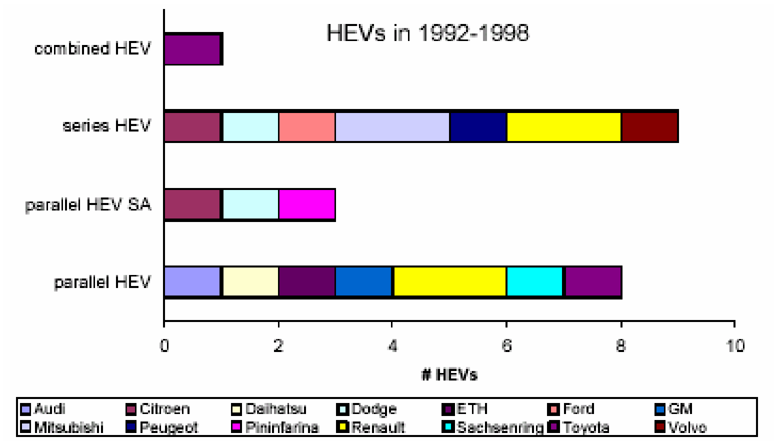
HEV Light Duty	date of presentation	driveline	ICE fuel	concern
Audi Duo III	September 1997	parallel HEV	diesel	Volkswagen
BMW 318 ISAD	1999	parallel HEV SA	gasoline	BMW
Chevrolet Triax (Hybrid)	October 1999	parallel HEV	gasoline	GM
Chrysler Citadel	January 1999	parallel HEV	gasoline	DaimlerChrysler
Chrysler Durango	2000	parallel HEV	gasoline	DaimlerChrysler
Citroën Saxo Dynavolt	September 1998	series HEV	gasoline	PSA
Citroën Xsara Dynalto	March 1998	parallel HEV SA	gasoline	PSA
Citroën Xsara Dynactive	March 2000	parallel HEV	gasoline	PSA
CSIRO aXcessaustralia	March 2000	series HEV	gasoline	CSIRO
Daihatsu Charade Social	October 1996	parallel HEV	gasoline	Toyota
Daimler Chrysler S-class	September 1999	parallel HEV	diesel	DaimlerChrysler
Dodge Intrepid ESX	January 1996	series HEV	diesel	DaimlerChrysler
Dodge Intrepid ESX2	1998	parallel HEV SA	diesel	DaimlerChrysler
Dodge Intrepid ESX3	1999	parallel HEV SA	CNG	DaimlerChrysler
Dodge PowerBox	2001	parallel HEV	gasoline	DaimlerChrysler
ETH-Z Hybrid	July 1996	parallel HEV	gasoline	ETH
Fiat Multipla Ibrida	May 1999	parallel HEV	gasoline	GM
Ford Escape US/Maverick	2000	parallel HEV	F T fuel	Ford
Ford Explorer	2001	parallel HEV SA	diesel	Ford
Ford P2000 LSR	1999	parallel HEV SA	diesel	Ford
Ford Prodigy	2000	parallel HEV SA	diesel	Ford
Ford Synergy 2010	January 1998	series HEV	diesel	Ford
GM EV1 Parallel Hybrid	1998	parallel HEV	gasoline	GM
GM Precept	2000	parallel HEV SA	gasoline	GM
Holden ECOmmodore	May 2000	parallel HEV	gasoline	GM
Honda Insight	September 1999	parallel HEV SA	gasoline	Honda
Honda Insight Japanese	September 1999	parallel HEV SA CVT	CNG	Honda
Honda Spocket	1999	parallel HEV	gasoline	Honda
Hyundai FGV II	May 1999	parallel HEV	gasoline	Hyundai
Mitsubishi Chariot	1995	series HEV	gasoline	DaimlerChrysler
Mitsubishi ESR	January 1994	series HEV	gasoline	DaimlerChrysler
Mitsubishi Pistachio	September 1999	parallel HEV SA	gasoline	DaimlerChrysler
Mitsubishi SUW Advance	October 1999	parallel HEV SA	diesel	DaimlerChrysler
Mitsubishi SUW Compact	September 1999	parallel HEV SA	gasoline	DaimlerChrysler
Nissan Tino Neo Hybrid	2000	parallel HEV	gasoline	Renault-Nissan
Peugeot 406 VERT	1996	series HEV	gasoline	PSA
Pininfarina Ethos	1997	parallel HEV SA	LPG	Pininfarina
Renault Koleos	March 2000	parallel HEV	gasoline	Renault-Nissan
Renault Next	December 1995	parallel HEV	diesel	Renault-Nissan
Renault Pangea	1997	series HEV	diesel	Renault-Nissan
Renault Scenic Hybrid	September 1998	parallel HEV	gasoline	Renault-Nissan
Renault Vert Monospace	1996	series HEV	gasoline	Renault-Nissan
Sachsenring Uni 1	September 1998	parallel HEV	gasoline	Sachsenring
Subaru Elten	February 2000	parallel HEV SA CVT	gasoline	GM
Suzuki EV-sport	October 1999	parallel HEV	gasoline	GM
Suzuki Pu3 Commuter	October 1999	parallel HEV	gasoline	GM
Toyota Corona	December 1997	parallel HEV	gasoline	Toyota
Toyota HV-M4	October 1999	parallel HEV	diesel	Toyota
Toyota Prius	December 1997	combined HEV		Toyota
Toyota Prius	2000	combined HEV		Toyota
Volvo ECC	1992	series HEV		Ford

Source: IEA-HEV, 2001

Trends concerning drivetrain configuration per make

The data from table Table 1.3-2 are separated into three periods: before 1999, 1999 and 2000. Because of the small number of HEVs in the database presented in 2001 these are excluded from this analysis. HEVs introduced in 1992-1998 are presented in .

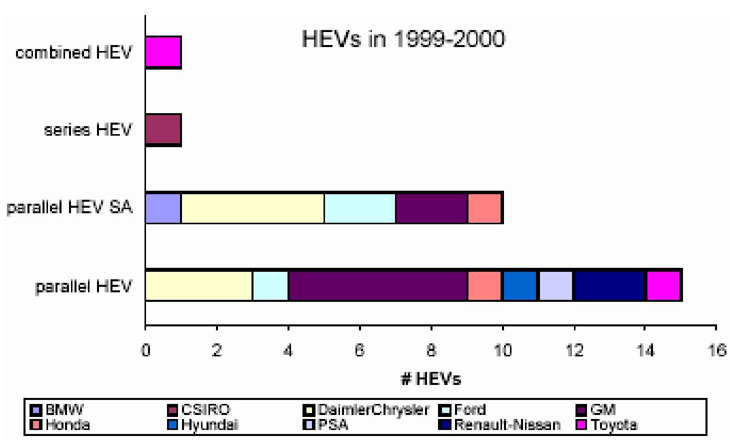
Figure 1.3-1: HEV drivetrain configurations per make in 1992-1998 (based on number of vehicles), derived from the IEA-HEV database



Source: IEA-HEV, 2001

From it can be seen that most of the HEVs presented in the period 1992-1998 were of the series hybrid type. Renault was the most productive OEM, presenting two series hybrids and two parallel hybrids. The only combined HEV in the Figure is the Toyota Prius, introduced in Japan in 1997. HEVs introduced in 1999 and 2000 are presented in .

Figure 1.3-2: HEV drivetrain configurations per concern in 1999-2000 (based on number of vehicles), derived from the IEA-HEV database



Source: IEA-HEV, 2001

It can be seen clearly that R&D in the field of combined and series HEVs is no longer state-of-the-art. R&D in the field of hybrid LD passenger vehicles concentrates on parallel hybrid vehicles, of which the most are conventional parallel hybrids. The "Big Three" (DaimlerChrysler, Ford and GM) account for 17 of the 27 hybrid vehicles introduced. No clear focus between conventional (#9) and starter-alternators (#8) can be determined for the "Big Three". DaimlerChrysler and Ford focus more on starter-alternator hybrids, however, while GM focuses more on conventional parallel hybrid electric vehicles.

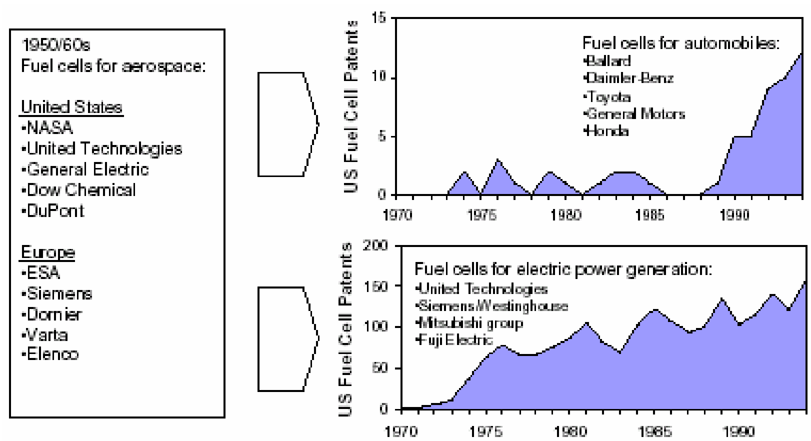
Manufacturers need to divide their limited development resources between hybrid-electric and fuel cell vehicles. Toyota, a big global player that already has a working hybrid-electric technology, says that fuel cells won't become a serious alternative in the near future. By 2012 Toyota believes that all its models will be hybrid (mostly engine-assist systems). Nevertheless Toyota has put a lot of effort into making a hybrid fuel cell vehicle publicly available from December 2002.
DaimlerChrysler on the other hand has cancelled most of its development work on (parallel) hybrids and is concentrating on increasing its leading position in fuel cell development. One way to cope with R&D on both hybrid technology and fuel cells is to regard the introduction stages as a continuum: hybrid technology within the near future and fuel cell technology for the long term. As R&D on hybrid technology is partly overlapping with fuel cell vehicle R&D, this seems to give manufacturers opportunities to use spin-offs of hybrid vehicle research for fuel cell vehicle development. Furthermore, joint ventures or mergers between OEMs (for example, DaimlerChrysler) offer the ability to finance profound efforts on both hybrid and fuel cell research at the same time. Other companies seem more reluctant to invest large amounts of money in dedicated technology for hybrid-electric and fuel cell vehicles. Instead they construct hybrids with a relatively large number of standard components to meet increasingly stringent consumption and pollution emission standards and await market demands for innovative technologies in the (near) future.

1.4 Fuel cell vehicles

1.4.1 Introduction

Fuel cells have been developed for aerospace (since the 1950s and 1960s) and electric power applications (since the 1970s) before becoming feasible for automotive application (since 1987). A technological breakthrough by the R&D company Ballard around 1987 made fuel cells feasible for automotive propulsion. Automakers with strong ties to the aerospace industry and past activity in fuel cells were among the first to recognise the potential of the technology (Daimler-Benz, General Motors).

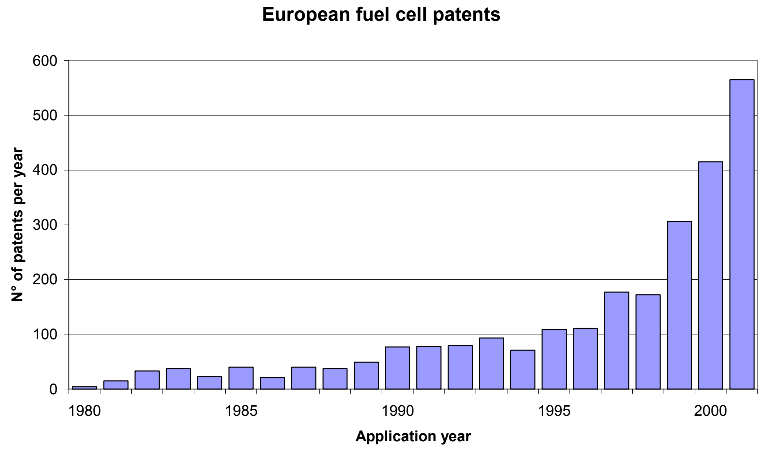
Figure 1.4-1: History of fuel cell research, based on US fuel cell patents Development of fuel cells for aerospace since 1950s/60s, for electric power generation since 1970s/80s, and for automotive propulsion since 1987.



Source: Steinemann, 1999

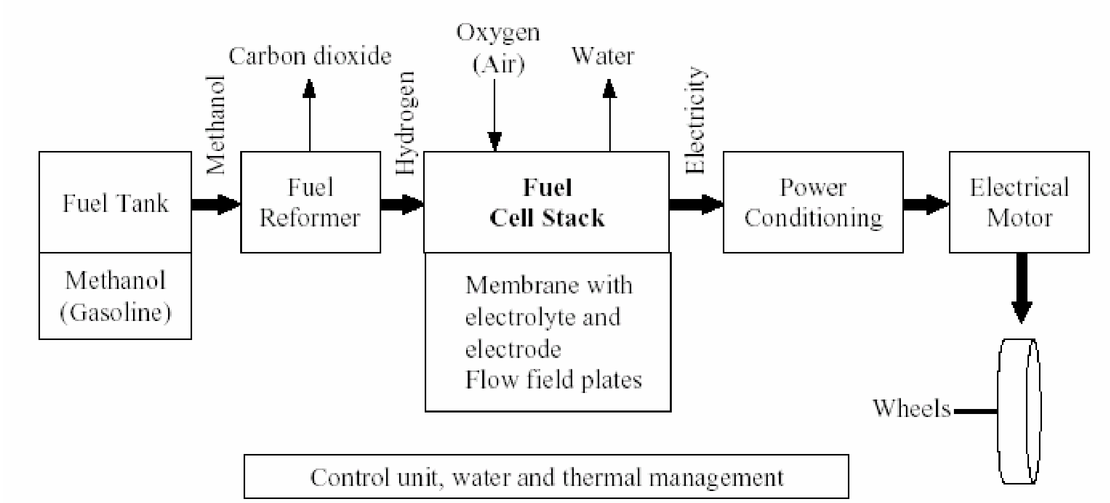
The following figure shows the European trend in fuel cell patents over the past 20 years. Due to automotive interest, research activities in fuel cells have increased spectacularly in the last few years.

Figure 1.4-2: Evolution of the yearly number of European patents applied in the area of fuel cells between 1980 and 2001 (IPC H01M8)



The following figure shows a typical configuration of the powertrain in a fuel cell vehicle.

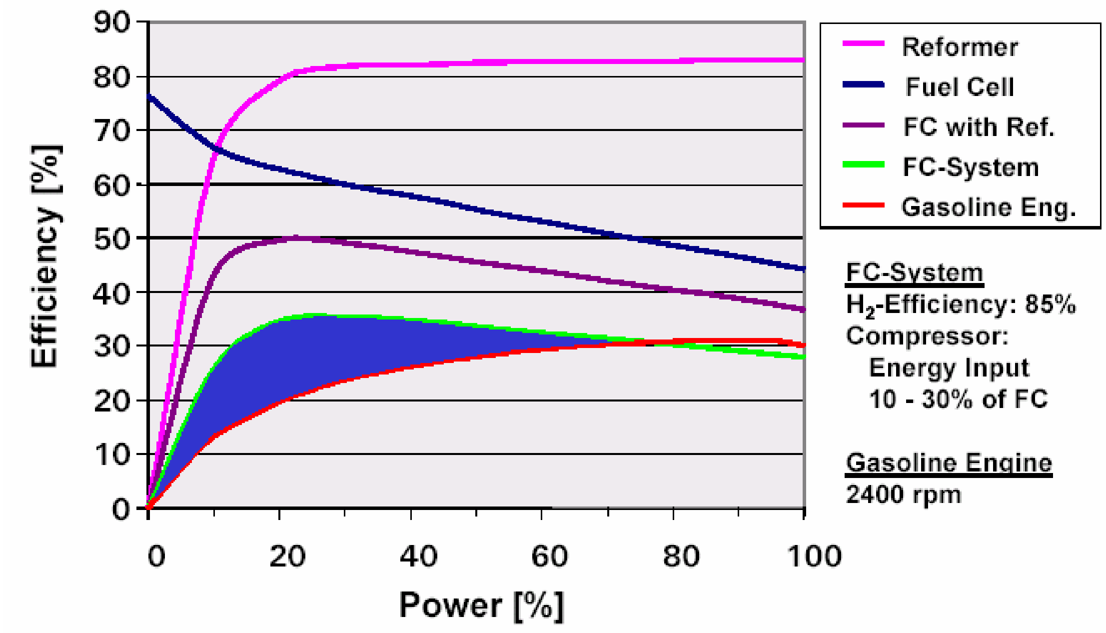
Figure 1.4-3: Basic components of a fuel cell powertrain.



Source: Steinemann, 1999

One of the main advantages of a fuel cell (FC) is that the efficiency of the fuel cell itself is largely independent of load. The efficiency of the total FC system including auxiliaries varies slightly with power, however. shows fuel cell, reformer and total FC system efficiency as a function of load in comparison with the efficiency of a gasoline engine.

Figure 1.4-4: Efficiency comparison of a PEM-FC with reformer vs. gasoline engine



Source: Nylund, 2002

1.4.2 Types of Fuel Cells

The type of fuel cell is typically distinguished by the electrolyte that is utilised and will fall into two broad category types: low temperature and high temperature. Operating temperature is a critical characteristic for transportation fuel cells due to quick start and thermal insulation requirements. As a result, most transportation fuel cell developments have been of the low temperature variety. It is important to note that not all fuel cells under development are hydrogen fuel cells as some high temperature units can recover the electro-chemical energy of other elements, such as carbon in hydrocarbon fuels.

1.4.3 Low Temperature Fuel Cells

Low-temperature fuel cells have been making significant progress in transportation applications due to their quick start times, compact volume and lower weight compared with high-temperature fuel cells. The three main types of low-temperature fuel cells are Proton Exchange Membrane (PEM) fuel cells, Phosphoric Acid Fuel Cells (PAFCs) and Alkaline Fuel Cells (AFCs).

1.4.3.1 Proton Exchange Membrane.

PEM fuel cells are also referred to as solid polymer fuel cells. These feature a number of transportation-friendly characteristics such as high power density, quick start-up, rapid response to varying loads and low operating criteria. These positive attributes outweigh its disadvantages of lower efficiency levels and its low tolerance for carbon monoxide contamination. The California Air Resources Board (CARB) found that "the

PEM fuel cell is coming closest to meeting automotive application requirements" and that a majority of research programmes for transportation are concentrating on PEM technology".[1] Ballard Power Systems and International Fuel Cells (IFC) are two leading PEM fuel cell stack suppliers, with orders from major automakers, such as Ford, DaimlerChrysler and GM. The majority of fuel cell demonstration vehicles have utilised PEM fuel cell stacks.

A special type of PEM is the Direct Methanol-Air Fuel Cell (DMFC), which utilises methanol directly as a fuel and ambient air for oxygen. This could provide a less expensive fuel cell technology since it eliminates the fuel reforming process. Current research has demonstrated only modest performance results, but the potential of DMFC has shifted some PEM research into this area. DaimlerChrysler and Energy Ventures, Inc are both working on DMFCs.

1.4.3.2 Phosphoric Acid

PAFCs operate at around 200°C, utilise widely available phosphoric acid as the electrolyte and have a slightly higher (one per cent) tolerance level to carbon monoxide than other fuel cell types. PAFCs are the most commercially developed type of fuel cell and are being utilised in stationary applications, such as hospitals, schools and utility power plants. One disadvantage of this type of fuel cell is that it requires a warm-up period before energy is generated, making it difficult for use in transportation applications. In addition, PAFCs are large and heavy which will limit their usage to heavy-duty applications. Georgetown University has been operating 30 and 40 foot PAFC buses since the mid 1990s, but has invested in PEM fuel cells to power buses more recently due to progress made with this type of fuel cell.

1.4.3.3 Alkaline

AFCs are one of the most developed fuel cell technologies due to their use by the NASA space programme, but until recently were too expensive for commercial applications. They have the advantage of being built from relatively inexpensive components but their low tolerance for CO_2 contamination requires both pure hydrogen and oxygen supplies. This CO_2 intolerance poses a large barrier for use of AFCs in transportation, although it is expected that AFCs will continue in the space programme.

1.4.4 High Temperature Fuel Cells

The two leading types of high-temperature fuel cells are Solid Oxide Fuel Cells (SOFC) and Molten Carbonate Fuel Cells (MCFCs). In general, high-temperature fuel cells are more efficient than low-temperature ones in generating electrical energy. In addition, they provide high-temperature waste heat, which is a benefit in stationary cogeneration applications but presents a problem for transportation applications.

1.4.4.1 Solid Oxide

SOFCs operate between 800°C and 1000°C, have a good tolerance for fuel impurities and use ceramic as an electrolyte, which reduces some problems associated with liquid electrolytes such as corrosion. As with other types of high-temperature fuel cells, transportation applications will be limited to the heavy-duty sector due to size and warm-up requirements. The SOFC is one of the least developed fuel-cell technologies, but shows promising potential. Delphi Automotive Systems and BMW are developing SOFCs as an auxiliary power unit in vehicles.

1.4.4.2 Molten Carbonate

Due to the high operating temperature (650°C) of MCFCs, this type of fuel cell has the advantage of being able internally to reform hydrocarbons, such as natural gas and petroleum-based fuels. However, its high operating temperatures cause corrosion problems and require the use of costly platinum metals for fuel-cell construction. MCFC technology promises high efficiency and is being developed for stationary applications. Fuel Cell Energy is one company demonstrating MCFC and expected it to be commercial by 2001 for stationary applications.

Table 1.4-1: Overview of fuel cell types and typical properties

Fuel Cell Type	PEM	AFC	PAFC	MCFC	SOFC
Operating Temperature (°C)	70-80	80-100	200-220	600-650	800-1000
Current Density	High	High	Moderate	Moderate	High
Stage of Development	Early prototypes	Space applications	Early commercial applications	Field demonstrations	Laboratory demonstrations
Likely Applications	Electric utility, portable power and transportation	Military and space	Electric utility and transportation	Electric utility	Electric utility
Advantages	• Low temperature • Quick start-up • Solid electrolyte reduces corrosion and management problems	• High performance	• High efficiency for cogeneration • Can use impure hydrogen fuel	• High efficiency • Flexibility of fuels	• High efficiency • Flexibility of fuels • Solid electrolyte reduces corrosion and management problems
Disadvantages	• High sensitivity to fuel impurities • Requires expensive catalysts	• Expensive removal of carbon dioxide from fuel and air supplies	• Low current and power • Large size and weight	• High temperature enhances corrosion and breakdown of cell components	• High temperature enhances corrosion and breakdown of cell components
Prospect for High Efficiency	Good	Good	Good	Good	Good
Prospect for Low Cost	Good	Good	Fair	Fair	Fair-Good

Sources: Karlhammer et al., 1998; Thomas and Zalbowitz, 1999.

Source: NAVC, 2000

1.4.5 Fuel reformer

1.4.5.1 Introduction

In addition to the technology difficulties mentioned previously, low efficiency levels, large size and weight, along with cost, remain the greatest obstacles to the commercialisation of fuel cells. Several factors affect the price of fuel cells. First, most fuel cells are currently built using expensive materials, particularly precious metal catalysts used in low temperature fuel cells. Second, fuel cells are currently constructed in limited quantities and thus do not achieve the economies of scale necessary for decreases in pricing. In order to be competitive, a fuel cell in the automobile sector will need to cost about $50/kW versus the present $1,000 to $3,000 per kW.

The other major barrier for the fuel-cell technology will be fuel sources. The ultimate goal for achieving zero emissions is to utilise pure hydrogen as a fuel source. Technical and cost hurdles, however, may make this infeasible in the near term. A number of hydrocarbon fuel sources are available, such as natural gas, methanol, gasoline and ethanol, but not one of the mentioned fuels has become a clear leader due to infrastructure and fuel purity issues.

Depending upon the base fuel used, either the current infrastructure can be used, or an entirely new one must be developed. The easiest fuel to use from a consumer standpoint is gasoline, since it requires no additional action or thought on the part of the consumer.

Gasoline, however, is one of the most difficult fuels to reform and lacks purity in its current form. Gasoline and other fuels such as methanol, ethanol, and CNG are hydrogen carriers so can be used as a fuel-cell fuel. Gasoline and other hydrocarbon fuels, however, can not be used directly (except methanol) in a fuel cell, so the key to their use will be effectively and efficiently separating the hydrogen. To do so, fuel reforming technology is utilised.

By introducing a fuel reformer, the overall system efficiency of the fuel-cell vehicle is diminished because energy is required to extract the hydrogen from the fuel and the potential for air pollutant emissions increases. Hydrogen provides the most efficient fuel, but requires a new infrastructure since its use outside industry is limited. Ovonic claims it has a solid hydrogen storage system that could potentially use existing infrastructure.

1.4.5.2 Reformer technology

A hydrocarbon fuel and air are heated to a high temperature, with or without catalysts, to create a synthesis gas of carbon monoxide (CO) and hydrogen. This synthesis gas is then reacted with water (steam), which splits to produce additional hydrogen. The freed oxygen from the water combines with the carbon monoxide to form carbon dioxide and hydrogen forms hydrogen. Remaining CO needs to be removed to avoid contamination problems with most fuel-cell catalysts. The carbon dioxide is released to the atmosphere.

On-board fuel processing is essentially reformation on a small scale. Companies developing on-board fuel processors include Nuvera Fuel Cells, Johnson Matthey and Hydrogen Burner Technologies.

Steam Reforming

In steam reforming (SR), fuel and steam are mixed in the presence of a catalyst to reform the hydrocarbons in the fuel into hydrogen, CO and carbon dioxide (CO_2). The resulting gas is sent to a shift reactor where the CO reacts with steam to form more hydrogen and CO_2. A purification step then removes remaining amounts of CO, CO_2 and other impurities to achieve high (97% to 99.9%) hydrogen purity. This process is the most developed and least expensive manner for generating hydrogen. The efficiency rate of steam reformation is approximately 70% to 80%. Conversion efficiency is reduced due to the endothermic nature of the reaction, which consumes fuel to produce the temperatures necessary for the reaction to occur - approximately 15% to 25% of the total fuel heating value. One way to increase efficiency is to utilise the waste heat from high-temperature fuel cells and PAFCs when reforming on-board. One limitation of SR is that only light hydrocarbons (e.g., natural gas, naphtha, gasoline and No. 1 fuel oil) can be used in the process. Air Products and Chemicals, the largest producer of hydrogen, uses steam reforming of natural gas as its primary method to produce hydrogen. Several automakers with fuel cell demonstration vehicles, such as GM, DaimlerChrysler, Toyota and Nissan have utilised SR of methanol for hydrogen production on-board.

Partial Oxidation

Partial oxidation (POX) is similar to SR in combining fuel and steam, but an additional step of adding oxygen is included. This extra step adds energy to the reaction making it exothermic causing some hydrogen product to be lost as heat. The process efficiency is approximately 50%. The exothermic nature of the reaction, however, allows for the reaction to be more responsive than SR to variable loads, an important feature for on-board processing. Heavier hydrocarbons can be used in POX, but they have lower carbon to hydrogen ratios which reduces the amount of hydrogen end product. When coal is used as a feedstock, the process is referred to as gasification. Although heavier hydrocarbons are a less expensive input, the additional oxygen purification of the air and the impurities within the heavier hydrocarbons make this process more expensive than SR. Epyx Corporation's (now Nuvera Fuel Cells) multi-fuel processor is an example of a POX based on-board reformer.

Autothermal Reforming

Autothermal reforming is a less developed process that combines SR and POX so that the heat production of POX offsets the heating needs of SR. Autothermal reforming produces a better concentration of hydrogen than POX but less than SR. Autothermal reformation may offer the best of both processes with better response to variable loads and a good efficiency rate.

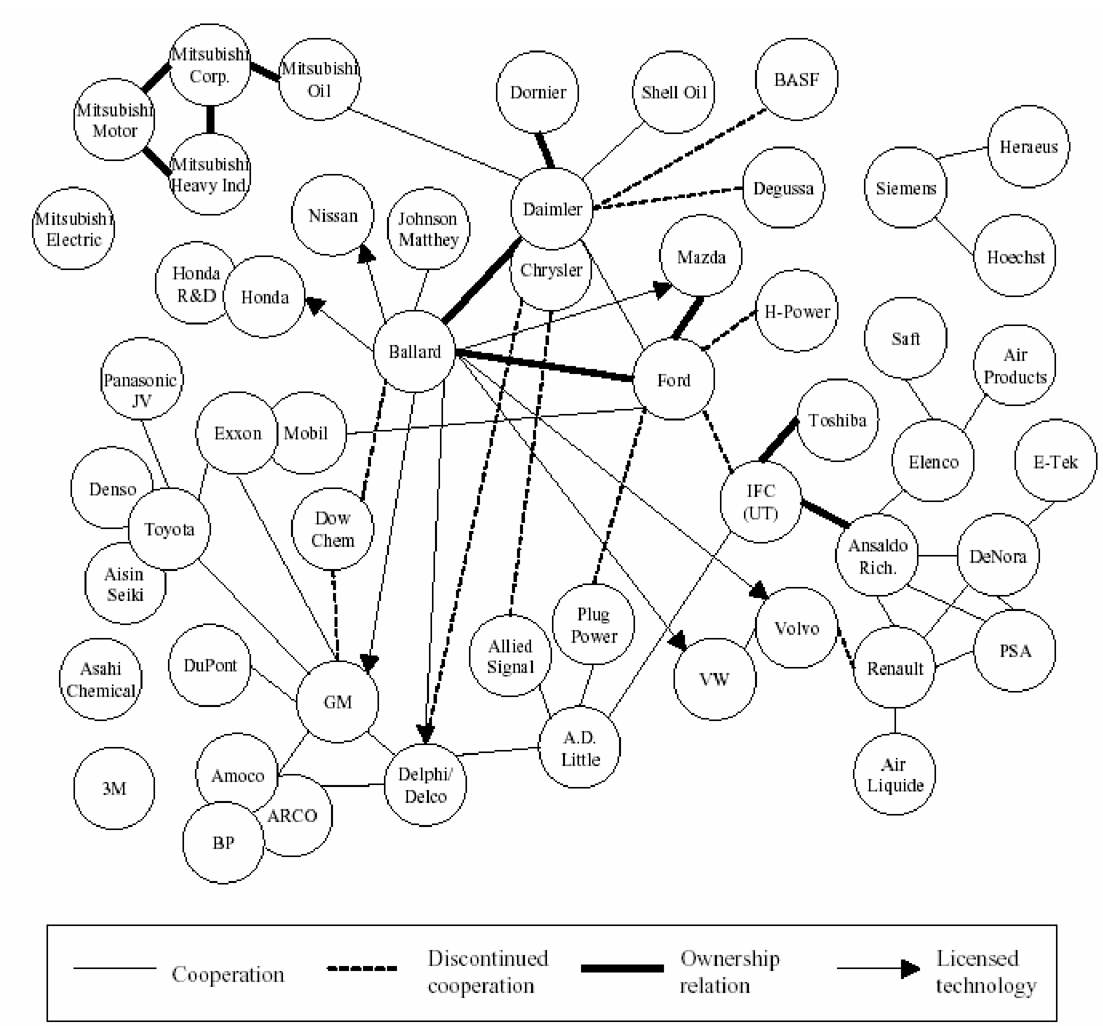
Johnson Matthey's Hot-Spot reformer is an example of on-board hydrogen production that starts with a partial oxidation reaction until threshold levels of hydrogen are reached and then the reaction becomes autothermic. Hydrogen Burner Technologies' Fuel- Flexible Fuel Processors also utilise autothermic reactions due to their lower operating temperatures and higher efficiencies.

1.4.6 Companies involved in fuel-cell research

In the attempt to acquire competence in automotive fuel cells, automakers have engaged in an extensive research network worldwide, as shown in Source: Steinemann, 1999 (From: News reports; Norbeck et al., 1996; Kordesch and Simader, 1996; Kalhammer et al., 1998).

. The figure shows the central position of Ballard, DaimlerChrysler, Ford, General Motors and Toyota, but it also shows the numerous links with non-automotive companies. Smaller automobile manufacturers and others that have decided to take a wait-and-see approach, are relying on licensing the technology from Ballard. Companies that have invested in fuel-cell R&D early on have chosen to either develop fuel cells internally or through collaborative research.

Figure 1.4-5: Global research network of companies pursuing the development of fuel cells for automobiles



Source: Steinemann, 1999 (From: News reports; Norbeck et al., 1996; Kordesch and Simader, 1996; Kalhammer et al., 1998).

The following table shows the fields in which these companies are working.

Table 1.4-2: Companies active in research and development of fuel cell components and automotive system integration.

System Integration	PEM Fuel Cell Stack
AlliedSignal	AlliedSignal
Ansaldo Ricerche	Ballard Power Systems
Ballard Power Systems	DeNora, E-Tek
DaimlerChrysler	DaimlerChrysler
Ford	Energy Partners
General Motors	General Motors
Honda	Honda
International Fuel Cells	H-Power
Mitsubishi Motor	International Fuel Cells
Nissan	Mitsubishi Motor
Plug Power	Nissan
Toyota	Plug Power
	Siemens
	Toyota

Membrane and Catalyst	Fuel Processor
3M	A.D. Little (Epyx)
Asahi Chemical	Amoco
Asahi Glass	Atlantic Richfield
Ballard Power Systems	Ballard Power Systems
Dow Chemical	DaimlerChrysler
DuPont	General Motors
Gore	Honda
Hoechst	International Fuel Cells
Johnson Matthey	Johnson Matthey
W.L. Gore	Mitsubishi Oil
	Mobil Oil/Exxon
	Shell Oil
	Toyota
	Wellman CJB

Source: Steinemann, 1999 (From: News reports)

Source: Steinemann, 1999 (From: News reports)

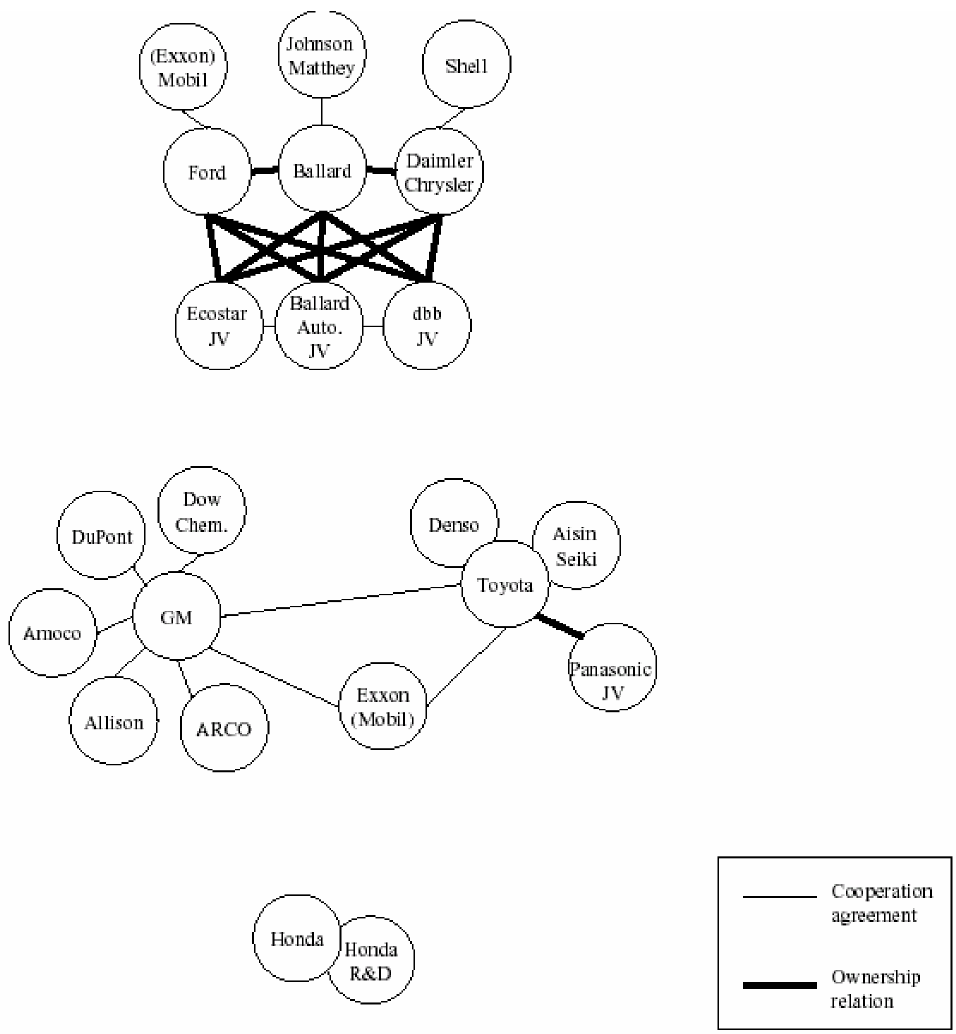
shows details of the organisational R&D approaches of DaimlerChrysler / Ford / Ballard, General Motors / Toyota and Honda.

DaimlerChrysler, Ford and Ballard have established a truly collaborative network of alliance partners covering all major components of a fuel-cell system. The alliance includes equity investments of the automakers in Ballard, three joint ventures that are majority owned by DaimlerChrysler (dbb Fuel Cell Engines, now XCELSSIS), Ford (Ecostar), and Ballard (Ballard Automotive), and links with oil companies.

General Motors and Toyota have established a similar alliance involving automotive suppliers, oil companies and chemical companies. While General Motors has licensed fuel cells from Ballard and co-operated with several partners on fuel cells in the past, Toyota has previously developed fuel cells almost entirely internally, involving only suppliers that are immediate members of its network. Through a joint venture with Panasonic, Toyota has also gained experience in electric motors for electric vehicles.

Honda followed a strategy of almost complete internal development of fuel-cell technology. Honda licensed fuel cells from Ballard, but developed its own fuel cells in parallel. Such an internal development strategy seems much more risky and missing the breadth of other alliances in covering all components of a fuel-cell system, but may reflect Honda's strong emphasis on R&D in engines and power products, which is regarded as one of the company's core competencies.

Figure 1.4-6: R&D networks of DaimlerChrysler / Ford / Ballard, General Motors / Toyota, and Honda in fuel cell technology



Source: Steinemann, 1999 (From: News reports)

The DaimlerChryser / Ford / Ballard alliance

The alliance between DaimlerChrysler, Ford and Ballard is organised along technical dimensions and covers all components of a fuel-cell system, as shown in Table 1.4-3. Ballard is responsible for developing the fuel-cell stack. Table 1.4-3 clearly shows the lead in patenting of fuel-cell stack, membrane and electrodes that Ballard has gained. By partnering with Johnson Matthey, a leading company in materials technology and precious metal based fuel-cell catalysts, Ballard can draw on Johnson Matthey's expertise in the area of fuel-cell electrodes. The co-operation with Johnson Matthey has contributed significantly to the improvement of Ballard's fuel cells.

DaimlerChrysler and Ford rely on Ballard to develop fuel cells, but both companies also develop their own proprietary fuel-cell technology. According to patent statistics, DaimlerChrysler and Ford do not develop fuel-cell electrodes, leaving responsibility for this component to Ballard and Johnson Matthey in the alliance.

The oil companies in the alliance focus on fuel reformer technology. Oil companies have vast resources and experience in hydrocarbon processing and catalytic technologies, both of which are the scientific basis for fuel reformers. Instead of trying to replicate this expertise, Ford and DaimlerChrysler decided to develop fuel reformers co-operatively with Mobil and Shell.

DaimlerChrysler and Ford's role in the alliance is clearly centred around the integration of fuel-cell technology into the automobile. While both companies are also involved in the development of components, they regard integration of fuel cells into the automobile as their main responsibility.

The alliance around DaimlerChrysler, Ford and Ballard clearly builds on technical complementarities of the partners in the alliance. The organisational split of the DaimlerChrysler/Ford/Ballard research alliance into units with technical responsibilities allows the companies to focus on technological capabilities and to divert non-core technologies to other units. In terms of intellectual property protection, the alliance provides an effective way of broadening the patent coverage.

Table 1.4-3: Competences in fuel cell related technology in the DaimlerChrysler / Ford / Ballard partnership (grey areas highlight technical competence, numbers represent patents held by the companies).

	Ballard	Johnson Matthey	Mobil Oil	Shell Oil	Ford [1)]	Daimler-Chrysler [2)]
Fuel cell stack	**37**	4	-	-	1	11
Polymer membrane	**4**	-	3	2	-	1
Fuel cell electrode	**8**	**12**	-	-	-	-
Fuel reformer	4	5	**5**	**16**	3	2
Electric drivetrain	-	-	3	-	**63**	52
Automobile integration	-	-	-	-	**186**	**211**

Source: Steinemann, 1999

1) Includes Ford Motor and Ford Global Technologies

2) Includes Daimler-Benz, DaimlerChrysler, and Chrysler

Numbers represent US patents held by companies in the following US patent categories, issued in the period 1985-1999: Fuel stack (429-012 to 429-013, 429-017 to 429-039), Polymer membrane (521-025 to 521-039), Fuel cell electrode (429-040 to 429-046), Fuel reformer (423-650 to 423-657, 423-246 to 423- 248, 423-437 to 423-438), Electric drivetrain (180-065, 318), Automobile integration (180). Source: US Patent Office database

1.4.7 Prototype fuel-cell vehicles

A number of prototype fuel-cell vehicles will be presented in this chapter. A more comprehensive overview will be given in the Annex.

Sources: [Fuel Cells 2000], [AMI, 2000], [Ashley, 2001]

1.4.7.1 DaimlerChrysler

NECAR

In 1997, DaimlerChrysler displayed a prototype MFCV, the compact methanol-powered NECAR 3 that featured a 50-kW fuel cell that ran the car and all standard features for passenger comfort. Earlier versions, the NECAR 1 and NECAR 2, were fuelled by gaseous hydrogen stored in bulky high-pressure cylinders, as is Daimler's fuel-cell powered transit bus called the NEBUS. Daimler used vans for its first two FCVs, while the space-saving features of liquid methanol fuel allowed the automaker to produce the NECAR 3 as its smallest passenger car. The NECAR 4, demonstrated in late 1999, uses liquefied hydrogen at – 253°C. The NECAR 4's fuel-cell equipment is located in the floor, leaving passenger and cargo space intact or unaffected. The car goes 450 km before refuelling, travels up to 140 km/h and emits water vapour as exhaust.

DaimlerChrysler introduced the NECAR 5 in November 2000, an MFCV that is expected to serve as the pre-production prototype. The company characterises the present status of the fuel-cell drive as fit for practical use. NECAR 5 is the first vehicle in which the entire fuel-cell system with methanol reformer has been accommodated within the underbody of the Mercedes-Benz A-Class compact car. The vehicle uses a Ballard *Mark 900* fuel cell, and can carry five passengers and their luggage to over 140 km/h.

F-Cell

On October 7 2002, DaimlerChrysler unveiled the Mercedes-Benz "F-Cell" A-Class, a small-scale series of 60 fuel-cell powered cars. These cars, which are nearing series-production standard, are no longer one-off research vehicles going under the name of NECAR (New Electric Car). Rather they will be tested in small fleets under everyday conditions by customers in Europe, the USA, Japan and Singapore as part of state-backed international alliance agreements, starting in 2003.

In the "F-Cell", the entire fuel-cell system is accommodated in the sandwich floor of the long-wheelbase Mercedes-Benz A-Class. Its tanks supply compressed hydrogen directly to the fuel-cell system, giving the "F-Cell" a cruising range of about 140 km. Hydrogen consumption is equivalent to 56 mpg (4.2 l/100km) gasoline.

The electric motor has an output of 65 kW. The vehicle gets a top speed of around 140 km/h.

Jeep Commander

In 1998 DaimlerChrysler unveiled a fuel-cell concept vehicle based on the Jeep Commander, with the original goal of having a fuel-cell/battery hybrid engine that utilised gasoline as its fuel. Since then, DaimlerChrysler has put gasoline reformer technology on the backburner and is pursuing methanol and direct-hydrogen systems more vigorously.

The company unveiled a working methanol hybrid fuel-cell system in the Jeep Commander 2 in October 2000. As the vehicle is a fuel-cell/battery hybrid concept, it has a nickel-metal-hydride battery to provide supplemental energy during acceleration, and for cold starts. The battery also captures energy from regenerative breaking.

1.4.7.2 Ford

TH!NK FC5

Ford Motor Company unveiled the TH!NK FC5, a family-sized fuel-cell sedan, in February 2000. The FC5 uses hydrogen extracted from methanol on-board the vehicle, using XCELLSIS's latest methanol reformer fuel-cell electric powertrain. Ballard's *Mark 900* fuel-cell stack powering the FC5 is designed for manufacturing in automotive production volumes and is significantly more powerful than any previous PEM fuel cell, generating 75-kW of power. It occupies half the space of Ballard's previous fuel cell, the *Mark 700*, and weighs about 30% less. Based on the 2000 Ford Focus, the TH!NK FC5's fuel-cell powertrain is located beneath the vehicle floor, so it does not compromise passenger or cargo space.

Prior to the TH!NK FC5, Ford introduced the P2000 FCV operating on hydrogen. Ford is also developing the P2000 SUV concept, a vehicle that features a fuel-cell engine with a methanol reformer.

Ford teamed with Ballard and DaimlerChrysler on fuel-cell engine research & development.

1.4.7.3 General Motors

Zafira

Through its German subsidiary Opel, General Motors introduced a methanol fuel-cell powered car in 1998, based on the Zafira. The car is a four-seater, with a 50-kW electric motor. GM is focusing much of its fuel-cell research and development at Opel's Global Alternative Propulsion Centre in Germany. In March 2000, Opel unveiled the latest version of the Zafira, running on hydrogen. Powered by its 7th-generation fuel-cell system, the Zafira now achieves full power nearly 12-times faster in freezing conditions than its predecessor. The Zafira was chosen to be the pace vehicle for the marathon at the 2000 Summer Olympics in Sydney, Australia.

HydroGen1

In November 2000, General Motors displayed the HydroGen1, its latest road-going, hydrogen-powered, fuel-cell vehicle. The HydroGen1 is a five-seat concept vehicle, based on Opel's Zafira compact van. Its hydrogen-fuelled fuel-cell unit powers a 57-kW electric motor that attains speeds of nearly 140 km/h and a range of about 400 km per

tank of hydrogen. Thermal efficiency reaches 53% to 67%. The HydroGen1 can start in temperatures as low as -40º C.
GM announced plans to begin high-volume production of fuel-cell vehicles before 2010, initially planning to use gaseous hydrogen in its fuel-cell vehicles. To speed up the innovation process, GM has teamed up with Toyota Motor Corporation and Giner, Inc., a research and development firm with extensive experience in developing direct methanol and other fuel-cell technologies.

GM Precept
General Motors also has the Precept concept car, in both hybrid and fuel-cell powered forms. The Precept has a four-wheel drive, dual-axle set-up. Electricity from the fuel cell is used to drive the electric motor on the Precept's front axle. GM expects the fuel-cell Precept will achieve 108 mpg (2.2 l/100km) gasoline equivalent.

1.4.7.4 Honda

FCX
Honda introduced its first prototype fuel-cell vehicle, the **FCX V1**, in September 1999. The first FCX ran on pure hydrogen, could carry two passengers, used a hydrogen-absorbing alloy to store fuel, and used a fuel cell developed by Ballard Mfg. The electric drive motor generated 49kW of output power.
The **FCX V2** operated on methanol and an on-board hydrogen fuel processor developed by Honda reformed the methanol into hydrogen for the fuel cell.
As Honda's fuel-cell vehicle technology evolved, the **FCX V3** was fuelled on pure hydrogen stored in a high-pressure hydrogen tank. The new fuel-cell system on the FCX V3 occupied much less room and passenger space increased to four. The output of the fuel cell was supplemented by Honda's Ultra Capacitor that provides instantaneous power response and higher fuel efficiency as it recycles regenerated braking energy. Peak motor output reached 60kW. The FCX-V3 was introduced in February 2001.
The **FCX V4** further reduced the size of the fuel-cell powerplant and related components, which provided room under the floor of the car for two hydrogen tanks with greater total capacity, and used a 78 kW Ballard fuel-cell stack. It also employed Honda's Ultra Capacitor for quick response and greater efficiency and range. The range of the FCX V4 with its 5,000-psi hydrogen tanks was 300 km. It also increased trunk cargo space for users with the relocation of the hydrogen storage equipment.
The FCX series of prototypes paved the way for the **FCX limited production vehicle**, the first fuel-cell vehicle in the world to receive government certification for commercial use. The FCX is classified by CARB and the EPA as a Zero Emission Vehicle (ZEV). Honda started a lease programme for a limited number of FCX's in the USA and Japan in December 2002. Over a two to three year period, Honda will lease about 30 fuel-cell vehicles in California and the Tokyo metropolitan area, two locations with access to a hydrogen fuel supply infrastructure.

1.4.7.5 Toyota

FCHV [Toyota website: Toyota's Fuel Cell Hybrid Vehicles]
Toyota introduced the FCHV-3, a fuel-cell hybrid vehicle (FCHV), at the International Symposium on Fuel Cell Vehicles held on March 1 and 2, 2001, in Tokyo.
The FCHV-3 features a hydrogen-absorbing alloy tank and a body based on the Highlander sport utility vehicle, as well as a highly efficient 90 kW fuel-cell stack and other unique FCHV systems developed by Toyota. Furthermore, the FCHV-3 has a secondary battery for storing energy created during braking and other features that ensures high-efficiency driving, such as precise control of the charge and discharge of the secondary battery and of supplementary power supply from that battery to the motor.
In parallel with these efforts, Toyota has initiated research on a wide range of fuel sources such as gasoline, natural gas and liquid hydrogen, as well as development of components for use with such types of fuel. In January 2001, Toyota announced a plan for the development of clean hydrocarbon fuel (CHF), an evolved form of gasoline.

At the 4th Toyota Environmental Forum in June 2001, Toyota announced that it has developed a new type of fuel-cell hybrid vehicle called the **FCHV-4**. The FCHV-4, powered by hydrogen stored in high-pressure tanks, was developed in tandem with the FCHV-3, a FCHV unveiled in February that uses hydrogen-absorbing alloy tanks.
In the FCHV-4, hydrogen is directly stored in high-pressure tanks. Adopting the body of Toyota's Highlander SUV (known as Kluger V in Japan), the FCHV-4 also features the Toyota FC Stack, a high-performance fuel-cell stack with an output of 90 kW. Coupling this wholly TMC-developed stack with a secondary battery that gives the vehicle regenerative braking capabilities and other attributes is representative of the FCHV-4's unique hybrid system.
Furthermore, the FCHV-4 has a newly developed heat pump air-conditioning system that uses CO_2 as the refrigerant instead of hydrofluorocarbons (HFCs).

FCHV-5 is a fuel-cell hybrid vehicle that generates electricity from hydrogen derived from CHF (Clean Hydrogen Fuel), using Toyota's original CHF reformer. Seen as the next-generation liquid fuel, CHF can be produced from crude oil, natural gas or coal and has a low sulphur content. CHF is also used as a fuel for gasoline-engine vehicles and can be supplied by current gasoline pumps. Therefore, FCHV-5 will be useful where hydrogen supply infrastructure is not available.
While the FCHV-5 shares several main fuel-cell components with the FCHV-4, such as its fuel-cell stack and motor, its CHF reformer packaged with a newly developed catalyst and heat exchanger, among other components, offers excellent acceleration and high fuel efficiency.

Roughly 20 FCHVs will be available from December 2002 throughout the USA and Japan. The first vehicles were delivered on December 2. Because the company still has to explore methods of lowering costs, improving cold-temperature performance and other technical issues, the vehicles will only be leased to select private sectors, institutional organisations, research facilities and technology-related companies. The Toyota FCHV represents an advance on the FCHV-4 hydrogen fuel-cell vehicle, which underwent 18 months of real-world testing in California and Japan, logging more than 80,000 miles of evaluation on test tracks and public highways. The FCHV runs on pure hydrogen as fuel, so all organisations that lease the vehicles must have access to a hydrogen-supply facility or infrastructure.

1.4.7.6 BMW

BMW and *Delphi Automotive* have produced their first development vehicle featuring a 5 kW PEM fuel-cell auxiliary power unit (APU). The APU provides sufficient energy for existing mechanically-driven subsystems, such as the air conditioning and water pumps. The APU could also be used to run devices without running the engine.

1.4.7.7 Nissan / Renault

Nissan is test-driving a prototype fuel-cell car based on the company's R'nessa SUV. The fuel-cell engine uses hydrogen from methanol stored on-board and processed through a fuel reformer.
In May 2000, in Japan, Nissan also showcased its fuel-cell powered electric Xterra utilising a PEM fuel cell using a methanol-reformer as well as a neodymium magnet synchronous traction motor combined with a lithium-ion battery. The vehicle is able to switch between fuel-cell power and battery power while in operation.
Nissan and Suzuki have joined a government-sponsored project to develop DMFCs for vehicles that is expected to result in a prototype by 2003.

Nissan Motor Co. and *Renault SA* have decided to develop cars with a fuel cell that runs on gasoline. The companies will spend $714 million on the project and will market the fuel-cell vehicles as early as 2005. Renault is also working with *PSA Citroen* to speed the development of a commercially viable fuel-cell car by 2010.

On 10 December 2002, Nissan Motor Co. said that it had gained government approval to test-drive its fuel-cell powered sport utility vehicle X-Trail FCV on public roads in order to start leasing fuel-cell vehicles in 2003, speeding up its original plans for a launch in 2005.

1.4.7.8 Mazda

Premacy FCEV
Mazda Motor Corp. plans to start test-runs of its Premacy FC-EV car powered by a methanol-reformer fuel-cell system and an electric motor, in Japan. Mazda aims to start marketing fuel-cell cars around 2005, after making alterations to the vehicles based on the results of the test drives.

1.4.7.9 Volkswagen

VW Bora HyMotion
Germany's *Volkswagen* has developed a fuel-cell powered car in partnership with Johnson Matthey (United Kingdom), Volvo (Sweden) and the Energy Research Foundation Netherlands ECN, supported by the European Union. In November 2000, Volkswagen showed its fuel-cell vehicle, the Bora HyMotion, based on the popular Jetta. Its storage capacity is 49 L of liquid hydrogen at cryogenic temperatures, allowing the car a maximum range of about 355 km. Its asynchronous electric motor has a power output of 75 kW and 240 Nm over a large rpm range. The Bora HyMotion accelerates from 0 to 97 km/h in 12.5 s and can reach a top speed of 145 km/h.

1.4.7.10 Hyundai

Hyundai Santa Fe FCEV
International Fuel Cells and *Hyundai* have worked together to produce four hydrogen-powered fuel-cell vehicles based on the Santa Fe sport utility vehicle. These zero-emission vehicles contain a 75-kW fuel-cell system and use a conventional automobile battery for start-up. Enova Systems will supply the electric drive train and power management systems for the vehicles.

1.4.7.11 Fiat

Fiat Seicento Elettra H2 Fuel Cell
Fiat has developed the prototype of its first fuel-cell car, Seicento Elettra H2 Fuel Cell. The two-seater car was developed with the support of the Italian Ministry of the Environment and runs on hydrogen.

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2 SURVEY OF RECENT MAJOR PUBLICATIONS AND RELEVANT ACTIVITIES OF THE MAIN MANUFACTURERS

by Luc Pelkmans (VITO)

2.1 Introduction

Most manufacturers still spend most of their efforts in improving conventional gasoline or diesel technology. Their main goal is to comply to future emission limits and to improve fuel economy.
The following are developments to be expected in the short-term related to conventional gasoline and diesel drivetrains:

General developments:

- Variable Valve Actuation & Cylinder Deactivation
- Variable compression ratio
- Engine downsizing
- Integrated powertrain control
- Further evolutions of OBD
- 42V systems (in stead of 12 or 14V)
- Integrated starter-generators (mild hybrid)
- Electrically assisted auxiliaries
- X-by-wire (gas pedal, breaking, steering wheel)
- Six-speed manual gearbox
- Intelligent transmissions (automated manual transmission)
- Dual-clutch transmissions
- Continuous variable transmission (CVT)
- High strength light-weight materials

Gasoline engines:

- Throttle-less engine control through variable valve control
- Gasoline direct injection
- Lean-burn technology
- Emission after-treatment for lean-burn engines ($DeNO_x$ or NO_x adsorbers)
- Controlled auto-ignition

Diesel engines:

- Further developments in common rail diesel injection and pump unit injectors. (piezo-controlled injection, ceramic injectors).
- $DeNO_x$ catalyst, SCR or NO_x adsorbers
- Particulate traps
- Homogenous Charge Compression Ignition (HCCI)

Apart from these developments, research is also being performed into new engine fuels, hybrid vehicles and fuel-cell vehicles.

2.1.1 Trends and opinions of the manufacturers

[ACEA, 2001]
2001 saw the introduction, or increased application, of a wide range of technical developments by ACEA manufacturers. Examples include: 2-step variable valve lift, valvetronic, fully variable intake manifold, the second-generation of common rail injection (high pressure), a new generation of bio-fuelled vehicles, series production of CNG single-fuel vehicles, application of advanced diesel technology to small cars, 6-speed automatic gearbox, along with increased application of CVT, robotised gearboxes, GDI, 6-gear manual boxes, electric power steering, route guidance systems, etc.

'Overview 2001' [MTZ, December 2001]
The editor of MTZ (*Motor Technische Zeitschrift*) presented a short overview of the new developments in the (German) automobile industry. Following the example of Mitsubishi (which has already sold one million GDI engines since 1996), all manufacturers are working on gasoline direct injection to improve fuel economy. Full variable valve control has also had a breakthrough for BMW.
In the diesel engine, the long-expected Piezo-diesel injectors of Siemens VDO have been put into series production. These may operate four times faster than electromagnetic injectors and this way it is possible to have five injection phases (instead of three) - e.g. two pre-injections, one main injection and two post-injections.
To date, Peugeot has been the only car manufacturer to offer particulate traps as a standard device. Most manufacturers are also working in this area.

"Engines for growth, is this the beginning of the end for IC engines?" (Global Viewpoints Europe) [*Automotive Engineering International*, June 2002]

An overview of the viewpoints of European manufacturers on future trends in vehicle technologies was published in the June 2002 edition of *Automotive Engineering International.*
Generally it was agreed that the combustion engine still has a good future. In particular, developments in variable valve control are looking very promising, leading to camless engines. With gasoline engines moving to lean-burn technology, throttle-less power control and auto-ignition and diesel engines evolving to homogenous charge (HCCI), there would be more and more convergence between gasoline and diesel technology. 42 V electric supply would pave the way for mild hybrids, incorporating integrated starter-generators in the drivetrain.
The emergence of the fuel cell as an alternative to the IC engine is steadily gaining momentum, although based on present indications it is likely to be at least 2010 or even beyond 2015 before meaningful production and sales are achieved, with cost and infrastructure difficulties continuing to concern most OEMs and suppliers questioned.

Because all the signs are that the IC engine is likely to remain the primary source of motion power for cars for many years to come, the types of transmissions now in use are likely to be further developed. There has been a market move in Europe towards six-speed manual gearboxes, an increase in the popularity of automatic transmissions and automated manual systems, and limited interest in continuously variable transmissions (CVT).

Some quotes:

Neville Jackson (Ricardo Consulting)

> "In the long term, IC engines can use the same renewable energy sources as alternatives such as fuel cells (hydrogen) while remaining the lowest-risk option in terms of manufacturing cost and servicing infrastructure. Engine downsizing, mild hybrids, dual-clutch transmissions, advanced fuel-injection systems, variable valve actuation, and integrated powertrain control are most promising technologies."

Don Law (Group Lotus):

> "After about 100 years with the compromises of traditional camshafts, currently there is a move toward more variable valvetrains. Active Valve Train (AVT) facilitates the ability to control gas-mixing and combustion processes and to deactivate valves and cylinders, changing the displacement of the engine and changing compression ratios. This allows for the introduction of different combustion mechanisms such as auto-ignition in gasoline engines and homogeneous-charge compression ignition (HCCI) in diesel engines. These camless engines then would see a convergence between gasoline and diesel technologies."

Bosch

> The company believes that for the long term (beyond 2010), combustion technologies such as HCCI for diesel and gasoline engines combined with a fully flexible air inlet path offer "further potential in reducing emissions without disadvantages in fuel consumption". For the short term, Bosch points to split injection and higher injection pressures for diesel engines and split injection combined with spray-guided gasoline direct injection technology for gasoline engines to be introduced or developed.
>
> Bosch is cautious about the advent of the fuel cell. Based on current information, the company believes there will be "no significant market entry for fuel cells concerning the main drive before 2020". Bosch views hydrogen generated via a gasoline reformer as the most likely fuel source because the retail supply infrastructure is in place and it would make sense as a transitional link between the fuel cell and IC engine.

Johann Löttner (Siemens VDO)

> Siemens sees a trend towards lower fuel consumption by using high-end technologies such as the valve lift control or piezo diesel injection. Siemens regards the fuel-cell "breakthrough" as being possibly 20 years away. Meanwhile, the company sees a growing market share for hybrid drives, but mainly in the form of an integrated starter-generator as a supplement to the IC engine to provide additional torque during accelerations.

Marc Bocque (PSA Peugeot Citroen)

Developments for gasoline engines will include more direct-injection applications and the use of electromechanical valves.

Pierre Beuzit (Renault)

Renault will address both gasoline and diesel engines through technologies such as camless systems, low-consumption supercharging, diesel emissions control, and through new environments in which those technologies operate: x-by-wire systems vs. hydraulic functions, 42-V electric supply, integrated starter-generator with stop-and-go booster, etc. Renault is working with its partner, Nissan, on hybrid technology and late this year will market an electric Kangoo with range extender, a small gasoline engine used to recharge the batteries for city use.

Renault has been actively involved in fuel-cell research and development for eight years and is working with Nissan on two projects: "medium-scale" production of fuel-cell vehicles with on-board hydrogen storage (primarily for the Japanese and US markets for 2004-2005) and full-scale production of "competitively priced" fuel-cell vehicles with a reformer for 2010.

Rinaldo Rinolfi (Fiat)

Emerging technologies such as throttle-less load control, fuelling system refinement, engine downsizing, electrically assisted auxiliaries and drives, gaseous fuels, intelligent transmissions and integrated powertrain control assure a further growth of IC engine technology.

Daimler-Chrysler

On their fuel-cell vehicle developments: "After fast initial progress, we are now in an engineering process to improve technology, cost, reliability, and performance. Series production will probably start at the beginning of the next decade after a period of extensive testing in the next few years.

As a fuel source, the most likely fuel-cell fuels are hydrogen for fleet applications and methanol for private users, both with fossil and renewable production options."

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2.2 Internal combustion engines

2.2.1 Gasoline direct injection & lean burn control

"Direct injection for the Audi A2" [*Automotive Engineering*, July 2002]

The application of gasoline-direct-injection technology is steadily gaining momentum in production cars, and the first **Audi** to receive it is the aluminium-bodied, spaceframe A2. Designated FSI, its possible arrival in a production car was signalled in 1997 when the A12 concept was shown at the Frankfurt Motor Show with a three-cylinder direct-injection gasoline engine. Also, direct injection was used for Audi's 2001 Le Mans-winning R8 racecar.

Audi cites potential fuel consumption reduction of up to 15% in production cars. The company lists the core elements of the technology as a common-rail fuel-injection system with high-pressure injection pump; a four-valve cylinder head with laterally located injector and intake port divided by a tumble plate; two-position tumble control; an external exhaust gas recirculation (EGR) system; optimised emissions treatment system with NO_x-storage catalytic converter and NO_x sensor; and two-line exhaust gas cooling with radiation cooler.

According to Audi, the greatest challenge apart from exhaust gas treatment was the implementation of the necessary software in the engine control unit (ECU) because of the many maps and the transitions between the operating states, calling for a computing capacity more than twice the norm. Advanced computer simulation techniques were applied to achieve a match of the 3-D maps. Injection pressures are up to 11,000 kPa (1600 psi).

The Audi engine has a two-position tumble flap in the intake port. When open it allows air unobstructed ingress. In its second position it moves against a tumble plate shielding the lower part of the intake port to channel intake air via a controlled path into the combustion chamber. Audi claims that this feature makes two operating modes possible, which are the fundamental requirements for the versatility of the FSI principle: homogeneous- and stratified-charge operation. Depending on load status and accelerator position, the engine electronics always switch to the optimum mode without the driver noticing. The FSI engine has a 12.1:1 compression ratio.

A problem with direct-injection-gasoline technology has traditionally concerned NO_x emissions, with excess air in the combustion process making it difficult to reduce NO_x to nitrogen gas completely by using a conventional catalytic converter. Audi says it has used a "series of measures" to solve this problem. EGR is one of these measures, resulting in untreated NO_x emissions being reduced by some 70% during stratified lean-burn operation.

Another measure is the engine being equipped with two catalytic converters, one of the regular three-way type positioned behind the manifold, and the other a NO_x "storage-type" converter located beneath the floorpan and specifically developed for a direct-injection-gasoline engine. It has a barium coating with which the oxides of nitrogen combine and is controlled via mapping and temperature. When the converter is

saturated, the engine's mixture is briefly made richer, raising the temperature of the slightly rich exhaust gas. The barium molecules in the converter release the oxides of nitrogen, which are then reduced to nitrogen, explains Audi. A NO_x sensor is positioned at the discharge end. NO_x-storage converters operate most efficiently between 250 and 500°C, therefore this range is the prerequisite for the lean-burn operation of the gasoline-direct-injection engine since NO_x emissions are particularly high in this mode. To ensure that exhaust gas temperatures remain within this range, the A2's exhaust system is fitted with an exhaust gas cooler positioned ahead of the NO_x-storage converter. To improve cooling efficiency particularly when exhaust gas temperatures are high, the heat sink is designed as a radiation cooler.
The A2 1.6-L FSI engine has an output of 81 kW (109 hp) at 5800 rpm and a maximum torque of 155 Nm (114 lb•ft) at 4500 rpm. Engine management is via a **Bosch** Motronic MED7. The engine is mated to a five-speed manual transmission.

"Mercedes' direct-injection-gasoline engine" [*Automotive Engineering*, June 2002]
On the eve of the Geneva Motor Show, **Mercedes-Benz** revealed that it is planning to introduce a 1.8-L four-cylinder, supercharged direct-injection-gasoline engine with balancer shafts. With 125-kW output, it is more powerful than the 2.0-L engine it will replace, but is said to be 19% more fuel efficient, returning a combined consumption of 7.8 L/100 km in the C-Class. The model will be designated CGI. As well as a supercharger, each engine will have an intercooler, four valves per cylinder, variable valve timing, balancer shafts, and an adaptive drive system—all under the heading of Twinpulse.

The move to direct injection is not wholly new to Mercedes. The 300SL Gullwing built from the early 1950s was the first series-produced car to use a four-stroke gasoline direct-injection engine. According to the company, the CGI engine has two separate intake ports that ensure optimum swirl in the mixture, thus making combustion fast and as complete as possible. Each port has an adjustable fuel flap. A high-pressure fuel pump is driven by the intake shaft. A pressure regulator controlled by the engine computer regulates the pressure in the fuel rail, which is directly connected to the injectors. The engine, which has exhaust gas recirculation and secondary air injection, meets EU-4 emissions requirements. Up to 35% of the exhaust gas can be recirculated. The engine has a linear oxygen sensor that becomes active immediately on cold engine start-up. A newly developed NO_x sensor with digital control is used.

The engine goes into production in the fall 2002.

2.2.2 Emission after-treatment for lean burn engines

"VW exhaust after-treatment by OMG" [*Automotive Engineering*, April 2002]
To reduce the fuel consumption of its vehicle fleet, **Volkswagen** AG developed spark-ignition engines with direct fuel injection. Engineers first had to develop a suitable exhaust gas after-treatment system to launch this new engine concept with stratified lean operation mode while meeting the stringent EU IV emissions standards. This was

achieved as part of an intensive cooperation between Volkswagen AG and **OMG**, formerly dmc^2 Degussa Metals Catalysts Cerdec AG.

Due to intensive co-operation of the development partners involved, it was possible to implement for the first time an exhaust gas after-treatment system based on NO_x-storage-catalyst technology for the emissions standards in the Volkswagen Lupo FSI (fuel stratified injection). The fuel consumption of the Volkswagen Lupo FSI is 4.9 L/100 km. The emissions and fuel consumption targets were successfully achieved by:

- A general exhaust gas after-treatment concept with a NO_x-storage catalyst and on-demand purging functions based on NO_x-sensor control
- Improvement of the ageing stability of the catalyst system by developing a stable NO_x-storage catalyst and light-off catalyst formulation, engine-out emissions reduction, and exhaust gas cooling devices
- Improvement in the desulfation characteristics of the NO_x storage catalyst and development of an active desulfation process.

European fuel-quality standards required the development of a new active and lambda-controlled desulfation process. Although the Volkswagen FSI exhaust gas after-treatment concept can withstand high fuel sulphur contents, sulphur-free fuel is required for best fuel economy. With widespread available sulphur-free fuel, advanced NO_x storing components with a wider NO_x activity window can be used, which leads to more frequent use of fuel-saving lean operation mode.

Since Spring 2000, several mineral oil companies have introduced sulphur-free fuel with less than 10 ppm in Germany. Volkswagen supports this trend, hoping that within a short time period the availability of sulphur-free fuel will be extended to other countries.

As soon as fuels with less than 10 ppm are available within the European Union on a widespread scale, new NO_x storing components with wider NO_x activity windows and higher desulfation temperatures can be employed. When catalyst deactivation occurs very slowly due to low sulphur concentrations, the chance for a "natural" desulfation to be performed before active sulphur regeneration must be initiated increases. Fuel economy will thus increase not only by rare desulfation. The main advantage will be more frequent use of lean-burn and stratified engine operation mode, especially at higher catalyst temperatures.

The researchers believe that worldwide improvements in fuel quality standards are needed for market penetration of FSI engines. As direct gasoline injection is the technology with the highest potential in reduction of CO_2 and fuel consumption, any initiative will be supported that promotes the FSI strategy.

2.2.3 Engine-assist systems

Integrated starter-generator systems have been a very common subject of research in the past five years. A number of vehicles with engine-assist systems are mentioned in the chapter on hybrid vehicles. The following are a few recent publications on the engine-assist systems itself:

Improving SUV fuel economy [*Automotive Engineering*, July 2002]
"Delphi is pursuing a strategy of engine shutdown and adding torque from an electric motor with its new 42V integrated starter-generator.
"Vehicle manufacturers are looking for ways to improve fuel economy of light trucks, including sport utility vehicles (SUV), without affecting performance or utility. One possible solution in accomplishing this objective is the 42-V integrated starter-generator (ISG) under development at Delphi Corp. The ISG offers the ability to reduce fuel consumption by switching the engine off during coasting and idle, and employing early torque converter lockup with torque smoothing, regenerative braking, and electrical launch assist. It also boosts onboard power generation and energy storage, allowing for increased vehicle electrical loads. "

Valeo and Ricardo ready the i-MoGen [*Automotive Engineering*, May 2002]
The 42-V mild hybrid-diesel technology demonstrator vehicle being developed by **Valeo** and **Ricardo** will be ready soon in a C category car. Valeo and Ricardo announced at last year's Frankfurt Motor Show that they had established a technical and strategic partnership that combined Valeo's electrical energy and thermal management systems with Ricardo's diesel powertrain and vehicle engineering expertise in systems integration and control [*AEI*, November 2001].
Called i-MoGen (Intelligent Motor Generator), the demonstrator vehicle will integrate a range of Valeo's 42-V systems, including the company's integrated starter-alternator, its HVAC system, intelligent engine cooling, and other electrical systems. A high-output, downsized 1.2-L diesel engine will constitute the core of the powertrain, together with a supervisory controller to co-ordinate system operation, both developed by Ricardo. The demonstration vehicle is expected to achieve its main technology targets of a fuel economy of less than 4 L/100 km; exhaust emissions of 50% of current Euro IV levels; acceleration from 0 to 100 km/h (0 to 62 mph) in 10 s; and "production vehicle refinement and driveability," according to the company.
The high-output, 1.2-L, four-cylinder HSDI diesel engine will produce 74 kW (100 hp). Both companies claim that the engine will reduce fuel consumption by 20% compared with a 2.0-L conventional diesel engine and offer possible total weight savings of up to 30%, which compensates for the additional weight normally expected in mild hybridisation. Valeo's high-efficiency, integrated starter-alternator system, which will be mounted on the crankshaft between the engine and the transmission, will perform a number of key functions including stop-and-go. This entails stopping the engine when it is not required and automatically restarting it when it is, so that when a driver waits at a traffic light, the engine is automatically stopped. When the driver re-engages a gear, the engine restarts.

Quiet starting is realised through the use of the integrated starter-alternator in motor mode. Since this unit is fully integrated into the powertrain and replaces the traditional starter motor, engaging of the starter's gear on the ring gear — a violent and noisy operation — is no longer needed, and noise is therefore significantly reduced. The starting time is only 0.3s as opposed to one full second with a conventional starter motor, leading to further reduction in emissions.

During acceleration, the integrated starter-alternator is used as an electric motor to give an extra boost to the engine so that despite the smaller power unit size, the i-MoGen powertrain can supply similar torque to that of a much larger and heavier 2.0-L diesel engine. The system also includes regenerative braking.

Maximum electrical output power from the Valeo integrated starter-alternator unit when running in alternator mode is 6 kW, or about three times higher than conventional alternators. This output is necessary to allow the operation of high-power electrical components such as the electrical HVAC compressor, or the electrically heated diesel particulate filter, a Ricardo solution.

A Valeo-developed dc/dc converter will be integrated to supply 14 V to the low-power electrical components that are not converted to 42 V. Valeo is collaborating with a battery specialist to develop and integrate fault-tolerant batteries with a battery state-of-charge function guaranteeing the reliability of all its 42-V systems.

THEMIS, a Valeo system capable of managing and optimising engine temperature according to the driving conditions, will be central to i-MoGen's engine cooling system. It features an electrical variable water pump, electronically controlled variable speed fans and an electronic coolant valve, replacing the conventional thermostat. Engine warm-up time is reduced by up to 50%. As an additional benefit, the THEMIS system enhances cabin comfort, continuing to provide heat even after the engine has been switched off.

Valeo's 42-V electrical HVAC system, based on an electrical compressor, will be integrated into the demonstration vehicle. It only uses energy "on demand." Because HVAC systems are notorious power consumers, the new system is set to bring "significant" fuel-economy benefits, claims Valeo. The system is also equipped with a 42-V, 1.3-kW cabin air heater that helps to compensate for the low heat rejection of a downsized diesel engine under warm-up conditions from a cold start.

2.2.4 Alternative fuel engines

The past trends in alternative fuel engines were discussed in detail in Chapter 1.6. In this chapter some published results in the area of natural gas, hydrogen and synthetic fuels will be shown.

2.2.4.1 Natural gas

Honda Civic GX CNG (Info: American Honda)

Powered exclusively by compressed natural gas (CNG), the Honda Civic GX CNG boasts the cleanest-burning internal-combustion engine in the world. American Honda announced that its 2001 and later CNG Civic GX is the first and only vehicle certified by the California Air Resources Board (CARB) as "AT-PZEV" earning "Advanced Technology-Partial ZEV" credits. This standard was created in the CA LEV II

regulations to recognize the benefits of near-zero emission vehicles as an option to producing pure battery electric cars under the ZEV sales mandate.
The 2002 Civic GX retains the title of cleanest internal-combustion powered vehicle ever mass produced. In addition to super ULEV tailpipe emissions and zero evaporative emissions, the GX emission control systems are warranted to keep the SULEV emissions SULEV for 15 years or 150,000 miles - a distinguishing feature of a certified AT-PZEV.

Engine: 1.7L 4 cylinder SOHC with natural gas sequential Multi-Point Fuel Injection
Tank Capacity: 7.2-8.0 gasoline gallon equivalent @ 3000 psi; 8.0 @ 3600 psi
Rated Power: 100hp @ 6100 RPM

“Natural gas FIAT Ducato ready for the market” [ENGVA News, August 2002]
As of September 2002, the new bifuel Fiat Ducato will be put on the market. The natural-gas version has a 2.0 litre, four-cylinder motor with more than 71 kW. The transporter has a combined range of 870 km.
In other Fiat news, the production of the natural-gas Multipla is off production from 2001 by some 90%, according to the Italian NGV marketing team at ENI. This is due in part to some engine durability problems that required additional vehicle modifications.

2.2.4.2 Hydrogen

As stated in Chapter 1.5, only a few car manufacturers are dealing with hydrogen for combustion engines. The main maker is BMW, but Ford has also presented research results.

BMW's hydrogen message [*Automotive Engineering*, May 2002]

BMW will offer its new 7 Series sedan with hydrogen as an alternative fuel source. "Within the production life cycle of our new 7 Series, we will be supplying customers with hydrogen vehicles," said Burkhard Göschel, Head of Development and Purchasing, BMW. "The future will be hydrogen-related." Göschel made the announcement in Berlin at the completion of a world tour organised by BMW to promote hydrogen as a future clean energy source.
While the production hydrogen 7 Series car is likely to be at least five years away, BMW has made no secret of its caution about fuel-cell technology as a motive force for its cars, preferring to develop hydrogen-powered, internal-combustion engine technology. BMW does, however, see <u>fuel cells as a power source for onboard electricity</u> for its cars, especially since a compact fuel cell takes up no more room than a conventional lead accumulator, but with 5 kW of output, outclasses it in performance and endurance. BMW has a fleet of 15 dual-fuel (gasoline and hydrogen) research cars based on the previous V12 7 Series and designated 750hl. These vehicles were demonstrated on the world tour. The cars have now covered 150,000 km.
Commenting on the debate on the practical effectiveness of the hydrogen-powered, internal-combustion engine vs the electric motor and fuel cell, Göschel said, "I have absolutely no problem at all here: Firstly because I know that good concepts can co-exist, and secondly because I know that if it comes to an either/or situation, the superior

concept will win over in the market. What is more important is that the automobile industry is increasingly assuming hydrogen will replace gasoline and diesel in the long term." Agreement on this is essential because of the need to establish volume production. It was therefore vital that the supply industry should be part of this process.

Hydrogen fuelling stations are to be built in some European cities, including London and Berlin. They will not be robotised as was the station for liquefied hydrogen built at Munich airport, but will be manually operated with specific safeguards. Michael D. Jones, Hydrogen Technology Manager with **BP**, says the company is evaluating various technologies for the manufacture and supply of hydrogen to the transport sector. "This includes the production of hydrogen from natural gas and from the electrolysis of water linked to renewable energy sources actually at the refuelling station," he said. "For a fully developed hydrogen structure, the cost of hydrogen can be competitive with that of today's conventional fuels. However, one challenge we will have to face is to make hydrogen economical for the early adopters of hydrogen-fuelled vehicles, which might have to bear a disproportionate share of the initial infrastructure investment."

The BMW 7 Series gasoline-hydrogen-powered car has a 140-L cryogenic—about -250°C—hydrogen tank in the trunk. It provides a cruising range of about 350 km. Using hydrogen, the 12-cylinder engine produces 150 kW to provide a performance similar to that of a BMW 7 Series with a 2.8-L six-cylinder engine.

Ford hydrogen engine [*Automotive Engineering*, April 2002]

A production-viable vehicle powered exclusively by a hydrogen-fuelled internal-combustion engine (H_2ICE) has been developed and tested. This low-cost, low-emissions vehicle is viewed as a short-term driver for the hydrogen-fuelling infrastructure ultimately required for fuel-cell vehicles. The vehicle features a highly optimised hydrogen ICE, a triple redundant hydrogen safety system, and a dedicated gaseous hydrogen fuel system. Engineers from the **Ford** Scientific Research Laboratory presented a paper on the vehicle during the SI Combustion Technical Session at the SAE Congress.

The engineers used an engine dynamometer facility to map a Zetec-based 2.0-L H_2ICE at both a constant fuel-air equivalence ratio of 0.55 when throttled and over a range from 0.12-0.70 when unthrottled to provide a starting point for vehicle-calibration development. The engine was tested with a 14.5:1 compression ratio and fixed cam timing, but without EGR or an after-treatment system. Following completion of the engine dynamometer development, the hydrogen engine team developed a plan to build and test the engine in a vehicle. This port fuel-injected four-valve-per-cylinder engine was integrated, together with a five-speed manual transaxle, into a P2000, an aluminium-intensive five-passenger family sedan developed by Ford to support PNGV work.

The vehicle control system consisted of an electronic throttle operated in a pedal follower configuration, an air meter based open-loop fuel control, and an electronically controlled coil on plug ignition. In addition, a PCV coalescing oil separator was added

to prevent recirculation of oil into the combustion chamber, thus reducing the potential for pre-ignition or backflash.
The fuel system was designed for safety as well as functionality. All of the major components of the hydrogen fuelling system were located in the vehicle trunk except for the fuel rail solenoid and the fuel injectors. The fuel line feeding hydrogen gas from the trunk to the engine was located under the floor pan.

Safety was a fundamental vehicle design consideration for this first prototype. The team built upon the experience of Ford's hydrogen fuel cell and compressed natural gas programmes to produce a unique system. This triple-redundant system combines active and passive ventilation with hydrogen detectors to enhance safety through redundancy. The heart of this system, the combustible gas detectors, consists of four sensors located in the engine compartment, passenger compartment, and trunk. Alarm conditions are triggered at hydrogen concentrations of 0.6, 1.0, and 1.6% (15, 25, and 40% of lower flammability limit for hydrogen). In addition to the detector, the safety system relied on several ventilation fans to circulate air within the trunk and engine compartments to prevent the formation of high concentration pockets of hydrogen within these areas and create more uniform mixtures at the sensors. Should hydrogen of sufficient concentration be detected, several measures are taken to minimise ignition potential. These measures include disabling the fuel supply and engine starter, opening the moon roof, and activating all ventilation fans if not already on.
Since hydrogen is significantly less dense than air, it will rise and disperse if it is not trapped. The passive elements of the safety system were designed to take advantage of this behaviour. Hood louvers and the trunk seal vents (depressions in the trunk seal) allow hydrogen to escape to the atmosphere from the engine compartment and trunk, respectively. Thus, these elements further improve the vehicle's safety, providing redundancy without intervention from the other system elements.

Results of vehicle testing indicate the following:

- Carbon-based engine-out emissions testing indicated that HC and CO are less than SULEV standards, and CO_2 emissions are reduced to about 0.4% of the tailpipe levels produced by a gasoline-fuelled engine of the same displacement
- The engine-out NO_x emissions ranged from 0.23 to 0.46 g/km (0.37 to 0.74 g/mi).
- A metro cycle fuel economy improvement of up to 17.9% relative to gasoline
- Smooth, acceptable drive feel in a city setting
- Acceleration performance would require improvement for full customer acceptability. At equal performance, the metro cycle fuel economy advantage, relative to gasoline, is expected to decrease to about 11%.

Future testing should investigate technologies such as boosting, EGR, and various configurations of exhaust after-treatment. Combinations of these are expected to substantially improve NO_x emissions, specific power, and fuel economy.

2.2.4.3 Synthetic fuels

For an overview of the main production players, please see Chapter 1.5.

Initiatives of some car manufacturers:

"Choren and DaimlerChrysler launch research initiative [Press release, April 8, 2002]

Stuttgart - April 8, 2002 - Choren Industries GmbH, headquartered in Freiberg i.Sa., and DaimlerChrysler AG launched an €11 million research project for the production of methanol and diesel fuel from biomass. DaimlerChrysler will test these advanced fuels in vehicles powered by either diesel engines or fuel cells to establish their suitability for use.
The research project, scheduled to end in mid-2003, is to clarify at what prices and conditions these renewable fuels can be produced. In addition, the researchers will evaluate the fuel quality and quantities available and compile a comprehensive energy and material balance, covering everything from the collection of biomass and processing through to fuel distribution. This will also involve an investigation into the size of facilities under the aspect of profitability.
DaimlerChrysler supports this research with more than €1 million. The Federal German Ministry of Economics provides €5.5 million to finance the project.

Prof. Klaus-Dieter Vöhringer, member of the Board of Management of DaimlerChrysler AG with responsibility for Research and Technology: "The EU is currently importing three quarters of its crude oil requirements. Without active countermeasures being taken, the import rate would rise to 90 per cent until 2020. The Near East, accounting for 75 per cent of the world's crude oil reserves, will raise its share in the world market from 40 per cent today to 50 per cent in ten years' time. This means that the world will become increasingly dependent on supplies from a politically unstable region. To safeguard energy availability, all types of energy will have to be used in future, especially fuels from renewable raw materials. These fuels will help to reduce the industrialized nations' dependence. They will also account for drastic reductions in the CO_2 emissions in road traffic since renewable fuels form part of an enclosed CO_2 material cycle."
Dr. Bodo Wolf, Managing Director of Choren Industries: "With fuels like diesel, methanol and even gasoline produced from biomass, it will be possible to secure the supply basis for fuels in the future."
A multi-stage process is used to convert the wide variety of biomass types investigated in the project into liquid diesel and methanol in a special facility in Freiberg. These two types of fuel are free from both aromatic hydrocarbons and sulphur. In a first step, biomass is processed into bio-coke in a cogeneration plant. The bio-coke is converted first into a raw gas rich in carbon monoxide and then into synthesis gas. The latter is then used to produce fuels such as diesel, methanol and gasoline.

DaimlerChrysler and Volkswagen Cooperate in Renewable Fuels [Press Release, September 16, 2002]

Together with DaimlerChrysler, Volkswagen will be involved in a research project with the Freiberg, Germany, company Choren Industrie GmbH for the manufacture of high-quality fuels from biomass. In this project in the pre-competitive environment, the two automakers intend to make more rapid progress in gaining well-founded experience with renewable fuels.

Whilst Volkswagen is initially interested in the production of synthetic fuels (SunFuel®) for internal combustion engines, diesel and methanol are at the centre of attention for DaimlerChrysler. In the course of this research project, fuel quality and quantity will also be assessed and a comprehensive energy and materials balance sheet drawn up - from the regional acquisition of biomass, via processing, up to the fuel distribution chain.

The various types of regionally derived biomass under investigation in this project are converted into liquid fuels in a multistage process. These fuels are free of aromatic compounds and sulphur. In the first stage, the biomass is processed into biocoke in a cogeneration plant and then further transformed into synthetic gas, from which the desired fuels can then be manufactured.

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2.3 Hybrid and electric drivetrains

2.3.1 Toyota

[Press Release Toyota Motor Corporation, April 22, 2002]
Toyota's hybrid car sales reached a total of 103,000 units worldwide at the end of March 2002, representing a 90% share of the world hybrid vehicle market.. The Prius was launched as the world first mass-produced hybrid car in December 1997. With more than 33,000 units sold by the end of 1999, the technology of the Prius debuted in the North American market in June 2000, soon followed by the start of sales in Europe in September that same year. The Prius is now sold in more than 20 countries.
Since the arrival of the Prius, TMC's hybrid vehicle line-up in Japan has grown to include the Estima Hybrid minivan, which came out in June 2001, and a mild hybrid version of the Crown luxury sedan, released in August 2001.

Toyota will try to have hybrid technology throughout its entire line-up by 2012.

Table 2.3-1: Cumulative Toyota hybrid vehicle sales* (unit = one vehicle)

Period / Model	1997	1998	1999	2000	2001	2002/1~3	1997~2002/3
Prius	323	17,653	15,243	19,011	29,459	7,402	89,091
Estima Hybrid	-	-	-	-	5,886	5,840	11,726
Crown w/ mild hybrid system	-	-	-	-	1,574	520	2,094
Coaster hybrid (bus)	9	3	12	15	9	8	56
Total by year/month	332	17,656	15,255	19,026	36,928	13,770	102,967
Cumulative total	332	17,988	33,243	52,269	89,197	102,967	

Source: Toyota Motor Company, 22 April 2002
*As calculated by TMC

2.3.1.1 Toyota Prius

Source: IEA-HEV (2001), www.toyota.com

The Toyota Prius is the world's first mass-produced hybrid vehicle and was introduced in December 1997 in Japan. A new version for the European and US market was introduced in the second half of 2000. The Toyota Prius is a charge-sustained vehicle.

The Japanese version of the Prius is equipped with a 1497 cm^3 four-cylinder gasoline-fuelled engine and the Prius' generator works also as the starter of this engine. The engine supplies 43 kW at 4000 rpm. The maximum speed in the engine map is limited to 4000 rpm as well in order to limit the exhaust emissions and fuel consumption. The engine has variable valve timing and the Miller cycle concept (meaning the engine's power stroke is longer than the compression stroke) allows a relatively high cylinder compression of 13.5:1. The maximum torque is 100 Nm.

Gear shifting is not required because of the planetary system that acts as a continuously variable transmission to keep engine revs in the range of best efficiency. Instead of a normal transmission, the engine drives the planet carrier of a planetary gear set. The sun gear of that set connects to a motor/generator, and the ring gear drives both the front wheels and a second motor/generator.

The electric drivetrain of the Prius gives it three advantages over conventional gasoline cars:

- Regenerative braking
- Zero emission driving is possible under idling or slow urban traffic conditions (note that this mode is not controlled by the driver but automatically by the energy management system)
- When needed, the battery power supplements the output of the engine.

Toyota created a new body for the Prius. For Europe, the vehicle is positioned as a medium-sized car, while for the USA and Japan the vehicle is appropriate to its intended role as a city car. Compared to the Toyota Corolla (with comparable dimensions) the Prius is about 15 cm shorter and 10 cm taller. With its weight of 1240 kg, however, the Prius is about 150 kg heavier than a comparable Corolla.

All the propulsion machinery and auxiliary components of the Prius are packaged under the hood. The 55 kg nickel-metal hydride battery pack is not placed nearby the engine (located at the front), but hides between the rear seat-back and the trunk.
The Prius is equipped with a drive-by-wire accelerator: the driver tells the motor management how much speed is required. The management system then decides where the necessary power should come from: engine or battery or both. The same accounts for the brake-by-wire system, the driver calls for the appropriate amount of retardation and the motor management co-ordinates this between the wheel brakes and the regenerative braking system The computer also makes sure that the generator runs frequently enough to keep the battery charged. All of this happens automatically, without asking for the attention of the driver.
When the battery is fully charged and the engine temperature is acceptable and the vehicle speed is sufficiently low, the engine never idles. It shuts itself off to save fuel. When pressing the accelerator gently, one moves away on battery power. For quicker accelerations, the gasoline engine comes to life and powers the Prius on its way. In normal driving the Prius maintains the battery state-of-charge within a narrow window. Driving mountain grades, for example, for a long time, might deplete the battery charge however.

The version of the Prius for the US and European markets

The recent version for the US and European markets differs in many ways from the older Japanese version. On the one hand, the powertrain has been adapted to meet the needs of US and European driving conditions, while on the other many general improvements have been implemented.
The maximum engine speed of the US and European version has been increased from 4000 to 4500 rpm. The engine's VVT-i system has been optimised, and the compression ratio reduced from 13.5 to 13. This results in a maximum engine power of 53 kW instead of 43 kW and an increased torque of 120 Nm. The power of the electric motor has been increased from 30 kW to 33 kW. The battery power is still 21 kW, but due to improved packaging the battery volume has been significantly decreased.
Drivetrain efficiency has been improved by decreased mechanical losses in the oil pump and decreased electrical losses in the electric motor. "Energy circulation" has also been reduced. In the Japanese version a significant amount of power is pumped around between generator and electric motor under certain driving conditions. The electric driving regime has been stretched from 45 km/h to 65 km/h.
The performance of the vehicle has been significantly improved. Acceleration from 0 to 100 km/h takes 12.5s instead of 15s as in the Japanese version. The fuel consumption at low speed driving conditions is up to 20% lower, while under high-speed driving conditions between 5% and 10% less fuel is consumed. Cold-start behaviour is improved due to a faster catalyst start-up and improved combustion. The US and European version of the Prius meets SULEV and EUR-4 emission standards.

By the end of 2000 Toyota had sold more than 45,000 Priuses in Japan. Introduction in the USA and in some European countries increased this number. The success of the Prius in these regions was largely depended on the purchase price Toyota asked and on the way policy-makers would treat hybrid vehicles. Tax reductions temporarily lowered the purchase price, helping potential customers get used to the Prius and hence hybrid vehicles. By the end of 2000 Toyota had sold more than 50,000 Priuses worldwide. In Japan, the Prius costs about $18,500 and in the USA about $20,000. In Europe the prices differ per country as a result of different vehicle tax regimes and varying fiscal stimulation measures for clean cars in general or hybrids in particular. In the Netherlands the Prius's base price is €24,500. It is probable that Toyota is not earning much money on the Prius. On the other hand it would certainly cost more to sell a modern fully electric car, which needs a very expensive battery pack to achieve even modest range and performance.

2.3.1.2 Toyota Estima Hybrid

"Technology from Tokyo", [*Automotive Engineering International*, January 2002]

The Estima Hybrid was launched in June 2001, with about 3250 vehicles delivered to customers. Estima was the name given to the Japanese-market rear-wheel-drive Previa minivan. Toyota revealed at the 1999 Tokyo Motor Show what was to become the replacement for the Estima in the guise of a concept showcasing the sophisticated THS-C Toyota Hybrid System. A conventional gasoline-engine-propelled Estima (still Previa in Europe) preceded the Hybrid and conformed to the universal transverse powertrain,

front-wheel-drive formula. The Estima Hybrid shares the same body shell and chassis, with several unique outer panels and parts to distinguish it.
The Estima is a fairly large vehicle by Japanese standards, but smaller than the American norm for minivans. It accommodates up to eight people in three-row seating. The Estima Hybrid has the world's first electric on-demand four-wheel-drive system, christened "E-Four."

While the Prius THS combines parallel and series hybrid systems employing a propulsion motor and generator, the Estima THS-C is a parallel system. In the Prius, the motor singularly drives the front wheels directly when moving off. The engine drives the front wheels via a planetary gear unit that acts as an electrically regulated (by the generator) CVT. The THS-C front powertrain comprises the IC; a double-pinion, planetary-gear, power-switching device and twin clutches; and a 216-V, 13-kW motor/generator producing 110 Nm. The rear-wheel drivetrain has its own motor/generator rated at 18 kW, 108 Nm, on 216 V.
The engine is an Atkinson-cycle (late intake-valve closing) version of the type 2AZ 2.4-L inline four-cylinder unit, given the suffix FXE, and producing 96 kW at 5600 rpm and 190 Nm at 4000 rpm. For short bursts of acceleration, the engine can assist the twin motors, driving all wheels and producing brisk performance. The THS-C chooses, alternates, and combines the three power sources, employing either or both of the twin motor/generators to replenish the compact nickel/metal-hydride battery pack placed under the third-row seat. The rear propulsion motor is deployed when the system determines the driver's desire for quick takeoff or it enhances vehicle stability in adverse surface conditions. The inverter with converter function transforms the storage battery's dc to 100-V ac (Japanese home voltage), allowing the use of home appliances and entertainment equipment. The Estima Hybrid's brake system is as advanced as the powertrain; an electronically controlled, hydraulically assisted system controls the four brakes independently for optimum retardation and stability.

The Estima Hybrid attains an equivalent fuel consumption of 42.6 mpg on the Japanese urban 10/15-mode cycle. The 70-L fuel tank allows the minivan to travel 1000 km (620 mi) if a steady 100 km/h (62 mph) is maintained. The vehicle is Japanese ULEV-rated.

2.3.1.3 Toyota Crown mild hybrid

“Technology from Tokyo”, [Automotive Engineering International, January 2002]
The Crown mild-hybrid sedan was introduced to the Japanese market in August 2001. As its name indicates, it is primarily driven by the IC part of the powertrain, a direct-injection, gasoline, inline, six-cylinder, 3.0-L engine driving the rear wheels via an electronically controlled four-speed automatic transmission. A 36-V, 3-kW, three-phase ac motor/alternator-generator is mounted alongside the engine, driving or being driven via a ribbed belt. A dedicated 36-V battery feeds electricity to the motor/generator and is recharged by the same motor/generator when driven by the engine. The THS-M (Toyota Hybrid System-Mild) is designed to assist the vehicle in moving off from standstill, during which time the engine is stopped to reduce emissions and conserve fuel. When the brake pedal is released, the motor cranks the engine to near idle speed to generate enough torque to move off. An electrically driven pump maintains required automatic fluid-pressure level for transmission of driving torque. With the accelerator pedal depressed, the engine is started by the motor/generator. On deceleration, braking

energy is recovered by the motor/generator and fed to the battery. It may be likened to GM's hybrid system for full-size pickup trucks that employ a similar stop-and- go strategy. The THS-M adds about $1300 to the price of a similarly equipped conventional IC-powered Crown sedan.

2.3.2 Honda

2.3.2.1 Honda Insight

Source: IEA-HEV (2001), www.hondanews.com

Honda unveiled a vehicle with its IMA system at the 1999 North American International Auto Show, called the Honda VV, announcing plans to introduce a production version in November 1999 under the name of Honda Insight. It was introduced at the IAA motorshow in Frankfurt in September 1999. The vehicle meets Californian ULEV standards. The Honda VV powertrain represented the further evolution of the IMA powertrain concept, introduced at the 1997 Tokyo Motor Show in the JV-X concept car. In the JV-X Honda used supercapacitors and a Continuous Variable Transmission, but for its successor switched back to NiMH batteries and a manual five-speed transmission. The engine-assist is coupled to a lean-burn 1.0 litre 3-cylinder gasoline engine with variable valve-timing.

2.3.2.2 Honda Civic Hybrid

The Honda Civic Hybrid Sedan is based on the Civic four-door sedan and was launched in December 2001 in Japan (*press release, December 13, 2001*). The Civic Hybrid went on sale in the USA in April 2002 as a 2003 model with an anticipated sales volume of 2,000 per month. A Super Ultra Low Emissions Vehicle (SULEV) version of the Civic Hybrid will go on sale in California in January 2003.

Honda Creates New IMA System For 2003 Civic Hybrid [Honda Press release, June 2, 2002]

The new IMA-system is more powerful than that of the Insight. The internal-combustion engine is the new inline four-cylinder, 1.3-L, i-DSI lean-burn (i-DSI = intelligent Dual Spark Ignition). The twin-spark-plug ignition employs staggered firing to ensure combustion of lean mixtures. The VTEC technology allows the valves of three of the four cylinders to be deactivated (fully closed) on deceleration, thus halving pumping loss. A thin dc brushless motor assists the engine on rapid acceleration and also helps cancel vibrations generated during single-cylinder deceleration. The storage battery is a Panasonic nickel/metal-hydride type with cylindrical cells and is placed behind the rear seatback, leaving ample luggage space. The transmission is Honda's steel-belt-and-pulley-type CVT. Honda claims 29 km/L (68 mpg) fuel consumption on the Japanese urban cycle, an improvement of 45% over the conventionally powered Civic 1.5.

During acceleration and other instances of heavy engine load, the motor-assist system contributes considerable torque, resulting in both lower fuel consumption and powerful acceleration. At cruising speeds, when engine load is lower, the motor-assist system shuts down.
During deceleration, the motor converts the dissipated energy into electricity (regenerative braking). The Cylinder Cut-off System reduces engine friction during deceleration, greatly improving the vehicle's electrical regenerative efficiency.
When stopping, at traffic lights for example, the engine shuts off automatically, then restarts immediately when the driver steps on the accelerator pedal.

New 1.3-liter i-DSI Engine with VTEC Cylinder Cut-off System

- The 1.3-liter i-DSI engine's rapid combustion characteristics combined with a configuration of two spark plugs per cylinder allows the fuel-air mixture to be made even leaner, for improved fuel economy.
- The rocker arms that open and close the intake and exhaust valves are configured for dual operation in either valve-lift mode or idle mode. Normally, they are engaged via a synchronising piston. During deceleration, the synchro piston is positioned inside the idle-mode rocker arm, disengaging the lift-mode rocker arm so that the valve remains at rest, effectively sealing off the cylinder. Three of the four cylinders can be shut down, achieving 50% lower engine friction during deceleration than the previous IMA System.
- Also featured are both a high-density, 900-cell three-stage catalytic converter and a lean burn-compatible adsorption-type NO_x catalytic converter. The result is a clean-burning engine that meets exhaust-gas emissions standards for ultra-low emissions vehicles set by the Japanese Ministry of Land, Infrastructure and Transport.

New Motor-Assist System

- The motor-assist system is composed of an ultra-thin DC brushless motor, a nickel metal hydride battery, and a Power Control Unit (PCU). The new system employs a higher-output motor, a more efficient battery, and a lighter, more compact PCU, resulting in greater packaging freedom.
- Improvements to the internal magnetic coils of the ultra-thin DC brushless motor, which boasts the world's highest output density and practical efficiency, achieve 30% greater assisting and regenerative torque than the previous model. A sintering diffusion bonding process is used to firmly fuse different metals together, allowing the most appropriate materials to be used in construction of the rotor to meet the different demand criteria for its inner section, which transmits torque, and for its outer section, which is in contact with the magnetic coils. Strengthening the section that transmits the torque and increasing the magnetic-flux density results in higher torque output.
- The inverter and the pre-driver have been combined, reducing the weight of the PCU by around 30%, and its volume by around 40%, in comparison with the previous system.

- The efficiency of the battery modules has been increased, resulting in reduced energy loss. The battery's storage box and peripheral equipment have been made more compact, for an approximate 30% reduction in volume.
- The lighter, more compact, more efficient PCU and battery have been integrated into a single Intelligent Power Unit (IPU) that can be stored behind the rear seat.
- Integrating the IPU allows the two cooling circuits previously used to be combined into one. Total volume of the PCU and battery has been reduced by around 50% over the previous system.

The Honda Civic Hybrid will be available in model year 2003 in the USA.
The price will be $20,550 for the automatic version, and $19,550 for the five-speed manual version.

2.3.3 PNGV Concept Cars

At the Detroit Auto Show in January 2000, three hybrid vehicle prototypes were presented by the so-called big-three in the USA (GM, Ford and DaimlerChrysler).
All three vehicles have been developed in the context of the Partnership for a New Generation of Vehicles (PNGV). All three manufacturers targeted 2000 as the year to show test cars that had three times the standard sedan's fuel economy (80 miles per gallon or roughly 3 l/100 km gasoline equivalent) and promises of no compromises in safety, performance or price (see http://www.uscar.com).

2.3.3.1 DaimlerChrysler Dodge ESX3

[USCAR, 2000]
The ESX3 builds on the knowledge and experience gained from its predecessors, the Dodge Intrepid ESX in 1996 and the ESX2 in 1998. It also draws on technology developed through the PNGV government-industry collaboration. But the ESX3 also bears distinctive DaimlerChrysler benchmarks: bold styling, high performance, and strong customer appeal.

The ESX3 Features a "mybrid" (mild hybrid) powertrain that minimises demands of electric motor and batteries, therefore lowering the cost and weight of hybridisation.
An all-aluminium, 1.5-liter direct-injected diesel is the primary propulsion, with additional power coming from a lightweight, high power, lithium ion battery.
A unique electro-mechanical automatic transmission (EMAT) developed by DaimlerChrysler engineers, provides the fuel efficiency of a manual transmission with the convenience of an automatic.

The lightweight body makes use of another DaimlerChrysler innovation, injection-molded thermoplastic technology, which achieves significant improvements in weight and cost. The ESX3 weighs in at just 2,250 pounds (1020 kg) while meeting all federal safety standards and providing the roominess and comfort of today's family sedan. The entire vehicle is more than 80% recyclable. A total rethinking of the car's electronic and electrical systems cut several pounds from the weight of electronics while providing an ergonomically satisfying system of driver controls, vehicle monitoring and diagnostic indicators, high-performance audio and video systems, and a state-of-the-art telematics package.

The vehicle achieves an average 72 miles per gallon (3.3 liters/100 km) fuel efficiency (gasoline equivalent), which comes close to PNGV's goal of up to 80 mpg (2.9 liters/100 km). Driving range is around 400 miles.
The estimated cost penalty for a high mileage, five-passenger sedan is around $7,500.

2.3.3.2 Ford Prodigy

[USCAR, 2000]
Ford Motor Company has developed a fuel-efficient, product-feasible hybrid-electric vehicle that is less complex and lighter than the other hybrids demonstrated under PNGV.
The LSR ('Low Storage Requirement') hybrid powertrain consists of a direct injection diesel engine, a starter/alternator, an automatically shifted manual transmission and a high-power battery. The vehicle has a very light and aerodynamic five-passenger aluminium-body.

The Prodigy is equipped with Ford's aluminium DIATA engine. The 1.2-liter compression-ignition, direct-injection engine is lighter and 35% more efficient than conventional (gasoline) engines. The four-cylinder DIATA generates 55 kW @ 4100 rpm.
Ford's LSR hybrid replaces the flywheel, starter and alternator with a single electric motor - the starter/alternator - packaged between the transmission and the engine. In combination with a small, high-power nickel-metal hydride battery and power electronics module, the starter/alternator can restart the engine in less than 0.2 seconds. It can generate the power for the vehicle electronic systems with 85% efficiency compared with less than 60% for a conventional system. And it can assist the engine as the vehicle accelerates and support the brakes during deceleration, thus recharging the battery for later use.

The LSR hybrid relies on an automatically shifted manual transmission that combines the operating ease of an automatic transmission with the efficiency of a manual transmission and is 20% more efficient than a comparable automatic transmission. In Auto Shift Manual mode, the transmission shifts gears without driver input, similar to an automatic transmission. In Select Shift Manual mode, the driver controls the shift timing, while the automatic controls handle the shifting and clutch actuation, which eliminates the clutch pedal.

In general the fuel economy of hybrid electric vehicles in city driving can be enhanced in four ways:

- The fuel supply to the engine can be turned off when no propulsion power is needed (for example, when coasting down a hill or when stopped at traffic lights) and the engine can be restarted instantly on demand.
- The engine size is decreased to improve efficiency, with electric power used to augment power demand when necessary.

- Regenerative braking can be used to recapture and re-use energy that otherwise would be lost to heat when braking. The alternator transforms this braking energy into electrical energy, which is stored in the battery for later use.
- Electric propulsion can be used with the engine off.

Ford researchers determined that a hybrid with only the first three capabilities could deliver fuel economy equivalent to a more complex and heavier hybrid with all four capabilities. In fact, they found that the LSR design required only very modest energy storage - less than that of a conventional starter battery. Thus, the LSR-concept of the Prodigy is able to improve costs and reduce complexity.

The vehicle achieves an average of 80 miles per gallon (2.9 liters/100 km) on diesel fuel (72 mpg gasoline equivalent). Driving range is around 660 miles.

2.3.3.3 GM Precept

Source: USCAR, 2000
The Precept is a five-passenger test car with a fuel economy of 80 mpg (gasoline equivalent) and is the product of six years of research and hundreds of millions of dollars.
Like Ford's Prodigy high-mileage car, Precept uses a small diesel engine linked to electric motors.
While the Prodigy gets about 70 mpg and sticks to the basic outlines of today's mid-sized sedans, GM's engineers had to break several conventions to get the extra 10 mpg. The Precept's Isuzu-built 1.3 litre three-cylinder diesel engine is in the rear of the car to improve airflow around the vehicle. One electric motor powers the front wheels while a "multi-purpose unit" built onto the diesel engine acts as another electric motor and a generator, recharging a battery pack under the seats. The motors help the 54-horsepower engine during acceleration and capture energy during braking.
Rather than rear-view mirrors, the car uses tiny cameras, and the doors use electronic controls rather than handles. GM engineers also tried to save weight by using aluminium and titanium rather than steel in many parts. The seats are made of mesh, and even the stereo speakers have a weight-saving design. The result is a car that is the size of a Chevrolet Malibu but weighs about 460 pounds less.

With a Cd of 0.163, the Precept is the world's most aerodynamic five-passenger family sedan. Such an efficient design accounts for 15% of the vehicle's fuel economy performance.

2.3.3.4 Comparison of commercial and PNGV concept hybrid vehicles

In the SAE paper “Evaluating Commercial and Prototype HEVs” [Feng, 2001] a comparison is made of the main characteristics of the commercial Toyota Prius and Honda Insight, with the PNGV concept vehicles of Ford, DaimlerChrysler and GM.

Table 2.3-2: Characteristics of commercial and prototyped HEVs

HEV Names	Type	Status	Curb wt. (lb)	Power Plant Type	Engine Size (L)	Engine Power (hp)	Battery Type	Motor Peak (kW)	Trans-mission Type	CAFE MPG [(a)]	0–60 time (s)	Data Sources
U.S. Prius	Gasoline Hybrid	Commercial	2,765	SI I-4	1.5	70	NiMH	33	CVT	58	12.1	b
Honda Insight	Gasoline Hybrid	Commercial	1,856	SI I-3	1.0	67	NiMH	10	M5	76	10.6	c, d
Ford Prodigy	Diesel Hybrid	Prototype	2,387	CIDI I-4	1.2	74	NiMH	16	A5	70	12.0	c, e
DC ESX3	Diesel Hybrid	Prototype	2,250	CIDI I-3	1.5	74	Li-ion	15	EMAT-6	72	11.0	c, f
GM Precept	Diesel Hybrid	Prototype	2,590	CIDI I-3	1.3	59	NiMH	35	A4	80	11.5	c, g

Source: Feng, 2001

Note:

a. CAFE fuel economy rating represents combined 45/55 HWY/CITY fuel economy and is based on an unadjusted figure.
b. EV NEWS, JUNE 2000, PP. 8.
c. REVIEW OF THE RESEARCH PROGRAM OF THE PNGV, SIXTH REPORT, NATIONAL RESEARCH COUNCIL, 2000.
d. Automotive Engineering, Oct. 1999, pp. 55.
e. On the basis of a), the starter/generator rated 3 kW continuous, 8 kW for three minutes, and 35 kW for three seconds. We assume 16 kW for a 12-s 0–60 acceleration
f. Automotive Engineering, May 2000, pp. 32.
g. Precept Press Release; the front motor is 25 kW and rear motor 10 kW, and so the total motor peak power is 35 kW.

2.3.4 Other developments of hybrid vehicles

2.3.4.1 Audi DUO

Source: IEA-HEV, 2001

The Audi Duo is based on the European version of Audi's commercial A4 wagon, and is powered by both a diesel engine and an electric motor in parallel. The diesel engine is the primary power unit and is a turbocharged direct-injection 1.9-liter engine, producing 66 kW at 4000 rpm and 210 Nm of torque at a low 1900 rpm. The electric motor is manufactured by Siemens and produces 21 Nm of torque. This torque is available continuously from 0 rpm up to its 10,000 rpm peak, where it develops its maximum power of 29 hp.

The Audi is a parallel hybrid, meaning both the electric motor and the diesel engine power the transmission. The transmission is essentially a five-speed gearbox in a six-speed box. A transfer gear that connects the electric motor to the transmission occupies the extra room. So the Audi uses just one single transmission for two dissimilarly revving power units.

The Duo can be operated in three modes by means of a switch: diesel engine only, electric motor only, and the "Duo" mode, which automatically selects electric or diesel power depending on power demand and e.g. battery state-of-charge. In the Duo position the default power mode is electric, but the computer will switch to diesel mode if it detects low battery voltage or a call from the helm for more power.

Power for the electric motor comes from a battery pack mounted on the floor of the storage compartment. The pack consists of 22 lead-acid batteries wired in series to produce a maximum of 264 volts and has a maximum capacity of 10-kilowatt hours.
Primary battery charging takes place while the car is stationary. A plug with cord resides behind the front grille and fits into a normal European 220-volt, 16-amp household plug. In only four hours, the batteries will charge from 15% to 90% of capacity. As is characteristic of lead-acid batteries, the remaining 10% takes another three hours.
Secondary battery charging takes place whenever the car is moving and the diesel engine is running.
The electric motor is always coupled to the transmission, so when the diesel is operating and the car is moving, the electric motor acts as a generator providing energy to the batteries.

2.3.4.2 Fiat Multipla Ibrida

Source: IEA-HEV, 2001
Another example of a parallel hybrid-electric vehicle is the Fiat Multipla Ibrida. The Fiat Multipla Ibrida is technically less advanced than, for example the Toyota Prius, because of the use of many standard components in this model, from both the conventional internal combustion-engine driven Fiat Multipla (body and gasoline engine) and the electrically driven Fiat Seicento (electric motor). Making use of standard components produces a relatively cost effective hybrid vehicle.

The Multipla Ibrida makes use of a 1.6 litre gasoline engine, which might be replaced later by Fiat's 1.2 litre 16 valve engine for fuel economy reasons. The parallel hybrid Ibrida works with a 29 kW 3 phase AC asynchronous electric motor (the same motor as used in the Fiat Seicento Elettra), fed by NiMH batteries (19 kWh, 216 V). The Multipla has an automatically shifted five-speed gearbox. A generator is separately connected to the engine. The vehicle has three modes of operation. The first mode is a completely parallel hybrid-electric mode: both the combustion engine and the electric motor drive the vehicle. At low speeds the system uses the electric motor whereas the combustion engine takes over as the speed increases. The electric motor operates during extra power demanding acceleration or hill climbing actions. Another mode is the pure-electric mode (where the vehicle runs as a Zero Emission Vehicle, ZEV), having a top speed of just 80 km/h. In this mode, the transmission system is fixed in second gear. An on-board charger can recharge the batteries. As a third mode, the vehicle can be operated in the electrical EA (extended autonomy) mode, which can be used to optimise the remaining range in EV mode in situations where the batteries have been depleted significantly. In this case, the combustion engine runs at low speed and high torque to drive the generator until the batteries are charged again. Afterwards, the engine shuts down and the system returns to pure EV mode again.

2.3.4.3 Citroën Xsara Dynalto

Source: IEA-HEV, 2001

French manufacturer Citroën showed the Xsara Dynalto at the 1998 Geneva motor show. This vehicle is not a completely new design but a conversion of the existing Xsara model. The car was converted to a hybrid by replacing the flywheel with Continental's ISAD system.
BMW has also built a prototype together with Continental. Production by both Citroën and BMW is expected to start within a few years.

2.3.4.4 Renault Ellypse

"The Ellypse concept car: a bubble of optimism in the automotive world" [Press release, September 3, 2002]

The Ellypse concept car illustrates Renault's commitment to sustainable development through its environmentally friendly design: its architecture favours easy removal and recycling of components at the end of the car's life-cycle, the new-generation diesel engine reduces fuel consumption and exhaust emissions (85g of CO_2/km), and it is equipped with advanced x-by-wire technology and 42-volt electrics.

Ellypse is equipped with an innovative 16-valve 1200cc turbodiesel engine, developing 72kW and 200Nm torque. The advanced common-rail injection system uses specific piezoelectric injectors with 10 holes (instead of the usual four or five) for injection pressure of some 2,000 bar.
Ellypse contributes to air quality by using a comprehensive and original emission control system. A four-way catalytic converter simultaneously processes carbon monoxide, nitrogen oxide, unburnt hydrocarbons and particulates. The on-board diagnostics system not only warns the driver when exhaust emission levels are exceeded, it also constantly analyses the physico-chemical composition of the emissions, fluids and gases inside the vehicle and will launch a maintenance alert when necessary.
The turbodiesel internal combustion engine is assisted by a 12kW starter-alternator which has three different functions. It works as an alternator to produce electricity, in particular through the recovery of energy when braking, as a starter motor for the internal combustion engine, and as an electric traction motor whose output can be added to that of the internal combustion engine, and can even propel the vehicle alone over short distances. Transmission uses a robotised gearbox that optimally adjusts fuel consumption to driving style.
The advanced technology of the powertrain combined with the car's low weight (980kg) result in excellent performance and emissions of just 85g of CO_2/km measured over the new MVEG cycle (equivalent to around 3.2 litres/100km).

Environmentally minded electrics and electronics
Specific electrics boost Ellypse's environmental rating. By supplying 42 volts rather than the usual 14, the starter-alternator is globally more efficient but also increases the number of electrically-powered functions. Electric air-conditioning, for example, contributes to optimal onboard energy management.
By entering the x-by-wire era, Ellypse solves the problem of hydraulic circuits, which are less efficient than electrical systems, and of mechanical fluids that represent an

environmental challenge both during (oil changes, leaks, etc.) and after (extraction) the vehicle's life-cycle. Hydraulic cylinders are replaced by electric actuators for the brakes, steering and robotized gearbox. The few remaining fluids (engine coolant and lubricants) are non-toxic and biodegradable. The designers have made it easier to recover these fluids at the end of the car's life-cycle by creating specific drainage points.

2.3.5 References

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2.4 Fuel-cell drivetrains

2.4.1 Introduction

"2001 in Review" [*Fuel Cell Technology News*, January 2002]

"The most important unresolved issue with fuel-cell vehicles is not the fuel cell, it's the fuel," says Thomas Moore, vice president and head of DaimlerChrysler's Liberty & Technical Affairs advanced technology development group. DaimlerChrysler demonstrated fuel-cell vehicles powered by four different fuels, as the company continues to investigate the best solutions to power the cars and trucks of the future.

DaimlerChrysler is investing more than $1.4 billion in fuel cell technology research and development during the period 2001 to 2004.

"Fuel Cells for Transportation" [*Fuels Cells 2000*]

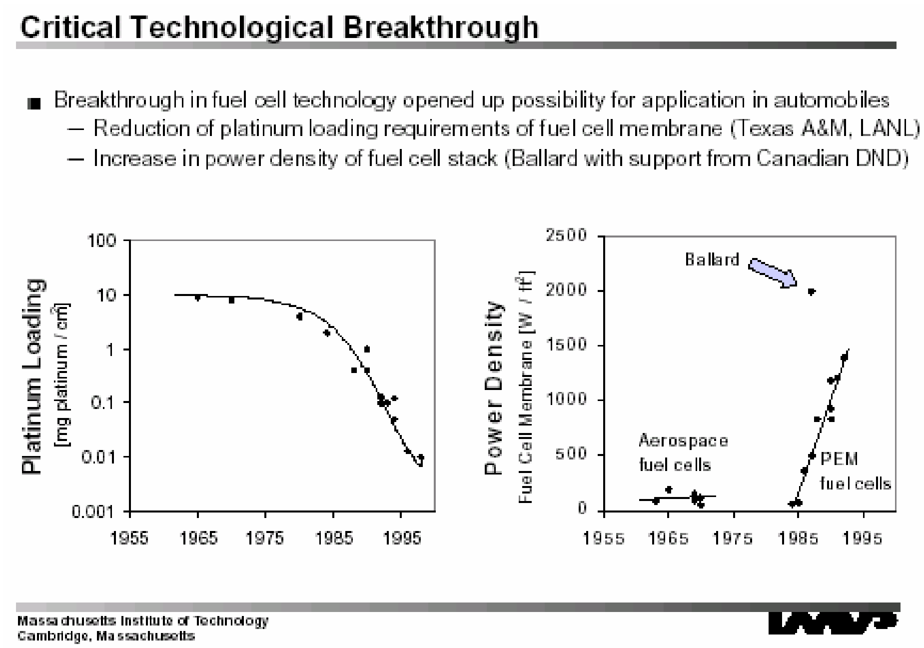
The following companies are testing fuel-cell vehicles in the USA: DaimlerChrysler, Ford Motor Co., Ballard Power Systems of Canada, General Motors, Honda, Hyundai, Nissan, Toyota and Volkswagen/Volvo. Other auto companies testing fuel-cell vehicles include BMW, Citroën, Daewoo Motor, Fiat, Mazda, Mitsubishi, Peugeot, and Renault.

Cost reduction is the key to commercial fuel-cell vehicles and the goal of researchers around the globe. In the USA, the Department of Energy supports cost-reduction research at national laboratories and in private industry.
That work is paying off. A few years ago, the fuel cell stack — only one part of the fuel cell power system — cost a prohibitive $5,000 per kW. The entire fuel-cell system (fuel-cell stack, reformer and associated controls) now costs about $300 per kW, based on mass production economies.
Developers are targeting full power system costs in the range of $50 per kW with high-volume production.

The key to reducing the price of a fuel-cell system is to reduce the costs of the subsystems:

- Ballard Power Systems, a leader in cost reduction, cut plate costs from $100 per plate to about $1.
- Dupont has announced that future membranes will cost no more than $10 per square foot when large production volumes are achieved, stating that the price could drop to nearly $5 per square foot.
- Researchers have also achieved a 90% reduction in the amount of precious metal catalyst required for PEM fuel cells, removing a fundamental cost barrier.

Figure 2.4-1: Some of the critical technological breakthroughs opening the possibility for automotive applications of fuel cells



Source: Steinemann, 1999

2.4.2 NAVC Survey results: fuel-cell fuels and reformers

Fuel-cell experts give their views [NAVC, 2000]

In November 2000, the Northeast Advanced Vehicle Consortium (NAVC) of Boston released a report entitled "*Future Wheels: Interviews with 42 Global Experts on the Future of Fuel Cells for Transportation, Fuel Cell Infrastructure, and a Fuel Cell Primer"*. The goal was to ask experts on fuel-cell transportation technology and infrastructure if there was any consensus on major issues related to the future of fuel-cell vehicles.

The major findings from these interviews are listed below. (Note: These are not "consensus items", they are simply the major themes that arose during the interviews.)

- Direct hydrogen stored on board the vehicle is the fuelling option that most experts believe will be the long-term choice for both passenger and transit fuel cell vehicles.
- Hydrogen for fuel-cell cars may come from many feedstocks. Many experts expressed the opinion that there will not be one global "fuel" choice, as with gasoline and diesel for internal combustion engines today; rather, different geographical regions will select the hydrogen feedstock that is most appropriate for that area (for example, geothermal electrolysis in Iceland, ethanol in Iowa, CNG in Texas, etc.). The emissions associated with the "well to wheels" use of hydrogen depend on the feedstock and process of reformation.
- There was no consensus on which on-board reformation fuel would be the best option or if on-board reformation should happen.

- The viability of methanol as an on-board reformate was a divisive question. While there were some experts who did not have strong opinions about methanol, the majority were either vigorously opposed to the use of methanol for a variety of reasons – with health and safety concerns most often cited – or favoured its use as an on-board fuel or as a hydrogen feedstock. Overall, more of the experts interviewed were opposed to the use of methanol than were in favour of it.
- The majority opinion was hydrogen storage technology should be the focus of R&D dollars. Breakthroughs in storage technology would have the biggest impact in accelerating the acceptance and commercialisation of fuel-cell vehicles.
- Opinions were divided over the role hybrid electric vehicles will play in the future. Some experts believe that hybrids are strictly transitional technologies; others believe that hybrid electric vehicles are a threat to the fuel-cell vehicles market; and yet others felt that hybrids will be complementary to fuel-cell vehicles because advances in hybrid electric drive trains will have direct benefits to fuel-cell vehicles.
- According to the interviews, the fuel-cell market for transportation will develop first in the bus fleet market at government subsidised large prices, and that significant market share of the light duty transportation market is more than 10 years out.
- Codes and standards related to hydrogen storage and transportation need significant work in the near term before there can be any significant market share for fuel cells.
- PEM (Proton Exchange Membrane), a low temperature fuel cell, was the overwhelming choice of experts for the transportation market. (Not necessarily the stationary market).
- Hundreds of millions of dollars are being spent on fuel-cell research and development both for stationary and mobile applications. The technology choices are advancing rapidly with new companies participating all the time, and a paradigm shift in the technology can happen at this stage with storage and infrastructure.

2.4.2.1 Methanol

One of the major areas of disagreement was over the use of methanol as a source of hydrogen. A majority of experts interviewed stated strong opinions either in favour of or against methanol, although there were some respondents who were relatively neutral.

Three of the automakers said they would not consider using methanol for their fuel-cell vehicles; one auto manufacturer strongly favours methanol as both a near and long term option; and two said that they would consider methanol as one of the viable fuel options.

The energy suppliers also had strong views on methanol. Two expressed strong reservations about selling methanol; the third company interviewed indicated some concern over methanol. Nevertheless, all three energy companies did say they would provide the market choice. There were also some strong arguments in favour of and against methanol by representatives of the alternative energy supplier world, and fuel-cell technology companies, and the industry consultants. Finally, a number of experts simply did not think that on-board reformation of any kind was viable and therefore did not support the use of methanol (see below for more on the experts' opinions regarding on-board vs. off-board reformation).

Ease of reformation and status of reformer technology

All respondents who expressed an opinion about methanol agreed that it is the easiest liquid fuel to reform on board the vehicle. It was also widely noted that the methanol reformer technology is several years ahead of other on-board reformation technologies, particularly gasoline reformers. Several experts said that, as a result, commercial introduction of fuel-cell vehicles would happen sooner with on-board methanol reformation than it would with other liquid fuels. One expert speculated whether the concerns raised over methanol's viability was being driven by a competitiveness over being "first to market".
One automaker noted that it is only pure methanol that is easy to reform. If there are any contaminants in the methanol (a likely scenario if methanol becomes widely used according to this automaker), the reforming temperature will need to be raised, which means that the ultimate methanol reformer will require the use of technology not too different from a gasoline reformer. The automaker also noted that the transient response time for a methanol reformer is "slower" than a gasoline reformer, which means that a larger battery will be required to handle the need for quick acceleration.

The cost of methanol

With regard to costs, a few experts cited specific cost estimates for retrofitting gas stations. A non-profit association expert estimated that methanol could be made available for approximately $60,000 per station. An energy company expert noted above estimated the costs to be between $50,000 and $100,000.

2.4.2.2 Gasoline

While the issue of gasoline as an on-board reformate did not provoke as strong a reaction as did methanol, there was no consensus among the interviewees with regard to its viability for on-board reformation, at least for the near to mid term. The experts were split between those who thought it was a good (or the best) liquid fuel option and those who thought it faced too many technical hurdles or would not make sense on a well-to-wheels basis in comparison with simply using the gasoline in a hybrid vehicle. Among the automakers, there were two one who strongly favoured gasoline – one saw it as viable only with solid oxide fuel cells, not PEM; two who felt it had some potential in the mid-term, but not as the only liquid fuel option; one who was open to the possibility of any near to mid term liquid reformate; and one who opposed all liquid fuel reformation, including gasoline.
Not surprisingly, all the energy companies favoured gasoline, although some did so more vigorously than the others, and the methanol representatives opposed it. Three fuel-cell companies felt gasoline has potential, while three others did not. Most of the hydrogen providers or hydrogen generation companies did not support gasoline. Finally, one industry consultant and one government agency believe that it had potential, while two other industry experts and two government representatives did not.

Overall, the sense was that, while not arousing the level of passion that methanol does, gasoline's future as an on-board reformate seems unclear.

Ease of reformation and status of reformer technology

This issue received the most comment, with experts generally agreeing that gasoline is significantly more difficult to reform than methanol. Even those who favoured gasoline cited reformation as a technical challenge. The experts noted that fuel cells will require a very different gasoline product than is available today, since fuel cells are easily poisoned by impurities such as sulphur and aromatics. Some experts noted that the trend is in the direction of cleaner fuel already, so this would dovetail with the need for a cleaner "fuel-cell gas". Others who opposed gasoline, including two methanol representatives, stated that the gasoline sulphur will have to be almost zero, much lower than is currently being proposed, and that it is very expensive to "remove the last bits of sulphur." Other simply asked "why bother" if gasoline is only a short-term option and there are other, preferred fuelling options. A few experts commented that it simply makes more sense to use gasoline in hybrids.

Many interviewees noted that high temperatures are needed to break the carbon-carbon bonds in gasoline, and some stated that high temperature reformation is a big technical hurdle (also discussed under "Efficiency" below).

There was general agreement among the experts that gasoline reformer technology is several years behind that of methanol reformers. Therefore, many noted, if gasoline is the chosen liquid fuel, there will be a delay in the introduction of commercially viable fuel-cell cars. Various estimates of the delay were given, from two years to five or six years. For those who opposed gasoline, this was cited as drawback for gasoline. For those who supported it, they cited other "pluses" as outweighing this concern.

One auto company believes that, because of the technical issues, the only viable way to reform gasoline on-board is with a solid oxide fuel cell (SOFC). This company states that SOFCs are not as sensitive to impurities as PEM, although it noted that many issues needed more work, including the issue of thermal management.

Another automaker believes that, due to these various technical challenges, it will probably be difficult to develop a gasoline fuel-cell car without any compromises for the consumer.

Finally, there were some experts who are opposed to any on-board reformation, including gasoline. One fuel-cell company said simply that "it makes no sense to put an oil refinery on a car". Another fuel-cell company expert stated his belief that auto companies do not want to be responsible for a power plant on their vehicles. This expert said that concerns over liability and the need for repair of a complicated reformation system would prevent on-board gas reformation from becoming a widespread commercial reality.

2.4.2.3 Ethanol

The majority of the interviewees did not think ethanol was a strong competitor against methanol and gasoline as an on-board reformate. Quite a few experts did say, however, that ethanol would be viable for certain regions where ethanol production is high, such as Brazil. Of the automakers, there was one who supported its use in certain geographic areas and one who was open to it; the others did not favour it, although they did not express strong opinions on it. An ethanol industry representative felt that ethanol could be more viable than gasoline or methanol and would provide significant benefits as a renewable fuel source for fuel cells.

On the issue of reformation, the experts gave contradicting opinions on the ease of reforming ethanol - whether the respondent said ethanol was easy or hard to reform depended partly on which other liquid fuel he or she was comparing it to. The automaker who liked ethanol commented that it is easier to reform than gasoline, as did a methanol representative and the ethanol industry expert. Several other experts stated that ethanol is hard to reform, with one automaker saying specifically that it was harder than methanol.

An energy company said it is similar to gasoline, with the same emissions and high-temperature reformation concerns.

An ethanol industry representative noted that a multifuel processor has been developed that reforms ethanol with higher efficiencies and lower emissions than gasoline.

Several experts questioned whether ethanol reformation was viable on an total energy efficiency basis however. One energy company said that ethanol reformation is a highly energy intensive process, with one litre of fossil fuel (fertiliser) producing one litre of ethanol with only a two-thirds energy density. An industry consultant also said that its efficiency is poor due to the carbon-carbon bonds. An alternative energy supplier also commented that it takes more energy to produce ethanol than ethanol provides.

One automaker who supports ethanol noted that it can be made from renewable sources and woody biomass, which would make it part of a sustainable cycle. The ethanol representative also noted that ethanol could provide a new market for agricultural products, and boost the economy of rural areas, since it uses agricultural, waste, and biomass feedstocks.

Two experts – an energy company and a hydrogen provider – said that there is a debate over ethanol's CO_2 emissions, with the hydrogen provider noting that it may have higher CO_2 emissions from methanol if it is made from corn grown with fertiliser.

The ethanol representative also noted that ethanol is less toxic than either methanol or gasoline and would help reduce dependence on imported energy supplies. This representative said that ethanol would be easy to make available because it can be distributed through existing infrastructure.

Finally, a significant number of experts mentioned cost as a determining factor in ethanol's viability. Many noted that the price of ethanol is supported by subsidies in the USA and that ethanol will only be viable in places where there is this kind of political support.

2.4.2.4 Synthetic Fuels

Opinions of the viability of synthetic, or gas-to-liquid, fuels varied, with five experts giving it positive reviews, four opposing its use, and roughly eight citing both pros and cons for its use as an on-board reformate. While most respondents did not specifically mention whether they saw synthetic fuels as near, mid, or long term prospects, they generally seemed to assume it was a mid to long term fuel. Many experts cited its value as a fuel that would be virtually free of sulphur and aromatics, thereby avoiding the concern of poisoning the fuel cell stack. A representative of a synthetic fuel company gave his opinion that the likely near-term fuelling choice would a low-sulphur fuel, which could be either gasoline or synthetic fuel. This expert noted that synthetic fuels are attractive because they offer the option of high hydrogen saturation. Several other experts, including one automaker and two energy providers, said, however, that it is just as easy to make a low sulphur gas, and that option would be cheaper than a gas-to-liquid (GTL) fuel. Other experts expressed doubts about the economic viability of synthetic fuels. Specifically, a hydrogen generator company and three energy companies asserted that GTLs are only cost competitive when oil prices are quite high.

Several experts said that synthetic fuels are useful as a means of carrying hydrogen from the natural gas wellhead to the retail stations, because a liquid fuel is easier to transport than gaseous hydrogen. The synthetic gas industry representative cited this as an advantage, and two companies that support the use of methanol said that synthetic fuels would be the second best means to carry hydrogen. In contrast, several experts questioned the sense of adding an extra step to the process of turning natural gas into hydrogen. A fuel-cell company and an automaker said that this was an unnecessary and inefficient way to process natural gas or gasoline.

2.4.2.5 Diesel and Natural Gas

Diesel: The vast majority of experts said that diesel is the hardest of all the liquid fuels to reform and therefore was not commercially viable. Most said that since gasoline is somewhat easier to reform, it would be hard to make a case for reforming diesel instead. Many experts commented that significant problem with diesel is the sulphur. One fuel-cell company said that they had experience with reforming diesel and found simply too difficult to get rid of the sulphur. A government agency noted that reforming diesel is not very economical either.
Several experts noted that the military would have an interest in using diesel as an on-board reformate, and that military applications would not be subject to the same cost and emission goals that drive the development of mainstream fuel-cell technology. One hydrogen generation company said that diesel reformation may also be desirable in Europe, where diesel ICEs are common.

Natural gas*:* Most experts agreed that it does not make sense to use natural gas on board the vehicle. Many commented that it brings the "worst of both worlds" of hydrogen storage and on-board reformation. They noted that, if we are going to deal with the on-board storage of compressed gas, it would be hydrogen, not natural gas. And, the reformation of natural gas poses many of the same problem that gasoline reformation does in terms of high-temperature reformation. Many noted, however, that current commercial hydrogen is currently made primarily from natural gas, and they favoured the continued use of CNG as a hydrogen feedstock.

2.4.2.6 Electrolysis

The majority of experts interviewed feel that electrolysis has potential as a hydrogen source. Those who strongly supported electrolysis were one hydrogen provider, one hydrogen storage company, three government representatives, and, naturally, the two companies that market electrolyser technology. Many others said only that electrolysis had potential, although some issues have yet to be resolved, and three other experts said it would have niche applications. There were only three respondents who discounted the viability of electrolysis: one automaker, one hydrogen generation company and one industry analyst. As a note, experts often switched between discussing centralised, retail station electrolysis and home electrolysis; we will try to clarify which is being discussed when possible.

The biggest concern cited, including by those who favoured electrolysis, was cost. Two automakers and three energy companies cited this as the key issue to be resolved. One energy company said that electrolysis is currently more expensive than making hydrogen from natural gas, which he viewed as the primary competitor for making hydrogen. A representative of the electrolysis industry said that electrolysis is currently the most cost-effective for refuelling small, low density fleets, but that, as the fuel-cell vehicles reach high volumes, hydrogen produced by steam reformation would be more economical. One fuel-cell company said it could be cost effective now in areas where electricity is cheap – for example, where the majority of electricity is inexpensive hydropower. Another fuel-cell company made a similar observation, stating that electrolysis will only have niche applications in these areas. An electrolysis representative said that home electrolysis would become more cost-effective with utility deregulation.

One industry analyst said that emissions from electrolysis would be too high to make it viable. This analyst asserted that, unless the electricity is produced by renewable sources, greenhouse gas emissions from electrolysis would be very high. For example, this expert noted that the US grid is now more than 50% coal-based, so electrolysis on the US grid would have a negative greenhouse gas emission impact. Another expert commented, however, that certain regions that are not heavily based on coal could look very good with regard to greenhouse gases.

2.4.2.7 Hybrid technology

Is hybrid technology a transitional or long-term technology?

An area of disagreement involves whether hybrid electric vehicles will be an interim step to fuel cells or a long-term technology. Experts fall into four categories in their responses. Some experts are uncertain about the future of hybrids. Some agree that hybrids will be a long-term solution while a larger number of respondents feel they are just an interim step. Another response is that hybrid electric vehicles will be both an interim step and a long-term technology.

Hybrids are only an interim step: Most respondents said that hybrid electric vehicles are an interim step to fuel cells. Many said that hybrid vehicles are just a passing phase because they can help fuel cells emerge. Hybrids, therefore, make a good transition technology. They allow time for the development of the electric drive train and for the general public to get accustomed to an electric propulsion system. Current hybrids with internal combustion engines and batteries could be the start of an evolution to fuel-cell vehicles. After internal combustion engine hybrids there could be a larger contribution from the electric system and less from the ICE. Then, a fuel cell could replace the internal combustion engine. Some companies are presently looking into hybrid fuel cells where the battery could help improve the performance of pure fuel-cell systems. The battery can be used for cold start-ups, as a device for storing regenerative braking, and additional acceleration. The final step in the vehicle evolution according to some is pure fuel cells.

Fuel-cell vehicles will be superior to hybrids: Another reason hybrid electric vehicles are just an interim step is because fuel cells have more benefits. Once fuel cells emerge they will be preferred over hybrid electric vehicles. Hybrids are more expensive than fuel cells fundamentally in mass production. They are more complicated than they should be. The two different propulsion systems in hybrid vehicles require more controllers and therefore more money to manufacture. Automobile companies are losing money on the hybrid vehicles they produce and the losses are not sustainable according to many. Depending on the driving conditions a hybrid vehicle may not be advantageous, according to some interviewees. Hybrids are beneficial in city driving because stop and go traffic makes use of the battery and recovery systems. They are less efficient in highway driving. Therefore, the concept of the hybrid is only advantageous in special applications and will be only a minor part of the market according to some experts.

Hybrids still use fossil fuels and cannot meet the requirements of the entire newly reformulated ZEV mandate. Regulators may not allow a petroleum-based fuel to be part of a clean technology.

Many of the experts who believe hybrids are an interim step add qualifiers to their response. Hybrid electric vehicles will be an interim technology to fuel cells but the length of their run depends on a number of factors. An automobile manufacturer says the interim step will last five to 10 years and a technology company predicts 15 to 20 years.

The hybrid's environmental performance is also a factor. Hybrid electric vehicles could closely compare to fuel cells in terms of emissions, efficiency and economics, as a recent MIT study "On The Road in 2020" analysed [Weiss, 2000], depending on the fuel-cell reformation fuel choice and the hybrid APU fuel choice and emissions. Another consideration is the fuel cell's commercial timing and infrastructure development. An automobile manufacturer comments that politics and the vested interests of industry to keep internal combustion engines in use plays a role. The major factor is how well fuel cells compare to hybrids and ICEs and customer acceptance.

The future is uncertain. An energy provider, a fuel-cell technology consulting firm, and a transit agency all agree that at this point in time it is unclear how hybrid vehicle technology will play out. Hybrids could displace fuel cells and be a long-term solution or hybrids could help fuel-cell vehicles develop and be an interim step. Hybrid electric vehicles are appealing because they have good fuel economy and reduced emissions compared to traditional internal combustion engines. The present emission differences between hybrid vehicles and fuel-cell vehicles are very small though, within errors of estimates at full cycle analysis, depending on hydrogen feedstocks, according to a few interviewees. If this small difference continues and hybrids are accepted, they could persist for the long-term. In 20 years or somewhat sooner though, fuel cells could become far superior to hybrids making them just an interim step. The energy provider will be more confident where hybrids are going in six to 18 months while the transit agency feels the answer will not become clear for 15 or 20 years.

Hybrids are a long-term technology: Four respondents agree that hybrid electric vehicles are a long-term solution. An energy provider feels that diesel hybrid electric vehicles will totally beat out fuel-cell vehicles. A hybrid that they are working on has good fuel economy, can meet emission standards, and is able to run not only on diesel but also synthetic fuels. The other three experts who think hybrids are long-term, two technology companies and a government agency, say hybrids will be a competing technology and will exist on the road with fuel cells. Fuel-cell vehicles will have a hard time beating hybrids in terms of efficiency. Hybrid electric vehicles have a good opportunity to seize a good size of the market in areas where fuel prices are high. There is not one single road for advanced automobile technologies. There will be internal combustion engine hybrids and fuel-cell hybrids as well as pure fuel cells and even pure electric vehicles.

Hybrids are both an interim step and a long-term competitor: Unlike the experts who feel hybrid electric vehicles are an interim step and do not know how long they will last, four respondents state that they will be around for the long term. They say hybrids are both a long-term technology and an interim step. Hybrids are a great transition technology, but they will be around for a long time because they use the existing infrastructure and are similar to what the general public is used to. Hybrid electric vehicles will help fuel-cell vehicles emerge, the two technologies will coexist, and then the hybrid technology will end, but only in the long-term.

2.4.3 General trends in fuel-cell technology research

Derived from "Fuel cells start to look real", [Steve Ashley, 2001]
http://www.sae.org/automag/features/fuelcells/

2.4.3.1 Introduction

Though any death-knell for the internal-combustion (IC) engine is decades off, the world's automakers seem to believe that the low-emissions, high-efficiency fuel cell will eventually deliver the power and performance that drivers expect. Despite difficult technical and market challenges to overcome, the latest crop of fuel-cell powered concept cars appears to exhibit many of the basic features required for eventual success. Not surprisingly, high costs will remain the biggest single impediment to commercial viability for years to come.

Despite the current high costs, steady and tangible progress in fuel-cell technology in recent years seems to have convinced many in the automotive and energy industries that the dependable IC engine will eventually be overtaken by a clean alternative power system. The prospect of ever tighter regulatory limits on exhaust emissions has led many car manufacturers to invest heavily in fuel cells to ensure they are participants, if and when the expected market transition occurs.

DaimlerChrysler, **Ford**, and their fuel-cell-stack development partner, **Ballard Power Systems** (the two automakers together own one third of Ballard and collaborate in a precompetitive development venture called XCELLSiS) have spent nearly a billion dollars so far on fuel-cell technology. Their current effort to mass produce fuel-cell cars and light-duty trucks over the next four years will cost billions more.

General Motors is making similar hefty investments in automotive fuel cells, while Japan's **Toyota**, **Honda**, **Nissan,** and **Mitsubishi** reportedly laid out close to a billion dollars on the new technology during the past decade. With an estimated $6-8 billion having already been sunk into the fuel-cell industry, including both stationary and portable power types as well as transportation versions (according to analysts at Citibank), automakers are working to take fuel cells off the lab bench and move them onto the showroom floor.

2.4.3.2 Hybrid-electric vehicles

Another reason fuel-cell technology is favoured is because it may be able to liberate electric cars from the electrochemical battery. While batteries are the cleanest automotive energy source, the technology is still highly problematic. And however responsive battery-powered electric cars are, their limited range and slow charging constrains them to a niche market segment, as GM's EV-1, Honda's EV-Plus, and other abortive electric car models have shown. Despite decades of research and investment, electrochemical batteries simply have not attained the power densities needed for effective automotive propulsion power.

One way to extend the range of the electric car is to carry fuel and a small IC engine on board to generate electricity to power the electric drivetrain. "Hybrids convert the problem of energy storage in a battery to one concerning the storage of fuel," explained Scott Staley, Chief Engineer for Fuel-cell Systems Engineering at Th!nk Technologies, Ford's electric-car enterprise. This hybrid-electric approach is employed in the recently introduced Toyota Prius and Honda Insight, which combine modest-size, high-efficiency combustion engines with batteries that supplement engine power during acceleration and hill-climbing, and recover energy from the brakes during stopping. Besides continuing to emit some pollutants, the combined electric and mechanical drives tend to make them complex and costly. Thus automakers must subsidise current hybrid car models heavily to make them affordable.

Nevertheless, because hybrid vehicles use proven technology that has yet to be fully optimised and refined, many experts believe they will provide strong competition to fuel-cell-powered vehicles well into the future. A recent study by Massachusetts Institute of Technology researchers concluded that hybrid-electric vehicles will be more common than fuel-cell powered cars two decades from now. Indeed, the influential

California Air Resources Board (CARB) recently reorganised its credit structure to emphasise hybrid-electrics as well as fuel-cell vehicles, while de-emphasising battery-powered electric cars and trucks.

Whether fuel-cell-powered or any next-generation vehicles attain commercial success depends on three factors: *technical feasibility* (it must work), an *appropriate fuelling infrastructure* (it must keep working), and *customer acceptance* (someone must buy it). Whereas the majority of today's efforts centre on developing technical feasibility, in reality, all three factors are interrelated and interdependent. While the latter two issues remain unclear, it is evident that the three key elements must be developed in parallel.

2.4.3.3 Fuel-cell technology

Though there are several types of fuel cells that use different fuels and materials, one version – the proton exchange membrane (PEM) variety – has emerged as the clear favourite for automotive use. Another type, the solid oxide fuel cell (SOFC), is seen as the dark-horse alternate. Another fuel-cell technology called an alkaline/air cell is being developed, though its prospects are considered more speculative. The biggest difference between the SOFC and PEM technologies is their operating temperatures. While PEM cells run at 80°C, SOFC units function at anywhere from 700 to 1000°C. Another difference is the membrane, which is a polymer in the PEM and a ceramic in the SOFC.
Many engineers believe that SOFCs, together with an on-board gasoline fuel processor or reformer, would be highly suited as auxiliary power units (APUs) for cars and trucks in the relatively near term. Engineers have long desired to rid automobiles of the alternator and its notoriously low efficiency. And as vehicles are crammed with more and more electronic equipment and move toward higher electrical loads, a larger burden will be placed on the alternator. An auxiliary power unit based on SOFC technology could provide an ideal alternative. A research alliance including BMW, Renault, and Delphi Automotive Systems is pursuing this fuel-cell application.

PEM fuel cells

The proton exchange membrane cell, which was developed by General Electric for NASA's Gemini space programme nearly four decades ago, is the favoured technology for auto applications because it is compact, runs at a low operating temperature, permits an adjustable power output, and can be started relatively rapidly. Innovations made in the 1980s at Los Alamos National Laboratories made the PEM cell more practical by substantially cutting the amount of precious metal catalyst needed to coat the cell's ultra-thin polymer membrane.
Ballard's prototype fuel-cell units, which are used by DaimlerChrysler, Ford, Honda, and Nissan (and others yet unacknowledged), comprise a series of carbon plate/PEM electrode assemblies. "Each assembly includes five main components," explained Paul Lancaster, Vice President, Finance at Ballard. "At either end is an electrode made of a carbon material with a coating of platinum-family catalyst that ionises hydrogen on one side of the unit and oxygen on the other. In the middle is a thin proton exchange membrane, which is a rubbery hydrophilic polymer electrolyte with solid sulfonic acid sites bonded onto it. These sites allow protons to be transported selectively through the membrane."

Although the latest enhancements to fuel cells are rather recent, researchers at Ballard and presumably GM have worked out most of the technical problems, boosting the stack's power density by determining how to keep the membranes moist but not flooded, and by optimising the flow lines that transport hydrogen, oxygen, and water through the stacks. Ballard, which has obtained nearly 400 patents in PEM technology, intends to have a car-sized power unit ready to go within four years at prices comparable to IC engines, according to Lancaster.

Clearly, fuel cells provide some advantages over IC engines: they are more efficient in extracting energy from fuel; they are quieter; and they could form the basis of a zero or very low emissions engine that runs on a renewable fuel. It should be noted that some engineers expect practical fuel-cell vehicles to be hybridised with batteries, ultracapacitors, or other energy storage devices to allow them to be run at lower power output levels and, thus, at higher efficiencies. "Fuel-cell stacks operate at 50% to 70% efficiency in the current power load of interest - about 60% in around-town driving," explained Byron McCormick, Co-director of GM's Global Alternative Propulsion Centre.
Ballard researchers say that they surpassed the minimum power density for automobile applications – about 1 kW/L – when they brought out the Mark 700 fuel cell a couple of years ago. The newer Mark 900 unit puts out as much as 1.35 kW/L, making it "sufficiently powerful for today's vehicles", Lancaster said. "Though that output translates into less power than today's IC engines provide, the torque characteristics of electric motors allow electric cars to offer superior performance."
But much more work remains to make the fuel-cell vehicle truly practical. "Though it's a solid-state device with no moving parts, which tends to keep things simple, it's a catalytic device – like a catalytic converter – so it has different wear modes," said Staley. "This means that after a certain amount of time it'll run out of gas, so to speak. Though we see no obvious roadblocks to being able to cycle a fuel cell through the lifetime of the car, we're not there yet."

Getting the cost out

Until recently, building a fuel cell sufficiently powerful to run a car was costly – even more than a vehicle powered by electrochemical batteries or a hybrid drive. To attain the power levels of a standard-issue IC engine in a midsize sedan, a fuel cell needs to produce from 60 to 90 kW. When NASA first started using fuel-cell technology in space, a PEM fuel cell cost about $500,000 per kW. Today that price has dropped to around $500 per kW (if mass produced) –- but that means that a fuel-cell engine still costs about $25,000, which is around seven times the price of a typical IC engine (about $3500).

Working for several years with specialists from Ford and DaimlerChrysler, Ballard researchers studied the automotive industry's needs for low-cost, high-volume fuel-cell stack manufacturing and specifically designed the Mark 900 unit to accommodate them. "The key to developing an efficient supply chain," explained Lancaster, "is to choose low-cost, readily available materials and cheap, scaleable, automated manufacturing processes. We did an actual commercial plant study for the annual production of 300,000 vehicle equivalents, considering the building, logistics, and other crucial details. Using a standard rule of thumb for value allocation in fuel-cell systems of 40%

for the stack, 40% for the system components, and 20% for the electric drive and transmission, we determined that fuel-cell powerplants could be sold at around $50-$60 per kW, perhaps less as volumes increase."

Facing the challenge of making economical fuel-cell units, Ballard worked with Ford and DaimlerChrysler to optimise its latest stack design for production. Said Lancaster, "Whereas the Mark 700 systems were basically hand-crafted units that needed carbon plates that were individually machined for two hours from blanks costing $100, the Mark 900 unit is made using a carbon sheet material called Grafoil which is supplied by US Carbon Graftek. This soft, natural graphite material comes in rolls. The sheet is first roller-embossed, die-cut, then impregnated, and heat-treated. Now each plate costs a few dollars." The manufacturing process also reportedly employs other high-volume production processes such as injection molding. Each PEM fuel-cell stack comprises hundreds of these identical plates sandwiched between polymeric membranes.

The Mark 900 fuel-cell stack puts out about 80 kW with hydrogen fuel and 75 kW fuelled with methanol reformate. "It's designed to fit within the OEMs' weight and space constraints, generally to fit under the floorboards," said Lancaster. "In addition, it is cold-start capable. We consider it the basis for our future commercial architecture, with ongoing refinement and improvement. Right now, we're testing its durability and reliability by putting it into real vehicles."

"In the Mark 900 stack, Ballard went for manufacturability and production-oriented design," noted Staley. "We expect that there'll be a couple more iterations in the design before we go into production. Of course, as OEMs, we're constantly pressing for higher power density and lower weight, higher production volumes, and lower cost."

According to Lancaster, Ballard's fuel-cell introduction strategy goes as follows: "In late 2001, we plan to start selling our first product, a portable power generator through Coleman Powermate. By 2002, we'll be producing fuel cells for transit buses. DaimlerChrysler already has gotten 33 orders. In the 2002-2003 period, stationary units for uninterrupted power supply and backup power will be introduced. By late 2003, we'll be ready for automotive applications."

2.4.3.4 Fuelling and infrastructure issues

A fundamental problem with fuel-cell technology is fuel selection and storage – supplying enough hydrogen to the stacks is still a struggle. All three of the principal fuels that carmakers are considering – hydrogen, methanol, and gasoline – pose serious challenges.

Though using hydrogen gas is the approach favoured by environmentalists because it is the cleanest, the elemental gas takes up significant space. With "direct hydrogen" fuelling, vehicles carry pressure vessels filled with this highly flammable gas. Hydrogen can also be stored as a liquid, but it must be kept at cryogenic temperatures, adding weight, complexity, and even greater safety issues than compressed hydrogen techniques.

Either way, hydrogen fuelling presents problems for engineers. The two most promising alternatives at the moment appear to be miniature on-board chemical factories called reformers (or fuel cells themselves) that extract hydrogen from methanol, gasoline, or other hydrocarbon fuel. Unfortunately, a reformer adds more weight and technical complexity to a car, while in-situ reforming technology is still far off. What's more, "reformed" hydrogen is not as pure a fuel as fuel cells would like to use, and is not likely to deliver the same performance as uncontaminated hydrogen gas.

Experts indicate that the choice will likely come down to a question of the fuelling distribution infrastructure, which is going to entail a tremendous cost burden no matter how it's accomplished. "I don't think that the fuel stack is going to be the limiting factor; the real pacing item is the fuel infrastructure," said McCormick. Christian Mohrdieck, Fuel-cell Vehicles Program Manager at DaimlerChrysler's Liberty and Technical Affairs, agreed. "The main issue with fuel cells is not the fuel cell, but the fuels themselves," he said.

Direct hydrogen

The most obvious solution is to use hydrogen directly as the fuel. In this scenario, service stations could install hydrogen tanks next to their pumps or perhaps, miniature electrolysis factories that produce the gas from water. This choice would remove the need for an on-board fuel reformer. It would also avoid producing carbon dioxide and other greenhouse gases in the reforming process, though some would be generated during the most common industrial hydrogen production method, which uses natural gas as a feedstock. (Note that the electricity for electrolysis usually comes from powerplants that burn hydrocarbons or split atoms.)

"The beauty of hydrogen production," said McCormick, "is that it's not dependent on one particular feedstock or processing route. You could use electrolysis of water or you could crack natural gas or petroleum."

Skeptics scoff, saying that establishing a national hydrogen network could cost hundreds of billions of dollars. Currently only a few hydrogen filling stations exist. Experts also note that refilling a vehicle with hydrogen requires careful safety procedures. For example, the pump has to be electrically well grounded. Proponents say that hydrogen availability will become less of an issue when automakers finally opt for hydrogen-fuelled cars, but as with most things in this field it's a question of what's going to come first, the donkey or the cart.

And while hydrogen packs more energy by weight than any other fuel (about three times more than gasoline), it is hard to store much of it in a fuel tank. This might not be much of a problem in a bus, but it is in a car. A reasonably sized, commercially available pressure vessel, operating at typical pressures of about 24 MPa and fully filled with hydrogen will take a car barely 190 km - not far enough for most drivers. Also, with hydrogen being the lightest and smallest of molecules, it is relatively difficult to contain, which poses safety problems.

Both DaimlerChrysler and GM have boosted range significantly and ameliorated packaging problems in recent concept cars by using liquid hydrogen storage, but the cryogenic technology to keep fuel at -253°C (just 20°C above absolute zero) remains problematic for reasons of extra weight, greater complexity, and safety.

Most experts hold that, in the long run, direct hydrogen fuelling will be the way to go. "It looks like direct hydrogen is the most likely final result," said Ben Knight, Vice President of Honda R&D America Inc. "It's the most sustainable fuel in the long term, compressed gas storage is well understood, and it's the only set up that clearly beats standard hybrid-electrics regarding total system efficiency. We also believe that direct hydrogen can allow cars to be refuelled quickly, and could eventually provide enough range. Nevertheless, we're preparing to handle all the possible fuels."

One possibility for solving the onboard hydrogen storage problem is simply to pack more of the gas into vehicles. Stronger pressure vessels could contain more hydrogen at higher pressures. Progress is being made in this area. Researchers at IMPCO Technologies Inc.'s Advanced Technology Centre in Irvine, CA, for example, will soon start safety and performance validation testing on the company's new in-tank regulator for hydrogen storage. The patented H2R 5000 flow regulator is a crash-resistant device that can operate at 34 MPa. They are also working to develop concepts to extend IMPCO's ultra-lightweight TriShield hydrogen storage tank technology to 69 MPa. Working with technical assistance from the US Department of Energy and more than $3.5 million of federal research funding, IMPCO has completed development of a commercially viable high-performance hydrogen storage cylinder featuring 7.5% hydrogen storage by weight. This technology is expected to permit a 645-km maximum driving range at a total vessel mass less than 68 kg.

Early this year, the company will also start commercialisation of a pressure vessel technology that stores 8.5% hydrogen by weight. Together with researchers at Lawrence Livermore National Laboratory and Thiokol Propulsion, a division of Alcoa Automotive, IMPCO engineers recently demonstrated a prototype storage tank technology capable of holding 11.3% hydrogen by weight.

Alternatively, vehicles could be designed to incorporate specially shaped conformal tanks in their bodies. "It's not clear just how big a pressure bottle (or how many) you can hide away in a car," said Staley, who adds that Thiokol is working on conformal tanks with funding from the Department of Energy.

Another option is to use materials that absorb hydrogen into their crystal structure (metal hydrides) or incorporate it chemically (chemical hydrides), to hold the fuel until needed. Energy Conversion Devices of Troy, MI, has reported good progress in metal-hydride technology based on magnesium. According to Staley, "in metal hydrides, the amount of stored hydrogen per unit weight is still low. And, it's like having a bunch of bricks in there, not unlike having batteries in a car, not to mention the extra weight for the thermal packaging."

GM's McCormick concurred: "Though it's somewhat promising technology, we're not expecting any breakthroughs over the next few years. You not only have to consider the weight percent of stored hydrogen, you've got to look into the energetics of the entire chemical reaction (even if it is close to an adsorption process). That concerns the heat involved when you put the hydrogen on the hydride and when you take it off. That bonding energy has to be managed; it enters into the total energy equation and lowers the net energy gained."

In chemical hydride storage schemes, stable, relatively benign compounds such as boron, sodium, and calcium hydride are processed with water in a catalytic fuel reactor to generate pure hydrogen. A sodium hydride storage system has been developed by Powerball Industries of West Valley City, UT, while sodium borohydride is being used by Millennium Cell Inc. of Eatontown, NJ. Questions remain about total system weight and what to do with the other reaction by-products, which often need to be recycled for reuse.

Some say that carbon nanostructures – graphite fibres with intricate, high-surface-area configurations – offer promise. Certain carbon nanostructure materials have been shown to absorb more than one-fifth their weight in hydrogen. It seems clear, however, that both hydride and carbon nanostructure storage technologies remain immature at this stage.

Methanol fuels

Automakers are also focusing on using methanol to power fuel cells. In this scenario, methanol fuel-cell cars would bridge the gap in the decade or more it might take to build a hydrogen-distribution network. Sceptics decry the cost of installing the needed storage tankage, but advocates claim that, like the case of diesel fuel, only one in 10 pumps needs to be methanol-capable for the fuel distribution infrastructure to be viable.

Today, there is no central distribution infrastructure for methanol, neither in industry nor at the pumps. DaimlerChrysler estimates that it will cost about $400 million just to add methanol tanks to a third of the service stations in California, New York, and Massachusetts. It's estimated that each methanol installation would cost from $50,000 to $60,000 per station. "Who's going to pay?" is the question often heard. Others say the cost issue is overblown. Said one industry observer: "Even if gasoline is used for fuel cells, the gasoline formulation won't be the same we use today (it'll have less sulphur), so you'll still need to install a new gasoline tank, which costs from $20,000 to $30,000 for each service station. From that perspective, the cost issues surrounding methanol tank installation don't seem so dire."
In November, Methanex Corp., the world's largest producer and marketer of methanol, entered into a strategic alliance with Mitsubishi Corp. and Mitsui & Co. Ltd. to promote methanol for fuel-cell vehicle applications in Japan. The parties to the agreement will work with Japanese governmental and non-governmental agencies to address any regulatory hurdles and encourage methanol-based fuel-cell vehicle demonstration programmes. They will also work with the Japanese automotive industry to ensure a common fuel specification and ensure that methanol of a suitable quality and quantity will be available at retail stations. In addition, alliance members will cooperate with potential Japanese methanol retailers to work toward commercialisation.

Today, methanol is produced on an industrial scale from natural gas, which is still available in fairly large quantities and often simply burned off as an uneconomic by-product of oil production. Renewable sources such as biomass can also serve as feedstocks for hydrogen production.
Some fuel cells run directly on methanol rather than hydrogen. DaimlerChrysler, for example, is working on a direct-methanol PEM fuel cell, said Mohrdieck, which it "demonstrated this fall on a go-cart powered by a small two to three kW motor." Instead of gaseous hydrogen, it uses a methanol/water mix for fuel. At the anode, the methanol breaks down into hydrogen and carbon, while the water breaks into hydrogen and oxygen. The hydrogen is used in fuel-cell membrane. The rest forms carbon dioxide and bubbles away. Perfecting this technology, which is still at the lab stage, "is still a number of years away," he said.

Considerable research effort is being expended by automakers to reform methanol because it is sulphur-free (sulphur poisons fuel-cell stacks) and operates at a relatively

moderate 300°C. But refining methanol into hydrogen is still a complex process involving many steps, each of which must take place at a particular temperature.
The methanol processor in DaimlerChrysler's new Commander 2 sport utility concept produces enough hydrogen to power the vehicle for about 200 km between fill-ups, said Mohrdieck. The SUV's range is limited by the small size of the methanol fuel tank - the result of carrying a bulky fuel reformer and two Mark 700 fuel-cell stacks. The fuel processor takes a half-hour to warm-up, which would be unacceptable to potential customers. The start-up delay follows from the need to heat the steam the unit uses to break down methanol into hydrogen.

XCELLSiS is working on a next-generation fuel processor that uses a catalyst rather than steam to decompose methanol into hydrogen. Not only does the new system feature a rapid start-up time and a fairly dynamic (load-following) operation, it is much smaller and weighs half as much as the reformer unit in the Commander 2.

Meanwhile, doubts are growing over the viability of methanol as a consumer product, at least in the U.S. Said one well-placed expert who wanted to remain anonymous, "My sense is that methanol is more and more becoming a losing proposition. DaimlerChrysler is pushing it, but GM, Toyota, Honda, and Nissan seem to be lukewarm about it." Beyond distribution difficulties, many consider methanol to be pretty noxious stuff - not only is it toxic if ingested, even splashing it on the skin can cause health problems. Current Japanese methanol-handling-method standards call for the use of gloves, for example. And because methanol dissolves in water, it poses a pollution threat to underground water supplies. Proponents, however, claim that methanol is no worse than gasoline.

Gasoline reforming

If fuel-cell cars were to extract hydrogen from gasoline on-board, the transition to the fuel-cell vehicle would be much simpler as the current infrastructure would need less drastic changes. But refining gas on the road is difficult – much harder than cracking methanol. The reformation reactions occur at 850-1000°C, making the devices slow to start and the chemistry "temperamental". While the process is routine in chemical plants and oil refineries, squeezing it under the hood is difficult. Another unsolved problem is finding ways to protect the fuel cell from the catalyst-poisoning sulphur in current grades of gasoline.

Despite its focus on methanol, XCELLSiS is also working with Shell Oil on gasoline-reforming technology, reported DaimlerChrysler's Mohrdieck. "It's a much more complicated technology that operates at higher temperatures, which means it requires different materials able to handle the high heat. Similarly, high operating temperatures are the primary reason we didn't pursue on-board solid oxide or molten carbonate fuel cells," he noted. "Gasoline reformation requires a catalytic shift reaction that runs through a series of catalytic beds in which precise temperatures are critical," according to Ford's Staley. "In addition, you get carbon monoxide out the end, which means death to fuel cells."

Despite the technology challenges, GM and ExxonMobil have recently announced the joint development of a promising gasoline fuel-processor technology. The automaker argues that while hydrogen will likely be the eventual fuel of the future, gasoline-processing technology will provide a critical transition in making fuel-cell cars and trucks practical. "GM is not particularly in favour of using methanol reformate," said McCormick. "If the end state fuel is hydrogen, why spend the time and money to put in a methanol infrastructure? Why not start with the existing gasoline infrastructure?" he asked. Added Greg Ruselowski, Director of Finance Planning and Infrastructure at GM Global Alternative Propulsion Centre, "Methanol use comes down to a question of the ultimate economics, various issues concerning the natural gas supply, and continuing worries about methanol toxicity, not to mention that it only has half the energy value of gasoline."

"GM is moving aggressively on gasoline reforming," said McCormick. "Our goal is to build an 80% efficient fuel processor." Generation 1 is a proof-of-concept bench model built at a facility near Rochester, NY. "We wanted to understand the fundamentals first," he noted.

GM's second-generation gasoline reformer unit - which, at 760 mm long, 460 mm high, and 200 mm deep, is about half the size of the previous system - uses a new robust catalyst technology. Engineers addressed a problem that had so far plagued them - how to prevent the catalyst from breaking down due to driving vibration. The catalyst is "supported" in a honeycomb-like device that holds it in place and prevents it from deteriorating. GM engineers have tested this system for more than 1000 h - about 20% of the time needed for automobile applications - with no reduction in performance. "Right now, we're integrating the new (catalytic) process with a 25-kW fuel-cell stack. After that, we'll continue to reduce the size and further cut the start-up time, while keeping the efficiency up and driving the cost out," he explained. The new catalyst will also be used in a next-generation fuel processor system that will be installed in a Chevrolet S-10 pickup that GM plans to demonstrate in early 2002. "Our rate of progress in gasoline reforming is surprisingly good," he stated. "Stay tuned..."

In general, "fuel-reforming technology requires the clever integration of all the components into a compact, lightweight, efficient, low-cost system", said Mark Voss, Engineering Manager for Modine Manufacturing Co. in Racine, WI. Modine has an exclusive agreement with XCELLSiS to supply heat transfer-related parts of fuel-cell systems. "The key is to couple the various subsystems together, some of which generate heat and others that use heat, so that the available heat is moved to where it's needed. Right now, we're focusing on the optimal materials choice in terms of durability and low-cost."

"Fuel-cell engine technology is still progressing in big technological steps where many disciplines such as process engineering, chemistry, heat transfer, special manufacturing skills, and so forth have to be optimised in a novel approach," said Gunther Dietrich, Senior Vice President, Development, Engineering, & Manufacturing, for XCELLSiS. "Under the arrangement, Modine, using its knowledge in solving thermal-management problems, will work together with XCELLSiS and its partners to bring fuel-cell engines to the marketplace." The company also will make radiators and heat exchangers for XCELLSiS-powered fuel-cell vehicles.

Another major question regarding hydrocarbon-fuel reforming is whether the chemical processing should be done onboard the car or at the service station. The answer depends on whether there is an eventual breakthrough in hydrogen-storage technology. A typical stationary reformer can run at higher-efficiency (about 90%), steady-state conditions, whereas onboard units must operate in load-following mode, making them less efficient (80-85%). Onboard reforming, of course, involves various hurdles including packaging issues, extra weight, and complicated controls.

Several automotive industry observers characterize the oil companies' general position on automotive fuel choice as surprisingly open. Said one, "Like us, they're asking if the technology is real, while trying to prepare to satisfy whatever need emerges. The oil companies are spending a fair amount of resources on this issue, but it's a classic chicken-and-egg problem of which comes first: the fuel or the fuel-cell engine. In addition, different fuels are probably better suited to different parts of the world. Though the oil industry seems to be a big, lumbering, monolithic giant that does what it wants, recent divestitures now mean it's more a collection of a lot of little guys who have to follow the market just like everyone else. This makes the huge investments that are going to be needed much more difficult to accomplish."

2.4.3.5 Balance of plant

Auto engineers will say that a lot more goes into developing a fuel-cell vehicle than the stacks and the fuel. The so-called "balance of plant" issues, though little spoken about, also figure strongly in the success of these next-generation vehicles. A variety of sophisticated devices are required to keep the stacks going, and the parasitic losses they can entail must be minimised.

Staley lists some of the balance of plant technologies involved: "Firstly, most fuel-cell units need pressurized air to boost the amount of oxygen in the stack for the reaction to take place, so efficient compressors are required. When air is compressed, it heats, so you need an intercooler to reduce temperatures. In addition, filters must be included to keep the air, hydrogen, and water streams clean as well as flow and recirculation devices to keep them moving. Humidifiers are needed to keep the gas stream moist so the membrane does not dry out. In a reformer vehicle, the moisture is a free by-product of the reaction. In the non-reformer case, a supply of water must be kept on hand so water is extracted from the stack exhaust and then fed back into a reservoir to make the process self-sustaining. Meanwhile, the exhaust stream is typically run through an expander to reduce the shaft load on the compressor. Finally, various energy recovery devices are used to retain heat for several of the reforming processes."

Similar to that of a battery-electric car, Staley continued, "the high-voltage, high-power output of the fuel-cell stack must be distributed to the rest of the car - to the drivetrain, and to a dc-to-dc converter to power the auxiliary electronics systems." In general, fuel-cell vehicles also use the same kind of computer controls, sensors, multiplexers, and analogue-to-digital converters as current IC-engine vehicles, though the control algorithms are different. The powertrain control is also close to that of a battery-powered vehicle; it's divided into torque-generating control for the drivetrain and a power-generating control for the fuel-cell system. Traction motor technology continues to follow the evolution of the electric drivetrain."

Generally speaking, "the balance of plant packaging is going well", said GM's McCormick. "It's getting progressively simpler as we integrate all the necessary components." Said his colleague Ruselowski, "At this stage, we're starting to get away from highly sophisticated aerospace technology, which was required at first, and moving toward more automotive-type technology."

2.4.3.6 Oversize radiators

Another rarely mentioned but important engineering issue concerning fuel-cell vehicles is the radiator system. Because fuel-cell engines are different than their IC counterparts, their radiators are also different. In particular, they are much larger. "We're going to have to find innovative ways to get the heat rejection you need in fuel-cell vehicles," said McCormick.
"PEM fuel cells run at 80°C because the membrane needs that temperature to keep the process going," explained DaimlerChrysler's Mohrdieck, "but we would really rather have a 120°C operating temperature like IC engines because it's difficult to get rid of low-temperature heat, particularly when exterior temperatures are high. It's actually one of the biggest technical challenges; fuel cells need a very large radiator, which makes packaging and styling difficult by adding size and large air openings that hurt the drag coefficient. It's going to be easier for American cars to accommodate these concerns because of their larger size," he noted. "In addition, fuel-cell vehicles require two radiator systems - one for cooling the electronics and the electric motor and another for cooling the stack, which makes it awfully complicated."

"Fuel cells have interesting heat-transfer properties that are significantly different than the heat properties of IC engines," said Staley. "In an IC engine, one-third of the exhaust heat goes out the tailpipe, one-third into the coolant, and one-third out the radiator. In a fuel-cell powerplant, 80% of the heat must be rejected through the radiator, which has to be sized to handle the heat produced at high power as well as be able to operate at high ambient temperatures. You need more surface area to reject lower temperature heat to the environment, particularly when it's hot out. All this makes for a big problem.
"Since the radiator is going to be bigger, it leads designers to try to divide up the heat loops into several radiator systems that can be packaged separately," Staley explained. "In addition, you've got different heats at different temperatures and your efficiency in rejecting heat to the atmosphere is different. The heat-transfer people are facing a whole new set of challenges, but they're doable - it's just going to require something other than standard automotive thinking."

Material compatibility is another issue. "With fuel cells, keeping control of the conductive paths is very important," Staley said. "Fuel cells want no ionic materials in them, so deionised water and special cooling fluids need to be used. Sophisticated ground fault-detection technology and deionising beds in some cooling circuits are also employed to accomplish this. Unfortunately, when you run these kinds of fluids through equipment, it tends to corrode them quickly." McCormick indicated that "GM has moved away from deionised water, which freezes easily, toward nonconductive coolants more appropriate to the fuel-cell environment." Staley expects that engineers will have to use stainless steel, some aluminium alloys, specially coated aluminium, and insulating polymers to do the job.

Fighting the deep freeze

"The freezability issue could be the Achilles heel of fuel cells," Staley stated. "Water is generated in the fuel cell when you 'key' off the vehicle. You'd like to just key off and walk away, but unless you use energy to get rid of the water, low temperatures could cause ice crystals to form that destroy the ultra-thin polymer membrane. It's a question of customer acceptance. The big issue is to bring the stack back to life quickly after it's been soaking all night at -20 to -40°C. The stack's not going to generate electricity until it's at 0°C. Ballard's doing tons of work on this issue - considering everything from insulating schemes to phase-change materials to plug-in block heaters like people use with diesel engines."

McCormick claims that GM engineers have made great success in handling freezability in its fuel-cell stack designs: "We can draw full power from a stack frozen at -40°C in a matter of seconds." Part of the improvement, he said, comes from cleaning water out of the system during the shut down procedure and from special coolants, adding that other undisclosed techniques provide the remainder of the fast start-up capability.

2.4.3.7 Attaining practicality and affordability

Though engineers are currently focusing on perfecting individual subsystems, many experts believe that true practicality for fuel-cell vehicles will come eventually from a total systems approach. "We need to improve the energy, weight, and volume efficiency of all the subsystems individually and then find that unique balance point where the total system meets our goals regarding energy efficiency, zero emissions, sustainability, and cost," said Honda's Ben Knight. Lightweight auto bodies are also going to be key since weight drives the powertrain system requirements.

"We're still just getting started, but now we see a path to a marketable fuel-cell vehicle," said McCormick. "More and more suppliers are working with us, with half of our development partners from outside the automotive business." He emphasized that "we're still in the precompetitive mode with fuel cells, and issues still need to be addressed such as industry codes and standards and fuel infrastructure issues - all of which are very important to the success of fuel-cell vehicles. We all need to work much more closely with the energy companies, government agencies, and the environmental people."

Regarding commercial introduction, he said, "There's little question that the initial introduction will be done in business fleets, since central refuelling avoids much of the infrastructure problem." The earliest individual sales will probably be accomplished using leasing arrangements to retain company control of the first fuel-cell vehicles until the technology is completely proven out.

To Staley, "the big issue is cost, cost, cost. Nobody's going to pay a premium for fuel-cell vehicles. In reality, fuel-cell vehicles are not going to be market-driven, but government-mandated," he stressed. "Americans have no concept of niche vehicles like city cars (with limited-range); they're used to having full-function vehicles, so that's what we're going to have to give them. The challenges involved with fuel-cell vehicles are making them the closest thing to Rocket Science I've ever worked on."

2.4.3.8 Energy Conversion Devices

Energy Conversion Devices Inc. (ECD) of Troy, MI, is developing a hydrogen-storage technology that could be a key to future zero-emissions fuel-cell-powered vehicles. The technique relies on metal hydrides - special alloys that incorporate hydrogen atoms in their crystalline structure when heat is removed. Hydrogen is released when heat is applied to the alloy. "A tank displacing about 120 L and containing around 120 kg of magnesium-based metal-hydride powder could store about 6 kg of hydrogen, giving an advanced fuel-cell vehicle about a 480-km range," said Bob Stempel, ECD President.

In most hydrogen-powered prototypes, pure hydrogen is stored as either a supercooled liquid that must be kept chilled at very low temperatures or as a compressed gas at pressures up to 34 MPa. In the former case, a cryogenic tank holds 31 g of hydrogen for every litre of storage volume. In the latter, a compressed gas system stores about 71 g of hydrogen for each litre of volume (depending on the pressure). By contrast, ECD's metal-hydride system can capture 103 g of hydrogen per litre volume.

In general, metal-hydride storage systems comprise three main parts: hydrogen gas, engineered metallic materials, and the interface region between them, according to ECD's Vice President of Advanced Materials Development, Rosa Young. "The metal alloys we have formulated are in loose, dry powder form," he said. "Hydrogen gas entering the storage vessel adsorbs onto the interface regions of the powder. Hydrogen molecules dissociate into individual hydrogen atoms and metal hydride is formed when these atoms arrange in a specific pattern with the metal atoms. Heat is also a factor. Removing heat drives the adsorption process. Adding heat reverses the chemical reaction and causes the hydrogen atoms to reform as hydrogen molecules."

In ECD's fuel-storage design, the hydrogen is pumped into a tank containing racks of canisters filled with a powdered magnesium-based alloy compressed into cakes. The system reportedly operates at relatively low pressures – around 2.4 MPa. The gas is desorbed from the hydride at a temperature of 286°C, with heat generated on start-up by a "catalytic burner" in each canister. Up to 20% of the hydrogen is consumed in starting the release process. Later, the heat would be supplied from the reaction in the fuel cell itself. The storage system also includes a refuelling heat exchanger and high-efficiency insulation. Company engineers have put the technology through more than 2000 fill-and-release cycles, enough to power a vehicle for several hundred thousand miles.

"Until recently, the (weight%) limit was 2 or 3 g of hydrogen per 100 g of hydride," said Stanford R. Ovshinsky, Co-founder of ECD. "By using a high percentage of magnesium with several other metals in our patented hydride powders, ECD is capable of storing 7 g of hydrogen per 100 g of hydride (7 weight%)." Most current metal hydrides can store 2 or 3% of their own weight in hydrogen.
Stempel says that ECD researchers are working on ways to boost the amount of hydrogen the magnesium-based metal-hydride alloys can store. "We're looking to increase the active surface area of the powders by increasing the porosity, and by adding small amounts of carbon and other useful additives," he said.
"We still have a lot of work to do on this technology before it's ready for the market," said Stempel. One drawback to metal-hydride storage is that it uses some energy in its cycling operation. The key to that issue is how to best capture the heat so the total system efficiency remains high. Another issue concerns speeding up the rate at which the hydride soaks up and releases the hydrogen to cut the wait at the pump. "We've resolved the thermodynamic issues of storing and releasing hydrogen from a metal hydride so a typical fill-up would require only 3 or 4 minutes," claimed Ovshinsky.

Shrinking both the size and weight of the tanks as well as the high cost are other concerns. At $4/lb, the magnesium-hydride powder alone would add up to $1000 to the vehicle's cost. Stempel acknowledges that the hydrogen storage technology ECD envisions is expensive, but on a systems basis, he thinks it can be cost-competitive.
Yet another technical challenge is ensuring the safety of the magnesium-based powder. Onboard tanks would be designed to resist puncture and fires, but the magnesium dust would be dangerously explosive during processing.

Last year, Texaco Inc. invested nearly $68 million in ECD, announcing it was primarily interested in ECD's proprietary fuel-cell technology and its hydrogen-storage system. More recently, Texaco Energy Systems Inc. (TESI) and ECD formed Texaco Ovonic Hydrogen Systems LLC, a 50-50 joint venture to further develop and advance the commercialisation of ECD's metal-hydride technology. Under the terms of the joint venture agreement, ECD will provide proprietary technology, while TESI will provide additional technological support and funding during the product development and pre-production phase of the company's operations.

"ECD's proprietary metal-hydride hydrogen-storage technology has the potential to overcome one of the key challenges of making fuel cells and other hydrogen-dependent energy sources practical, efficient, and safe," said William M. Wicker, Texaco Senior Vice President. "We are confident that the formation of this joint venture will move us forward to achieving this important goal."

2.4.3.9 The California Fuel Cell Partnership

The California Fuel Cell Partnership is a voluntary alliance of automakers and energy companies, as well as state and federal government organisations, working to demonstrate and promote awareness of fuel-cell vehicle technology. The partnership – which was formally established in April 1999 – includes automakers (DaimlerChrysler, Ford, GM, Honda, Hyundai, Nissan, Toyota, and Volkswagen); energy providers (BP, Shell, and Texaco); fuel-cell companies (Ballard Power Systems and International Fuel Cells); and government agencies (the California Air Resources Board, California Energy Commission, South Coast Air Quality Management District, US Department of Energy, and US Department of Transportation).

The joint project is aimed at demonstrating the everyday practicality of fuel-cell vehicles, initiating discussion on the topic of fuel-cell infrastructures, and preparing the California market for this new technology. Between 2001 and 2003, the partners intend to test more than 50 cars and buses incorporating innovative drive technologies under everyday operating conditions – fuelled by hydrogen, methanol, and perhaps a purer form of gasoline.

The partnership opened the West Sacramento Fuel Cell Vehicle and Fuelling Facility in the fall of 2000. Hydrogen is the fuel of choice at the 5100 m^2 facility. It features a large, above-ground tank of liquid hydrogen that delivers hydrogen fuel at pressures up to 34 MPa. It is the only hydrogen fuel facility in Northern California and one of two in the state. The other is in Palm Springs. The partnership hopes to add a third in-state refuelling facility in the Bay Area.

The partnership recently added four companies with expertise in developing hydrogen-fuelling stations as associate partners. The companies – Hydrogen Burner Technology, Pacific Gas and Electric, Proton Energy Systems, Inc., and Stuart Energy Systems – will assist in exploring the development of a hydrogen fuelling infrastructure in California. Each will provide at least one hydrogen fuelling station for the partnership's demonstration program.

2.4.4 Direct Methanol Fuel Cells

Direct methanol fuel cells (DMFC) are a special type of PEM fuel cells. Instead of hydrogen, they utilise methanol, combined with water, directly as a fuel and ambient air for oxygen. This could be a less expensive, more convenient technology because it enables the use of a liquid fuel without the need of an on-board reformer. Some drawbacks of DMFC's are low power density and lower efficiency than PEMFC's.

Souce: *Fuel Cell Technology News*, January 2002

Researchers at Los Alamos National Laboratory (Los Alamos) are developing the materials, components, and operating conditions that will improve the potential of DMFCs for transportation applications. Recently, Los Alamos demonstrated peak power of 0.15 W/cm^2 in a DMFC operating continuously at a constant voltage of 0.4 V for 2,000 hr. with fuel utilization close to 90%. The overall energy conversion efficiency achieved of 36% compares favourably with a system based on on-board reforming of methanol. Researchers at Los Alamos are also working with Motorola to develop DMFC technology for portable power applications.

Researchers at Pennsylvania State University (PSU) are developing a PEMFC that can operate at elevated temperatures up to approximately 200°C to improve prospects for DMFCs. The researchers have synthesized and evaluated a new class of ion- exchange membranes for PEMFC fuel cells consisting of polymers based on the polyphosphazene system, particularly those that contain sulfonate, carboxylate, phosphate, and phosphonate anion substituents. The polymers are used to increase the stability of the membrane and reduce methanol crossover while maintaining conductivity similar to conventional membranes used in lower temperature PEMFCs. PSU will develop and optimise a high- temperature DMFC system for experimental measurements at temperatures up to 200^{o}C.

"Beyond the internal combustion engine, the promise of fuel cell vehicles" [*AMI*, 2000]

In November 2000, DaimlerChrysler, along with Ballard Power Systems, demonstrated a DMFC prototype one-person vehicle. The small three-kilowatt system is the result of an ongoing collaboration between the research groups of DaimlerChrysler and Ballard. Mazda Motor Corporation is joining DaimlerChrysler Japan Holding Ltd. and Nippon Mitsubishi Oil Co., Ltd., in a government-supported project to demonstrate MFCVs. Daimler and Mazda will provide one car each for test runs, and Nippon Mitsubishi will provide the fuel needed for the tests. The project will cost more than 1 billion yen ($9.3 million) and is expected to receive between 200 and 300 million yen (between $1.8 and $2.8 million) in support from Japan's Ministry of International Trade and Industry.

2.4.5 News from vehicle developments

For years, Toyota Motor Corp. and Honda Motor Co. raced to become the world's first automaker to put a fuel-cell vehicle into practical use. The stakes were high and the honour of ushering in a new era of eco-friendly vehicles awaited at the finish line. http://www.h2fc.com/news.html

The race has ended in a tie since both Honda and Toyota delivered their first fuel-cell cars in Japan and California on December 2, 2002..

2.4.5.1 Toyota

"Engines and electric motors – the Japanese industry is pursuing a high-tech mix of internal combustion engines, hybrid IC/electric powertrains, and fuel cells" [*Automotive Engineering*, August 2002]

H. Watanabe (Toyota): "Expectation for fuel-cell vehicles is really overheating. The number of these vehicles appearing on the public road will be negligible. The fundamental premise is that it will be well into the 2010's when real production FC vehicles will appear.
Compared to the conventional gasoline IC car's 14% efficiency from well to wheel, and the gasoline IC/electric hybrid's 26%, the Toyota FCHV-4 with high pressure gaseous hydrogen storage achieves 29% efficiency, based on the (methane) well-to-tank efficiency of 58%. The vehicle itself attains 50% efficiency in the tank-to-wheel comparison using hybrid technology. Without hybrid technology, the vehicle's efficiency drops to 38%.
Ultimately, Toyota aims at obtaining 60% tank-to-wheel efficiency. Combined with improved hydrogen production that raises the well-to-tank efficiency to 70%, a future Toyota FCHV could achieve a 42% efficiency in the well-to-wheel comparison."

Tokyo Motor Show 2001 [*Automotive Engineering*, December 2001]
By far the most significant technology from Toyota is the **FCHV-5**, the latest in the company's experimental fuel-cell hybrid vehicle line. Toyota emphasizes the hybrid part, as the FCHV series has always had and will have a secondary storage battery, whereas GM has made it known that it is dispensing with one. The FCHV-5 is, according to Toyota, a running vehicle, equipped with a CHF (clean hydrocarbon fuel, referring to a cleaner variant of gasoline not yet commercially available) reformer that separates hydrogen and feeds the fuel-cell stack, which, again, is of Toyota's own design and construction.

"Toyota Advances Marketing of Fuel Cell-Electric Hybrid SUV – Limited Numbers Will Be Offered in Japan and the US Around the End of This Year" [Press release, July 1, 2002]

July 1, 2002 – TORRANCE, CA – Toyota Motor Sales (TMS), U.S.A., Inc., announced that it, and parent company Toyota Motor Corporation, will start limited marketing of a fuel cell hybrid (FCHV) sport utility vehicle (SUV) in Japan and the US around the end of this year, much earlier than originally planned. The earlier launch reflects the successful results of a year of testing in the two countries of the FCHV-4 prototype, and Toyota's response to society's expectations for cleaner mobility solutions.

The SUV, based on the Kluger-V in Japan and the Highlander in the United States, will be a newly developed FCHV featuring conventional vehicle-like performance based on improvements to the FCHV-4's reliability, cruising distance, functionality and other aspects. Lowering costs, cold temperature performance and other issues remain. Therefore, the fuel cell-powered SUVs, to be available by lease, will be offered only to select private sectors, technology related companies, institutional organizations and research facilities. Although terms have yet to be determined, Toyota plans to lease a total of approximately 20 units during the first year to entities that have access to hydrogen-supply infrastructure and after-sales service.

Toyota began testing the FCHV-4 on public roads in Japan in June 2001 and the United States a month later. So far, FCHV-4s have covered a cumulative 110,000 kilometres on and off the test track, providing valuable insight toward the commercialisation of FCHVs.

”Toyota Delivers First Two, Market-Ready Zero-Emission-Certified Hydrogen Fuel-Cell Vehicles” [Press release, December 2, 2002]

Dec. 2, 2002 - Torrance, CA - Toyota Motor Sales (TMS), U.S.A., Inc., today delivered its first two market-ready hydrogen fuel-cell vehicles to the University of California, Irvine (UCI) and the University of California, Davis (UCD).

The two vehicles are the first of a total of six "Toyota FCHV" fuel-cell vehicles that will be leased to the two UC campuses. The four additional vehicles will arrive later next year. Each vehicle will be leased for a total of 30 months.

The Toyota FCHV represents advancement on the FCHV-4 hydrogen fuel-cell vehicle, which underwent 18 months of real-world testing in California and Japan, logging more than 80,000 miles of evaluation on test tracks and public highways. The vehicle has gone through rigorous crash testing during its pre-market evaluation.
During that time the vehicle's hydrogen fuel system has proven to be reliable, durable and user-friendly.

The Toyota FCHV-4 and FCHV are based on the Toyota Highlander five-passenger mid-size sport utility vehicle (SUV). Its fuel-cell stack is solely developed and built by Toyota.
The Toyota FCHV system features four 5,000-psi hydrogen fuel tanks. Hydrogen gas feeds into the fuel-cell stack where it is combined with oxygen. The chemical reaction of combining hydrogen and oxygen to form water generates a peak of 90 kW of electricity. The electricity from the fuel-cell is used to power the 109-hp (194 lbs-ft of torque) electric motor and to charge the vehicle's nickel-metal hydride batteries which also feed power-on-demand to the electric motor. Water vapour is emitted through the vehicle's tailpipe.

By applying the hybrid technologies honed in the Toyota Prius gas-electric hybrid vehicle, the Toyota FCHV fuel-cell-electric system precisely regulates power flow from the fuel-cell stack and battery to achieve high efficiency, excellent acceleration and a smooth quiet ride. The FCHV has a top speed of 96 mph. It has a lighter body shell than the Highlander, thanks to the use of aluminium in the roof, fenders and other components. At 0.326 Cd, the FCHV is one of the world's most aerodynamic SUVs, thanks to its flat, well-sealed underbody. Not only has the Toyota FCHV been certified by CARB as a zero-emissions vehicle, its environment-friendly air conditioning system uses CO_2 rather than CFC as a coolant.

Toyota FCHV Main Specifications

Dimensions	L 4,735 mm W 1,815 mm H 1,685 mm
Weight:	1,860 kg
Seating capacity:	5 persons
Performance:	
Max cruising range	290 km
Maximum speed	155 km/h
Fuel cell stack:	
Name	Toyota FC Stack
Type	Polymer electrolyte fuel cell
Output	90 kW
Motor:	
Type	Permanent magnet
Maximum output	80 kW
Maximum torque	260 Nm
Fuel:	
Type	Pure hydrogen
Storage method	High-pressure hydrogen storage tanks
Max. storage pressure	35 MPa
Secondary battery:	
Type	Nickel-metal hydride (NiMH)
Monthly lease price:	
30-month lease	$10,000

2.4.5.2 Honda

"Honda Fuel Cell Vehicle First to Receive Certification - Honda FCX Slated for Commercial Use" [Press release, July 24, 2002]

TORRANCE, Calif., July 24, 2002 --- The Honda FCX has become the first fuel cell vehicle in the world to receive government certification, paving the way for the commercial use of fuel cell vehicles, American Honda Motor Co., Inc., announced today.

Both the U.S. Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) have certified the hydrogen-powered Honda FCX as meeting all applicable standards. The FCX has been certified by CARB as a Zero Emission Vehicle (ZEV) and by the EPA as a Tier-2 Bin 1, National Low Emission Vehicle (NLEV), the lowest national emission rating. The FCX will also meet applicable US safety and occupant protection standards.

Honda will start a lease program for a limited number of FCXs in the US and Japan by the end of this year. During the first 2-3 year period, Honda will lease about 30 fuel cell vehicles in California and the Tokyo metropolitan area, two locations with access to a hydrogen fuel supply infrastructure. The company currently has no plans, however, for mass-market sales of fuel cell vehicles.

This latest version of Honda fuel-cell vehicle achieves 15% more maximum drive motor torque than previous models and also provides improvements in mid-to-high range power output characteristics and acceleration. It also has an increased driving range of 220 miles, about 25 miles more than the previous model.

“Honda to market fuel cell car from Dec 2” [Press release, November 22, 2002]

TOKYO, Nov 22 (Reuters) - Honda Motor Co says it had won Japanese government approval to market fuel cell cars and would start marketing the environmentally friendly vehicles from December 2, the same day as Toyota Motor Corp.

Japan's top two automakers will become the first in the world to put the zero-emission hydrogen fuel cell vehicles on the road, but full commercialisation is still years away. Commercialisation of fuel cell cars is expected to take at least 10 years since they require massive spending on infrastructure to build hydrogen fuelling stations.
Japan at present has only three such stations.

Honda said it would also deliver five of its "FCX" fuel cell vehicles to the city of Los Angeles on December 2. In July, Honda became the first automaker to be certified by the U.S. Environmental Protection Agency and California Air Resources Board (CARB) to market the cars.

Toyota said this week it planned to deliver its "FCHV" fuel cell vehicles to two universities in California on December 2. A spokesman said the automaker expects CARB approval by the end of this month.

Honda plans to release about 30 of its four-seater FCX cars in Japan and the United States over the next two or three years. In Japan it will begin leasing the FCX to the Cabinet Office for 800,000 yen ($6,522) a month over a year.
Toyota will charge 1.2 million yen ($9,784) for its five-seater FCHV in Japan under a 30-month contract with four ministries initially.

[Press release, December 2, 2002]

The City of Los Angeles became the first commercial customer in North America for a hydrogen-powered fuel-cell car on December 2, 2002, when the first of five 2003 Honda FCX automobiles was delivered. American Honda Motor Co., Inc., is supplying hydrogen-powered 2003 model year Honda FCX fuel cell vehicles to the city under a lease agreement. City employees will use the vehicles for daily business trips.

Honda FCX specifications

<u>Vehicle</u>			
Dimensions:	L : 4.165m	W : 1.760m	H : 1.645m
Max. speed :	150km/h		
Driving Range:	355km		
Seating Capacity:	4 adults		
<u>Motor</u>			
Motor Type:	AC synchronous		
Maximum Power Output:	60kW		
Maximum Drive Torque:	272Nm		
<u>Fuel Cell Stack</u>			
Stack Type:	PEFC (proton exchange membrane type - Ballard)		
Power Output:	78kW		
<u>Power storage</u> :	Honda Ultra Capacitor		
<u>Fuel</u> :	Compressed gaseous hydrogen		
Storage Method:	High-pressure hydrogen storage tank (5,000 psi)		
Fuel Capacity:	156.6 litre		

2.4.5.3 General Motors

GM fuel-cell-vehicle advances [*Automotive Engineering*, September 2001]

General Motors has revealed a fuel-cell strategy aimed at putting a million fuel-cell vehicles (FCV) on the road by the end of the decade, rather than targeting limited production at an earlier time as other manufacturers have announced. The company said it will conduct pilot programs and will field FCVs in fleet applications to develop the technology, but will not subsidize costly fuel-cell technology to make it competitive with internal-combustion technology.

"We are not too concerned with being first to market," said Byron McCormick, Co-director of GM's Global Alternative Propulsion Centre. "We plan on being the first company to sell a million fuel-cell vehicles." Toward that end, the company showed its fuel-cell technology at two recent events.

Earlier this year, at its Desert Proving Grounds near Phoenix, AZ, the company showed the HydroGen1 FCV, which was undergoing hot-weather testing. The company had already learned that its scroll-type compressor could not take the heat. After multiple compressor failures, engineers/technicians cobbled together a unit from the parts of the failed ones. A slight mismatch in the gears and the elimination of sound shielding for ease of continued service imparted a high-pitched whine reminiscent of an old Boeing 707 taxiing for takeoff. "It normally sounds like a quiet vacuum cleaner," said a spokesman. This compares to DaimlerChrysler's NECAR family of FCVs, which has used a reciprocating compressor that chugs like a lawn mower.

Driving the HydroGen1 is much like driving many other EVs; good off-the-line acceleration but limited passing acceleration at speeds of around 80 km/h. Though the HydroGen1 uses a liquid-hydrogen fuel, and the company plans to initially introduce gasoline-fuelled FCVs, the prototype has helped the company gain expertise with fuel-cell performance over a variety of conditions.

The next-generation fuel cell, dubbed Stack 2000, will boast several key advances over the HydroGen1's. Perhaps most importantly, GM has been able to eliminate the humidifier that was previously needed to provide the proper humidity to the compressed air forced through the cell. The company is guarding the technology that lets the cell run without a humidifier, but eliminating that component removes 10 water-management devices from the system and improves the cell's freeze performance at extremely low temperatures. The humidifier was also bulky, taking up as much space as the current-generation fuel-cell stack itself, according to Martin Woehr, Manager of stack design.

Another key goal in the drive toward mass production is the reduction of the precious metals needed in both the fuel cell and the reformer to break gasoline down into hydrogen. Stack 2000 uses about 70 g of precious metals in the reformer and fuel cell, about twice the amount used in a typical catalytic converter for an IC engine, said Woehr. However, some catalysts use as little as 5 g; employing the same techniques, the total amount needed for the cell and reformer should fall to about 35 g, he predicted.

Stack 2000 would give the HydroGen1 better performance than does its older fuel cell, but the new unit is to arrive in a different package in early 2002. It will be installed in a Chevrolet S-10 midsize pickup truck and provide 35% more efficiency than the unit in the HydroGen1. Stack2000 produces 94 kW continuously, with 129 kW peak power, compared to 80 kW and 120 kW for the HydroGen1 stack.

GM plans to use gasoline as a primary fuel, instead of methanol as proposed by other manufacturers, the use of gasoline adding about 30% to the cost and complexity of the reformer, according to Daniel O'Connell, a staff engineer for fuel processing at GM. The gasoline reformer adds a CO-removal step to the methanol reformer's two-step process, and it runs at a higher temperature. But the increase in cost and complexity is incremental, not substantial, so they are not significant deterrents to the idea, he said.

GM also addressed performance enthusiasts, who fear that fuel-cell cars will be slow and little fun for enthusiastic driving. The company pointed out that adding power to a fuel cell is a simple matter of making the stack larger. This is much less expensive than tooling up for a V8 powerplant, for example.

Further, the efficiency characteristics of a fuel cell are opposite that of an IC engine. That is, the fuel cell runs most efficiently at a lower percentage of its maximum power, while IC engines are less efficient when running at low power levels. So performance-oriented vehicles with powerful fuel cells will actually be more efficient than economy models when they are driven moderately.

FCVs will also look different than today's cars because of "the ability to, in radical ways, change the packaging of the car," said Woehr. The company's stylists are already noodling possible designs for FCVs that exploit that flexibility, he said.

The new Gen III gasoline fuel processor in the S-10 reforms "clean" gasoline onboard, extracting a stream of hydrogen to send to the fuel-cell stack. Onboard gasoline reforming is significant because all other fuel cells run on either pure hydrogen or hydrogen extracted from methanol, said Burns. "But, right now, you can't get hydrogen or methanol at your corner gas station and it would cost hundreds of billions of dollars to create such an infrastructure," he explained. "Developing gasoline-fed fuel cells makes the technology much more attainable—even within this decade." GM intends to make gasoline-fed fuel cells an interim strategy until a hydrogen infrastructure is established.

The Gen III gasoline processor also has the capability of starting in less than three minutes, compared to the previous 15-min start time. It has a peak efficiency of 80%. The processor takes gasoline and "cracks" it into its hydrogen components. Said Burns, "To our knowledge, no one else has cracked gasoline in an onboard system."

GM's driveable fuel-cell lab [*Automotive Engineering*, July 2002]

GM developed a new catalyst for its next-generation fuel processor. The fuel-cell catalyst helps convert fuel into electricity, and needed to be designed so it would not break down from vibration during driving. Engineers designed the catalyst to be held in place by a honeycomb-like device. The company planned to install the catalyst in a fuel-cell-powered Chevrolet S-10 that the company intended "to demonstrate in early 2002." In May 2002, GM did it.

The S-10 extracts hydrogen from gasoline. It is equipped with a fuel processor, which currently takes up the better part of the bed, that reforms low-sulphur gasoline via a series of chemical reactions. The fuel is mixed with air and water and then passed over a series of catalysts to remove the hydrogen from the carbon. The hydrogen is then sent to the fuel-cell stack, where it is combined with oxygen from the air to produce electricity.

GM claims that linking the reformer technology in the vehicle to a fuel-cell stack could result in an overall efficiency gain of up to 40%, a 50% improvement over a conventional internal-combustion engine. With the onboard gasoline reformer, carbon dioxide emissions would be cut by up to 50% - even more if the reformer was placed at the gas station.

According to Larry Burns, Vice President of Research and Development, and Planning, the gasoline can also be reformed at personal residences or businesses. "In most cases you already have natural gas, water, and electricity coming into your home or place of business," he said. "To create hydrogen, all that is missing is a natural gas reformer or an electrolyser. Bottom line, the (fuel-cell) transition will happen faster (than previously thought) because there will be so many competing ways to refuel without replacing the existing infrastructure."

While oil companies, natural gas companies, electric utilities, and other energy providers are in a race to provide the fuel to power viable fuel-cell vehicles, just as OEMs and suppliers are in a race to provide the fuel-cell technology, Burns believes that right now "gasoline remains a very viable alternative, especially given the existing fuel-distribution infrastructure." The end goal, according to GM, is to use whatever combination of feedstocks necessary to produce hydrogen, be it crude oil, natural gas, or renewable forms of energy.

In the mean time, engineers at GM will continue to put the S-10 fuel-cell pickup through a variety of tests to more clearly determine the vehicle's range, efficiency, emissions, and fuel-reforming characteristics. Burns expects GM to put "affordable, profitable fuel-cell vehicles on the road" by the end of the decade.

2.4.5.4 DaimlerChrysler

Chrysler Group – Jeep Commander 2 (methanol fuel reforming fuel-cell concept vehicle) **[*Automotive Engineering*, July 2002]**

Remaining engineering tasks:
“Heat and water management are the two major technical challenges facing the fuel-cell engine. The low operating temperature of the fuel-cell stacks and the limited frontal area of the vehicle create major problems for heat rejection, especially at higher ambient temperatures. Further thermal integration of the fuel processor also is needed to improve overall engine efficiency. Water management includes keeping a positive water balance for the fuel-cell engine and freeze prevention of the de-ionised water used for humidification. The current PEM requires humidified anode and cathode gases for proton transport to produce electrical power. De-ionised water is necessary to prevent a cell-to-cell electrical short circuit inside the stacks. This creates a major challenge when fuel-cell vehicles must be operated or parked in sub-freezing temperatures.
Operating pressure of the fuel-cell stacks varies with power output. At high power output, the system operates at a water surplus, while it runs at a water deficit at low power. Since the fuel-cell stacks operate at about 80°C, maintaining equilibrium water balance depends strongly on operating profile and ambient temperatures.

To be competitive with the internal combustion engine, the fuel reforming system weight needs to be reduced by at least an order of magnitude, along with its cost. DaimlerChrysler’s 5th generation New Electric Car (NECAR 5) shows a major reduction in system volume, but not in its weight. A lighter fuel processing system will have lower thermal mass, resulting in a faster cold start. The cost also must be reduced drastically before fuel-cell vehicles can enter the mass market. Reduced precious metal utilization with innovative manufacturing techniques are critical goals that must be achieved.”

http://www.mercedes-benz.com/e/innovation/fmobil/fuelcell/default.htm

“60 Mercedes-Benz "F-Cell" passenger cars enter practical testing” [Press release, October 7, 2002]

On October 7, 2002, DaimlerChrysler unveiled the Mercedes-Benz "F-Cell" A-Class, the world's first, small-scale series of 60 fuel-cell-powered cars. These cars, which are nearing series-production standard, are no longer one-off research vehicles going under the name of NECAR (New Electric Car), rather they will be tested out in small fleets under everyday conditions by customers in Europe, the U.S., Japan and Singapore as part of state-backed international alliance agreements, starting in 2003. The continued development of this technology will from now on be pursued primarily in day-to-day operation and over the course of extensive field testing. The Mercedes-Benz "F-Cell"

A-Class marks a further milestone in the car industry's ongoing quest to produce emission-free vehicles which are no longer dependent on fossil fuels.
Just eight years on from the world's first ever unveiling of a fuel-cell-powered vehicle, the Mercedes-Benz "NECAR 1" on April 13, 1994, researchers at DaimlerChrysler have succeeded in making the groundbreaking principle of zero-emission fuel-cell technology a feasibility in near-production-standard vehicles, an altogether unprecedented achievement. 20 experimental vehicles have marked the progress of this new form of propulsion for the future as it has been developed.

"30 Mercedes-Benz Citaro urban buses with fuel-cell drive" [Press release, October 7, 2002]

The first of 30 Mercedes-Benz Citaro urban buses with fuel-cell drive also received its first showing on October 7, 2002. These vehicles, which are again being built under conditions nearing series-production standard, are due to be tested out from 2003 by the transport operators in ten cities around Europe where they will be subject to the rigorous demands of regular-service bus operation. This test, which is the first of its kind anywhere, will be conducted under a broad scope of contrasting conditions, with the buses having to prove themselves in the chill Northern winter, the blazing summers of the South, as well as in extremely hilly regions, such as the Stuttgart area.

The participating cities are:

Amsterdam, Netherlands	London, Great Britain
Barcelona, Spain	City of Luxembourg
Madrid, Spain	Porto, Portugal
Hamburg, Germany	Stockholm, Sweden
Stuttgart, Germany	Reykjavik, Iceland

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18. Automotive Engineering International, July 2002: “GM’s driveable fuel-cell lab”
19. Automotive Engineering International, September 2001: “GM fuel-cell-vehicle advances”
20. Automotive Engineering International, July 2002: “Jeep Commander 2: Chrysler Group Engineers provide an inside look at one of the pioneering methanol fuel reforming fuel-cell concept vehicles”
21. “60 Mercedes-Benz "F-Cell" passenger cars enter practical testing”, Mercedes-Benz Press Release, October 7, 2002
22. “30 Mercedes-Benz Citaro urban buses with fuel-cell drive”, Mercedes-Benz Press Release, October 7, 2002, http://www.mercedes-benz.com/e/innovation/fmobil/fuelcell/default.htm

2.5 Patent review

Both US and European patents were looked at, using the following links:

United States Patent and Trademark Office (USPTO):
 http://www1.uspto.gov
Online European Patent Register (Epoline):
 http://register.epoline.org/espacenet/ep/en/srch-reg.htm
Information on IPC classification :
 http://www.wipo.int/classifications/fulltext/new_ipc/index.htm

A patent search can show the focus of manufacturers towards certain technologies. As an example, the research for fuel cells has been looked into.
The following table shows an overview of the main companies working on fuel cells in the past seven years [On-line European Patent Register, dd 10/12/2002]. The data of 2002 do not reflect the entire year.

Table 2.5-1: European fuel cell patents for the main companies between 1995 and 2002

	1995	1996	1997	1998	1999	2000	2001	2002	1995 - 2002
Total n° of European fuel cell patents	109	111	177	172	306	415	565	247	2102
Siemens Aktiengesellshaft (Germany)	8	14	30	7	19	46	51	3	178
Ballard Power Systems (Canada)	9	7	8	15	24	27	36	9	135
Matsushita Electric Industrial (Japan)	0	4	6	4	16	23	21	15	89
Forschungszentrum Jülich (Germany)	4	6	13	8	8	13	28	6	86
International Fuel Cells (U.S.)	4	5	2	15	18	17	3	0	64
Toyota (Japan)	7	2	5	7	19	7	15	2	64
General Motors Corporation (U.S.)	1	1	5	4	6	19	4	2	42
Honda (Japan)	0	5	3	0	3	6	13	7	37
DaimlerChrysler (Germany)	0	0	0	1	5	11	10	7	34
Nissan Motor Co (Japan)	0	0	0	0	0	1	20	9	30
Sulzer Hexis (Switserland)	3	5	2	1	3	2	6	2	24
Johnson Matthey (U.K.)	1	2	4	3	4	2	7	1	24
Proton Energy Systems (U.S.)	0	0	2	5	6	8	1	0	22
OMG (Germany)	0	0	1	1	4	0	10	2	18
Nippon (Japan)	2	1	0	1	1	7	5	0	17
Du Pont de Nemours	8	2	3	0	0	3	1	0	17
Motorola Inc. (U.S.)	0	0	0	1	1	3	7	3	15
Plug Power Inc. (U.S.)	0	0	0	3	3	7	1	0	14
Nuvera Fuel Cells (Italy)	0	2	1	1	3	1	3	1	12
3M Innovative Properties Company (U.S.)	0	0	0	0	3	5	3	1	12
Hydrogenics Corporation (Canada)	0	0	1	0	0	0	6	3	10
Manhattan Scientifics (U.S.)	0	0	0	0	1	2	6	0	9

More detailed search results are given in the Annex.

3 MAJOR TECHNICAL AND ECONOMIC GOALS AND OBSTACLES

By Luc Pelkmans (VITO), Staffan Hultén & Robin Cowan (MERIT)

3.1 Hybrid vehicles

3.1.1 Challenges for hybrid vehicles

Source: IEA-HEV, 2001

The development and introduction of hybrid vehicles brings challenges and problems that have not yet been completely solved. Knowing that 'conventional' vehicles have been optimised for more than a century now, it is of course not surprising that the introduction of a largely different drivetrain technology is confronted with a number of hurdles. Without a solution, the following problems may turn out to be disadvantages:

3.1.1.1 Weight

Hybrid-electric vehicles often comprise more components than do their conventional opponents and this tends to increase the weight of the vehicle. The battery in particular can give rise to significant weight increase. In general, more weight means more energy required to propel a vehicle, reducing the potential energy benefits of hybrids (even if part of this energy may be recovered during braking).

3.1.1.2 Complexity

The complexity of hybrid propulsion systems is partly due to the use of new technology and partly due to integration aspects concerning the energy flows and communication between the various components, governed by the powertrain control algorithm. In the first instance this could have consequences for the reliability and durability, for which extremely high standards have been set by conventional combustion engine technology.

3.1.1.3 Price

Containing more and relatively high-tech components, a hybrid-electric vehicle is probably more expensive to produce than is a conventional vehicle. In the early introduction phase, where production volumes are small, the market price of hybrids will be higher. Tax incentives and other financial stimulation measures may overcome this. In the long run hybrids can only be successful if the commercial price without these financial measures comes down to a reasonable level, where in lifetime costs a slightly higher purchase price may be cancelled out by savings due to lower fuel consumption.

Furthermore, aspects such as the necessity of battery-charging infrastructure or consumer acceptance are of utmost importance when trying to introduce hybrids.

3.1.1.4 Production cost

Hybrid vehicles cost more to manufacture than do conventional vehicles due to higher-cost propulsion systems (used synonymously with “powertrains”). Estimates of additional cost range from $ 2,000 (€2,080 EUR) for a ‘mild’ parallel hybrid to $ 10,000 (€10,400 EUR) for a full- performance series hybrid with substantial electric range. The powertrain in a typical $20,000 car in the US costs about $2,500, or 12.5% of the price.

3.1.1.5 ICE Evolutions

In analysing the chances for a successful introduction of hybrid vehicles it is important to have a clear view of the development potential of ‘conventional’ vehicles. ICE developments of the last decades have shown considerable improvements in fuel economy and emissions, thanks to the application of new engine concepts, enhanced motor management systems, improved fuel injection systems and enhanced catalysts. These developments are still in progress and it is to be expected that ICE developments will be able to lower the fuel consumption and emissions of conventional engines considerably with respect to the current levels. In order to be a viable solution the fuel economy and emission levels of hybrid vehicles should not only be better than those of current ICE vehicles, but should also outclass those of future ICE vehicles. Exhaust gas emission legislation will become stricter in the next five years, and if vehicle manufacturers manage to cope with such limits by only improving already existing technologies, their solutions could be cheaper and less risky than developing and introducing new hybrid technology.

3.1.1.6 Fuel Cells

The same observation, by the way, can be made with respect to other new propulsion technologies that are being developed. These have to compete with the improved conventional technology of the future and with each other. Fuel-cell technology is developing rapidly. Small-series pilot production is expected for 2004. Hybrid vehicles may serve as an intermediate technology, introducing electric propulsion into the powertrain, and thus paving the way for fuel cells. Fuel cells, when introduced sufficiently quickly, could even render the introduction of hybrids obsolete. From the other point of view, a successful introduction of hybrids in the coming years could postpone the necessity for fuel-cell vehicles.

Table 3.1-1: Alternative fuels for HEVs (Use in Hybrid Electric Vehicles versus Use in Conventional Vehicles)

+ means fuel has a relatively higher ranking when used in HEVs
- means fuel has a relatively lower ranking when used in HEVs
= means no change in ranking when fuel is used in HEVs

		DISI Engines					CIDI Engines			
Fuel Parameter	Vehicle Parameter Affected	Methanol	Ethanol	CNG	LNG	LPG	Low-Sulfur Diesel	Fischer-Tropsch	Biodiesel	Dimethyl Ether
Composition	Engine Emissions	=	=	=	=	=	=	=	=	=
Source	Energy Security	=	=	=	=	=	=	=	=	=
Energy Density	Payload Volume	-	-	-	-	-	=	=	=	-
Specific Energy	Payload Weight	-	-	-	-	-	=	=	=	-
Vapor Pressure	Payload Weight	=	=	-	-	-	=	=	=	=
Gas-eous State	Maximum Power	NA	NA	+	+	+	NA	NA	NA	NA
Fuel + Tank Volume and Weight	Range	-	-	-	-	-	=	=	=	-
Ease of Cold Start	Operability	-	-	+	+	+	=	=	=	+
Latent Heat of Vaporization	Engine Performance	-	-	NA	NA	NA	=	=	=	=
Octane or Cetane Number	Engine Performance	=	=	=	=	=	=	+	=	+
Overall Sum	**All**	-	-	-	-	-	=	=	=	=

Note: The base fuel for all comparisons is federal reformulated gasoline for DISI engines and California reformulated diesel for CIDI engines.

3.1.2 References

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3.2 Fuel-cell vehicles

3.2.1 Introduction

Source: Rovera, 2001
The automotive Industry is pursuing a huge R&D effort aimed at developing an alternative to the traditional internal combustion engines by exploiting the fuel-cell technology.
In the simplest form, the fuel-cell engine uses hydrogen as fuel. An electrochemical cell combines hydrogen and oxygen from the air to produce electricity and heat, emitting only water vapour. The electric power is than used to supply an electric power-train.
The high efficiency of the energy conversion taking place in the FC and the absence of noxious or environmentally dangerous emissions make this solution very attractive today.
In addition, the need for alternative energy sources, in view of the progressive depletion of natural hydrocarbons, could favour the use of hydrogen as energy carrier of the future.

Many significant results have already been achieved by OEMs, suppliers and research laboratories: running prototypes of FC vehicles are now demonstrated on the road. The California Fuel Cell Partnership promotes the demonstration of FC and hydrogen-fuelled ICE vehicles on real operating conditions; such program includes the use of different fuels (compressed and liquid hydrogen, methanol and reformulated gasoline) with related refuelling infrastructures.

These successes do not minimize structural obstacles to the diffusion of the FC engine technology. The choice of the fuel with reference to various primary energy sources, the development of new infrastructures required to produce and distribute the new fuels, the learning time of the new FC technologies (fuel storage, on-board reforming, membrane electrodes assembly, etc.) including the definition of new standards related to safety and to other relevant homologation issues, the engineering optimisation (reduction of volume and weight, efficient auxiliaries), cost reduction, all require a long development time-frame (15-25 years). In the mean time demonstration programs are expected to be followed by the growth of niche markets, mainly supported by public administrations sensitive to environmental issues where motivations could help in overcoming the economic and infrastructure obstacles above mentioned.

Hydrogen fuel cells offer in effect the highest benefits in terms of efficiency and emissions, but the production and distribution of hydrogen, its safe on-board storage imply problems that require a vast amount of R&D investments to achieve a reliable engineering level and the costs sustainable by the private automotive mass market.

The on-board reforming of hydrocarbon fuels appears very attractive in terms of facilitating the infrastructure problems, but on the other side it will also add costs to the vehicle. Moreover the overall efficiency (well to wheel) is decreased so much with respect to the hydrogen FC engine to become comparable to the level of the ICE adopting advanced technologies. The amount of CO_2 emitted by the reformer-FC vehicle would therefore be equivalent to the ICE one. The lower level of NO_x ,still promised by FC with reformer, may not be a barrier to future ICE's. Combining new exhaust treatment technologies with fuel reformulation, similar emission levels could be achieved by thermal engines.

Considering the overall picture, it is not surprising if market and cost forecasts do not show in the medium term any real challenge of fuel-cell to ICE powertrains; in the longer term the changes in availability of primary energy resources may however favour the adoption of fuel cell in transportation means.
In the meantime a successful application of fuel cells is expected in other industrial fields such as stationary and residential electric generation, portable electronics supply, auxiliary power units.
Costs and technology improvements of the ICE constitute nevertheless a serious barrier to the final success of the fuel cell engine in transportation.

The early FCV market introduction targets tentatively announced over the past few years by several automakers appear unlikely to be met, primarily because of on-board technology challenges. Although there are still significant challenges in fuel-cell cost, systems integration, and controls, the principal technical obstacle appears to be the development of practical and cost-effective on-board reformers (i.e. for liquid fuels) to produce the hydrogen required by the fuel cell. This is due not only to the inherent technical complexity of the reforming processes but also to the unique challenges of the on-board environment. This holds for all liquid fuels, although methanol reforming is inherently less technically demanding and may be more advanced in its development to date. Reforming of conventional gasoline appears to be somewhat more difficult, although its proponents claim a high degree of R&D success. But for all on-board fuel reformers, major challenges of economic feasibility remain even after technical success is achieved.

3.2.2 Mobile versus stationary fuel-cell applications

Source: UBA, 2000
Fuel cells offer advantages over other methods of generating electricity since they have a high degree of efficiency, low emissions across the entire fuel cycle and can generate electrical and thermal energy at the same time. But there are major differences between mobile and stationary fuel cell applications. From an environmental viewpoint we therefore need to address fuel cells in different ways depending on their uses and the required power outputs, considering at the same time the differing state of progress in research and development.

Table 3.2-1: Differences between mobile and stationary fuel-cell applications

Fuel cells in motor vehicles	Fuel cells in stationary applications
requirements for dynamic operation and load shifts	stationary operation with high electrical efficiency
optimised solely for electrical efficiency (h 25-40 %)	optimised for cogeneration of power and heat (also cooling in the summer months; h >85 %)
numerous additional hardware components (catalytic burner, reformer, compressor, electric motor, battery, etc.)	compact and flexible design drawing on mains fuels available close to the point of consumption (e.g. natural gas)
heavier by design than competitors with internal combustion engines (conflicting objectives: consumption vs. weight)	weight is immaterial in stationary applications
production of new fuels for road traffic applications (methanol, hydrogen)	can use fossil fuels (e.g. natural gas) and existing supply systems
rolling noise is dominant from 40-50 km/h upwards, therefore noise emissions are not reduced invariably	low noise compared with existing cogeneration plants based on internal combustion units

Source: UBA, 2000

It makes sense even today to use fuel cells in stationary power supply operations, e.g. in cogeneration plants. In some areas fuel cells can convert fossil fuels, such as natural gas, into electricity much more efficiently than conventional power stations and heating plants.

But the use of fuel-cell technology for road vehicles is quite a different matter. Fuel-cell vehicles depend on hydrogen or methanol, which must first be produced in a relatively energy-intensive process from fossil or non-fossil primary fuels. If we assume fuel-cell vehicles are to be introduced around 2005, the technical input and the costs it implies mean only rather small proportions of these fuels are likely to be produced from renewable sources (e.g. solar electrolysis, hydrogen from biomass).

Even if electric power for hydrogen electrolysis were generated entirely from renewable sources, the amount required to produce and process the hydrogen is at least double that needed to produce gasoline from crude oil. This is the ratio of the electric power (e.g. solar) required to synthesise hydrogen compared with the primary fuel consumption entailed in refining and processing gasoline from crude oil. At the same time, electricity from renewable sources could be used directly, therefore much more efficiently, and thus replace fossil fuels in power generation plants.

The high losses incurred in synthesising and processing hydrogen mean that, on present evidence, it does not represent an environmentally viable option. Even the idea of synthesizing methanol from natural gas - with high calorific losses - cannot be recommended, since the natural gas could be used to fuel vehicles with low-emission internal combustion engines (ICEs). Moreover, the benefits of lower carbon dioxide emissions are attributable almost entirely to the use of low-carbon natural gas and not the engine type. Internal combustion engines, too, can take advantage of this.

Fuel-cell technology will only yield environmental benefits if vehicles are efficient enough to make up for the calorific losses incurred in producing the fuel. In other words, a fuel cell must be at least 30% to 35% more efficient than an engine powered by gasoline or natural gas if high primary fuel inputs are to be avoided. It is anything but a foregone conclusion that this target can be achieved by comparison with advanced internal combustion engines, since the hypothetical objectives for the next millennium call for fuel cell units with a consumption of 20% or, at most, 25% below that of diesel engines.

3.2.3 Fuel-Cell Vehicle Challenges and Solutions

Source: Knight, 2001

Timely and effective fuel reforming technology development may be the most difficult challenge to early FCV commercialisation. Many criteria must be met, from reliability, durability, and efficiency to feasibility of manufacture, safety, cost, and quality. To bring FCVs to market as early as possible, this challenge must be met successfully within the same timeframe as cost-effective fuel cells and related infrastructure.
This is especially so for the on-board reforming of liquid fuels: gasoline, ethanol and methanol. Not all fuels are equally easily reformed, and their reformers are at varying stages of development. Competitive off-board reforming of natural gas and liquid-fuel hydrogen carriers also face substantial challenges.

3.2.3.1 Similarities and Differences In Commercialisation Pathways Among Fuels

Some of the most difficult challenges to commercialisation are common to all FCVs and require similar solutions.

These key challenges include proving and building of consensus on the long-term societal value of FCVs, resolution of infrastructure costs, the development of practical fuel conversion and cleanup technologies, and the assembly of all the factors needed for successful market development. Proposed pathways to solution of each of these specific challenges are provided in this study.
Although some of the most critical challenges to commercialisation are common to all FCV fuel types, there are also other major differences in barriers and solution pathways among the different fuel choices considered here. Specific technological needs and overall infrastructure cost differences create quite different business cases, leading in turn to differences in the levels and nature of governmental involvement that may be required to accelerate commercialisation. Differences in apparent societal benefits among the FCV fuel types appear to parallel some of these differences in technological and cost obstacles; that is, higher benefits seem to go with higher costs and risks.

3.2.3.2 The Hydrogen Trade-off

One major difference among fuels, as highlighted in this study, is seen in the early infrastructure cost. This cost is much higher for gaseous hydrogen than for any of the liquid FCV fuels. While this difference is easily interpreted as a major disadvantage of the hydrogen alternative, a more realistic interpretation must include the offsetting costs of the on-board fuel reformers required by the liquid fuels as well as their developmental uncertainties. These reformer costs are also expected to differ among the liquid fuels. In addition, hydrogen may offer greater long-term societal benefits.

In effect, the hydrogen option moves the fuel processing off the vehicle and into the fuelling station, thereby shifting but not eliminating the fuel processing costs: The hydrogen infrastructure costs more, but the hydrogen FCV is likely to cost less than its liquid-fuelled FCV competitors. Which cost dominates? An analysis of comparative costs for this essential step may show hydrogen to be competitive with some of the liquid fuels. Collaborations between automakers and fuel providers may be required to properly treat those cost shifts.

3.2.3.3 Key Challenges and Solutions for the Hydrogen Fuel-Cell Vehicle

The on-board hydrogen-carrying FCV carries substantial advantages, notably in its generally superior long-term environmental performance, mechanical simplicity, and lighter weight. It also faces a variety of unique challenges in cost, on-board fuel storage, fuel supply, perceived safety, and regulatory challenges. The most critical challenges include the following:

- Present development trends in both central hydrogen production systems and local station-site production alternatives such as electrolysis and steam reforming **will need improved technology** to produce hydrogen at the assumed costs during this decade. A pressing need is a low cost fuel compressor/storage system built on a large scale. A related need is for a low-cost packaged hydrogen generation system. These should be in place before FCV market introduction, requiring an early start even under the most optimistic development and deployment scenarios.
- Meanwhile a variety of **less economical hydrogen fuel supply methods will be used** while vehicle volumes are relatively low. Almost all hydrogen is currently made by reforming natural gas at large central plants. This hydrogen can be compressed and stored in tube trailers (a costly option suitable only for introductory use) for delivery to the fuelling site, or liquefied and delivered by cryogenic tanker truck. Other and more promising solutions include station-site hydrogen production via electrolysis of water or reforming of natural gas with existing technologies such as small scale partial oxidation or autothermal reforming.
- During this transitional period of the first several years, fuel sales will be in low volumes so costs per vehicle and station will be high. **Mechanisms for infrastructure and/or fuel price writedowns** will be needed for hydrogen, and will almost certainly require at least short-term incentives and regulatory support.
- The **superior long-term environmental advantages of hydrogen** will help to justify substantial government incentives and related regulatory support for such interim supplier and consumer cost writedowns. Those temporary writedowns will be needed, since the higher short term operating costs will serve as a disincentive for investors to provide fuel without risk reductions such as contractual arrangements with the government or vehicle manufacturers.
- Pressurised **hydrogen refuelling technology** has already been shown to be practical and safe. Present industry efforts to standardize fuelling connectors improve user convenience are expected to continue and will meet this need in time without higher-priority support. But there must be an extensive education effort to reassure the public of hydrogen's safety.
- **A combined energy station concept shows promise** for reducing hydrogen fuelling costs, merging stationary electric power needs with FCV hydrogen demand through combining a stationary fuel cell with hydrogen production through reformer

or electrolysis at potential refuelling sites including conventional fuelling stations, homes, places of work and shopping centres. Site-specific economic analyses are needed as well as further development, downsizing, and cost reductions in fuel cell and hydrogen-generation technology.

- **On-board hydrogen fuel storage** initially will most likely be in the form of high-pressure gas rather than cryogenic liquid or hydrides for the early demonstration vehicles. Automotive designers will need to reconsider vehicle configurations to provide space for adequate hydrogen storage. Carbon-wrapped tanks will reduce both storage volume and weight but work must continue to improve their economics and safety assurance. Furthermore, because of pressurised hydrogen's inherent fuel storage volume disadvantage, early hydrogen vehicle makers will need either to accept somewhat lower range (although well beyond EV limits) or aggressive vehicle weight reductions to get fully competitive range.
- Efforts must begin well before a pilot phase to **educate local permitting officials** in the realities of hydrogen handling and delivery for vehicular use. Focusing first on the pilot test areas, substantial evidence of success must be shown in time to help induce automakers to move ahead into that demonstration phase.

3.2.3.4 Key Challenges and Solutions for the Methanol Fuel-Cell Vehicle

Assuming the successful and timely development of a cost-effective on-board methanol reformer, there are several other crucial challenges to be addressed, ranging from fuel price and taxation practices to refuelling infrastructure investment risks and toxicity concerns.

- The crucial concern for the methanol FCV is the timely development of a market-ready **on-board reformer**. This reformer technology appears to be advancing quickly but must be on a clear path to economic viability before the decision can be made to begin low-volume commercial production.
- The delivered price of fuel cell grade **methanol can be competitive**. This assumes production from remote natural gas with sea, rail, and truck delivery to refuelling sites. These delivery mechanisms are already available, with direct California experience for the M85 alternative fuel vehicle program of a decade ago. However, this conclusion is highly sensitive to changes in assumptions such as methanol feedstock competition.
- **Refuelling infrastructure investment** is much smaller for methanol than hydrogen, but its financial risk is still a significant deterrent, particularly in view of the possibility of later breakthroughs in gasoline-type reformers for FCVs. As in the case of hydrogen, it will be necessary to develop government incentives and possibly form consortia of investors to share that financial risk.
- **Methanol toxicity and groundwater effects are potentially delaying challenges** despite indications that these risks are manageable. Some conventional fuel providers and regulators are concerned about liabilities that might arise from dispensing methanol, both with regard to groundwater contamination and direct human ingestion. Clarifying studies of these issues as well as of refuelling safeguards now under development are needed soon. Public education on the actual likelihood and results of accidents should also begin well before actual market introduction.

- **Direct methanol fuel cells** are in development, and would simplify fuel cell vehicle technology by eliminating the separate on-board reformer as well as complexities such as compressed hydrogen storage. Advantages could include reduced FCV cost and improved reliability as well as reduced overall size. However, most observers agree that although this technology may emerge soon in stationary or portable power products, it is not widely expected to appear in market-ready vehicles until near or after the end of this decade. Early FCV commercialisation efforts should proceed with reformer-based technology rather than delaying commercialisation to await DMFCs.

3.2.3.5 Challenges and Solutions for the Gasoline and Naphtha Fuel-Cell Vehicles

The successful commercialisation of gasoline-type fuels in fuel cell vehicles will depend almost entirely on the development of a practical on-board gasoline reformer. Although its formal evaluation is beyond this study's scope, the concerns of many industry observers must be acknowledged regarding the unique difficulties faced in gasoline reformer development. This may necessitate the use of direct hydrogen or other fuel for the initial pilot phase vehicles and a later transition to gasoline. Other key challenges that must be resolved include the following:

- If gasoline is used, essentially **no special infrastructure investments** will be required unless sulphur contamination of fuel proves to be a serious problem. There would be no severe onsite fuel storage and dispensing challenges. However, it will be essential to improve conventional levels of quality control in avoiding contamination of the fuel in transit. Alternatively, onsite fuel cleanup devices or full-scale onsite gasoline reformers, hydrogen cleanup, storage, and dispensing facilities for hydrogen FCVs could be considered.
- **If naphtha or other FCV-only alternatives are necessary, they may also have benefits** of being easier to reform as well as more fire-safe. Their expected lower RVP and evaporative emissions in turn may help qualify the fuel for a partial ZEV low fuel cycle emission score similar to the methanol FCV fuel option, a significant benefit under projected California ZEV regulations although still not a full ZEV rating as hydrogen will receive.
- Naphtha or other FCV-only gasoline substitutes would require **infrastructure investments similar to those of methanol FCVs.** New or separate gasoline tanks and pumps would be required at the local fuelling station, in addition to some refinery and delivery modifications.

3.2.3.6 Challenges and Solutions for the Ethanol Fuel-Cell Vehicle

The primary challenges to ethanol FCVs are the projected national availability of feedstocks and the cost of the fuel. These relegate ethanol to a limited role as an element of a dual-fuel ethanol/gasoline strategy. In this approach ethanol would be unused at any stations unless gasoline prices rise substantially. This, however, may be a practical approach to assuring future fuel flexibility that could be needed unexpectedly for either economic or environmental reasons. Its use requires only the adaptation of gasoline reformer technology and fuel delivery equipment to accept ethanol, at little or no incremental cost.

A significant technical challenge is the lack of an acceptable multi-fuel on-board reformer. Ethanol requires technology similar to (and simpler than) that needed for gasoline and can even use essentially the same reformer. Gasoline-type reformer development and commercialisation within this decade are still in doubt among industry experts.. All other challenges to ethanol commercialisation are similar to those for naphtha. Key challenges to ethanol include the following:

- **The high cost of ethanol** is the principal challenge, due to the inherent process inefficiencies and transportation distances involved as well as competition for the available supply.
- **Inadequate US ethanol supply is likely** for later and more widespread FCV use. Ethanol could still be used in fuel cell vehicles with a dual fuel strategy in concert with gasoline or naphtha. Competing high-value ethanol used as a gasoline blending component and MTBE replacement will increase already-serious fuel price pressures and make a dedicated ethanol vehicle and infrastructure a high risk proposition. The California economy may benefit from an ethanol infrastructure's development in the State to augment or replace Midwest and foreign imports, but its production up to California's maximum feasible feedstock supply with currently envisioned technology would be totally consumed by high-value gasoline oxygenation use under recent Federal directives.
- **Potential ethanol health and safety difficulties** requiring early resolution include potential groundwater BTX contamination, flame invisibility, and reformer fouling due to additives that may be needed to deal with other safety concerns. Early clarifying studies and refinement of standards are required.
- **The economic and environmental implications** of various ethanol fuel source pathways need to be studied in more detail, ranging from early out-of-State corn-based production and shipment to later use of California forest and agricultural wastes. Near-term biomass use may have valuable net positive environmental impacts.

3.2.4 Fuel Processors

Source: NAVC, 2000

The main challenges for on-board fuel processors include size, weight, cost, efficiency, start-up time and ability to respond to transient loads. Additional concerns include maintenance issues of the on-board fuel processors and impurities that arise from onboard reformation that can poison fuel cell catalysts, such as CO and sulphur.

Most methanol processors utilise the steam reformation process and have less complexity than gasoline processors since methanol can be reformed at lower temperatures.

However, the endothermic nature of steam reformation requires up to 30 minutes before reaching reformation temperatures. The methanol processor is considered further along than gasoline processors, with a number of prototype vehicles released. For example, Daimler-Benz's NECAR 3 utilises a methanol processor with a PEM fuel cell and has been able to respond to transient loads. Other companies with methanol demonstration vehicles include GM, Toyota and Nissan.

Gasoline processors tend to utilise partial oxidation and auto-thermal reforming. Due to the exothermic nature of the reformation process, the processor can essentially be used for any type of hydrocarbon. Start-up time is less of an issue with these processors.
However, the high temperatures mean that the gasoline fuel processor needs to be designed to be heat resistant, often making them bulkier and heavier than methanol processors.

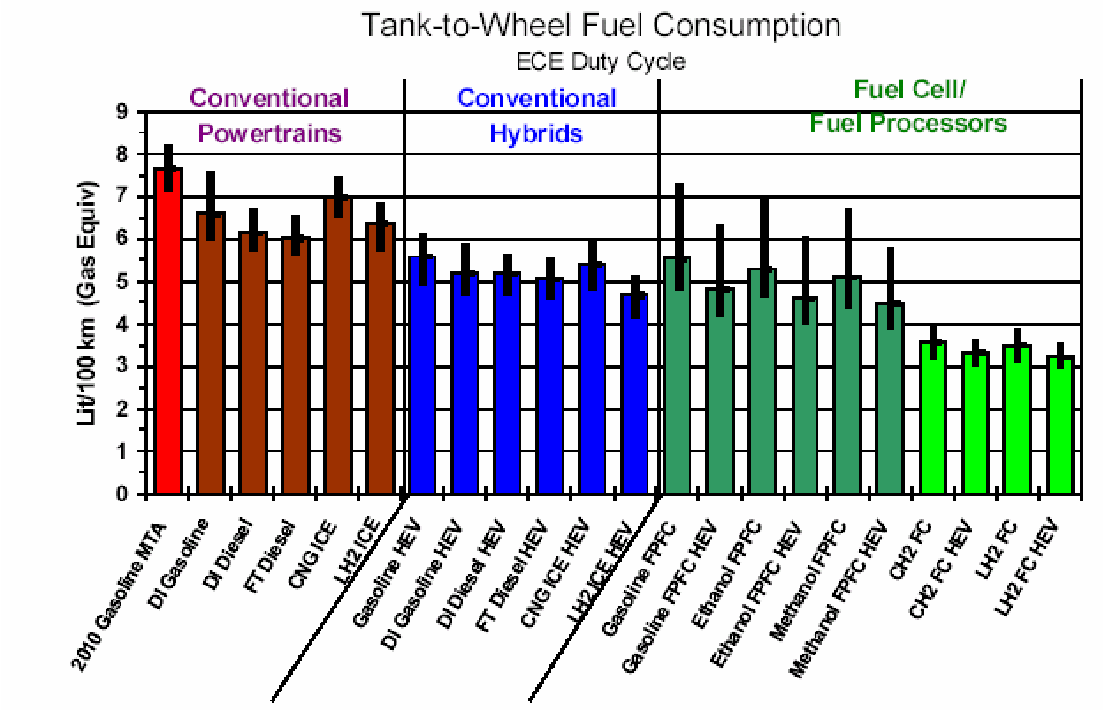
3.2.5 Fuel-Cell Efficiency

Source: NAVC, 2000
In considering the relative efficiency and emissions associated with fuel cells, it is necessary to consider the entire system. Consumers can gage fuel efficiency from in-use operation, but what is not considered by the average consumer is the amount of energy that was expended and emissions generated in delivering the fuel to the vehicle as not all emissions are reflected in the cost of the fuel. For example, a direct hydrogen fuel cell vehicle appears to be a highly efficient, zero emission vehicle because the only tailpipe by-product is water, when in reality appreciable energy could be expended and emissions may have been generated during production of the hydrogen fuel. All of this must be incorporated in a well-to-wheels analysis to arrive at the true emissions and fuel economy related to a particular fuel choice.

3.2.5.1 Vehicle efficiency (tank-to-wheel)

Fuel cells are more efficient than internal combustion engines because they operate at lower temperatures and waste less energy as heat. Current technology efficiencies of an internal combustion engine includes losses of more than 80% of the fuel energy, mostly as waste heat (either as thermal radiation via the cooling system or through the vehicle exhaust), whereas for a hydrogen fuel cell the energy loss is much lower, around 50%. Of course if a reformer is added to the vehicle to convert a liquid fuel into hydrogen, the losses of this reformer have serious impact on vehicle fuel consumption.

Figure 3.2-1: Tank-to-wheel fuel consumption of different alternatives



Source: GM, 2002

Source: GM, 2002

compares fuel consumption for vehicles with conventional powertrains, hybrid vehicles and various fuel cell vehicles. It is clear that hybrid vehicles have big potential for fuel consumption reduction, even hybridisation of fuel-cell powertrains has a significant impact. As expected, the fuel-cell vehicles directly fuelled with hydrogen are most fuel efficient. There comes, however, the matter of energy losses involved with off-board hydrogen production.

3.2.5.2 Overall energy efficiency (well-to-wheel)

There are several processes that influence the overall energy efficiency of a fuel-cell vehicle. Basically the energy losses are divided into well-to-tank losses and tank-to-wheel energy losses.

The well-to-tank losses are related to:

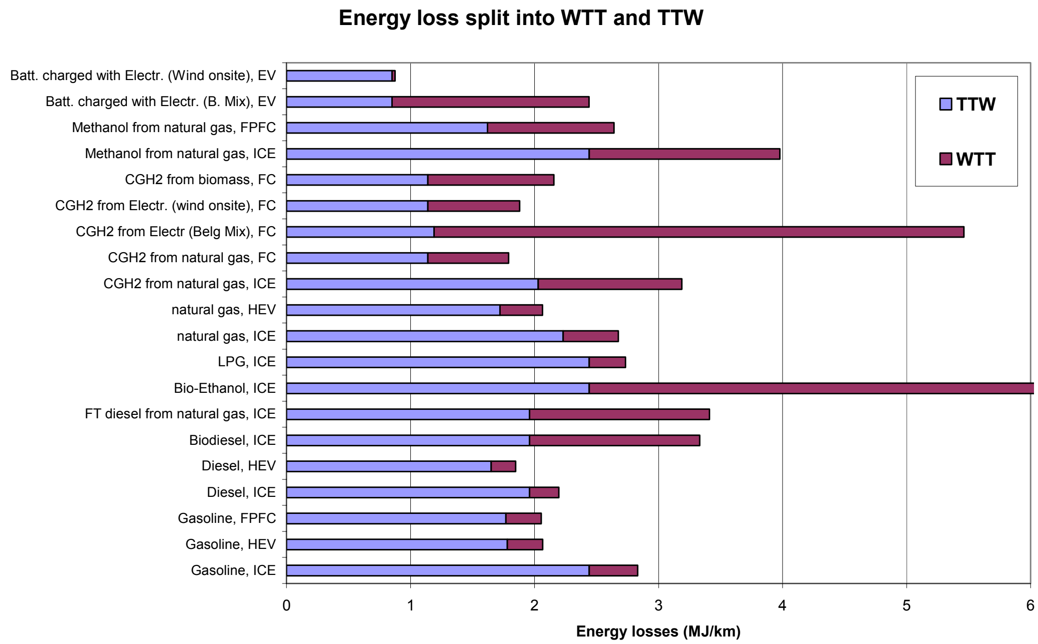
- Feedstock recovery
- Transportation of feedstock
- Fuel production
- Fuel distribution
- Fuel storage and handling (liquefaction or compression).

The tank-to-wheel losses are related to:

- On-board fuel reformation
- Fuel cell efficiency
- Powering auxiliaries (compressors, etc.)
- Transmission losses.

The following figure gives an overview of the well-to-wheel losses of different alternatives.

Figure 3.2-2: Well-to-wheel energy use of different alternatives



Source: GM, 2002

Some noticeable effects:
- Hybridisation gives a major improvement in energy efficiency for gasoline and diesel vehicles
- Biofuels, FT fuels or electricity (net) based fuels generally cause high WTT energy losses
- The way hydrogen is produced for fuel-cell vehicles has a major impact on total energy efficiency
- Fuel-cell vehicles generally have a better TTW efficiency than do ICE vehicles or even hybrid vehicles. They seem to lose that advantage in the WTT part (fuel production and distribution)
- Only the electric vehicle, with batteries charged from a local wind power station achieves a major reduction of energy losses compared to hybrid diesel technology. The high price and low energy potential of wind power, however, will prevent this technology from general introduction. Also, the low driving range and long recharging time are disadvantageous for battery electric vehicles.

3.2.5.3 Gasoline versus direct hydrogen

When using gasoline as a baseline fuel for fuel-cell vehicles, well-to-tank losses are considerably lower than direct hydrogen use. It is important to bear in mind, however, that direct hydrogen is the most efficient fuel that can be used in a fuel cell. Whereas gasoline still must go through a reformer which uses energy to convert the hydrocarbon fuel into hydrogen and the gas produced is not 100% hydrogen, reduces the fuel-cell stack efficiency. Also note that while the production efficiencies of gasoline and diesel are low, these efficiencies do not reflect the losses potentially associated with purifying the fuel to fuel-cell quality.

The last significant energy loss in a fuel-cell system is in the fuel-cell stack itself. To minimize CO_2 build-up in the stack (when using a reformer), and to avoid starving any of the cells in the stack, essentially too much hydrogen must be fed to the fuel cell, resulting in some pass-through of hydrogen, and therefore unused energy, into the exit gas stream. Also, energy must be expended to overcome the resistance to electrochemical changes at the electrodes, which shows up as heat loss. In addition, the fuel cell is most efficient at steady-state, and less so when either maximum or minimum power is required. Ideally, to maximise the potential of a fuel cell, its operating range should be fairly narrow. This will likely mean that some type of load levelling device must be used, such as a battery leading to further losses in the system.

3.2.5.4 Hybrid fuel-cell vehicles

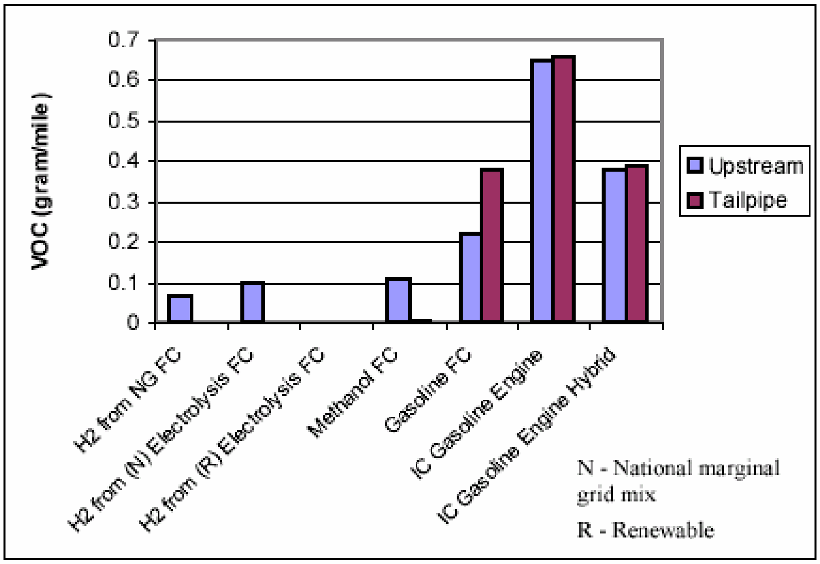
A solution for minimising the fuel-cell system losses due to reformers and the stack itself, especially during varying load operation, is to couple the fuel cell with a hybrid-electric drivetrain. The main advantage of a hybrid fuel-cell vehicle is the ability to recapture regenerative braking energy that can be used later to supplement the fuel cell. In supplementing the fuel cell with regenerative braking energy, the fuel cell can operate at near constant, or minimally varying power loads, thereby maximizing its efficiency.
However, this load levelling device option needs to be weighed against the impact it has on vehicle weight and efficiency.

3.2.6 Fuel-Cell Emissions

In its most simple configuration, a fuel cell produces electrical energy, water and heat using fuel (hydrogen) and oxygen in the air. It is the promise of high efficiency and zero emissions potential that has fuelled research and development into making fuel-cell vehicles viable for the mass market, especially since EPA estimates that motor vehicles in the USA account for 78% of all carbon monoxide (CO) emissions, 45% of nitrogen oxides (NO_x) emissions, and 37% of volatile organic compounds (VOC) nationwide [NAVC, 2000]. While direct hydrogen fuel cells are classified as zero emission vehicles, this is zero localised (or tailpipe) emissions and does not include emissions produced during hydrogen fuel production off-board. All fuel reformers, whether off-board or on-board, generate emissions. Therefore, like efficiency, emissions need to be viewed from a lifecycle standpoint — well to wheels.

The following figures look at both upstream emissions and vehicle emissions. As illustrated, criteria pollutants are dramatically reduced for fuel-cell powered vehicles, with the exception of fossil fuel electrolysis and to some extent gasoline reformed fuel cells. Hydrogen production from electrolysis is penalised for relying on electricity generation, resulting in potentially large NO_x emissions depending upon how the electricity is produced.

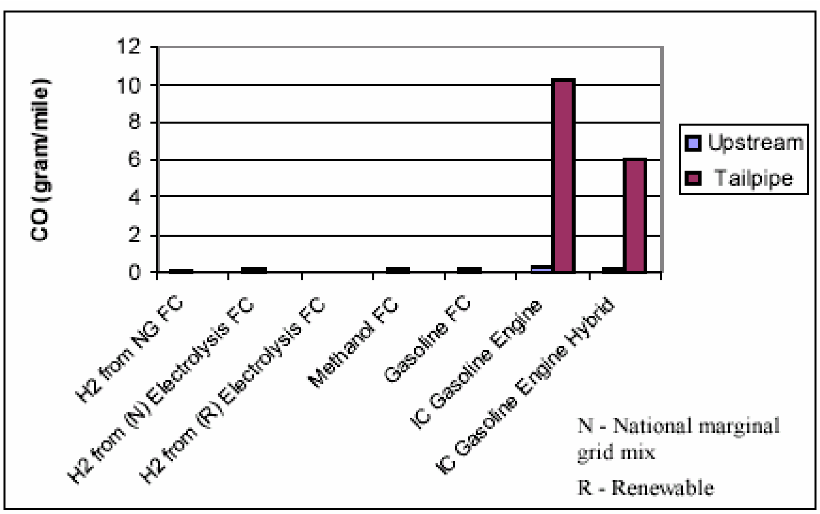
Figure 3.2-3: VOC emissions



Sources: Thomas et al., 1998 and Stodolsky et al., 1999.

From: NAVC, 2000

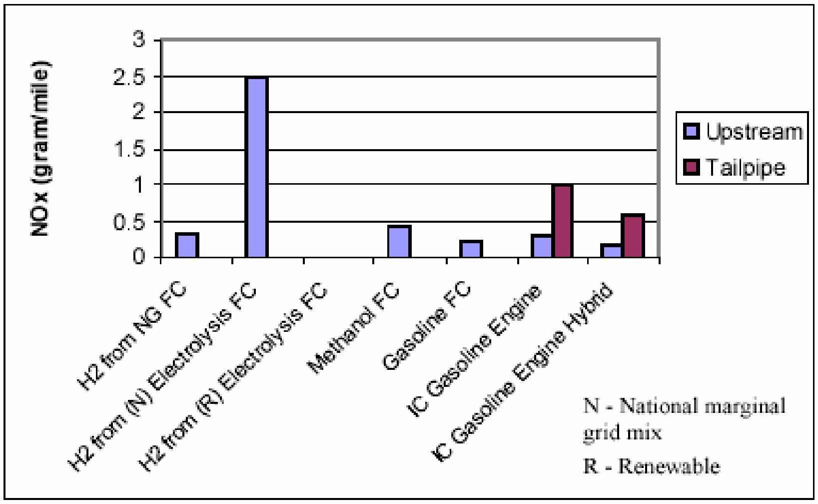
Figure 3.2-4: CO emissions



Sources: Thomas et al., 1998 and Stodolsky et al., 1999.

From: NAVC, 2000

Figure 3.2-5: NO_x emissions

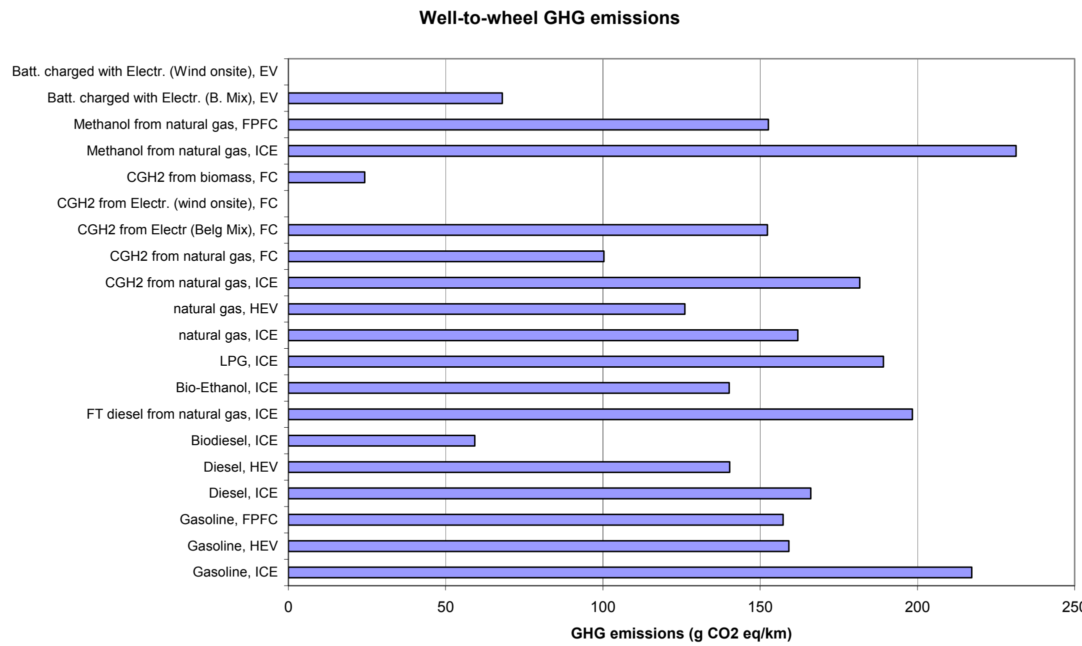


Sources: Thomas et al., 1998 and Stodolsky et al., 1999.

From: NAVC, 2000

Considering well-to-wheel emissions of greenhouse gases (CO_2, N_2O, CH_4), it is mainly the energy from renewable fuels that is best. In the case of the carbon-containing fuels derived from biomass, the GHG emissions are negative after fuel supply because CO_2 is removed from the atmosphere during the growth of the plants and the carbon is bound in the delivered fuel. During vehicle operation, the carbon bound in the fuel is emitted as CO_2 and the GHG emissions become positive (depending how much fossil fuel is needed for processing and transporting the fuel).

Figure 3.2-6: GHG (greenhouse gas) emissions



Source: GM, 2002

Fuel-cell vehicles offer the potential to greatly reduce well-to-wheel GHG emissions when fuelled with renewable fuels in general. An elimination of well-to-wheel GHG emissions can be achieved when FC vehicles are fuelled with hydrogen provided by wind or solar energy.

Concerning energy use of GHG emissions, gas-to-liquid pathways (e.g. FT diesel) and methanol do not show any real benefit over diesel powertrains or gasoline FPFC powertrains.

3.2.7 Conclusion

There is currently much research being done on fuel cells and a number of challenges are still to be met in order for these to become competitive [CTIP, 2002], [US DOE, 2000]:

- The costs of producing the fuel cell stacks need to be reduced
- Breakthroughs in storage technology would have a large impact in accelerating the acceptance and commercialisation of fuel cell vehicles
- The size and weight of all components of the fuel-cell power system have to be reduced in order to improve overall fuel efficiency
- Fuel cells need to be able to start faster and respond better to rapid changes in power requirements.
- Durability and reliability in extreme operating conditions must be increased.
- The processing systems that convert hydrocarbon fuels (such as gasoline) into hydrogen for the fuel cell need to be improved

- Experience needs to be gained of operating, fuelling, maintaining and repairing a sufficient fleet of buses operated over a sufficiently long period of time to allow thorough de-bugging of the drive-line technology and for setting standards and guidelines for updating its design
- Public awareness of and support for the new technology needs to be obtained
- Hydrogen-specific regulations must be introduced addressing safety
- Hydrogen infrastructure needs to be established.

Finally, the main advantages of the fuel-cell vehicle will have to be carefully assessed in comparison to the alternatives: other systems, too, show significant improvements over conventional systems with regard to emission reductions. Regenerative hydrogen can also be used in internal combustion engines. Furthermore, it must be determined when, to what extent, and at which costs regenerative hydrogen can be made available for use in fuel cell vehicles.

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3.3 Technical and economic goals and obstacles: Some suggestions for a framework

By Robin Cowan and Staffan Hultén (MERIT)

3.3.1 Introduction

This chapter will address technical and economic goals and obstacles of more fuel efficient and low emission vehicles. Our framework is based on a discussion of the relative attractiveness of electric vehicles or hybrid vehicles compared with gasoline and diesel cars.
We will look at the importance of three types of factors for creating a virtual circle of increasing demand, supply and technological development of electric and hybrid vehicles. These factors are:

1. Demand-side factors, for example a) changes in taste,
   b) creation of market niches, and
   c) learning by using.
2. Supply-side factors, for example a) a crisis in the existing technology,
   b) dedicated R&D, and
   c) learning by doing and economies of scale.
3. The environment of the industry, for example a) regulation, and
   b) scientific results.

In the 1970s, many projections of the penetration of the electric vehicle in the automobile market were made. The predictions concerned the proportion of the 1995 automobile market that would be held by the electric vehicle. They ranged from a low of 0.3% of the market to a high of 100%, with an average of 6.7%, which was thought would amount to 3.16 million cars (Estimates made or commissioned by Exxon and Gulf Oil were 5% and 25% respectively). A standard assumption made in many of the predictions was that the storage capacity of batteries would increase and that the costs of storing energy in batteries would fall, and that fuel cells would appear on the market. Nonetheless, projections made in 1995 for the year 2005 were even more optimistic and projections by for example Daimler-Chrysler in 1999 and PSA Peugeot-Citroën in 2001 for the launch of fuel-cell cars suggest a breakthrough of these cars within five to 15 years.

3.3.2 Theoretical discussion

Recent literature in economics, particularly in the economics of technology, has emphasised the importance of path dependence in the economy. The focus has been on the way in which trajectories get reinforced simply by agents pursuing their own self-interest. The aspect of path dependence that has been emphasised is the tendency of a path dependent system to stick to its path, and the difficulty it has in moving to a new path or trajectory. As a particular technology system or regime is developed and matures, it becomes entrenched, and the costs of switching to a different trajectory, even if a better one, become greater and greater. The analytical work in this tradition, and to a lesser extent the empirical work as well, has focused on the aspects of a technological system that provide the re-enforcing mechanisms of learning, coordination, and technological inter-relatedness and how these aspects contribute to technological lock-in. The explanatory building blocks in this literature have been derived from observations of existing technological systems the presence of installed bases, network externalities, accumulated learning and so on. This is natural, given that the literature was initially driven by observations of technological lock-in, which is an end of process phenomenon, and is itself explained by just these factors. But for a technological lock-in to exist, there must have been a trajectory or path established which was then re-enforced. To the extent that the beginning of the process, wherein a trajectory is established, has been studied, the explanatory building blocks have been the same. Implicitly, path creation phenomena have been treated as a sort of subset of path dependence phenomena.

In this chapter we focus attention specifically on the beginning of the process, when paths or trajectories are created. This issue is of particular interest when an established, entrenched trajectory exists. If a new technology appears, it must somehow create its own path, either as part of the existing trajectory, or as a new, perhaps independent one, that can compete with, or live beside the existing trajectory. The possibilities for the actors interested in the new technology to create a beneficial environment depend on the types of entrenchment that exist. We can distinguish between a lock-in that is primarily determined by the supply-side and a lock-in that is primarily determined by the demand-side. In the first case the problem is about reversing the way engineers and managers make cost calculations and invest in technology development. In the second case, a market sustained lock-in the issue is to change consumers' preferences. To escape a purely technological lock–in investments need to be made in the competing technology to push its underlying knowledge frontier closer to the dominating technology. This can sometimes be easy if the old technology is considered to be dated and not very attractive. To escape a pure market lock-in, the focus should be directed towards the way consumers value products and technologies. Even if consumers know that a product is harmful it can be impossible in the short run to change consumer patterns. A dramatic case is the time it took to decrease the number of smokers. In real-life technology and market forces often mutually support a lock-in making an escape extremely difficult.

The concern of this chapter is how creating a path for a new technology might happen. We take a particular case, namely the electric and hybrid automobile. The internal combustion vehicle exists in a well-established, strong technological system. Advocates of the electric vehicle and the hybrid vehicle claim that they can play an important role in the transportation system, to some extent substituting for and to some extent complementing existing technologies. If these car technologies can gain a significant foothold, then all of the forces of path dependence will come into play. The central question for this paper is how it might gain that foothold.

3.3.3 Automobiles

The history of the automobile in the twentieth century is to a very great extent about cars powered by the internal combustion engine. Early in the century, internal combustion, steam and battery-stored electricity were all used to power automobiles. But by 1910 the internal-combustion engine was placed such that it has dominated ever since. The steam engine has effectively disappeared as a locomotive source following the conversion of the railways to diesel-electric and electric in the middle third of the century. Electricity remains a source of locomotive power in rail technologies and in some other particular niches. Golf carts, forklift trucks, vehicles used by the disabled, and some delivery vehicles are powered by batteries. But in general, throughout the century, the internal-combustion engine has been developed and integrated with other parts of the economy, forming a strong, coherent and entrenched technological system.

The total market for electric cars amounts to a couple of thousand cars annually. In Europe over the last 10 years, different countries at different times have provided the largest market for electric vehicles. Switzerland was the first country to boast hundreds of electric vehicles sold annually. In the early 1990s sales decreased and Germany became the engine of electric vehicle sales and some years came close to sales of 1,000 vehicles. Within a few years the market was saturated and France became the new leader. In 1996 France became the first country in modern times to sell more than 1,000 electric vehicles but since then sales have fallen by more than a half. The next great advance for electric traction in cars was the launch of the hybrid Toyota Prius that is selling more than 1,000 cars a month in Japan. Toyota has now sold more than 100,000 hybrid vehicles between 1997 and 2002. Honda plans to sell 24,000 hybrid Civics in the USA in 2002-03.

Placing these figures in perspective, it is evident that electric vehicles and hybrid vehicles for road transport is a small market even in comparison with the greater market for electric vehicles. One of the most important markets segments for electric vehicles serves indoor needs, ranging from small vehicles running on railway platforms to trucks used in factories to transport goods. The world market for these different types of electric vehicles is more than 100,000 vehicles annually. For these uses, electric traction has clear advantages over other traction technologies. For example, for transport in secluded places where exhaust fumes are unwanted - a golf course, a factory, an airport, a railway station or in some cases a protected inner city area - electricity clearly dominates gasoline-powered internal combustion. A paradoxically important factor has been the advantage of low speed because of close contact with humans. While high-speed vehicles can be made to travel slowly, there is no need to bear the costs of the extra engineering to create a high-speed vehicle, so again electricity has an advantage. This advantage exists in several of the locations mentioned above, but also exists for vehicles for the mobility impaired. A third factor contributing to success for the EV in some areas has been that the vehicles have performed well with lead-acid batteries. In some cases the heavy and low performant lead-acid batteries give distinct advantages, for example in indoor factory trucks where the weight of the batteries helps stabilise the truck when heavy goods are being moved.

3.3.4 Technological lock-in and escape

Path creation is often associated with escape from an existing lock-in. A new technology endeavours to create a space for itself in the context of an existing, perhaps hostile, technological system. In the context of personal transport, the internal combustion system exists, and in many ways is an environment hostile to the electric vehicle. In one extreme view, escape from this lock-in involves effectively replacing the gasoline-based system with an electricity-based system. This would be a very strong version of escaping an existing lock-in. Less extreme views look to introduce hybrid vehicles in which -electricity replaces only a small part of the existing system. Here, the escape would involve only part of the existing locked-in system, and so is both much weaker and, some would say, much more realistic as a goal.

The theoretical literature on path dependence and technological lock-in has emphasised the processes and types of events that produce a technological lock-in. Some initiating events may give a technology an early advantage, but it is the processes that emerge in response which produce the vested interests that lock in the technology. Users become unwilling to switch technologies because they have invested time and money in the technology that dominates; producers benefit from production economies of scale and investments in R&D. As mentioned in our introduction, in the formal literature, less attention has been paid to the processes by which a lock-in is escaped and a new path created. In the paragraphs that follow, we give some theoretical consideration to this issue. While the literature has not spent much energy addressing this explicitly, one general vision of escape can be formulated using ideas that emanate from that literature.

Brian Arthur (1994) discussed this problem in general terms. Exit or escape from an inferior equilibrium in economics depends very much on the source of the self-reinforcing mechanism. It depends on the degree to which the advantages amassed by the current state are reversible or transferable to an alternative one. When co-ordination effects are the source of lock-in the advantages can be transferred, assuming that there is a co-ordination mechanism that allows a switch en masse to the new technology. If learning effects and specialised fixed investments in capital improvements are the source of reinforcement, generally advantages are not reversible and not transferable to an alternative equilibrium. Repositioning the system is then difficult.

The general problem facing actors aspiring to develop the electric vehicle is that the entrenchment of the internal-combustion technology restricts the possible courses of action. At first glance, problems seem insurmountable. A co-ordinated move is difficult because the internal-combustion technology and service infrastructure are not well suited to the electric vehicle. An expansion of the industry based on the exploration of new demand frontiers seems to be non-existent: the railway gave us fast inland transportation and the jet plane intercontinental flights, and it is difficult to imagine a similar unexploited market for electric vehicles. Building the industry by making incremental investments seems impossible because future users demand complementary products like service and recharging facilities.

At this abstract level, all of the hurdles faced by the electric vehicle described in the previous paragraph are faced by any new technology. This suggests that technological change is close to impossible. But we know this to be false from the historical development of other technologies. How then does it happen?

We organise the discussion that follows around the three possible loci of entry to the problem. Every market has a demand-side, a supply-side, and an environment in which the market operates and in which the product marketed operates. Each of these three provides an avenue of entry into the lock-in or escape problem. On the supply-side we see firms, that perform R&D and make a variety of commitments to either the new or the old technology. On the demand-side we see consumer tastes, learning and again technological commitments. The environment includes regulation, exogenous scientific and technological development, and possibly activities in other industries, sectors or economies. We will use this taxonomy to organise the discussion below on escape from lock-in.

Drawing on the discussion in Cowan and Hultén (1996), we provide possible routes by which paths can be created. We also discuss their relevance to the electric vehicle.

3.3.5 On the Demand-Side

Changes in taste. The growing awareness of the environmental effects of consumption has created mass markets for environmentally adapted products. Tastes of consumers have, in general, changed dramatically over the last decade. We refer, of course, to the increased taste for environmental friendliness. This change has been instrumental in precipitating many policy changes.

Tastes as regards automobile services have been generated and developed in the era of the gasoline automobile. They have been tailored to and by the gas car. This means that to compete as an automobile, the electric vehicle must provide all the services provided by the gas car, or close to all of them plus something extra. In today's context, if there is to be an extra, it is obviously environmental. The question is, then, how much of what the gasoline car provides are consumers willing to give up in order to gain the environmental benefits the electric vehicle provides. Put another way, the taste for the environment referred to above may, and typically does, conflict with other tastes: for example the taste for individual, private control over long distance travel, that is to say, desire for the kind of services that the current automobile provides. The automobile is an extensively diffused consumption product, which indicates that consumers in general receive significant amounts of utility from its bundle of services. To rest heavily on consumer tastes as the key to introducing electric vehicles as an identifiable part of the transportation system implies the belief that tastes for environmentally friendly goods are extremely strong.

Market Niches. The growth of emerging technologies is facilitated if there exist a relatively large number of consumers willing to invest in the new technology before low-cost production (internal production economies), and well-developed after-sales services (external consumption externalities) emerge. Early adopters provide the learning and scale economies needed to generate these externalities. In a market niche a new technology is "protected" from severe competition from established technologies that the market has accepted. If the technology is very valuable to consumers in that niche, then the early adoption problem is solved. But a niche will only provide the necessary learning and scale to make a new (or resurrected) technology viable if it is relatively large, and if the demanders in it press the suppliers for economic and technical improvements.

Like most technologies, automobile technologies first appeared in specific niches. The internal-combustion car found unexploited niches such as race cars for the rich (Rao, 1994, p34). The electric vehicle was initially primarily directed to established niches like taxi cabs, where bench-marking was immediately possible. While far from the only difference in the technological trajectories in the early 1900s, the fact that the internal-combustion car found niches containing no established competitors whereas the electric vehicle attempted to compete head-to-head with an existing, successful service, may have been important. The ICC niche really was protected from competition; the EV niche had competition, and thus comparison with other technologies built in from the start. The current situation for the EV seems different: it can dominate in niches or uses in which pollution must be kept to a minimum, for example golf courts, indoor environments, and sensitive inner-city areas.

Learning by using is an important force in the early development of a technology. It can be instrumental in moving a technology beyond its initial market niche to attract a wide body of potential users. But for this transition to occur, the learning must take place on a wide front. No matter how demanding the consumers of golf carts, technological change made to produce the perfect golf cart will not make the electric vehicle desirable to the highway driver. Similarly, if the overwhelming concern of early adopters is the environment and they are little concerned with other features of the automobiles, they are unlikely to provoke suppliers to improve performance in other ways. If, on the other hand, early adopters present variety in their uses and reasons for adopting, they are likely to present suppliers with many avenues along which improvements will increase the demand for the technology. There is evidence that the new early adopters of electric vehicles and hybrid vehicles may be doing that. Hybrid vehicles for example are being bench-marked against both the car maker's specifications and against internal-combustion cars. This is a sign that these cars can be taken seriously and that they have to deliver performance in the same way as any other car.

3.3.6 On the Supply Side

A crisis in the existing technology. Generally speaking, if an existing technology enters a period of crisis in which it fails to deliver the things that users demand, an opportunity exists for a new technology to emerge. This has taken place in agricultural pest control in several areas: chemical controls began to fail, and this provided an opening for the introduction of integrated pest management (Cowan and Gunby, 1996).
It must be admitted, though, that there is no real crisis in existing transportation technology. Gasoline or diesel cars are still regarded as the best means of private transportation by most consumers. The technology performs as people expect and at predictable costs. In fact, it defines our perception of automobiles and private transportation. In addition, a steady rate of technical progress continues to make the gasoline car gradually more attractive to users. The internal-combustion car is also narrowing the window of opportunity for hybrid vehicles by decreasing emission levels and by offering cars with high mpg.

Dedicated R&D. If there are agents trying to develop a new technology, the R&D performed in that endeavour can produce technological advance that makes the new technology a viable competitor to the old. Until recently, at least, that has not occurred in the electric vehicle case. The EV market was, until 1980-85, dominated by the four pillars of: 1) simple delivery vans in Great Britain, 2) golf carts, 3) indoor trucks and small vehicles for indoor use, and 4) home-made cars. The technology used in these cars was essentially the same as the technology used in 1910-20. The R&D programmes spurred on by World War II and the oil crisis of 1973 produced no basic changes in the technology. The lead-acid battery kept its position, the traction system remained the same, and small scale production was omnipresent.
Despite the absence of a technological break-through producing a major shift in the cost structure of electric vehicles, the fundamental characteristics of the industry appear to be changing. New batteries (Toyota Prius has a nickel-metal hydride battery and Peugeot 106 Electric has a nickel-cadmium battery) with better storage capacity and enhanced power ratings are being introduced. New electric motors and techniques to recapture braking energy are technical changes designed to improve performance. The battery in the hybrid Honda Civic is being charged by the electric motor, which becomes a generator during braking or when the car is coasting and decelerating. The prices of electronic components decrease with increases in scale. Gradually the small manufacturers should increase the sizes of their plants and new entrants have plans for

large-scale production. New recharging techniques make possible fast recharging - 10 to 30 minutes for a 20% recharge instead of eight hours for a complete recharge.

Learning by doing and economies of scale. To be able to compete with the internal-combustion car, electric vehicles and hybrid vehicles need to be produced in much larger quantities than is the case in 2002. First, production costs can be decreased by running longer production lines that result in learning by doing when production equipment can be adjusted to the demands of the alternative cars and when personnel learn about how to build these cars. Second, increased production allows the construction of more efficient production plants compared with present small-scale production. Positive effects of learning by doing and bigger production plants would today be present in the production of Japanese hybrid vehicles. French production of electric cars is fitted into the production of other car models.

3.3.7 The Environment

Regulation. Regulation is a common factor in the creation of a new technological path. Regulation can serve two purposes: as a co-ordination mechanism; and as a forcing device. Often, a switch from an existing path to a new one demands that all agents switch more or less simultaneously. Unless all agents have perfect knowledge about the preferences and constraints of all other agents, a situation of excess inertia can occur (Farrell and Saloner, 1985). Here, even though all agents would prefer to switch to the new path, it is impossible to do so, since the costs of being first (or being alone) on the new path are very high. Thus, in spite of the fact that all would prefer to move, none is willing to start the ball rolling. Here regulation serves as a co-ordination mechanism. This is the case with a switch from chemical control to integrated pest management to control insect pests in the cotton industry in Texas. All farmers knew that integrated pest management would be preferred but none could switch profitably unless all switched at the same time. State legislation permitted counties to mandate the switch. As a consequence, IPM was adopted and the industry survived and prospered. This is in contrast with the Mexican industry, now moribund, which faced exactly the same problems with chemical controls, but for which no regulation emerged (see Cowan and Gunby, 1996).

Regulation can also serve to force technical change, and so to force a change from one trajectory to another. Raising environmental standards often has this feature. It is just this sort of environmental regulation, intended to force automobile manufacturers to invest in technical change that is now one of the principal forces in the construction of an electric vehicle industry. Local regulations limiting the access to city centres helped to increase the demand for electric vehicles in Switzerland. The decision in California to force car manufacturers to supply low, ultra-low and zero-emission vehicles in 1998 was instrumental as an incentive for the car industry to develop electric vehicles. But after presenting some dramatic technical advances in the early 1990s the large producers of gasoline cars changed strategy. They claimed that it is difficult and wasteful to build electric or hybrid cars and that the gasoline car can be made much more fuel efficient relatively easily. This strategy enabled the American car manufacturers to strike a deal with the regulating authority (CARB) in 1996 that meant a postponement of the forced introduction of electric vehicles until 2003.

This is an illustration of one of the general difficulties with regulation: it can conflict with vested interests. While regulation can serve to create a niche for an emergent technology, or can force its development in other ways, this is not always enough. Again, if the old technology is sufficiently entrenched, it can control not only a part of the technological system, but also part of the institutional system.

Scientific results. Science may provide tools to measure better the external effects of an industry; basic science can also serve as a foundation from which inventors and entrepreneurs can create inventions and innovations. Consequently scientific results can put developmental pressure on an old technology both by questioning its global efficiency and by providing knowledge about alternative technologies.
In fact, the electric vehicle industry is thriving on scientific results that question the global efficiency of the competing technologies. The gasoline car produces emissions that pollute locally and globally, and there are fears, based on research on the effects of this pollution, that irreparable damage is being done to the environment by the gasoline car, among other technologies. Without scientists measuring the pollution and estimating the future effects of it the electric vehicle would be far less interesting. On the other hand science has not, yet, provided an easy way out of the lock-in of the automobile industry. It is true that scientific measures show that one kilogram of an aluminium battery has the potential to store as much energy as one third of a kilogram of gasoline. This would represent a dramatic change in the economics of electric and gasoline cars. The problem of how to construct the battery remains however.

Technological advance outside the industry. The ascendancy of the gasoline car was propelled by the implementation of Taylorism and factory automation by Henry Ford.
An important part of the explanation for the electric vehicles' under-performance of the market in the 1970s and 1980s relative to projections is that progress in battery technology did not live up to expectations. Current electric-vehicle technology uses lead-acid batteries or alkaline batteries---the same basic technologies used 80 years ago. These batteries are heavy and have low storage capacity. Currently, lead-acid can store about 30-45 watt-hours per kilogram (Wh/kg). Gasoline, by contrast, stores 13000 Wh/kg. Nickel-cadmium batteries now have capacities of 60 Wh/kg and the nickel-metal hydride batteries in the Prius has a storage capacity of 80-90 Wh/kg.
Some of the progress in battery technology is no doubt due to the new market for batteries, namely as a part of portable electronic goods. The growth in this market, and the accompanying demand for lighter, long-lasting batteries that can be quickly re-charged, has created a strong enough demand for improvements so that they are, in fact, taking place.
It is not clear, of course, just how much of the R&D on batteries for portable electronics will facilitate improvements in the batteries for electric vehicles, since the two are very different. The technological trajectory of batteries for the electric vehicle, which is now on a path of improvement, may again be derailed because demand for improvements in battery technology arises from a very different sector. An important problem is the drive towards expensive raw materials pushes the price tag upwards for electric and hybrid vehicles. The hybrid Honda Civic HX costs 4,600 USD more than the gasoline version.

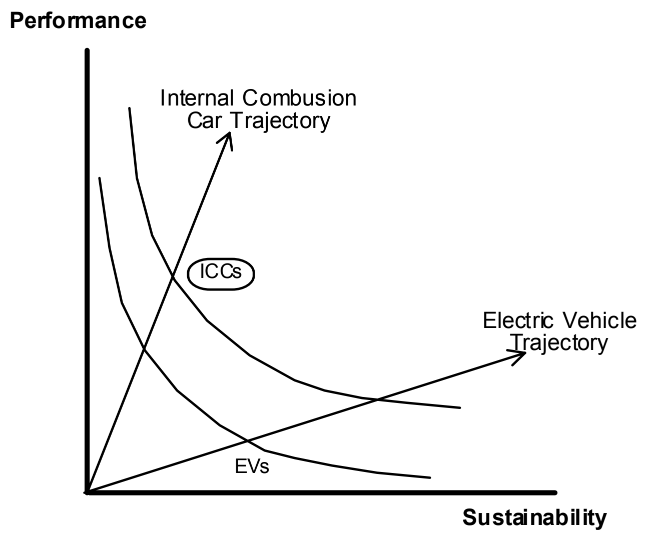
3.3.8 Micro-economic Analysis of Automobile Technology Choice

The discussion above has focused on several avenues by which new technologies can gain a market presence in the face of entrenched technologies. There is another useful way of examining the situation faced by the electric vehicle, though, drawn from standard micro-economic theory.

Consumers will choose the technology that puts them on the highest possible indifference curve. See in particular the work of Lancaster (1971) who argues that demand for goods is underpinned by demand for characteristics that the goods have. This form of analysis can be used when we observe that automobiles have several characteristics about which consumers care. This allows us to use the insights from the literature on product variety, product differentiation and characteristics space. We can aggregate the properties of automobiles into two: performance, including such things as speed, range, acceleration, continuous use; and sustainability, including things such as emissions, noise, resource depletion. Consumers care about both, and the two technologies, internal combustion and battery-electric perform, differently on these two axes. In the early development of the car it was evident that the three competing technologies had very different mixes of performance characteristics. Steam gave a prospective buyer the highest pay-offs from a performance point of view, the internal-combustion technology showed the fastest advances technology wise and was also cost competitive, the electric car had as its strongest feature driver friendliness. As the technology paths were constructed by demand and supply side forces, two things stand out: the fast technology advances for internal combustion made it attractive for entrepreneurs, steam and electric withdrew to restricted market niches where their performance characteristics were appreciated. In the language of today's information technology experts, the killer application for the internal-combustion car was an engine that continuously developed and new features that gradually diffused from expensive to less expensive models. The internal-combustion car still travels along this trajectory.

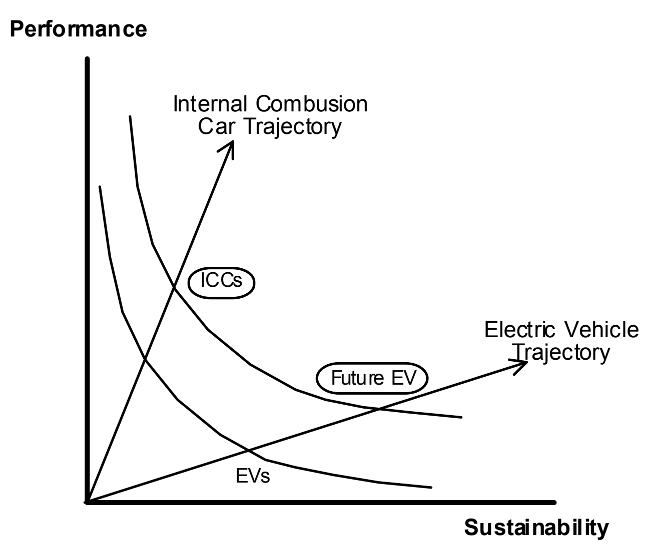
In the figure below we show a product space for electric vehicles and internal-combustion cars. ICEs dominate in one dimension (performance) and EVs dominate in another (sustainability). We show an indifference curve that might be typical of consumers. Given the utility function that drives this indifference curve, the ICE technology clearly dominates, and consumers maximise utility by adopting it (see figure 3.3-1).

Figure 3.3-1: A graphical representation of the EC-ICC decision.



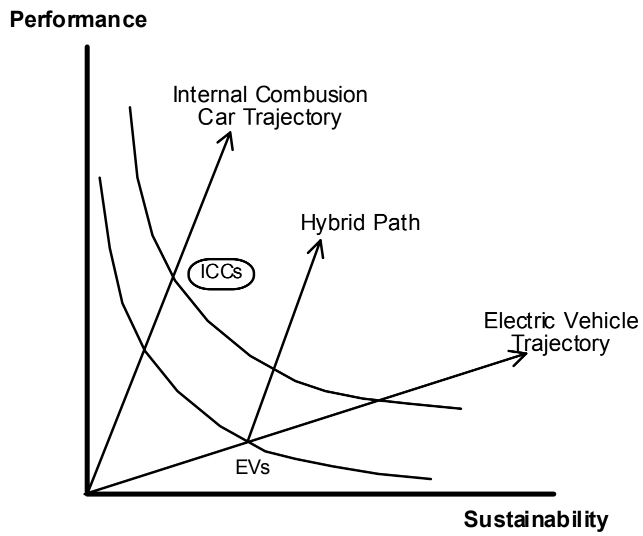
This presents a possible graphic interpretation of the possibilities for EVs. There are four options. A first option is that the EV producers can improve the product characteristics by progressing on its trajectory as a transportation mode whose predominating characteristic is its environmental friendliness (.). In terms of the discussion of modes of path creation, this option, which effectively involves technical advance in the EV, corresponds to three possibilities. The emergence of an effective niche, which is both large and dynamic, will generate learning by using and doing, both of which will advance the EV along its trajectory. Similarly, dedicated R&D as well as technical developments outside the EV industry, can have the same effect of advancing the technology.

Figure 3.3-2: Technical advances of the EV.



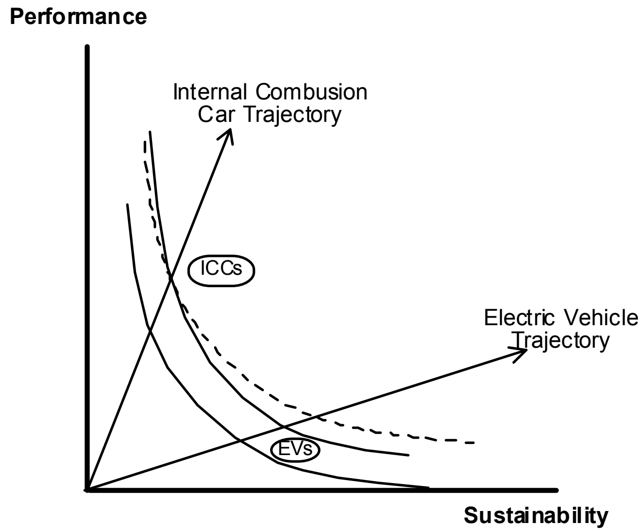
A second option is to introduce more of the performance characteristics of the internal-combustion car. This option would probably be a hybridisation option. (.) Here again, niche development can be the operative force. But in this case, pressure from the members of the niche not only creates demand for technical improvements, but also technical improvements that change the path or trajectory that the technology was following. Users demand, for example, longer range, and better acceleration. This forces manufacturers to think again, and, in the example discussed here, to made a significant change to the trajectory. This sort of change can allow a rapid expansion of demand beyond the initial niche, as some consumers who were bound by performance constraints find that those constraints are no longer binding on the new and improved technology.

Figure 3.3-3: The hybrid option.



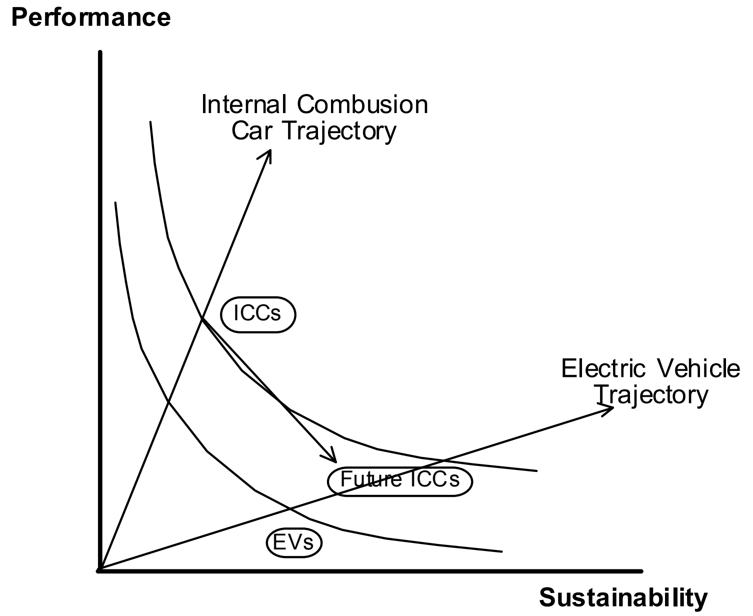
The third option is to influence the shape of the indifference curve, through, for example, persuading consumers that the environment is seriously threatened by the internal-combustion automobile. This is a demand-side phenomenon, in which the creation of a new path is driven by changes in the nature of goods demanded by consumers. If consumers now demand environmentally friendly goods, their indifference curves will change shapes on the axes in , sustainability becomes more valuable, so indifference curves rotate clockwise. This change favours goods or technologies that provide sustainability, and the electric vehicle, being perceived to do so, becomes more viable. This process is often accompanied by changes in the environment. In this particular case, scientific results having to do with environmental effects of a variety of activities have spurred this transition in consumer tastes. illustrates this type of change: the old indifference curve is shown as a broken line, the new one as a solid line. We can see that as tastes change and the curve rotates, the EV becomes more viable even with no technical change on its part. In essence, the social infrastructure is changing and creating a new path along which the EV can travel.

Figure 3.3-4: Changing tastes and utility functions.



The final option is to force the IC to take on some of the characteristics of the EV (.). This will certainly only happen through regulation. The zero-emission mandate in California is just this sort of regulation. One response of the automobile manufacturers to this regulation is to reduce emissions of their internal combustion vehicles. Promises of technical change of this sort have allowed them to negotiate with CARB, and to reduce the stringency of the mandate. In effect, what they are promising to do is to give the ICC some of the desirable features of the EV. This will, by adding costs to the ICC, reduce the level of the aggregate variable we have called performance. The ACEA agreement in Europe works in the same way as the manufacturers commit themselves to produce internal-combustion cars with gradually lower emissions of carbon dioxide. This sort of scenario is illustrated in . If the internal-combustion car technology will follow such a path its supporters will ultimately bet on the ”sailing ship effect” that the technology can produce in the environmental dimension will be big enough to counter all the adverse effects in the performance dimension.

Figure 3.3-5: A more sustainable ICC.



3.3.9 Conclusion

The electric vehicle and the hybrid vehicle have been difficult to market in large numbers because the internal-combustion car defines what a car is. If we believe that it is an attractive option to support the creation of markets for electric and hybrid vehicles this can be done either by intervening in the demand for cars, in the supply of technology and production, or by regulation and scientific results.

If we speculate on the relative efficiency of the different strategies as presented in our micro-economic analysis, based on our knowledge of historical examples and simple economic models, we can make the following concluding observations:

A mix of the strategies (technological development of electric vehicles, hybrid option, changes in consumers' taste and more stringent environmental legislation of ICCs) is possible, and probably optimal because of the intertwining of technological forces and market forces reinforcing the entrenchment of the gasoline car.

It is better to force the internal combustion car to take on properties of the electric vehicle than vice versa since sailing ship effects have helped few technologies to remain market leaders. And, if the electric car moves closer towards the internal-combustion car's performance the adherents of the electric-vehicle technology implicitly accept that performance is more important than environment. As the two technologies move closer to each other, will the internal-combustion car lose much more in performance than it gains in environmental sustainability and the electric vehicle loose much more in environmental sustainability than it gains in performance? If this wasn't true the internal-combustion car would be the environmental alternative and the electric vehicle the performance vehicle.

Long-term information to consumers about adverse effects of technologies sometimes gives results. And, in the same way as governments and individuals can sue tobacco firms and more recently gun manufacturers for the negative external effects of these products, governments and individuals can, in the future, sue car manufacturers for negative external effects arising from consumers driving internal-combustion cars.

3.3.10 References

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4 ANNEX

4.1 Research activities & Pilot applications

4.1.1 EU research projects

Table 4.1-1: EU RTD: Running projects (Land Transport Technologies 1998 – 2002)

Title		Starting Date	Duration (months)
GET-DRIVE- Driveability Development of Downsized. Highly Turbocharged Gasoline Engines	Gasoline engines	01/02/02	30
GET-ENGINE -Gasoline Engine Turbo-charging - Advanced Engine Cycle Development	Gasoline engines	01/01/01	26
G-LEVEL- Gasoline Direct Injection-low Emission levels by Engine Modelling	Gasoline engines	01/03/00	36
VCR -Variable Compression Ratio for CO_2 Reduction of Gasoline Engines	Gasoline engines	01/03/00	39
CRICE- Common Rail-Based Improved Combustion for Low Emissions	Diesel engines	01/02/01	36
D-CYCLE -Advanced Diesel Cycle Development for Mid-Size Engines with High-Pressure Piezo Common Rail	Diesel engines	01/05/02	30
D-ISELE- Diesel lnjection for Small Engines with Low Emissions	Diesel engines	01/01/01	33
D.LEVEL- Diesel -Low Emission Levels By Engine Modelling	Diesel engines	15/02/00	36
ELEGT- Electrical Exhaust Turbocharger	Diesel engines	NA	36
FPEC -Free Piston Energy Converter	Diesel engines	NA	36
HY-SPACE -Heavy-Duty Diesel Whole SPACE Combustion	Diesel engines	NA	36
I.LEVEL- Injector Flows -Low Emission Levels by Engine Modelling	Diesel engines	01/03/00	36
NEDENEF- New Diesel Fuels for New Diesel Engines	Diesel engines	01/03/02	36
SPACE LIGHT -Whole Space Combustion for Diesel Light Duty Vehicles	Diesel engines	01/01/01	36
ATECS -Advanced Truck Engine Control System	Engines control	01/01/00	36
ELVAS- Development of an Electromagnetic Valve Actuation System for High Efficiency Engines	Engines control	01/02/01	36
FUNIT- Future Unit Injector Technologies	Engines control	01/02/00	36
LIVALVES -Lightweight Valves for High Efficient Engines	Engines control	01/04/00	36
PICE- PLN.Based Improved Combustion for Low Emission		01/01/01	36
AHEDAT -Advanced Heavy Duty Engine Aftertreatment Technology	Aftertreatment	01/05/02	36
ART-DEXA -Advanced Regeneration Technologies for Diesel Exhaust Particulate Aftertreatment	Aftertreatment	01/02/00	36
COMET- Coated Sintered Metal Trap	Aftertreatment	01/05/02	36
IMPECC- Infrared Microsystems for Pollution Emission Control on Cars	Aftertreatment	01/02/01	30

KNOWNOX- Development of Continuous Catalytic NOx Reduction for lean Burn Cars		01/01/00	24
LOTUS- low Temperature Active Urea-Based Selective Catalytic Reduction of NO_x		01/01/00	24
NANOSTRAP- Nanostructured Sulphur Traps for the Protection of High Performance NO_x Storage/Reduction Catalysts in low Emission Engine Applications		01/06/02	36
STYFF-DEXA -Simulation Tool for Dynamic Flow Analysis in Foam Filters		NA	36
SYlOC-DEXA- System level Optimisation and Control Tools for Diesel Exhaust Aftertreatment		01/02/00	36
ClEVER- Compact low Emission Vehicle for Urban Transport	**New fuel engines and propulsion**	NA	36
EREBIO -Emission Reduction from Engines and Transmissions Substituting Harmful Additives in Biolubricants by Triboreactive Materials		NA	48
PlANET- Platform on Auto-lgnition Numerical Engine Simulation Tools		01/03/99	36
Beltless engine- Validation of Fully Electrical 14V/42V Power Components for Internal Combustion Engine including the Total Thermal Management	**Mechatronics/ active safety**	01/02/01	30
VERTEC -Vehicle. Road. Tyre and Electronic Control Systems Interaction: Increasing Vehicle Active Safety by Means of a Fully Integrated Model for Behaviour Prediction in Potentially Dangerous Situations		01/05/02	36
APOLISS -Applications of lightweight Sandwich Sheets	**Low weight structur es**	01/02/01	36
LlRECAR- light and Recyclable Car		01/01/01	24
TECABS -Technologies for Carbon Fibre Reinforced Modular Automotive Body Structures		01/04/00	48
ALICE -Advanced Lightweight Graphite-Based Composite Components for Low Emission Combustion Engines	**Low weight /components/**	NA	48
MG-CHASSIS -Advanced Manufacturing Technology for Automotive Chassis Components through Extensible and Sustainable Use of Mg Alloys		01/02/01	48
MG-ENGINE- Lightweight Engine Construction through Extended and Sustainable Use of Mg Alloys		01/04/02	36
ACES -Acoustic Characteristics of Equivalent Vehicle Noise Sources	**Noise and vibration**	01/04/02	36
ARTEMIS -Acoustic Research on Turbocharged Engine Modelling of Exhaust and Inlet Systems		01/09/01	36
CALM -Community Noise Research Strategy Plan		01/10/01	36
RATIN -Road and Tyre Interaction Noise		01/06/00	36
ROTRANOMO- Development of a Microscopic Road Traffic Noise Model for the Assessment of Noise Reduction Measures		01/05/02	30
SMILE- Simulation Methods of Interior Noise Levels Aerodynamically Excited		01/01/01	36
TROWS -Tyre and Road Wear and Slip Assessment		01/04/00	36
VIBSEAT- Evaluation and Improvement of Suspension Seat Vibration Isolation Performance		?/?/02	36
VISPER -Vehicle Integral Simulation for Pass-by Noise Reduction		01/03/01	36

3D-STRUCTURES -Lighter and Safer Automotive 3D-Structures at Low Investments through the Development of the Innovative Double Sheets Hydroforming Technology	**Manufacturing processes**	01/01/01/	36
EMF- Electromagnetic Forming of Tube and Sheet Metal for Automotive Parts		NA	36
HIGH DENS -Application of High Density P/M Gears for Automotive Gearboxes by Densification of the Surface Layer		01/05/00	48
HYDROSHEET- Sheet Hydroforming for the Automotive Industry		01/03/00	36
HYDROTUBE- Reduction of CO_2 Impact by Weight Reduction Achieved by Bending and Hydroforming of Steel and Aluminium Tubular Parts for Body and Chassis Applications		01/03/00	36
IDEAL- Integrated Development Routes for Optimised Cast Aluminium Components		NA	36
COSIME- Continuous Simulation of EMC in Automotive Applications	**Advanced design**	01/02/00	30
GEMCAR -Guidelines for Electromagnetic Compatibility Modelling for Automotive Requirements		01/01/00	36
IDD- Integrated Design Process for On-Board Diagnosis		01/02/00	36
TROPHY -Towards the Prediction of Hydroplaning: Numerical Simulation and Experimental Validation		01/06/01	36
ADVANCE -Advanced Virtual Analysis of Crash Environments	**Passive safety**	01/02/01	36
CHILD -Advanced Methods For Improved Child Safety		01/06/02	36
HUMOS2 -Development of a Set of Human Models for Safety 2		NA	36
IMPACT- Improved Failure Prediction for Advanced Crashworthiness of Transportation Vehicles		01/07/00	36
ROLLOVER- Improvement of Rollover Safety for Passenger Vehicles		NA	36
SIBER- Side Impact Dummy Biomechanics and Experimental Research VITES -Virtual Testing for Extended Vehicle Passive Safety		01/02/01	36
WHIPLASH 11- Development of New Design and Test Methods for Whiplash Protection in Vehicle Collisions		01/02/01	3601/03/01
CLARESCO -Car and Truck Lighting Analysis: Ratings and Evaluations for Safety and Comfort Objectives	**Human/ vehicle interaction**	NA	36
CLEANRCAB- Innovative and Efficient Air Quality Management System for a Healthy. Comfortable and Safe In-Vehicle Environment		NA	36
EUCLIDE- Enhanced Human-Machine Interface for On-Vehicle Integrated Driving Support System		01/03/01	36
ROADSENSE- Road Awareness for Driving via a Strategy that Evaluates Numerous		01/02/01	36
ERANET- Exemplary Research and Development Network for Technology Exchange in Land Transport and Marine Technologies	**Thematic networks**	NA	26
EVPSN 2 -European Vehicle Passive Safety Network 2		01/02/02	24
FURORE- Future Road Vehicle Research -A Roadmap for the Future		01/05/02	15
PREMTECH II -Efficient and Low Emitting Propulsion Technologies		01/07/01	48

D-ULEV- Low CO_2 ULEV Diesel Passenger Car	Technological platforms	01/01/01	48
GET CO_2 -Gasoline Engine Turbocharging -Advanced Gasoline Powertrain for Reduced Fuel Consumption and CO_2 Emissions		01/01/01	42
SUVA- surplus Value Hybrid		01/01/01	36

4.1.2 Links related to pilot applications and field trials

4.1.2.1 Hybrid Electric Vehicles (HEV) and Electric Vehicles (EV)

http://www.ott.doe.gov/hev/what.html
http://www.ott.doe.gov/hev/components.html
http://www.hybridcars.com/
http://www.usc.edu/dept/engineering/illumin/archives/spring2000/textver/hybridvehicles.htm
http://www.escapehev.com/index.asp (*Example of an HEV*)
http://4wheeldrive.about.com/cs/hybrids/
http://www.hybridcars.com/Hybrid_Links.htm (*HEV Links*)
http://www.ieahev.org/electric.html
http://www.evaa.org/evaa/index.htm
http://www.sdge.com/EV/
http://www.eaaev.org/
http://www.evac.ca
http://www.rqriley.com/ev-tech.html
http://www.maxwell.com/pdf/corp/investors/uc_system_design.pdf (*UltraCapacitors*)
http://ev.inel.gov/fop/general_info/FutureCarSlides2002.pdf
http://evworld.com/index.cfm
http://www.evs19.org/ (HEV, EV)
http://www.skat.ch/publications/online/various/electric_vehicles/EVWebSitesHybridVehicles.htm

4.1.2.2 Alternative Fuel Systems (AFS)

http://www.energy.gov/
http://afdcweb.nrel.gov/documents/altfuelnews/
http://afdcweb.nrel.gov/siteindex.html
http://www.itepsa.com/etpjonline/afeonline.html
http://www.car-stuff.com/carlinks/future.htm
http://www.altfuels.com/
http://www.energy.ca.gov/links/afv.html
http://www.hpower.com/
http://www.h2fc.com/news.html
http://www.eren.doe.gov/hydrogen/pdfs/hydrofut.pdf
http://www.ifp.fr/ifp/Search.jsp

4.1.2.3 Various Future Trends

http://www.afdc.doe.gov/siteindex.html
http://www.thinkquest.org/library/lib/site_sum_outside.html?tname=20463&url=20463/library.html
http://www.ccities.doe.gov/
http://www.ccities.doe.gov/vbg/consumers/future.shtml
http://www.crc4mse.org/MEL/AUTO/MEL_auto_P2000.html
http://www.crc4mse.org/MEL/AUTO/MEL_auto_Synergy.html
http://www.globaltechnoscan.com/31may-6june/car.htm
http://www.transportation.anl.gov/ttrdc/index.html

http://ev.inel.gov/fop/
http://www.calstart.org/calindex3.html (Advanced transportation)
http://library.thinkquest.org/26471/thefuture.html
http://pages.prodigy.net/imagiweb/reports/file00/jul1.htm
http://www.edmunds.com/future/
http://www.americanplasticscouncil.org/apcorg/newsroom/articles/fuel_tanks.html

4.1.2.4 Vehicles recycling systems and trends

http://www.autorecyc.org/docs/about/recycle_statistics.htm (International recycling statistics)
http://www.plastics-in-elv.org/ (Plastics in end of life of vehicles-ELV)
http://www.environmental-center.com/articles/article1143/article1143.htm (EU ELV rules)
http://europa.eu.int/comm/research/leaflets/recycling/en/page2.html (EU vehicle recycling web site)
http://www.autorecycling.nl/engels/1vogelvlucht/10.php (Autorecycling in the Netherlands)
http://www.rco.on.ca/reincarnate.html (Recycling council of Ontario)
http://eerc.ra.utk.edu/ccpct/presentations/glu/glu.ppt (Automotive Recycling initiatives in the EU and date from USA)
http://www.standardandpoors.com/nordic/pdfs/europescarmakers.pdf (Automarkers and recycling)
http://www.faraday-plastics.com/ELV.doc (ELV directive for the future in the UK)
http://www.delphi.com/pdf/techpapers/2002-01-0595.pdf (European ELV future plans)
http://www.vke.de/pdf-files/pravda.pdf (Plastics in ELV)
http://www.salyp.com/2831.htm (Information from an ELV centre)
http://europa.eu.int/comm/research/growth/gcc/projects/in-action-recycling.html#02 (Recycling car parts in Europe)
http://www.plasticsresource.com/recycling/ARC99/Mcauley.htm (Graphics)
http://www.oit.doe.gov/aluminum/factsheets/autoalscrapsorting.pdf (aluminium and recycling in cars)
http://www.holden.com.au/images/sc18_downloads/brochures/RecyclingGuide.pdf (recycling of different car parts and future)

4.1.2.5 Research centres, universities, federations

http://www.uscar.org (United States Council for Automotive Research)
http://www.ta.doc.gov./pngv (Partnership for a New Generation of Vehicles)
http://www.nas.edu/trb/ (Transportation Research Board)
http://www.mira.co.uk/ (Projects in the field of vehicle development)
http://www.ott.doe.gov/technologies.shtml (Office of Transportation Technologies)
http://www.jari.or.jp/en/index.html (Japan Automobile Research Institute)
http://www.ertico.com (Partnership for the implementation of Intelligent Transport Systems and Services)
http://www.alexcommgrp.com/efv (Alternative Fuel Vehicle Group)

4.1.3 Developers of Fuel Cells (Worldwide)

The following businesses, institutes and organisations are involved in development of fuel-cell stacks. Links to websites are included, as well as the technology type.

Acumentrics Corporation, Massachusetts, USA (SOFC)
Advanced Measurements Inc., Alberta, Canada (Fuel Cell Testing Systems)
Anuvu Incorporated, California, USA (PEM)
Apollo Energy Systems, Inc., Florida, USA (AFC)
Arbin Instruments, Texas, USA (Fuel Cell Testing Systems)
Argonne National Laboratory, Illinois, USA (PEM, MCFC and SOFC)
Avista Laboratories, Washington, USA (PEM)
Azienda Energetica Municipale (AEM spa Milano), Milano, ITALY (PAFC)
Ball Aerospace & Technologies Corp., Colorado, USA
Ballard Generation Systems, Inc., New Jersey, USA (PEM)
Ballard Power Systems, Inc., British Columbia, CANADA (PEM)
BCS Technology, Inc., Texas, USA (PEM)
Case Western Reserve University, Ernest B. Yeager Center, Ohio, USA (PEM)
Celsius, Malmo, SWEDEN (PEM)
Ceramatec, Utah, USA (SOFC)
Ceramic Fuel Cells Ltd., Victoria, AUSTRALIA (SOFC)
Consejo Superior de Investigaciones Cientificas, Madrid, SPAIN (PEM, MCFC, SOFC)
Coval H2 Partners, California, USA (PEM)
CSIRO Energy Technology, New South Wales, AUSTRALIA
DAIS Corporation, Florida, USA (PEM)
DCH Technology, Inc., California, USA (PEM)
DE NORA s.p.a., ITALY (PEM)
dmc-2 (Degussa Metals Catalysts Cerdec), Michigan, USA (PEM)
Desert Research Institute, Nevada, USA (PEM, PAFC)
Draeger Safety, Colorado, USA (PEM)
EBARA Ballard Corporation, Tokyo, JAPAN (PEM)
Electric Power Research Institute, California, USA (PAFC and MCFC)
Electro-Chem-Technic, Oxford, UNITED KINGDOM (PEM, PAFC)
ElectroChem, Inc., Massachusetts, USA (PEM)
Element 1 Power Systems Inc., California, USA
Elf Atochem North America, Pennsylvania, USA (PEM)
Emprise Corporation, Georgia, USA
Energia Ltd., Virginia, USA
Energy Conversion Devices, Inc., Michigan, USA (RFC)
Energy Partners, L.C., Florida, USA (PEM)
Energy Visions Inc., Ottowa, Ontario, CANADA (DMFC)
Esoro AG, Faellanden, SWITZERLAND (PEM)
ETH Materials, Zurich, SWITZERLAND (SOFC)
eVionyx, New York, USA (Metal-Air FC)
Federal Energy Technology Center, West Virginia, USA (MCFC and SOFC)
FEV Motorentechnik GmbH, GERMANY (PEM, SOFC)
Florida Solar Energy Center, Florida, USA (PEM)
Forschungszentrum Julich, GERMANY (DMFC, SOFC & PEM)
FuelCell Energy, Connecticut, USA (DFC)
Fuel Cell Resources Inc. - Georgia, USA (PEM membranes)
Fuel Cell Systems - West Sussex, UNITED KINGDOM (AFC)
Fuel Cell Technologies, Ltd., Ontario, CANADA
Gas Technology Institute, Illinois, USA (MCFC, PAFC, , PEM and SOFC)
Gaskatel GmbH, Kassel, GERMANY (AFC & PEM)
Gaz De France, La Plaine, FRANCE (PAFC, PEMFC, SOFC)
GE Energy and Environmental Research Corp., California, USA (PEM, MCFC, SOFC)
Global Thermoelectric Inc., CANADA (SOFC)
Greenlight Power Technologies, CANADA (Fuel Cell Testing Systems)

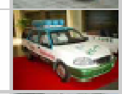
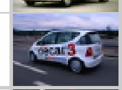
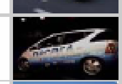
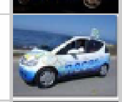
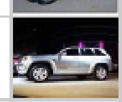
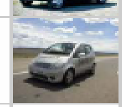
GreenVolt Power Corporation, CANADA (AFC)
H Power, New Jersey, USA (PEM)
Hitachi Works, Ibaraki, JAPAN (MCFC)
Hoku Scientific, Hawaii, USA (PEM)
HTceramix - Lausanne, SWITZERLAND (SOFC)
H-Tec - Wasserstoff-Energie-Systeme GmbH, Luebeck, GERMANY (PEM)
Hydro Quebec Research Institute, Quebec, CANADA
Hydrocell U.K., UNITED KINGDOM (AFC, PEM)
Hydrogenics Corporation, Toronto, CANADA
Hydrovolt Energy Systems, California, USA (SOFC)
ICP-CSIC, Madrid, SPAIN
ICTP-CSIC, Madrid, SPAIN (PEM)
ICV-CSIC, Madrid, SPAIN (SOFC)
IdaTech, Oregon, USA (PEM)
InnovaTek, Inc., Washington, USA
Ion Power, Inc., Delaware, USA (PEM)
Japan Automobile Research Institute, Inc., JAPAN (PEM)
JLG Industries, Pennsylvania, USA (PEM)
Lawrence Berkeley Laboratory, California, USA (PEM)
Lawrence Livermore National Laboratory, California, USA
Los Alamos National Laboratory, New Mexico, USA (PEM)
Lund Institute of Technology, Lund, SWEDEN (SOFC)
Lynntech, Inc., Texas, USA (PEM)
Manhattan Scientifics Inc., New Mexico, USA (PEM)
Massachusetts Institute of Technology, Massachusetts, USA (PEM, SOFC)
Materials and Electrochemical Research Corporation, Arizona, USA (PEM)
Materials and Systems Research, Inc., Utah, USA (SOFC)
McDermott Technology, Inc., Ohio, USA (PEM, SOFC)
Medis Technologies, ISRAEL (PEM)
Metallic Power, California, USA (ZFC)
Mitsubishi Electric Corporation, JAPAN (PAFC)
Mitsubishi Heavy Industries, Inc., New York, USA (PEM & SOFC)
MTU Friedrichshafen GmbH, GERMANY (MCFC)
National Aeronautics and Space Administration, Ohio, USA (regenerative FCs)
National Aerospace Laboratory, JAPAN (PEM)
National Fuel Cell Research Center, California, USA
National Renewable Energy Lab, Colorado, USA (PEM)
Netherlands Energy Research Foundation, NETHERLANDS (PEM, MCFC and SOFC)
NexTech Materials, Ltd., Ohio, USA (PEM & SOFC)
Ontario Hydro Technologies, Ontario, CANADA (SOFC)
Pacific Northwest National Laboratory, Washington, USA (PAFC, MCFC and SOFC)
Pivotal Power, Nova Scotia, CANADA (Fuel Cell Components)
Plug Power, LLC, New York, USA (PEM)
Procyon Power Systems, Inc., California, USA (AFC, PEM)
Protonetics International, Inc., Colorado, USA (Protonic Ceramic fuel cell)
Protonex Technology Corporation, Massachusetts, USA (PEM)
Proton Energy Systems, Connecticut, USA (PEM, Regenerative)
Proton Motor GmbH - Starnburg, GERMANY (PEM)
Refrac Systems, Arizona, USA
Risø National Laboratory, Roskilde, DENMARK (SOFC)
Rocky Mountain Institute, Colorado, USA (PEM)
Sandia National Labs, New Mexico, USA
Schafer Corporation, California, USA (PEM)
Schatz Energy Research Center (SERC), California, USA (PEM)
Siemens Westinghouse Power Corporation, Pennsylvania, USA (SOFC)
South Coast Air Quality Management District, California, USA (PAFC, PEM)
Southeastern Technology Center, Georgia, USA (PEM)
Southern States Power Co., Louisiana, USA (PEM)
Southwest Research Institute, Texas, USA (PEM)

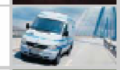
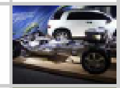
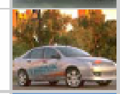
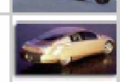
Sulzer Hexis Ltd., SWITZERLAND (SOFC)
TATA Energy and Resources Institute (TERI), INDIA (MCFC)
Technology Management, Inc. (TMI Systems), Ohio, USA (SOFC)
Teledyne Energy Systems, Inc., Maryland, USA (Fuel cell testing, PEM, Hydrogen generation)
TNO Energy & Environment, Apeldoorn, NETHERLANDS (PEM)
Toshiba Corporation, Yokohama, JAPAN (PAFC and PEM)
Toyota Motor Corporation, JAPAN (PEM)
United States Department of Energy (main), Washington D.C., USA (PAFC, PEM, MCFC and SOFC)
United States Department of Energy (Office of Transportation Technologies), Washington D.C., USA (PAFC and PEM)
United Technologies Research Center (UTRC), Connecticut, USA (PAFC and PEM)
UTC Fuel Cells, Connecticut, USA (PAFC and PEM)
VTT Chemical Technology, FINLAND (PEM)
Warsitz Enterprises, California, USA (PEM)
Westinghouse Savannah River Company, Georgia, USA (PEM, SOFC)
Worcester Polytechnic Institute, Massachusetts, USA (PEM)
XCELLSIS, Kirchheim/Teck-Nabern, GERMANY (PEM)
ZSW, Center for Solar Energy & Hydrogen Research, Ulm, GERMANY (PEM, MCFC and SOFC)
Ztek Corporation, California, USA (SOFC and Hydrogen Reformers)

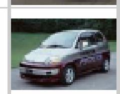
4.1.4 Overview of fuel-cell vehicle prototypes

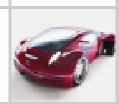
Table 4.1-2: Overview of fuel-cell vehicles [Car Chart 2002]

FUEL CELL VEHICLES

Automaker	Vehicle Type	Year Shown	Engine Type	Fuel Cell Size/type	Fuel Cell Mfr.	Range (mi/km)	MPG Equivalent	Max. Speed	Fuel Type	Commercial Intro.	Picture
BMW	Series 7 (745 h) (Sedan)	2000	ICE (fuel cell APU)	5kW/ PEM	UTC	180mi 300km	N/a	140 mph	Gasoline/ Liquid Hydrogen	Limited intro in 2000 (Munich airport)	
	Mini-Cooper (concept)	2001	Standard 4-cylinder ICE	None	None	N/a	N/a	N/a	Liquid hydrogen		
Beijin Green Power Co. w/ Tsinghua University	12 passenger van	2002	Fuel cell	18 kW/ PEM	In China	103mi 165km	N/a	N/a	Compress. hydrogen		
Beijin Green Power Co. w/ Tsinghua University	Station wagon	2002	Fuel cell	18 kW/ PEM	In China	N/a	N/a	45mph 72km/h	Compress. hydrogen		
Coval H2 Partners	T-1000 (small pickup truck)	1998	Fuel cell/ battery hybrid	6.5kW/ PEM	De Nora	245mi 394km	N/a	65mph 105km/h	Liquid hydrogen		
	London Truck	1998	Fuel cell/ battery hybrid	63 kW/ Alkaline	N/a	125 mi 200 km	N/a	62 mph 100 km/h	Compress. hydrogen	2001 in Westminster, England	
Daihatsu	MOVE EV-FC (micro van)	1999	Fuel cell/ battery hybrid	16kW/ PEM	N/a	N/a	N/a	N/a	Methanol		
	MOVE FCV – K II (mini vehicle)	2001	Fuel cell/ battery hybrid	30 kW/ PEM	Toyota	N/a	N/a	N/a	Compress. hydrogen	Japan road testing in 2002	
Daimler Chrysler	NECAR 1 (180 van)	1994	12 fuel cell stacks	50kW/ PEM	Ballard	81mi 130km	N/a	56mph 90km/h	Compress. Hydrogen	First FCV	
	NECAR 2 (V-Class)	1996	Fuel cell	50kW/ PEM	Ballard	155mi 250km	N/a	68mph 110km/h	Compress. hydrogen		
	NECAR 3 (A-Class)	1997	2 fuel cell stacks	50kW/ PEM	Ballard	250mi 400km	N/a	75mph 120km/h	10.5 gal. Of Liquid methanol	First methanol reforming FCV	
	NECAR 4 (A-Class)	1999	Fuel cell	70kW/ PEM	Ballard Mark 700	280mi 450km	N/a	90mph 145km/h	Liquid hydrogen		
	NECAR 4 - Advanced (California NECAR)	2000	Fuel cell/ battery hybrid	75 kW/ PEM	Ballard Mark 900 (XCS-HY-75)	124mi 200km	53.46 mpg equiv. (CaFCP est.)	90mph 145 km/h	4 lb. Of Compress. hydrogen		
	Jeep Commander (SUV)	1999	Fuel cell/ battery hybrid	PEM	Ballard	600mi 970km	N/a	N/a	Methanol		
	NECAR 5 (A-class)	2000	Fuel cell/ battery hybrid	75 kW/ PEM	Ballard	280mi 450km	N/a	95mph 150km/h	Methanol	Awarded a road permit for Japanese roads	
	NECAR 5.2 (A-class)	2001	Fuel cell/ battery hybrid	N/a	Ballard	N/a	N/a	N/a	Methanol	Fleet vehicles expected in 2003	
	DMFC go-cart (one-person vehicle)	2000	Fuel cell	3kW/ DMFC	Ballard (XCS-Me-75)	9.3mi 15km	N/a	22mph 35km/h	Methanol		

	Jeep Commander 2 (SUV)	2000	Fuel cell/ (90 kW) battery hybrid	50 kW/ PEM	Ballard	300mi 400km	24mpg (gasoline equiv.)	N/a	Methanol		
	Sprinter (van)	2001	Fuel cell	75kW/ PEM	Ballard	93mi 150km	N/a	75mph 120km/h	Compress. Hydrogen	Delivered to Hamburg parcel service, Hermes	
	Natrium (Town & Country Mini Van)	2001	Fuel cell/ (40 kW) battery hybrid	54kW/ PEM	Ballard; Millennium Cell reformer	300 mi 483 km	30 mpg equiv.	80mph	Sodium Borohydride (recyclable)	Uses 53 Gallon fuel tank	
ESORO	Hycar	2001	Fuel cell / battery hybrid	6.4 kW/ PEMFC	Nuvera	360 km	N/a	120 km/h	Compress. Hydrogen	Switzerland's first FCV	
Fiat	Seicento Elettra H2 Fuel Cell	2001	Fuel cell/ battery hybrid	7kW/ PEMFC	N/a	100mi 140km	N/a	60mph 100km/h	Hydrogen		
Ford Motor Company	P2000 HFC (sedan)	1999	Fuel cell	75kW/ PEM	Ballard Mark 700	100mi 160km	67.11 mpg equiv. (CaFCP est.)	N/a	Hydrogen	First FCV by Ford	
	P2000 SUV (sport-utility vehicle) (concept)	1999	Fuel cell	PEM	Ballard	N/a	N/a	N/a	Methanol		
	Focus FCV	2000	Fuel cell	75 kW/ PEM	Ballard Mark 900 (XCS-HY-75)	100mi 160km	N/a	80mph 128km/h	3,600 psi Compress. hydrogen		
	TH!NK FC5	2000	Fuel cell	65 kW/ PEM w/ reformer	Ballard Mark 901	N/a	N/a	80mph/ 128km/h	Methanol		
	Advanced Focus FCV	2002	Fuel cell / battery hybrid	85 kW / PEM	Ballard Mark 902	160 – 200 miles	N/a	N/a	4 kg Compress. H2 @ 5,000 psi	Fleet introduction in 2004 (CA)	
GENESIS Project: Ford, H Power & Millennium Cell	Custom built aluminum Mercury Sable	2000	Fuel cell/ battery hybrid	PEMFC	H Power	500mi	~25mpg	N/a	Sodium Borohydride		
VENTURER Project: Ford, NJDOT & H Power	Retrofitted 1996 Geo Metro	1999	Fuel cell/ battery hybrid	4.2 kW/ PEMFC	H Power	400mi	N/a	N/a	Compress. hydrogen		
Fuji Heavy Industries	Subaru Sambar	2001	N/A	N/a	Ballard	N/a	N/a	N/a	Methanol		N/A
General Motors/Opel	Sintra (mini-van)	1997	Fuel cell	50kW/ PEM	N/a	N/a	N/a	N/a	N/a	Wants to be 1st automaker to sell 1 million FCVs	
*Hydrogenics works with GM on FC development	Zafira (mini-van)	1998	Fuel cell	50kW/ PEM	Ballard	300mi 483km	80mpg equiv.	75mph 120km/h	Methanol	GM has ceased efforts regarding methanol	
	HydroGen 1 (Zafira van)	2000	Fuel cell/ battery hybrid	80kW/ PEM	GM*	250mi 400km	N/a	90mph 140km/h	16 gal. Of Liquid hydrogen		
	HydroGen 3 (Zafira van)	2001	Fuel cell	94 kW/ PEM	GM*	250 mi 400 km	N/a	94 mph 150 km/h	Liquid hydrogen	Will start 3 yr. Japanese road test in 7/2002	
	Precept FCEV	2000	Fuel cell/ battery hybrid	100kW/ PEM	GM*	500mi 800km (est.)	108mpg equiv. (est.)	120mph 193km/h	Hydrogen (stored in metal hydride)		
	Chevy S-10 (pickup truck)	2001	Fuel cell / battery hybrid	25kW/ PEM	GM*	525 mi	40 mpg	Governor kicks in at 70 mph	Low sulfur, clean gasoline (CHF)	Fleet gasoline reforming in 2005	

	AUTOnomy (concept)	2002	Fuel cell	N/a	N/a	N/a	Projected 100 mpg	N/a	N/a	Concept only	
	Hy-Wire	2002	Fuel cell	94 kW/ PEM	GM*	N/a	N/a	97 mph 160 km/h	3 cylinders of 5000 psi Compress. hydrogen	2010	
GM (Shanghai) PATAC	Pheonix (mini van)	2001	Fuel cell / battery hybrid	35 kW / PEM	GM*	N/a	N/a	N/a	Compress. hydrogen		
Virginia Tech FCV: GM, DOE, Honeywell	Chevrolet Suburban	2000	Fuel cell/ battery hybrid	85 kW / PEMFC	Honeywell	N/a	N/a	N/a	Hydrogen		
Honda	FCX-V1	1999	Fuel cell / battery hybrid	60kW/ PEM	Ballard	110mi 177km	N/a	78mph 130km/h	Hydrogen (stored in metal hydride)	Goal = 300 FCVs / year starting 2003	
	FCX-V2	1999	Fuel cell	60kW/ PEM	Honda	N/a	N/a	78mph 130km/h	Methanol		
	FCX-V3	2000	Fuel cell / Honda ultra capacitors	62kW/ PEM	Ballard	106mi 173km	N/a	78mph 130km/h	26 gal. Of Compress. hydrogen at 3600 psi	Completed Japanese road testing	
	FCX-V4	2001	Fuel cell / Honda ultra capacitor	78kW/ PEM	Ballard Mark 900 series	185mi 300km	N/a	84mph 140km/h	130 L Compress. H2 @ 5,000 psi	30 FCXs in 2-3 yr.s leased in Torrance, CA and Tokyo, Japan Fall 2002	
	FCX	2002	Fuel cell/ ultra capacitor	78kW / PEM	Ballard Mark 900 series	220mi 355km	N/a	93mph 150km/h	156.6 L Compress. hydrogen @ 5000 psi	1st FCV to receive CARB & nat'l EPA emission certs.	
Humboldt State U. / Schatz Energy Research Center	Kewet (two-seater coupe)	1998	Fuel cell	9kW/ PEM	De Nora	30mi 48km	N/a	35mph 56km/h	Liquid hydrogen		
HyperCar	Revolution (concept car)	2001	Fuel cell/ battery hybrid	N/a	N/a	330 mi 531km	99 mpg	86 mph	Compress. hydrogen		
Hyundai	Santa Fe SUV	2000	Fuel cell	75kW/ PEM	UTC	100mi 160km	N/a	77mph 124km/h	Hydrogen		
	Santa Fe SUV	2001	Fuel cell	75kW/ PEM	UTC	250mi 402km	N/a	N/a	Hydrogen (new IMPCO tank)	2003 - 2004 limited intro. to power utilities & research institutes	
Mazda	Demio (compact passenger car)	1997	Fuel cell	50kW/ PEM	Ballard	106mi 170km	N/a	60mph 90km/h	Hydrogen (stored in metal hydride)		
	Premacy FC-EV	2001	Fuel cell/ battery hybrid	75 kW/ PEM	Ballard (XCS-Me-75)	N/a	N/a	77mph 124km/h	Methanol	2005 – awarded a road permit for Japanese roads	
Metallic Power (CEC / MSRC / SCAQMD)	Geo Force	2002	Fuel Cell/ battery hybrid	4 x 1.25kW/ Zinc-Air FC	Metallic Power's telecom backup power zinc fuel cells	+300mi	N/a	+50mph	Small Zinc Pellets		
Mitsubishi	SpaceLiner (concept)	2001	Fuel cell/ battery hybrid	40kW/ PEM	Ballard	N/a	N/a	N/a	Methanol	Commercial target date in 2005	

Nissan	R'nessa (sport-utility vehicle)	1999	Fuel cell / battery hybrid	10kW/ PEM	Ballard	N/a	N/a	44mph 70km/h	Methanol		
	Xterra (SUV)	2000 / 2001	Fuel cell / battery hybrid	75kW/ PEM	Ballard Mark 900	100mi	N/a	75mph	Compress. hydrogen	Target date of April 2003	
PSA Peugeot Citron	Peugeot Hydro-Gen	2001	Fuel cell / battery hybrid	30 kW	Nuvera	300 km	N/a	95 km/hr	Compress. hydrogen		
	Peugeot Fuel Cell Cab "Taxi PAC"	2001	Fuel cell / battery hybrid	55 kW / PEM	H Power	188 mi 300 km	N/a	60 mph 95 km/h	80 Liters Compress. hydrogen (300 bar)	2006	
	H2O fire-fighting concept	2002	Battery / fuel cell APU	N/a	N/a	N/a	N/a	N/a	N/a		
Renault	FEVER (Laguna station wagon)	1997	Fuel cell / battery hybrid	30kW/ PEM	De Nora	250mi 400km	N/a	75mph 120km/h	Liquid hydrogen	2005-2010	
Suzuki	Covie	2001	Fuel cell	N/a	GM	N/a	N/a	N/a	N/a		
Teledyne / Energy Partners	Green Car	1991	Fuel cell	15kW/ PEM	Energy Partners	60mi 97km	N/a	60mph 97km/h	Compress. hydrogen		
Toyota	RAV 4 FCEV (sport-utility vehicle)	1996	Fuel cell/ battery hybrid	20kW/ PEM	Toyota	155mi 250km	N/a	62mph 100km/h	Hydrogen (stored in metal hydride)		
	RAV 4 FCEV (sport-utility vehicle)	1997	Fuel cell/ battery hybrid	25kW/ PEM	Toyota	310mi 500km	N/a	78mph 125km/h	Methanol		
	FCHV-3 (Kluger V/ Highlander SUV)	2001	Fuel cell/ battery hybrid	90kW/ PEM	Toyota	186mi 300km	N/a	93mph 150km/h	Hydrogen (stored in metal hydride)		
	FCHV-4 (Kluger V/ Highlander SUV)	2001	Fuel cell/ battery hybrid	90kW/ PEM	Toyota	155mi 250km	N/a	95mph 152km/h	Compress. Hydrogen (3600 psi)	Compl. Japanese road testing. 20 leased / year in Japan & US end of 2002	
	FCHV-5 (Kluger V/ Highlander SUV)	2001	Fuel cell/ battery hybrid	90kW/ PEM	Toyota	N/a	N/a	N/a	Low sulfur, clean gasoline (CHF)		
Toyota / Lexus	*Minority Report* concept FCV for year 2054	2002	Fuel cell	500 kW (670 hp)	N/a	N/a	N/a	N/a	N/a	Movie concept only	
VW	HyMotion	2000	Fuel cell	75kW/ PEM	N/a	220mi 350km	N/a	86mph 140km/h	13 gal. Of Liquid Hydrogen		
	HyPower	2002	Fuel Cell / super-capacitors hybrid	40kW/ PEM	Paul Scherrer Institute	94 mi / 150 km	N/a	N/a	Hydrogen		
Zevco	Millennium Taxi	1999	Fuel cell/ battery hybrid	5kW/ AFC	Zevco	N/a	N/a	N/a	Hydrogen		

4.2 Patent review

U.S. and European patent search engines were used for this patent review.

4.2.1 Total number of US patents on internal-combustion engines

The following table shows the total number of US patents of manufacturers on internal-combustion engines.

Source: http://www1.uspto.gov/web/offices/ac/ido/oeip/taf/tecasg/123_tor.htm

Table 4.2-1: Number of US patents on internal combustion engines, listed by company

Rank Ordered Listing of Organizations Receiving 5 or More Utility Patents During the Period 1997-2001, Having Primary Classification in Class 123, Internal-Combustion Engines (technology class is determined by the primary classification assigned to the patent- see 'Explanation of Data'). (patent ownership is determined by the first-named assignee listed on a patent).

First-Named Assignee	1997	1998	1999	2000	2001	Total
~Individually Owned Patent	123	159	135	129	195	**741**
HONDA GIKEN KOGYO KABUSHIKI KAISHA (HONDA MOTOR CO., LTD.)	76	63	61	48	103	**351**
TOYOTA JIDOSHA K.K.	56	84	76	45	71	**332**
ROBERT BOSCH GMBH	48	66	46	80	89	**329**
FORD GLOBAL TECHNOLOGIES, INC.	25	43	51	52	82	**253**
CATERPILLAR INC.	43	32	34	73	52	**234**
YAMAHA HATSUDOKI KABUSHIKI KAISHA, YAMAHA MOTOR CO., LTD.	40	73	29	35	27	**204**
NISSAN MOTOR COMPANY, LIMITED	24	15	40	48	48	**175**
SANSHIN KOGYO KABUSHIKI KAISHA	27	40	36	37	34	**174**
MITSUBISHI DENKI KABUSHIKI KAISHA	30	14	23	29	55	**151**
HITACHI, LTD	22	21	21	30	30	**124**
DENSO CORPORATION	4	20	23	36	28	**111**
UNISIA JECS CORPORATION	26	16	17	23	27	**109**
CUMMINS ENGINE CO., INC.	18	22	22	25	17	**104**
GENERAL MOTORS CORPORATION	25	19	23	21	16	**104**
DAIMLER-CHRYSLER AKTIENGESELLSCHAFT	0	0	13	41	45	**99**
DAIMLER-BENZ AKTIENGESELLSCHAFT	28	38	25	6	1	**98**
MITSUBISHI JIDOSHA KOGYO KABUSHIKI KAISHA	11	28	26	12	5	**82**
CHRYSLER MOTORS CORPORATION	24	15	20	13	2	**74**
INA WALZLAGER SCHAEFFLER OHG	0	6	19	20	25	**70**
SIEMENS AKTIENGESELLSCHAFT	3	6	14	20	19	**62**
SUZUKI MOTOR CORPORATION	2	6	22	14	17	**61**
FORD MOTOR COMPANY	39	9	6	5	1	**60**
NIPPONDENSO CO., LTD.	32	22	2	3	1	**60**
SIEMENS CANADA LTD.	0	1	16	12	24	**53**
BRUNSWICK CORPORATION	8	10	13	11	9	**51**
ISUZU MOTORS LIMITED	3	8	7	12	20	**50**
FEV MOTORENTECHNIK GMBH & CO. KG	9	10	11	7	9	**46**
EATON CORPORATION	13	2	12	6	12	**45**
DELPHI TECHNOLOGIES, INC.	0	0	0	5	39	**44**
AISIN SEIKI KABUSHIKI KAISHA	4	8	11	13	7	**43**
DAIMLERCHRYSLER CORPORATION	0	0	4	12	24	**40**
LUCAS INDUSTRIES PUBLIC LTD. COMPANY	12	9	5	7	7	**40**
SIEMENS AUTOMOTIVE CORPORATION	3	8	5	11	12	**39**
MAZDA MOTOR CORPORATION	8	5	4	12	9	**38**
KIORITZ CORPORATION	5	2	15	8	6	**36**
FUJI JUKOGYO KABUSHIKI KAISHA	9	10	8	4	4	**35**

First-Named Assignee	1997	1998	1999	2000	2001	Total
WALBRO CORPORATION	11	6	6	5	7	**35**
HYUNDAI MOTOR CO., LTD.	7	7	8	6	6	**34**
DETROIT DIESEL CORPORATION	3	3	3	11	12	**32**
PORSCHE AG	8	5	7	5	6	**31**
DIESEL ENGINE RETARDERS, INC.	2	6	3	9	10	**30**
BAYERISCHE MOTOREN WERKE AG	2	6	3	7	10	**28**
FILTERWERK MANN + HUMMEL GMBH	2	1	5	12	8	**28**
INA WALZLAGER SCHAEFFLER KG	9	15	4	0	0	**28**
OUTBOARD MARINE CORPORATION	6	7	6	4	5	**28**
BRIGGS + STRATTON CORPORATION	4	4	1	6	8	**23**
ORBITAL ENGINE COMPANY (AUSTRALIA) PTY. LTD.	3	6	6	5	3	**23**
NAVISTAR INTERNATIONAL TRANSPORTATION CORP.	4	2	6	8	2	**22**
AKTIEBOLAGET ELECTROLUX	1	7	4	4	5	**21**
GENERAL ELECTRIC COMPANY	0	1	1	3	16	**21**
ZEXEL CORPORATION	10	3	5	2	1	**21**
AVL LIST GMBH	0	1	5	5	9	**20**
C.R.F. SOCIETA CONSORTILE PER AZIONI	0	6	2	7	5	**20**
FUJI OOZX INC.	7	5	6	0	2	**20**
NIPPON SOKEN, INC.	6	4	3	4	3	**20**
VISTEON GLOBAL TECHNOLOGIES, INC.	0	0	0	2	17	**19**
DANA CORPORATION	1	1	1	4	11	**18**
ANDREAS STIHL AG & CO.	0	1	1	5	10	**17**
INSTITUT FRANCAIS DU PETROLE	0	6	2	7	2	**17**
VOLKSWAGEN AKTIENGESELLSCHAFT	3	2	5	5	2	**17**
AB VOLVO	5	2	3	2	4	**16**
KOMATSU LTD.	3	2	3	3	4	**15**
SUZUKI KABUSHIKI KAISHA	2	5	2	2	4	**15**
BORGWARNER INC.	0	0	0	3	11	**14**
MITSUBISHI HEAVY INDUSTRIES CO., LTD.	0	0	6	3	5	**14**
SIEMENS ELECTRIC LIMITED	6	7	1	0	0	**14**
TECUMSEH PRODUCTS COMPANY	1	1	4	2	6	**14**
MOTORENFABRIK HATZ GMBH + CO. KG	1	1	2	6	3	**13**
SIEMENS AUTOMOTIVE S.A.	4	4	1	1	3	**13**
SOUTHWEST RESEARCH INSTITUTE	0	5	3	2	3	**13**
ISUZU CERAMICS RESEARCH INSTITUTE CO., LTD.	1	5	3	3	0	**12**
AISAN INDUSTRY CO., LTD.	0	4	2	4	1	**11**
AVL GESELLSCHAFT FUR VERBRENNUNGSKRAFTMASCHINEN UND MESSTECH	8	2	1	0	0	**11**
BEHR GMBH & CO.	2	3	2	1	3	**11**
KOHLER CO.	2	3	1	2	3	**11**
MAGNETI MARELLI S.P.A.	1	3	1	2	4	**11**
FUTABA DENSHI KOGYO KABUSHIKI KAISHA	0	3	4	1	2	**10**
KIA MOTORS CORP.	5	5	0	0	0	**10**
META MOTOREN-UND ENERGIE-TECHNIK GMBH	1	2	2	3	2	**10**
MOTOREN-UND TURBINEN-UNION FRIEDRICHSHAFEN GMBH	3	3	0	0	4	**10**
NGK SPARK PLUG CO., LTD.	1	3	2	1	3	**10**
PHILLIPS & TEMRO INDUSTRIES INC.	1	1	4	4	0	**10**
TCG UNITECH AKTIENGESELLSCHAFT	0	0	1	3	6	**10**
DEUTZ AG	0	0	2	4	3	**9**
HARLEY-DAVIDSON MOTOR CO., INC.	1	0	2	4	2	**9**
M.A.N.-B & W DIESEL A/S	0	4	1	1	3	**9**
MAHLE GMBH	1	2	2	2	2	**9**
MANNESMANN VDO AG	0	0	0	1	8	**9**
VOLVO LASTVAGNAR AB	0	0	0	0	9	**9**
DOLMAR GMBH	0	1	0	4	3	**8**
J. M. VOITH TURBO GMBH & CO. KG	2	4	1	0	1	**8**
KUBOTA CORPORATION	1	2	1	2	2	**8**
MECEL AB	2	3	1	2	0	**8**
PERKINS ENGINES COMPANY LIMITED	0	0	1	1	6	**8**
TOYODA JIDOSHOKKI SEISAKUSHO KABUSHIKI KAISHA	0	3	2	2	1	**8**
ALLIED-SIGNAL INC.	1	0	2	3	1	**7**
ANDREAS STIHL MASCHINENFABRIK	3	3	1	0	0	**7**
AUDI AG	2	2	1	0	2	**7**
BOMBARDIER MOTOR CORPORATION OF AMERICA	0	0	0	0	7	**7**
DEERE + COMPANY	0	0	1	0	6	**7**
DIESEL TECHNOLOGY COMPANY	1	2	0	4	0	**7**

First-Named Assignee	1997	1998	1999	2000	2001	Total
GUL & CO DEVELOPMENT AB	0	0	0	7	0	7
HYDRAULIK-RING GMBH	0	0	0	3	4	7
ISAD ELECTRONIC SYSTEMS GMBH & CO. KG	0	0	0	6	1	7
KOKUSAN DENKI CO., LTD	0	0	2	2	3	7
KOMATSU ZENOAH CO.	0	0	0	3	4	7
MECHADYNE PLC	0	0	0	0	7	7
MOTOROLA, INC.	3	3	1	0	0	7
NORTHROP GRUMMAN CORPORATION	2	3	1	0	1	7
PIERBURG AG	1	4	2	0	0	7
SCANIA CV AKTIEBOLAG	0	2	1	0	4	7
STANADYNE AUTOMOTIVE CORP.	1	2	2	2	0	7
VALEO EQUIPEMENTS ELECTRIQUES MOTEUR	0	1	4	1	1	7
BASF CORP.	3	2	1	0	0	6
BORG-WARNER AUTOMOTIVE, INC.	4	0	2	0	0	6
COMPETITION CAMS, INC.	0	0	1	1	4	6
FEDERAL-MOGUL WORLD WIDE, INC.	0	0	2	2	2	6
HITACHI CONSTRUCTION MACHINERY CO., LTD.	0	1	2	1	2	6
INTERNATIONAL TRUCK AND ENGINE CORP.	0	0	0	0	6	6
KEIHIN CORPORATION	0	0	0	3	3	6
MIKUNI CORPORATION	2	3	0	0	1	6
NIPPON PISTON RING CO., LTD.	0	1	2	1	2	6
OY WARTSILA DIESEL INTERNATIONAL LTD.	1	3	2	0	0	6
U.S. PHILIPS CORPORATION	1	2	3	0	0	6
UNITED STATES OF AMERICA, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION	0	1	1	4	0	6
VDO ADOLF SCHINDLING AG	0	5	0	1	0	6
WESTPORT RESEARCH INC.	0	1	2	0	3	6
WOODWARD GOVERNOR COMPANY	0	2	2	1	1	6
CUMMINS ENGINE COMPANY LIMITED	0	0	0	0	5	5
DESIGN AND MANUFACTURING SOLUTIONS, INC.	0	0	0	1	4	5
FICHT GMBH & CO. KG	0	0	2	3	0	5
INDUSTRIAL TECHNOLOGY RESEARCH INSTITUTE, TAIWAN	1	0	1	2	1	5
KAWASAKI JUKOGYO KABUSHIKI KAISHA	1	0	3	1	0	5
MAGNETI MARELLI FRANCE	1	0	2	1	1	5
MAN B&W DIESEL AKTIENGESELLSCHAFT	0	0	3	1	1	5
MATSUSHITA ELECTRIC INDUSTRIAL CO., LTD.	1	2	1	0	1	5
R. E. PHELON COMPANY, INC.	0	3	2	0	0	5
ROVER GROUP LIMITED	2	2	1	0	0	5

The following overview presents a number of US patents in different areas in automotive research. The list is far from complete, but offers an idea of what manufacturers are working on.

Patents are derived from the USPTO Patent Full-Text and Image Database.
http://patft.uspto.gov/netahtml/search-bool.html

4.2.2 Developments in ICE technology

United States Patent **6,449,572**

Kurz , et al. **September 10, 2002**

Method and device for classifying the driving style of a driver in a motor vehicle

Abstract

In a method for classifying the driving style of a driver in a motor vehicle, measured variables indicative of driving style are recorded and driving-style classification figures are determined by a comparison with reference values, parameter settings corresponding to the driving-style classification figures being carried out to adapt the functioning of a regulation and control unit. In order to improve the handling of a motor vehicle with the aid of a driver classification, it is provided that presettings for the driving-style classification figures are stored in the regulation and control unit of the motor vehicle, it being possible to prescribe driving-style classification figures for a plurality of different driver reaction stages, and that the current driver is classified in a prescribed driver reaction stage in the motor vehicle by measuring classifying indicators, and driving-style classification figures corresponding to the driver reaction stage are activated in the regulation and control unit.

Assignee: **DaimlerChrysler AG** (Stuttgart, DE)

United States Patent **6,390,056**

Hertzberg , et al. **May 21, 2002**

Method for operating a spark ignition engine with direct fuel injection

Abstract

In a method for operating a spark ignition engine with direct fuel injection, in which the engine is operated either with charge stratification or with a homogeneous charge, the open and/or closed positions of the inlet and exhaust valves are controlled with variable timing depending on the engine operating condition. The timings are determined on the basis of basic timing settings, which are provided in basic timing performance graphs for operation with charge stratification and homogeneous charge operation. The basic timing settings are modified by means of correction values to raise the temperature of the exhaust gas for internal exhaust-gas recirculation and for causing a movement of the charge in the cylinders.

Assignee: **DaimlerChrysler AG** (Stuttgart, DE)

United States Patent **6,092,507**

Bauer , et al. **July 25, 2000**

Control arrangement for a direct-injecting internal combustion engine

Abstract

The invention is directed to a control arrangement for a direct injected gasoline engine. A sensor detects at least one operating variable of the engine and an actuator adjusts the air supplied to the engine. A control unit switches the engine between a stratified charge mode of operation and a homogeneous mode of operation in dependence upon the one operating variable of the engine. The control unit drives the actuator so as to cause the actuator to undergo a defined displacement when the control unit switches between the modes of operation so that the torque of the engine is essentially the same before and after the switchover between the modes of operation.

Assignee: **Robert Bosch GmbH** (Stuttgart, DE)

United States Patent **6,125,801**

Mendler **October 3, 2000**

Lean-burn variable compression ratio engine

Abstract

The efficiency of a spark-ignition internal-combustion engine having an adjustable fuel-to-air mixture ratio is improved significantly by reducing the fuel-to-air mixture ratio and increasing compression ratio. The increase in compression ratio and the reduction in fuel-to-air mixture ratio causes the engine to operate at higher efficiency and with lower air pollution levels, and without detrimental engine knock or misfire.

Inventors: **Mendler; Edward Charles** (3522 Northampton St., NW, Washington, DC 20015)

4.2.3 DeNO$_x$ catalysts

United States Patent **6,413,483**

Brisley , et al. **July 2, 2002**

Catalytic converter for a lean burn internal combustion engine

Abstract

A layered exhaust gas catalyst containing Pt in a first layer and Rb in a second layer is more selective for catalysing the reaction between NO_x and/or nitrate with hydrocarbons and/or CO than for catalysing the reaction between hydrocarbons and/or CO with oxygen. NO_x can be reduced to N_2 under constant lean to stoichiometric conditions without the need for rich spikes.

Assignee: **Johnson Matthey Public Limited Company** (London, GB)

United States Patent **6,370,871**

Suzuki , et al. **April 16, 2002**

Internal combustion engine having lean NO_x catalyst

Abstract

An internal combustion engine having a lean NO_x catalyst is capable of relieving a load upon an engine fuel injection device by eliminating the use of sub-injection, and of well purifying an exhaust gas and recovering from S-poisoning even by eliminating the use of the sub-injection. The internal combustion engine has a combustion heater for allowing a flow of combustion gas through an engine intake passageway to raise temperatures of engine related elements, a lean NO_x catalyst, provided in an engine exhaust passageway, for purifying an engine exhaust gas, and a combustion gas introducing passageway for introducing at least some proportion of a combustion gas emitted by the combustion heater, toward upstream of the lean NO_x catalyst in the engine exhaust passageway from the engine intake passageway when making a request for a reproducing process of the lean NO_x catalyst.

Assignee: **Toyota Jidosha Kabushiki Kaisha** (Toyota, JP)

United States Patent **6,230,487**

Blumenstock , et al. **May 15, 2001**

Method for regenerating a catalytic converter

Abstract

The disclosure is directed to a method for improving the exhaust-gas quality, which is reduced by sulphur influence, in combustion processes with exhaust-gas catalytic converters. In the method, the oxygen storage capability of the catalytic converter is determined and is compared to a threshold value. When there is a drop below the threshold value, the exhaust-gas temperature is increased and/or an exhaust-gas composition, which acts in a reducing manner, is generated forward of the catalytic converter.

Assignee: **Robert Bosch GmbH** (Stuttgart, DE)

United States Patent **5,921,076**

Krutzsch , et al. **July 13, 1999**

Process and apparatus for reducing nitrogen oxides in engine emissions

Abstract

A process and apparatus for reducing the nitrogen oxide content in oxygen-containing emissions is provided, particularly for internal-combustion engines, particularly of diesel engines and directly injecting Otto engines for motor vehicles. The nitrogen oxides contained in the exhaust gas are reduced by a suitable reducing agent, such as hydrogen or hydrocarbons, on a $deNO_x$ catalyst. For achieving an improved conversion rate for the nitrogen oxides, a combination of hydrogen and hydrocarbons are used as reducing agents. In different operating ranges of the internal-combustion engine only hydrogen, only hydrocarbons, or hydrogen and hydrocarbons are added. Preferably, for this purpose, the quantity of supplied hydrogen or hydrocarbons is reduced or increased with an increasing engine load and/or catalyst temperature and/or rotational engine speed.

Assignee: **Daimler-Benz AG** (Stuttgart, DE)

4.2.4 Alternative fuel engines

United States Patent **5,806,490**

Nogi , et al. **September 15, 1998**

Fuel control system for a gaseous fuel internal combustion engine with improved fuel metering and mixing means

Abstract

A fuel management system for a gaseous fuel internal combustion engine is disclosed in which a mass air flow sensor as well as a mass gas flow sensor provide input signals to an electronic control unit (ECU) which then determines the air/fuel ratio. The ECU in turn generates output signals to a fuel valve to control the mass of fuel flow to the engine and thus the air/fuel ratio. A turbocharger bypass valve, a precooler for the gaseous fuel supply, a pressure accumulator upstream from the fuel valve, as well as a system to calibrate the engine to the specific gaseous fuel is described to enhance the accuracy of the fuel management system. An improved pressure balanced valve for controlling the fuel flow to the engine is also provided as well as a cylinder pressure transducer to optionally provide an output signal to the ECU to determine the air/fuel ratio.

Assignee: **Hitachi America, Ltd., Research and Development Division** (Tarrytown, NY)

United States Patent **6,431,471**

Anzinger , et al. **August 13, 2002**

Bi-fuel injector, in particular for combustion engines, and method of injection

Abstract

A flushable bi-fuel injector, in particular for combustion engines, comprises a nozzle body incorporating a nozzle exit (11), a movably held valve needle (12) for opening and closing the nozzle exit (11), a first supply channel (13) for supplying a first liquid or a first fuel to the nozzle exit (11); and a second supply channel (23) for supplying a second liquid or a second fuel or a liquid additive to the nozzle exit (11). A ring-shaped slide gate (21) or a ring piston is arranged in a ring-shaped chamber (20) within the nozzle body (1). The slide gate (21) can be hydraulically activated to either side via differential pressure. Depending on its position, the slide gate (21) connects either the first supply channel (13) or the second supply channel (23) to the nozzle exit (11). During operation, depending on operational requirements, either a first liquid or a first fuel or a second liquid which can be a second fuel or a starting fuel, is conveyed to a combustion chamber of an internal combustion engine, with the pressure differential between the first liquid and the second liquid causing switchover of the supply in the bi-fuel injector.

Assignee: **DaimlerChrysler AG** (Stuttgart, DE)

4.2.5 Hybrid vehicles

United States Patent **6,394,209**

Goehring , et al. **May 28, 2002**

Motor vehicle serial hybrid drive for I.C. engine operated only at or near full load

Abstract

A serial hybrid drive has an internal combustion engine, a generator coupled mechanically to the internal combustion engine, an energy store coupled electrically to the generator, and at least one electric drive motor electrically connected to the generator and the energy store. The internal combustion engine/generator unit is operated along an operating characteristic whose power corresponds to the temporally smoothed power requirement of the electric drive motor, and the internal combustion engine is always operated at or near full load. In such case, the energy store has an energy storage capacity of at most a few kilowatt hours and a high power density, and compensates for the short-term power differences between the instantaneous power requirement of the electric drive motor and the power output by the internal combustion engine/generator unit and corresponding to the temporally smoothed power requirement of the electric drive motor.

Assignee: **DaimlerChrysler AG** (Stuttgart, DE)

United States Patent **6,371,877**

Schroeder , et al. **April 16, 2002**

Starter--generator system

Abstract

A starter--generator system for motor vehicles permits implementation of various starting methods including direct start and impulse start. The system also facilitates additional operating modes, including generator operation and/or recuperation operation. The starter-generator system electric machine which can be used as the starter and the generator is to be connected by way of a planetary drive with a shaft train situated between an internal-combustion engine and a transmission, the planetary drive being at least partially usable as a centrifugal mass for impulse starting operations.

Assignee: **DaimlerChrysler AG** (Stuttgart, DE)

United States Patent **6,344,008**

Nagano , et al. **February 5, 2002**

Hybrid vehicle

Abstract

A hybrid vehicle comprises: a first driving force source; a transmission for transmitting the torque of the first driving force source therethrough to wheels; a second driving force source; and a torque transmitting route interposed between the driving force source and the wheels for inputting the torque of the second driving force source. The hybrid vehicle further comprises a torque adding route for synthesizing the torque outputted from the transmission and the torque transmitted from the second driving force source, to output the synthesized torque to an output member.

Assignee: **Toyota Jidosha Kabushiki Kaisha** (Toyota, JP)

United States Patent **6,315,068**

Hoshiya , et al. **November 13, 2001**

Drive control system for hybrid vehicles

Abstract

A drive control system for a hybrid vehicle, in which the output torques of an electric motor and an internal combustion engine are synthesized by and outputted from a torque synthesizing/distributing mechanism. The target speed of the engine is determined on the basis of the output demand for the engine and the output speed of the torque synthesizing/distributing mechanism, and the target speed of the motor is determined on the basis of the target speed of the engine and the output speed of the torque synthesizing/distributing mechanism. The output of the engine is controlled to the output torque which is determined on the basis of the output demand for the engine and the target speed of the engine, and the output speed of the motor is controlled to the target speed.

Assignee: **Toyota Jidosha Kabushiki Kaisha** (Toyota, JP)

United States Patent **6,307,276**

Bader **October 23, 2001**

Method for operating a parallel hybrid drive for a vehicle

Abstract

In a method for operating a parallel motor vehicle hybrid drive, with an internal combustion engine which is connected to a drive shaft via a clutch and a manual transmission, and with a three-phase machine which is directly coupled with its rotor to a countershaft of the manual transmission and is connected to an electrical energy store via a three-phase converter, a time average of the driving torque required during a respective predeterminable travel time interval is determined by a hybrid drive control unit. The power outputs of the internal combustion engine and of the three-phase machine are controlled so that the internal combustion engine outputs driving torque corresponding to the time average determined, and the three-phase machine outputs the difference between the driving torque currently required and the driving torque delivered by the internal combustion engine.

Assignee: **DaimlerChrysler AG** (Stuttgart, DE)

4.2.6 Fuel-cell systems

4.2.6.1 Online European Patent Register

A restricted European Patent search has been done through the following web-site: http://register.epoline.org/espacenet/ep/en/srch-reg.htm

Fuel-cell patents can be found in the following IPC classification:

H 01 BASIC ELECTRIC ELEMENTS

H 01 M PROCESSES OR MEANS, e.g. BATTERIES, FOR THE DIRECT CONVERSION OF CHEMICAL ENERGY INTO ELECTRICAL ENERGY (electrochemical processes or apparatus in general C25; semiconductor or other solid state devices for converting light or heat into electrical energy H01L, e.g. H01L 31/00, H01L 35/00, H01L 37/00)

8/00 Fuel cells; Manufacture thereof
Note: In this group, fuel cells are electrochemical generators wherein the reactants are supplied from outside

8/02 Details (of non-active parts H01M 2/00, of electrodes H01M 4/00)
8/04 Auxiliary arrangements or processes, e.g. for control of pressure, for circulation of fluids
8/06 Combination of fuel cell with means for production of reactants or for treatment of residues (regenerative fuel cells H01M 8/18; production of reactants per se, see sections B or C)
8/08 Fuel cells with aqueous electrolytes
8/10 Fuel cells with solid electrolytes
8/12 operating at high temperature, e.g. with stabilised ZrO_2 electrolyte
8/14 Fuel cells with fused electrolytes
8/16 Biochemical fuel cells, i.e. cells in which micro-organisms function as catalysts
8/18 Regenerative fuel cells
8/20 Indirect fuel cells, e.g. redox cells (H01M 8/18 takes precedence)
8/22 Fuel cells in which the fuel is based on materials comprising carbon or oxygen or hydrogen and other elements; Fuel cells in which the fuel is based on materials comprising only elements other than carbon, oxygen, or hydrogen
8/24 Grouping of fuel cells into batteries, e.g. modules

4.2.6.2 Website: the Hydrogen and Fuel Cell Investor

In the following link a very extensive overview is given of US-patents in the fuel cell area. http://www.h2fc.com/patents.html

Selected FC related patents held by:
Avista Labs - Ballard - Energy Conversion Devices - Ford - FuelCell Energy - General Motors - H Power - Honda - Hydrogenics - Manhattan Scientifics - Medis - Motorola - Nuvera - OMG - Plug Power - Proton Energy Systems - Siemens - Stuart Energy - Toyota - UTC Fuel Cells - Others

Ballard Power Systems

9/3/02	US6444345: Fuel cell system **(Xcellsis GmbH)**
9/3/02	US6444179: Autothermal reformer
8/20/02	US6437011: .alpha.,ß, ß-trifluorostyrene-based composite membranes
7/23/02	US6423439: Membrane electrode assembly for an electrochemical fuel cell
7/9/02	US6416895: Solid polymer fuel cell system and method for humidifying and adjusting the temperature of a reactant stream
7/2/02	US6413664: Fuel cell separator plate with discrete fluid distribution features
6/25/02	US6410175: Fuel cell system with improved starting capability
3/19/02	US6359019: Graft polymeric membranes and ion-exchange membranes formed therefrom
2/26/02	US6350538: Fuel cell with fluid distribution layer having intergral sealing capability
12/11/01	US6329089: Method and apparatus for increasing the temperature of a fuel cell
11/27/01	US6322914: Method and apparatus for distributing water in an array of fuel cell stacks
11/13/01	US6316134: Fuel cell electric power generation system
10/23/01	Method of reducing fuel cell performance degradation of an electrode comprising porous components
9/25/01	US6294149: Process for operating a water vapor reforming system, a reforming system operable thereby and a fuel cell system operating process **Xcellsis**
9/18/01	Continuous method for manufacturing a Laminated electrolyte and electrode assembly
9/04/01	US6284397: Rotary piston blower for supplying an oxidant stream to a fuel cell
8/21/01	US6276473: Hybrid vehicle having a an internal-combustion engine, a fuel cell system and an electric drive motor **Xcellsis**
7/31/01	US6268075: Process for the water vapor reforming of a hydrocarbon or a hydrocarbon derivative, reforming system operable thereby, and fuel cell operating process **Xcellsis**
7/10/01	US6258861: .alpha.,ß,ß-trifluorostyrene-based composite membranes
7/10/01	US6258239: Process for the manufacture of an electrode for a solid polymer fuel cell
6/5/01	US6241792: Method for producing a hydrogen-rich and low carbon monoxide gas **Xcellsis**
5/15/01	US6232008: Electrochemical FC stack with improved reactant manifolding and sealing
5/15/01	Hydrogen separating membrane, methanol reformation system equipped therewith, and operating method therefor **Xcellsis**
5/01/01	US6223844: Fuel cell engine having a propulsion motor operatively connected to drive a fluid supply device **Xcellsis**
4/03/01	US6210820: Method for operating fuel cells on impure fuels
2/20/01	US6190791: Proton exchange membrane (PEM) fuel cell system and process of operating same **Xcellsis**
1/30/01	Reactor unit for a catalytic chemical reaction, especially for a catalyzing methanol reformer **Xcellsis**
08/22/00	US6106964: Solid polymer fuel cell system and method for humidifying and adjusting the temperature of a reactant stream
8/1/00	US6096448: Method and apparatus for operating an electrochemical fuel cell with periodic fuel starvation at the anode
6/13/00	US6074773: Impregnation of microporous electrocatalyst particles for improving performance in an electrochemical fuel cell
5/23/00	US6066409: Electrochemical fuel cell stack with improved reactant manifolding and sealing
5/16/00	US6063515: Integrated FC electric power generation system for submarine applications
5/9/00	US6060190: Fuel Cell membrane electrode assembly with porous electrode substrate
5/2/00	US6057053: Compression assembly for an electrochemical fuel cell stack
2/23/99	US5874182 Method and apparatus for reducing reactant crossover in a liquid feed fuel cell
11/23/99	US5991670: Power control system for a fuel cell powered vehicle **dbb Fuel Cell Engines GmbH, now Xcellsis**
8/10/99	US5935726: Method and apparatus for distributing water to an ion-exchange membrane in a fuel cell

Ford

6/18/02	US6406805: Method for storing purged hydrogen from a vehicle fuel cell system

4/30/02 US6378636: Method and system for providing for vehicle drivability feel after accelerator release in an electric or hybrid electric vehicle
4/9/02 US6368735: Fuel cell power generation system and method for powering an electric vehicle
12/11/01 US6329091: Fuel reformer system for a fuel cell **Ford Global Technologies, Inc., Dearborn, MI**
9/25/01 US6294128: Method of making a supported plurality of electrochemical extruded membranes **Ford Global Technologies, Inc., Dearborn, MI**
9/18/01 US6290594: System and method for ventilating hydrogen gas from a vehicle **Ford Global Tech., Inc., Dearborn, MI**
10/4/83 US4407902: Chemically regenerable redox fuel cell and method of operating the same **Ford Motor Company**
3/25/80 US4195119: Fuel cell **Ford Motor Company**
4/20/76 US3951689: Alkali metal/sulfur cell with gas fuel cell electrode **Ford Motor Company**

General Motors

8/13/02 US6432568: Water management system for electrochemical engine
8/6/02 US6428921: Fuel cell stack compression method and apparatus
7/9/02 US6416893: Method and apparatus for controlling combustor temperature during transient load changes
7/2/02 US6413662: Fuel cell system shutdown with anode pressure control
7/2/02 US6413661: Method for operating a combustor in a fuel cell system
6/18/02 US6406806: Fuel cell voltage monitoring and system control
5/28/02 US6395414: Staged venting of fuel cell system during rapid shutdown
5/28/02 US6394207: Thermal management of fuel cell powered vehicles
5/21/02 US6391484: Fuel processor temperature monitoring and control
4/23/02 US6376112: Controlled shutdown of a fuel cell
4/23/02 US6376111: System and method for controlling the humidity level of a fuel cell
4/16/02 US6372376: Corrosion resistant PEM fuel cell
4/2/02 US6365289: Cogeneration system for a fuel cell
3/26/02 US6360835: Thermal management of fuel-cell-powered vehicles
3/19/02 US6358642: Flow channels for fuel cell
3/19/02 US6358638: Cold start-up of a PEM fuel cell
3/19/02 US6358637: Freeze-protecting a fuel cell by vacuum drying
2/26/02 US6350539: Composite gas distribution structure for fuel cell
11/27/01 US6323626: DC/DC converter for a fuel cell having a non-linear inductor
10/30/01 US6309773: Serially-linked serpentine flow channels for PEM fuel cell
10/23/01 US6306531: Combustor air flow control method for fuel cell apparatus
9/25/01 US6294278: Combination of low and high temperature fuel cell device
8/21/01 US6277513: Layered electrode for electrochemical cells
7/31/01 US6268074: Water injected fuel cell system compressor
7/24/01 US6265092: Method of controlling injection of oxygen into hydrogen-rich fuel cell feed stream
7/17/01 USRE37284: Corrosion resistant PEM fuel cell
5/1/01 US6223843:Electrochemical propulsion system
10/17/00 US6132689: Multi-stage, isothermal CO preferential oxidation reactor **(fuel processor)**
8/15/00 US6103409: Fuel cell flooding detection and correction
8/8/00 US6099984: Mirrored serpentine flow channels for fuel cell
6/20/00 US6077620: Fuel cell system with combustor-heated reformer
6/13/00 US6074692: Method of making MEA for PEM/SPE fuel cell
5/16/00 US6063516: Method of monitoring CO concentrations in hydrogen feed to a PEM fuel cell
12/14/99 US6001499: Fuel cell CO sensor
8/31/99 US5945229: Pattern recognition monitoring of PEM fuel cell
3/23/99 US5886614: Thin film hydrogen sensor
6/7/98 US5776624: Brazed bipolar plates for PEM fuel cells
6/9/98 US5763113: PEM fuel cell monitoring system
1/13/98 US5707755: PEM/SPE fuel cell
9/23/97 US5670115: Hydrogen sensor
4/29/97 US5624769: Corrosion resistant PEM fuel cell

Honda

7/16/02 US6420061: Fuel cell stack
7/9/02 US6416899: Fuel cell stack
6/18/02 US6406809: Fuel cell comprising a separator provided with coolant passages
4/30/02 US6378637: Fuel-cell-powered electric automobile
2/26/02 US6350540: Fuel cell with gas diffusion layer flow passage
9/25/01 US6294280: Fuel cell stack **Honda Giken Kabushiki Kaisha, Tokyo**
9/18/01 US6290877: Method of starting and stopping methanol reforming apparatus and apparatus for supplying fuel to said apparatus
07/10/01 US6258475: Fastening structure for fuel cell stack **Honda**
07/03/01 US6255011: Fuel cell stack **Honda**
06/05/01 US6242119: Fuel cell system and draining method for the same **Honda**
2/6/01 US6182717: Process for filling hydrogen into a hydrogen storage tank in automobile **Honda**
1/30/01 US6180273: Fuel cell with cooling medium circulation arrangement and method
9/26/00 US6124060: Solid polymer electrolytes
4/4/00 US6045933: Method of supplying fuel gas to a fuel cell
10/12/99 US5965288: Gas humidifying device for use with a fuel cell
7/14/98 US5780179: Fuel cell system for use on mobile bodies
5/19/98 US5752988: Method for producing electrode unit for fuel cell
4/7/98 US5736269: Fuel cell stack and method of pressing together the same
3/3/98 US5723228: Direct methanol type fuel cell

Toyota

9/3/02 US6444338: Fuel cell system with improved startability
8/27/02 US6440597: Seal and fuel cell with the seal
8/27/02 US6440598: Separator for low temperature type fuel cell and method of production thereof
8/6/02 US6428915: Apparatus for regulating humidity of process air in fuel cell system
7/9/02 US6416894: Hydrogen generator with fuel cell and control method for the same
7/2/02 US6413491: Reformer, method of reforming, and fuel cell system equipped with the reformer
5/21/02 US6390030: Fuel reformer for mounting on a vehicle
8/7/02 US6383678: Separator for fuel cell and a method for producing the separator
5/7/02 US6383672: Temperature regulator for fuel cell
2/26/02 US6350423: Apparatus and method for reducing carbon monoxide concentration and catalyst for selectively oxidizing carbon monoxide
1/15/02 US6338472: Mist atomizer and mist atomizing device for fuel cells
12/25/01 US6332901: Carbon monoxide reducing device for reducing carbon monoxide in a reformate gas
9/25/01 US6294276: Hydrogen manufacturing and supplying apparatus and electric motorcar **Toyota**
9/18/01 US6291094: Separator for fuel cell, fuel cell incorporating the same, and method of production of the same **Toyota**
8/28/01 US6280872: Electrode for fuel cell and a method for producing the electrode **Toyota**
8/21/01 US6277511: Fuel cell **Toyota**
7/3/01 US6255008: Fuel cell system capable of reducing electric power loss **Toyota**
6/19/01 US6248466: Gas separator for a fuel cell, and fuel cell using the same gas separator for a fuel cell **Toyota**

4.2.6.3 US patent search

The following overview shows some more interesting patents on fuel cells, with their abstract.

United States Patent **6,408,966**

Benz , et al. **June 25, 2002**

Fuel cell vehicle

Abstract

A fuel cell vehicle comprises an electric drive system and a fuel cell system for providing electric energy for the drive system. According to the invention, the electric drive system is set up for regenerating braking energy, and devices are provided for the direct utilization of the regenerated braking energy in at least one energy-consuming component of the fuel cell system. This direct braking energy utilization in the fuel cell system increases the degree of energy utilization without the requirement of a separate intermediate energy storage device for the intermediate storing of regenerated braking energy.

Assignee: **Xcellsis GmbH** (Kirchheim/Teck-Nabern, DE)

United States Patent **6,423,435**

Autenrieth , et al. **July 23, 2002**

Fuel cell system with an assigned hydrogen generating arrangement

Abstract

A fuel cell system has at least one fuel cell and a hydrogen generating arrangement for feeding the fuel cell anode with a hydrogen-containing product gas from a conversion reaction of a hydrocarbon starting substance or hydrocarbon derivative with of water fed supplied by way of a water feeding system. Water recovery devices are provided for condensing water out of the process gas supplied by the hydrogen generating arrangement, and/or out of the cathode waste gas carried away from the fuel cell cathode, and returning the condensed-out water into the water feeding system.

Assignee: **DaimlerChrysler AG** (Stuttgart, DE)

United States Patent **6,387,559**

Koripella , et al. **May 14, 2002**

Direct methanol fuel cell system and method of fabrication

Abstract

A fuel cell system and method of forming the fuel cell system including a base portion, formed of a singular body, and having a major surface. At least one fuel cell membrane electrode assembly is formed on the major surface of the base portion. A fluid supply channel including a mixing chamber is defined in the base portion and communicating with the fuel cell membrane electrode assembly for supplying a fuel-bearing fluid to the membrane electrode assembly. An exhaust channel including a water recovery and recirculation system is defined in the base portion and communicating with the membrane electrode assembly. The membrane electrode assembly and the cooperating fluid supply channel and cooperating exhaust channel forming a single fuel cell assembly.

Assignee: **Motorola, Inc.** (Schaumburg, IL)

United States Patent **6,380,638**

Bitsche , et al. **April 30, 2002**

Hybrid propulsion for fuel-cell cars

Abstract

The invention relates to a hybrid drive for an electric vehicle having a fuel cell, an energy store, an electric traction motor and electrical auxiliary loads. The invention proposes providing two separate circuits, provided with switching devices, for selectively connecting the electric traction motor and the electrical auxiliary loads to the fuel cell or to the energy store, and providing a switchable connecting line between the fuel cell and the energy store.

Assignee: **DaimlerChrysler AG** (Stuttgart, DE)

United States Patent **6,376,113**

Edlund , et al. **April 23, 2002**

Integrated fuel cell system

Abstract

The invented system includes a fuel-cell system comprising a fuel cell that produces electrical power from air (oxygen) and hydrogen, and a fuel processor that produces hydrogen from a variety of feedstocks. One such fuel processor is a steam reformer which produces purified hydrogen from a carbon-containing feedstock and water. In the invented system, various mechanisms for implementing the cold start-up of the fuel processor are disclosed, as well as mechanisms for optimizing and/or harvesting the heat and water requirements of the system, and maintaining desired the feed ratios of feedstock to water in the fuel processor and purity of the process water used in the system.

Assignee: **IdaTech, LLC** (Bend, OR)

United States Patent **6,360,835**

Skala **March 26, 2002**

Thermal management of fuel-cell-powered vehicles

Abstract

Method for managing the temperature of a fuel-cell-powered electric vehicle having at least one high temperature heat transfer circuit and one low temperature heat transfer circuit each using the same dielectric heat transfer medium as the other. The circuits are in flow communication with each other and the heat transfer medium is pumped from one circuit to the other in response to the thermal demands of the vehicle.

Assignee: **General Motors Corporation** (Detroit, MI)

United States Patent **6,311,650**

Lamm **November 6, 2001**

Vehicle having a driving internal-combustion engine and having a fuel cell system for the power supply to electric consuming devices of the vehicle and method for operating such a vehicle

Abstract

In a method of operating a vehicle having a driving internal-combustion engine and a fuel cell system which has a reforming reactor with a shift reactor connected on the output side, in a cold-starting phase, hydrogen-containing gas from the electrically warmed-up reforming reactor is fed together with the fuel to the internal-combustion engine for reducing the pollutant emission. After the warming-up of the shift reactor, the gas is supplied to the fuel cell whose anode exhaust gas together with the fuel is supplied to the internal-combustion engine for reducing pollutants.

Assignee: **DaimlerChrysler AG** (Stuttgart, DE)

United States Patent **5,646,852**

Lorenz , et al. **July 8, 1997**

Method and device for vehicle fuel cell dynamic power control

Abstract

A method and an apparatus are provided for controlling the power of an electric drive unit in a vehicle. The drive unit is supplied with electrical energy by a fuel cell in the vehicle. On the basis of a power request which is determined from the accelerator pedal position, the air flow rate required to provide the set power from the fuel cell is calculated and set by controlling rotational speed of a compressor arranged in the air intake line to the fuel cell. To prevent the fuel cell from producing more electrical power than the drive unit can absorb, the drive unit acts limits the power request by emitting appropriate error messages. The set value for the power is fed to the drive unit and can be corrected such that the drive unit never demands more power than the amount of power instantaneously produced by the fuel cell to prevent fuel cell collapse.

Assignee: **Daimler-Benz Aktiengesellschaft** (DE)

4.2.7 Reformers

United States Patent **6,375,906**

Edlund , et al. **April 23, 2002**

Steam reforming method and apparatus incorporating a hydrocarbon feedstock

Abstract

A fuel processing assembly adapted to produce hydrogen gas from a carbon-containing feedstock. The fuel processing assembly includes a fuel processor, such as a steam reformer. The fuel processing assembly further includes a feed assembly adapted to deliver a carbon-containing feedstock, such as a hydrocarbon, to the fuel processor. In some embodiments, the fuel processing system includes a fuel cell stack that includes at least one fuel cell adapted to produce electrical power from hydrogen gas produced by the fuel processor.

Assignee: **IdaTech, LLC** (Bend, OR)

United States Patent **6,329,091**

James **December 11, 2001**

Fuel reformer system for a fuel cell

Abstract

An on-board reforming system for a vehicle fuel cell having a pair of hydrogen purification units linked together. The first hydrogen purification unit generates a first hydrogen stream at a first pressure. The second hydrogen purification unit generates a second hydrogen stream at a second pressure. The first hydrogen stream is fed to a metal hydride storage bed for charging thereof. The hydrogen in the metal hydride storage bed is combined with the second hydrogen stream to feed the fuel cell.

Assignee: **Ford Global Technologies, Inc.** (Dearborn, MI)

United States Patent **5,935,277**

Autenrieth , et al. **August 10, 1999**

Reforming reactor, particularly for the water vapor reforming of methanol

Abstract

In a reforming reactor suitable particularly for the water vapor reforming of methanol in mobile applications such as vehicles, a reaction space is filled with a catalyst pellet fill and has a movable reaction space wall which exerts a position-fixing pressure onto the catalyst pellet fill. According to the invention, a filling device is provided through which catalyst material can be filled from the outside into the reaction space through a passage opening formed in one of the reaction space walls.

Assignee: **Daimler-Benz AG** (DE)