DEVELOPING STRATEGY FOR SUSTAINABLE TECHNOLOGY

The case of fuel cell technology in the automotive industry

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ABSTRACT
This paper explores company response to emergent radical technologies in strongly regulated environments. It is argued that the automotive industry provides a valuable case due to requirements to conform to high emission standards in which radical technological changes seem unavoidable to address them. Current activities of firms with respect to fuel cell technology, and differences in strategy among individual automotive firms are described in the first part. In the second a set of explaining factors for varying strategies is made, based on two case studies. It is concluded that a combination of strong environmental pressure, availability of resources, strong R&D culture, and a strong external network will be more inclined to invest in fuel cell technology than others.

Key words: innovation, sustainable technology, technology strategy, fuel cell technology

1 INTRODUCTION

In the debate on sustainable development it is increasingly argued that current environment related activities of industry are incremental in nature, and will not be sufficient to anticipate growth of world population and affluence. More radical breakthroughs are thought to be required (Fussler 1996, Von Weizsäcker et al 1997). Technology can play an important role in achieving these breakthroughs reducing environmental impact with orders of magnitude up to a factor 4 to 20 (Weterings Opschoor 1991, Jansen and Vergragt 1992). In many cases new technologies make obsolete the current technology, requiring leading firms to develop new competencies and let go of old ones. Diffusion of such radical or destructive technologies (Abernathy and Utterback 1978, Utterback 1994), or disruptive technologies (Christensen, 1997) is well documented. Leading firms are seldom inclined to invest in such technologies, due to organizational inertia (Utterback 1994), resources dependency in fixed assets (Abernathy and Utterback 1990), or incorrect market appreciation (Christensen 1997). Increasingly small upcoming firms are seen as the vehicle for bringing about technological breakthroughs, instead of relying on incumbent firms. However, recent events with regard to the auto industry seem to show a different pattern. Understanding company response to strong regulation therefore forms an interesting case for studying radical technological development.

The automotive industry has been under increasing pressure in the last decades with respect to reduction of emissions, and energy efficiency. Especially the zero emission regulation in California, requiring car firms to sell 10% of their cars with zero emission in 2003, has left the industry with a serious challenge. There is increasing industry-wide consensus that zero emission vehicles will be a requirement in the (mid)long term. Given that current internal combustion engines (ICE) have limits in achieving this goal, alternatives have been explored in the last decades, e.g. electric vehicles (EVs), fuel cell electric vehicles (FCV), and hybrid configurations (HEV). The combination of strong external pressure (regulation), and the availability of new technologies poses critical problems for car firms: how to protect current competencies in for instance ICE technology, how to deal with uncertainty of the potential of the technology, how to keep a competitive edge. The auto industry provides a case for studying and understanding motivations and strategies of individual firms with regard to radical technology in a strongly regulated environment.

This paper gives an overview of fuel cell activities of leading automotive firms. Secondly, based on this description differences in strategies between car firms with regard to fuel cell technology will be characterized. Thirdly a set of explaining factors for varying strategies is presented.
Data were gathered by reviewing of current literature, websites, and press releases on the subject. These data were enriched by interviews held at General Motors and Bayerische Motoren Werke (BMW) in order to uncover the historical process of strategy development, and obtain a deeper understanding of their motivations for their strategy.

The results of this research can contribute to a better understanding of firm behavior with regard to radical technology, and help identify conditions under which firms might be more likely to invest in radical environmental technologies.

2 FUEL CELL TECHNOLOGY

A fuel cell is an electrochemical device that converts fuel and oxygen into electricity and water in a chemical process. Individual fuel cells consisting of electrodes placed on a membrane are stacked up to form a fuel cell stack, thereby increasing the power unit of the total stack. In combination with an electric motor fuel cells form an alternative to the internal combustion engine. The drive train would be electric as is the EV using batteries. The main difference between fuel cells and batteries is that in the latter energy is stored chemically in the battery, while in fuel cells energy is stored in the fuel, which could be supplied continually (dependent on the amount of fuel is available). This could provide one of the main advantages of fuel cells over batteries: the range of FCVs could potentially be higher than battery driven EVs.

Fuel cells can be broadly grouped based on their working temperature. In the high temperature range (600-800° Celsius) solid oxide fuel cells (SOFC), and molten carbonate fuel cells (MCFC) have a relatively high efficiency (55-70%), and are mainly used for stationary electricity generation. In the low temperature range (80-200° Celsius) proton exchange membrane fuel cells (PEM FC) and direct methanol fuel cells (DMFC) are generally seen as the most promising for smaller and mobile applications. Energy efficiencies vary from 35-50%.

PEM FC is generally seen as one of the most promising fuel cell types for automotive applications. Its working temperature is low, it has a high power density, it has a relatively high energy conversion energy, and it is relatively cheap in comparison to DMFC. Due to several breakthroughs in PEM FC in the eighties the automotive industry became interested to explore opportunities to use PEM FC as an alternative for the internal combustion engine. Especially strong investments of Daimler-Chrysler from 1992 in the leading fuel cell developer and manufacturer Ballard, have put fuel cell technology on the map in the automotive industry. Since then a race seems to be on between the major car manufacturers who will be first to market, announcing challenging dates for market implementation (Toyota and Nissan in 2003, DaimlerChrysler, General Motors and Mitsubishi in 2004).

Despite these activities there are still many barriers for fuel cell success. Costs have come down in recent years but are still not close to the ICE mainly due to the use of platinum as a catalyst and high membrane costs.. Also the performance (e.g. power density, weight) is still insufficient for current car application. Another problem relates to infrastructure: PEM FC are fuelled by hydrogen. Hydrogen handling and storage are still problematic while there is a lack of fuelling stations. To overcome these problems methanol and gasoline have been suggested as intermediate fuels for the coming years; as a result methanol/gasoline to hydrogen reformers would be incorporated in FCVs, adding to cost, weight and complexity. Car manufacturers have demonstrated that technical hurdles have been overcome. It is now a question of making it marketable.

In 1999 R&D investments in fuel cell technology by car manufacturers were approximated at $1.5 - 2B in total over the last decade (Kalhammer 1998). In comparison, similar amounts of investments are required to bring one model to market; therefore investments can be called moderate relative to investments in ICE technology.

More impressive is DaimlerChrysler's announcement to invest $1B a year in manufacturing capabilities for fuel cell technology while General Motors and Toyota keep progressing rapidly on the performance of their fuel cell technology. According to the advisory board for the California Air Resources Board (CARB) the "*unprecedented combination of resources by powerful organizations acting in their own interest with strong public support cautious optimism about the prospects for fuel cell engines can be held*".

One of the driving factors in the application of fuel cells as a propulsion unit is regulation. The zero emission vehicle (ZEV) mandate requires the six biggest car firms that 10% of their sold cars have zero emissions of NO_x, CO, and HC, starting in 2003. Given the limitations of internal combustion engines to achieve zero emission, research in battery technologies, fuel cell technologies, and reformer technologies have increased considerably since the beginning of the nineties.

In conclusion, fuel cell technology is an emerging technology with potential value for the automotive industry as an alternative to the ICE. Regulation might well have spurred investments in the technology, which by now has a promising momentum.

3 AUTOMOTIVE ACTIVITIES IN FUEL CELL TECHNOLOGY

Research and development of automotive firms with regard to fuel cell technology have increased considerably over the last decade. Activities of some of the most important players will be discussed to give an impression of individual approaches to address zero emission regulation in general, and assess individual fuel cell strategy in particular. Data are extracted from EV World, Fuel cell 2000, press releases by the companies, complemented by company interviews.

3.1 DaimlerBenz (until May 1998) – DaimlerChrysler (from May 1998)

R&D efforts in fuel cell technology of DaimlerBenz stem from the eighties, but became more substantial in the beginning of the nineties. Its research collaboration with one of the leading fuel cell manufacturers, the Canadian based Ballard, lead to the NECAR 1 in 1993, a minivan in which most space was devoted to fuel cell related technology. Since then DaimlerBenz, and later DaimlerChrysler has been the frontrunner in this technology. This has resulted in a range of prototypes for cars (NECAR 2 to 4) and buses (NEBUS). DaimlerChrysler and Ballard teamed up in 1996 joined by Ford in 1998 to form the 'Alliance'. Three joint ventures were set up focusing on commercial fuel cell drive systems (Xcellsis, headed by DaimlerChrysler), power systems (Ballard Power Systems, headed by Ballard) and electric drive systems (Ecostar, headed by Ford). Investments in Ballard have exceeded $700M over the last decade (Kalhammer, 1998), while DaimlerChrysler CEO Schrempp announced it will invest $1B yearly in manufacturing capabilities at the recently held Hanover World Fair.

DaimlerBenz has had extensive experience with electric drive systems, and hybrid vehicles in the past. However, its activities in these alternatives seem minor in relation to their commitment to fuel cell technology. Fuel cell technology is believed to be fundamentally better suited for very rapid, low-cost manufacturing than conventional engine production (DaimlerChrysler announcement in Kalhammer, 1998). Furthermore fuel cell technology promises to generate extremely low emissions, with excellent range and efficiency (Borroni-Bird, in Moltavelli 2000). According to Xcellsis director dr. Panik the first commercial FCVs will be introduced in 2004, as much as forty thousand the first year, and steadily increasing in the years thereafter:

> *"We have a schedule and we are sticking to it" (Panik in Moltavelli 1999)*

Concerning the preferred fuel DaimlerChrysler follows a two-track strategy. Pure hydrogen gas will be used to fuel fleet vehicles with fuel cells (buses and taxis); onboard reformed methanol will be used for passenger cars. Gasoline, the preferred fuel by Chrysler and other firms in the industry, was pursued as an option until 1999, leading to a gasoline powered fuel cell Jeep at the Los Angeles Auto show. Due to disappointing results this model forms the dead end of this research trajectory. Also its collaboration with Shell, which is developing a gasoline reformer, came to an end due to the choice for methanol.

While the industry seems to shift towards gasoline DaimlerChrysler is hanging on to methanol and hydrogen. This seems partly due to the time schedule to go to market with FCVs in 2004: compared to methanol reformers, gasoline reformers are much more complex and will take longer to become price competitive. DaimlerChrysler seems determined to be on top with fuel cell technology:

> *"It's a competition-driven international race, and the company that is first to production will get to make the rules" (Panik, in Moltavelli 2000)*

No dominant design with regard to FCVs exists as yet which seems a driving factor for investments. In parallel DaimlerChrysler pursues to gain industry consensus on the technology, for instance by taking the initiative to join the car industry, oil industry and government agencies to demonstrate FCVs in California, aligning technology with infrastructure. In the California Fuel Cell Partnership (CFCP) Honda, Ford, Volkswagen, Hyundai, Nissan are participating from the car industry; Shell Hydrogen, BP, and Texaco from the oil industry; and among others California Air Resources Board (CARB), Department of Energy (DOE), Department of Transportation (DOT) from government side. Furthermore it has started a large testing program in Iceland, evaluating fuel cells in buses, boats and cars in the first to be 'hydrogen-society'.

3.2 General Motors

Industry leader General Motors has the most experience in EVs, in which it has invested over $1B over the last decade (Schnayerson 1996). In 1996 the EV1 was brought to market, in 1999 followed by the EV generation II, using different battery types for increased range. Sales of the EVs have so far been disappointing, but the EV program has not been cancelled. General Motors perceives electric drive train technology as a crucial element to address zero emission regulation. The EV program can prove to be valuable in terms of electric drive train development, but also in market acceptance, and infrastructure development issues (Kalhammer, 1998). Where EV is the main priority, increasingly General Motors focuses on fuel cell technology and hybrid technology to complement its technology portfolio.

> *"GM's response to ZEV is to develop a whole portfolio of technologies, including EV1." (Stewart/GM, EV World 1999)*

Fuel cell technology was first explored by General Motors in the sixties in programs initiated by NASA. Only in the beginning of the nineties larger programs were started to research fuel cell technology. It seems this was partly motivated by increased efforts of DaimlerChrysler. Whereas in these beginning years fuel cell stacks were purchased from a.o. Ballard, in recent years General Motors develops and tests its own fuel cell stacks. Reformer technology is developed in collaboration with Delphi Automotive Systems. The latest fuel cell stack of General Motors show considerable progress in performance, which appear to be close to competitive with Ballard's fuel cell stacks. General Motors' motivation for in-house fuel cell research is to ensure:

> *"…full understanding of all aspects of PEM fuel cell technology to permit informed future decisions on technology selection and partnering"*

Although recently the GM Precept was launched on the Detroit Motor Show 1999, the first prototypes originate from German General Motors-subsidiary Opel: the Zafira (1998) and the Sintra (1997). Recently the next generation Opel Zafira using fuel cells developed by

General Motors was presented. While in earlier models methanol was used as the preferred fuel, hydrogen is used in this model. This represents General Motors' perspective that methanol is not the preferred fuel; it is generally believed that General Motors is shifting towards gasoline, but that at the time of the model presentation no satisfactory gasoline reformer was available (Krantz, 2000). Illustrative in this respect is its collaboration with Exxon to develop such gasoline reformer technology.

Together with research partner Toyota General Motors hopes to have production-ready vehicles in 2004. Mass-production is however not expected before 2008 due to complexities with the technology, high costs, problems with infrastructure, and usual development time of this type of technology.

3.3 Ford

Ford has an extensive record on testing alternative technologies related to hybrid and electric cell vehicles. With regard to fuel cell technology its activities are thought to be limited to evaluation of components, and testing of system alternatives. Its main focus seems on the one hand to develop a set of fuel flexible vehicles achieving low emissions, whilst developing the competencies for electric drive train technologies (both valuable for EVs as well as FCVs).

Early explorations into fuel cell technology stem from the US-partnership partnership for next generation vehicles (PNGV), together with Chrysler and GM. More spectacular was its participation in the 'Alliance' with DaimlerChrysler and Ballard in 1998, investing $425M in three joint ventures. With the participation Ford has secured a position in fuel cell technology, might it break through. Ford does not mention a timeline for its bringing a FCV to market, which shows their relative weak commitment to FCVs.

Ford's focus on electric drive trains is illustrated by their position in Ecostar, holding 62% of its shares (Ballard 17%, DaimlerChrysler 21%), and with its participation in Norwegian EV producer PIVCO. Its marketing oriented EV-activities are joined in a new venture Th!nk, which focuses on marketing electric and fuel cell EVs.

3.4 Toyota

Toyota has been a leader in environmental issues in the automotive industry for decades. Its EV program stems from the seventies which resulted in several models on the market (for instance the RAV4). More recently it 'stunned' the industry with its hybrid vehicle, the Prius, which had an unexpected Japanese market entry in 1997. After its relative success in Japan the Prius will be brought to market in Europe and the US.

The same unexpected technology advancements might occur again with regard to fuel cell technology, so the industry suspects. Toyota has an extensive fuel cell program which studies major issues related to FCVs in house, from fuel cell stack development to system integration studies (Kalhammer 1998). Although Toyota has announced bringing a FCV to market in 2003 (public announcement 1998), Toyota was quick to downplay that prediction. According to Kalhammer (1998) Toyota is committed to be first to market, and is confident it can achieve that before DaimlerChrysler.

Like many firms Toyota keeps open the fuel issue by exploring both methanol and hydrogen. In recent years a shift towards gasoline can be discerned. This might be a result of partnerships with oil companies and with GM: both have preferences for gasoline reforming to overcome infrastructural problems. However this would delay the introduction of FCVs considerably due to the development stage of gasoline reformers.

Of the top five automotive companies Toyota is one of the few firms pursuing a hybrid fuel cell design. NiMH batteries are added to the fuel cell system in order to reduce peak loads. The complexity related to hybrid designs might well be mastered by Toyota due to its competence and experiences in hybrid design.

3.5 Honda

Like Toyota Honda is one of the environmental leaders of clean technology. It was one of the first to comply to Californian ULEV standards, and has had substantial experience in the development of EVs and fuel cell technology development. Despite the relative success of its commercial electric vehicle, the EV Plus, the program on EVs was stopped. Honda's arguments have been the lack of market for, and high costs of EVs. Environmental groups suspects Honda has deliberately cancelled the program to frustrate the EV market. Undeniably Honda is more interested in developing hybrid cars, of which the Honda Insight is the first to marketed in the US.

FCEVs are seen as one of the most realistic options to achieve zero emission. Other drivers are however in play: fuel cell technology can reduce greenhouse emissions (more stringently regulated in Japan) and can reduce Japan's dependence of oil by switching to natural gas as the intermediate fuel. Its fuel cell program started in 1989, but was strongly scaled up in 1996. A modest staff focuses on mastering all aspects of fuel cell technology, before choosing suppliers. Honda announced it would produce 300 vehicles in 2003 (Kalhammer 1998).

Like many other car companies Honda's prototypes explore both hydrogen (with metal hydride storage technology) and methanol fuelled vehicles. This reflects the firm strategy to keep its options open. To test FCVs under real life conditions it has participated in the CFCP.

3.6 BMW

BMW's activities in fuel cell technology were kept relatively quiet until recently, when it revealed its 7 series sedan where a fuel cell was used as an auxiliary power unit (APU). The APU provides power to the ever increasing electrical power demand in cars, and the fuel cell forms an alternative for the limited battery. Until that point BMW had only participated in smaller demonstration projects exploring fuel cells for propulsion purposes. The results of these studies made BMW chose not to pursue the propulsion function with fuel cells given the limitations of fuel cells on the one hand (costs, performance), and excellent properties of the internal combustion engine.

> *"Fuel cells for propulsion purposes are a solution for a question which was never asked. " (K. Pehr, Director of Hydrogen Development, Focus, 1999)*

BMW, as one of the world's leading engine developers, addresses the regulated demand for zero emission by starting with the fuel: hydrogen. BMW has had extensive experience in hydrogen storage and handling, which has lead to a range of running prototypes with liquid hydrogen fuelled ICE vehicles. Natural gas is seen as the intermediate fuel until a sufficient infrastructure for hydrogen is built up. Meanwhile BMW is trying to gain industry support for hydrogen via several platforms. Methanol, so BMW argues, makes no sense from an infrastructural as well as environmental point of view.

Both the EV program of the eighties and the fuel cell program for propulsion seem to be at a dead end; hybrid vehicles are said to be too complex. However, the fuel cell program for other applications is going strong. Apart from a low temperature fuel cell (PEM), a high temperature fuel cell (SOFC) with lower costs and easier fuel requirements have been chosen for further development as an APU. Suppliers are Ballard-competitors International Fuel Cells (IFC) and Delphi Automotive Systems; BMW has gained industry support on its APU application due to its recent partnering with Renault.

3.7 Volkswagen

Relatively little activities with regard to fuel cell technology are carried out by Volkswagen, the number four automaker in the industry. In response to zero emission regulation and efficiency standards Volkswagen has committed itself to developing and marketing high efficiency models, for instance the Lupo (direct injection, diesel). Programs on hybrid, electric and FCVs have been strong in the past, but have been downscaled in the beginning of the nineties (Hoogma 2000). It is speculated that Volkswagen has increased its research efforts on fuel cell technology recently, which is illustrated for instance by its participation in the CFCP in 1999.

With respect to fuel cells Volkswagen has collaborated with a.o. Renault to develop a FCV prototype, using a methanol reformer. This was a relatively small European project.

3.8 Other car firms

Of the other car firms Nissan probably has the most extensive program. Its fuel cell activities have lead to several prototypes; it has announced to demonstrate a production ready FCV in 2003. Nissan's activities seem largely motivated by the fact that they are one of the seven big firms to conform to ZEV regulation in 2003.
Mitsubishi commenced with a fuel cell program in the beginning of the nineties, which was cancelled due to economic downturns. Mazda's fuel cell program has been modest, and has focused on hydrogen fuelled FCVs. Both Mazda and Mitsubishi developed hybrid versions, using an additional battery for peak loads.
Nissan and Mitsubishi and Mazda have been taken over (by Renault and DaimlerChrysler and Ford respectively); it is unclear what the influence of these takeovers are for their respective fuel cell programs.

In Europe fuel cell activities have been limited outside of DaimlerBenz and BMW. Several companies have participated in European Union sponsored projects, Renault, Peugeot-Citroen and Fiat, which were relatively small in comparison to programs carried out at earlier mentioned firms. Commitment towards fuel cell technology by these companies therefore seem limited.

4 VARIANCE IN FC TECHNOLOGY STRATEGIES

Environmental regulation and the emergence of new technologies, fuel cells and batteries for instance, provide car firms with a range of strategic options. As can be seen from the last paragraph car companies have different approaches. In the following the most characteristic differences in strategies among car firms will be assessed. In 4.1 the general AFV strategy will be characterized, while in 4.2. the strategy with respect to fuel cell technology will be central.

4.1 Strategy with respect to emerging technologies

Observing the industry firms seem to focus on acquiring competencies which might become important in the future. However, there are strong differences between firms in the priorities and focus points of their competence development.

General Motors and Ford can be best characterized as keeping their options open with respect to emerging technologies: among others fuel cells, batteries, electric drive trains, hybrid vehicles, hydrogen based ICE vehicles, hydrogen storage and handling technology. Given their size they can afford investing in most technologies keeping track of the industry leaders, without making distinct choices with respect to a particular option. However both have a focus on EV related technologies which indicates their vision that the future car will in fact be electric: be it driven by an ICE, a fuel cell, or a battery.

Although the Japanese companies Honda and Toyota also keep their options open they have chosen to focus on hybrid technology on the short term. These models are already on the market, while Ford and General Motors presented prototypes at the Detroit Motor Show in 2000. Production ready models are not expected before 2003, which illustrates the lead the Japanese have on this technology. Given the speed at which the Japanese firms have proved to integrate and commercialize HEVs, also their progress on fuel cell technology is watched carefully. The Japanese focus on hybrid vehicles seems largely motivated by a stronger commitment to energy efficiency and related CO2 emission reduction. Hybrid technology could be a key competence for developing FCVs in the long term to avoid peak loads for the fuel cell system.

Strategies at German companies differ considerably with respect to emerging technologies. DaimlerChrysler has a distinct focus on fuel cell technology, after having explored EV in the eighties and nineties. It is the only firm having announced to build manufacturing capabilities for FCVs. Given that from this point on investments increase exponentially DaimlerChrysler's commitment for FCVs seems very strong.
BMW focuses on the fuel rather than on the technology. Investments in hydrogen storage and handling complement their efforts of building a successful ICE based on liquid hydrogen. Its efforts towards electric drive trains and hybrid vehicles seem limited.
Volkswagen, like other European manufacturers Renault and Peugeot-Citroen, rely more on ICE technology on the short and medium term. Volkswagen brought to market the first three liter car (running 100 km on 3 liter) using direct injection technology.

In conclusion, the way car firms respond to environmental regulation differs considerably and can have severe impacts on strategic positions of individual firms.

4.2 Investments in FC technology

Although investment levels of car firms are kept confidential, indications can be given of the size of the fuel cell program at individual firms between 1990 and 2000, the period in which fuel cells were put on the map in the automotive industry.

DaimlerChrysler is a frontrunner in its investments in fuel cell technology having invested $725M in the 1998 partnership with Ballard and Ford. It will be the first to invest in manufacturing capabilities, which require investments of around $1B yearly.

Closely following are Toyota, General Motors, Ford and Honda having committed serious investments in fuel cell technology. Mostly have carried out in house R&D in fuel cell technology, or have invested heavily in fuel cell manufacturers (for instance the $420M investment of Ford in Ballard). All of above firms have demonstrated several prototypes with increasing performance, and have announce production ready models around 2004.

Smaller but still substantial programs are carried out at firms like Nissan, BMW, Chrysler (before the 1998 merger with Daimler Benz), and Mazda. These programs also have lead to several prototypes through the years, however R&D activities are more limited with respect to fuel cell technology, and complementary technologies (e.g. reformers). BMW has a considerable program but is not focused on propulsion. The firms do not have the intention to be a leader in the technology, but want to be knowledgeable on the competencies required.

Limited programs can be discerned at Renault, Volvo, Volkswagen-group, Mitsubishi and Hyundai. Most of these companies have bought fuel cells from either Ballard or one of its competitors for testing and exploring consequences for vehicle integration. In small programs one or two prototypes are developed. No in depth knowledge is created with respect to fuel cell technology.

Small programs with little or no investments in fuel cells can be seen at Fiat, Peugeot-Citroen, Daewoo, Suzuki, and Fuji. Table 1 summarizes the characterizations and the positions of individual car firms.

Another way to investments of car firms in fuel cell programs is measure the amount of patents issued by firms. Steinemann (1999) counted US patents between 1985 and 1999 showing DaimlerChrysler as the frontrunner with 22 patents, followed by Toyota (10), General Motors (9), Honda (8), Ford (3), and Nissan (1). It must be noted that patents are a limited method to assess investments: the lack of patents might also reflect the high confidentiality of a program. Nevertheless the amount of patents issued by DaimlerBenz/DaimlerChrysler reflect their commitment to the technology.

Table 1 Size of fuel cell program between 1990-2000

Size of fuel cell program	**Characterization of size**	**Firms**
Extensive FC program	In house FC technology development/strong investments in FC technology development at third parties. Active in developing complementary assets (reforming technology, electric drive train technology) Several prototypes. Announcement of production ready car in 2003-2004. Approximate investment levels between $600M – $1B More than 5 patents	DaimlerChrysler, Toyota, General Motors, Ford, Honda
Considerable FC program	Considerable investments in FC technology development at third parties/ limited or no in house FC technology development. Considerable efforts in developing complementary assets (reforming technology, electric drive train technology) One or two prototypes. No announcement of production ready car in 2003-2004. Approximate investment levels between $300M – $600M Less than five patents	Nissan, BMW, Chrysler (before 1998), Mazda
Modest FC program	No in house FC technology development/ limited investments in FC technology development at third parties. Active in developing a select amount of complementary assets. One or two prototypes. No announcement of timeline. Approximate investment levels between $50M – $300M No patents	Renault, Volvo, Volkswagen-group, Mitsubishi, Hyundai
Limited FC program	No in house FC technology development/limited investments in FC technology development at third parties. Limited activities in developing complementary assets (reforming technology, electric drive train technology) One prototypes on breadboard level. No announcement on timelines. Approximate investment levels less than $50M No patents	Fiat, Peugeot-Citroen, Daewoo, Suzuki, Fuji

4.3 Technical differences

Fuel preference

The most striking difference between automotive firms is their fuel preference to power the FCV. Through the years a shift in preference can be discerned from hydrogen, to methanol, and currently towards gasoline. In last two cases reformers are required to produce a hydrogen rich gas.

Activities to create competencies in hydrogen related technology remains strong, for instance in storage technology, hydrogen handling, refueling systems (of which BMW showed an automatic version at the World Trade Fair in Hanover 2000), and ICE technology working on hydrogen (especially BMW). Hydrogen is still seen as the best alternative for petroleum based fuels in the long term.

Methanol was chosen during the middle of the nineties due to the relatively easy process of reforming methanol in a hydrogen rich gas. DaimlerChrysler was one of the leaders in this process, and Toyota, Ford, and General Motors followed this line to use methanol as an intermediate fuel. During this period the oil industry got increasingly involved in fuel cell technology, and the issue of infrastructure. Vested interests in gasoline or diesel over methanol of oil firms made the car industry shift towards gasoline. Shell (with DaimlerChrysler until recently) and Exxon (with General Motors) have increased efforts for developing a gasoline to hydrogen reformer. Predictions on production availability range from 2005 to 2010, making the 2004 deadline for FCV market entry unrealistic. For this reason it seems DaimlerChrysler continues its efforts on methanol powered FCVs.

The issue of fuel choice for FCVs is currently the most disputed technical problem. A great deal of stakeholders are involved in this issue, which will largely form the dominant design of FCVs in the future.

Hybridization
Fuel cell systems are especially strong when it comes to providing a steady power output. They are less developed in following peak demands as required in cars. Both the fuel cell as the reformer need to take several hurdles to achieve this. Furthermore peak demands requires the maximum output of the fuel cell system to be at least 60kW; while in normal conditions 25-30kW is sufficient. Using a battery parallel to the fuel cell makes it possible to respond to peak power relatively quickly, while requiring only half of the amount of (expensive) fuel cells. However, hybridization increases complexity of the system considerably.

As said earlier the Japanese, Toyota, Mazda and Mitsubishi, have demonstrated hybrid FCV models, either with Nickel metal hydride (NiMH) batteries (Toyota) or with an ultracapacitor (Mazda). Also Renault has developed a hybrid version. This technical choice seems to reflect optimism in mastering the complexity issue.
Most other firms, DaimlerChrysler, General Motors, Ford and Honda, have chosen to develop a fuel cell system with an output of 50-75kW.

Application of fuel cell technology
BMW is the first to show a model using fuel cells as an auxiliary power unit (APU), replacing the traditional battery. Renault has announced to join BMW in its efforts. Instead of PEM fuel cells, BMW is shifting its attention to high temperature SOFC, which is less sensitive to CO poisoning than PEM FC. DaimlerChrysler several months later showed its version of an APU on fuel cells. This application does not address zero emission objectives set in California but seems to be winning ground as a more realistic application in cars.

A range of other technical differences can be mentioned (e.g. hydrogen storage technology, battery choice) but above are the most critical. They illustrate that no dominant design has been developed yet. This can explain the current race which seem to be going on to be first to market with a FCV.

4.4 Organization

The last factor of differences in the way companies organize their activities around fuel cell technology development. Differences in creating networks and complementors include:

- *Supplier collaborations*: DC and Ford have taken a stake in Ballard, while other firms carry out FC research in house (General Motors, Toyota, Honda).
- *Industry collaborations*: two distinct competitive R&D-'blocks' can be discerned in DaimlerChrysler-Ford-Mazda, and General Motors-Toyota. Also in Europe the collaboration between Volkswagen-Volvo-Renault has been a way to join forces in fuel cell research.
- *Industry-oil collaborations*: Mostly all big players are involved in discussions with the oil industry in order to secure a fuelling infrastructure for future FCVs:
- *Government related collaborations*: Most big players are involved in industry-government research collaborations, PNGV in the USA, EUCAR in Europe, and J-CAR in Japan.

Apart from above collaborations in recent years mergers and acquisitions have been high on the agenda in the automotive industry. How this affects strategy on fuel cells remains to be seen.

5 EXPLAINING FACTORS FOR STRATEGY VARIANCE

As has been argued different strategies among automotive firms can be discerned with regard to fuel cell technology development. Firms differ in their processes of assigning investments on alternative fuel technologies like fuel cell technology, they show variance in the technical decisions made how to implement fuel cell technology, and lastly different organizational choices can be discerned.

Theories on corporate environmental management gives several explaining factors for investment and commitment of a firm to environmental technology. Determining factors include amount of environmental pressure (Cramer 1999), financial resources (Moors 2000), and internal firm characteristics like strategic vision of top management and product champions (Everett et al., 1993), and firm-internal technology network (Moors 2000). Theories on technology dynamics and strategic management can help in explaining technical choices made during the development process, for instance the choice for fuel, and hybridization. The resource based view of the firm focuses on available and envisioned competencies as determinants for technology choices (Den Hond 1996).

In the following above factors will be carefully examined in the case of fuel cell technology, to what extent individual factors explain the observed patterns, and to what extent these factors are sufficient in explaining the observed strategies.

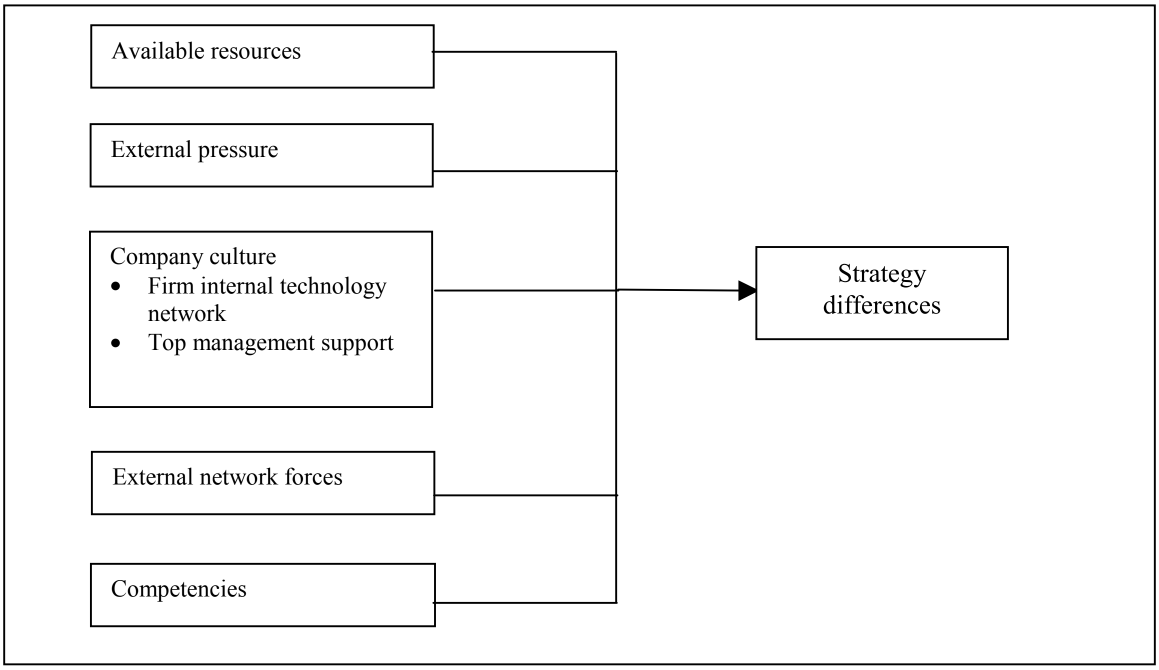

Figure 1 Factors influencing strategy differences of automotive firms with respect to fuel cell technology

5.1 Available resources

Companies with high returns, high profit margins, and a healthy financial situation can be expected to have more financial resources to explore new technologies with high potential. This pattern can be observed for the majority of firms in the industry.

Of the top eight companies in sales (based on 1999 figures) the top three (General Motors, Ford, and Toyota) have significant fuel cell programs. The same accounts for firms as DaimlerChrysler (5) and Honda (8).
Not in line with expectations are the relatively modest fuel cell programs of the Volkwagen group (4), Renault-Nissan (6, although Nissan has had a considerable program), and Peugeot-Citroen (7). Furthermore DaimlerBenz, before its merger with Chrysler has been the foremost investor of fuel cell technology, while being a relatively small player. Most smaller firms have had experience with fuel cells in small programs. However relatively big programs are discerned within BMW, Mitsubishi (although cancelled due to economic downturns), and Hyundai.

In other words, tying investment levels in fuel cell technology with firm size does explain the majority of firm investments. However, there are several big players investing relatively little, and several small players investing relatively much in fuel cell technology which point to other factors in play.

5.2 External pressure /market opportunities

Theory suggests that companies under strong external pressure will be more inclined to invest in fuel cell technology than companies under weaker external pressure. The Californian ZEV regulation is by far the most stringent regulation impacting companies to develop alternative technologies. The ZEV regulation provides different regulatory requirements for companies in the industry, thereby differentiating external pressure within the industry (CARB, 1999):

- *Large volume manufacturers*: manufacturers with sales over 35.000 sales/yearly must meet at least 40% of its ZEV requirements with ZEV vehicles; the remainder may be met using partial ZEV allowance, which is calculated with a comprehensive credit scheme. Partial ZEV allowance can be attained with hybrid vehicles and low emission ICE vehicles.
- *Intermediate volume manufacturers*: manufacturers with sales between 4.500 – 35.000 yearly may meet its ZEV requirements with up to 100% partial ZEV allowance vehicles. As a result for these firms incentives are weak for developing cars with zero emission like EV and FCV.
- *Small volume manufacturers*: with less than 4.500 sales yearly is not required to meet the percentage ZEV requirements.

All manufacturers falling in the 'large' category, General Motors, Ford, DaimlerChrysler, Honda, Nissan and Toyota have extensive fuel cell programs, except Nissan which has downscaled its program due to financial limitations. Given that intermediate volume manufacturers (for instance BMW, Volvo, Volkswagen) can meet standards with HEVs or ICE vehicles, fuel cells do not form an immediate answer to their needs. The amount of pressure therefore proves a strong explaining factor for investments of large volume manufacturers, and modest investments by small and intermediate volume manufacturers.

However, again DaimlerBenz before its merger with Chrysler forms the exception: already started in 1993 with its fuel cell program, Daimler did not have requirements for the ZEV regulation. Its behavior is the first mover can therefore not be explained with external pressure alone. It can be hypothesized that without Daimler's activities in fuel cell technology, other companies would not have followed. Increased investments by competing giants like General Motors and Ford might well be explained by keeping track with Daimler in this technology.

5.3 Company culture

Firm internal technology network
Moors (2000) argues that firms with a strong internal technology network will be more inclined to invest in radical technology. A high density of technical specialists will provide more access to scientific and technical knowledge opening up the opportunities of new technologies. One of the metrics of internal technology network is R&D levels within the companies, indicating commitment to research, and the ambition to be a technological leader.

In the last decade technological innovation is increasingly seen as a way of differentiation for car firms, and a way to stay ahead of competition. Typical firms investing large amounts in R&D are Ford, DaimlerChrysler, Toyota, General Motors, Honda and BMW. In general these companies are seen as the early innovators in a number of technologies within the industry. Furthermore, DaimlerChrysler has the ambition to be a technological leader with an innovating culture, which might well explain part of their strong interest in fuel cell technology. The same accounts for Ford, General Motors, and Toyota. Naturally

R&D investments are made possible by firm size, and they are therefore related to the earlier mentioned point of resource availability.

Strategic vision, leadership
Leadership and strategic vision are two aspects related to innovation potential of firms. In the case of fuel cell technology top management commitment seems to play an important role.
DaimlerBenz has been the frontrunner in fuel cells, which was strongly pushed by CEO Schrempp. Currently head of research, Dr. Panik, has an important role of making the program work. He is said to be a firm believer in fuel cell vehicles.
In the past the role of leadership has been demonstrated by GM's commitment to EVs, Ford's investments in environmental technology (W. Clay Ford Jr.), but also in cutting back on research programs (Volkswagen when Piech became CEO, Hoogma 2000).

5.4 Competencies of the firm

Competencies of firms prove an explaining factor for decisions made with respect to the *technical design* of the FCV.
Japanese companies (mainly Toyota) have strong competencies in hybrid design, and explores this further in a hybrid version of a FCV. It indicates Toyota's strategy of being a leader in HEV related technology.
The same holds for the US companies, General Motors and Ford, to be leaders in EV drive train technology. There is a shared vision within General Motors that future cars will be driven electric: then EV technology becomes a crucial component to master (Schnayerson 1999).
In Germany discussions on a hydrogen society have been going on much longer than in the US or in Japan. As a result hydrogen based vehicles has been researched by German companies for a long time, expectedly resulting in strong competencies. This might well explain Daimler's and BMW's initiating role in fuel cell technology and related hydrogen discussions.

Apart from a race to be first to market individual firms are developing competencies they feel are important to survive on the long term, or which they can trade with competitors.

5.5 External network

In a study in the metal industry Moors (2000) has shown the importance of external networks as a way of creating knowledge on new technologies. Firms with extensive research networks have shown to be more inclined to develop radical technology than others.
No definite conclusions on this point can be reached without extensive interviews with individual firms. In first instance however early contacts between DaimlerBenz and fuel cell manufacturer Dornier seems to have given DaimlerBenz a jumpstart on its fuel cell program. The same seems the case for the early involvement of General Motors in fuel cell technology, due to their involvement in the department of defense program on fuel cells.
Further research should be done on unraveling external relations of car manufacturers and understand their influence on technology choices within the firm.

5.6 Analysis: explaining strategies

How does the above factors combined explain strategies taken by individual firms? Four cases will be analyzed to demonstrate how the factors interact.

General Motors' strategy can be largely explained by the fact they are one of the companies required to sell zero emission cars in California in 2003. Because large amount of resources are available, and there is top management commitment to be the technological leader in the industry (company culture factor), General Motors is committed to being competitive on a range of technologies including battery technology and fuel cell technology. Due to its size it is an interesting partner for suppliers, and consequently it has extensive external networks providing the company with crucial knowledge. Similar arguments are applicable to Ford.

DaimlerBenz/DaimlerChrysler has not been under severe pressure due to the ZEV mandate until it merged with Chrysler. Its high commitment to fuel cell technology stems from its mission to be a technological leader, its strong research culture (both company culture factors), combined with the closeness to fuel cells in its external network, mainly fuel cell manufacturer Dornier. Furthermore hydrogen experiences are culturally formed in discussions on creating a hydrogen society in Germany for many decades. Since the start fuel cell technology has been supported by top management, which has publicly indicated its vision of a hydrogen fueled future.

Although in the same culture, BMW does discuss hydrogen as the future fuel, but has not committed to fuel cell technology as the preferred technology. Partly this can be explained by the limited pressure on BMW to develop zero emission vehicles (no ZEV mandate), combined with the relative small research budget (resources). Furthermore BMW is known for its engineering rather than research culture, and shows less ambition in becoming the technological leader in the industry (company culture factors).

Toyota and Honda both have extensive R&D programs, high ambition to be among the technological leaders, and a strong environmental focus (company culture factors). Furthermore they both have the pressure to develop ZEV credits, combined with sufficient resources to set up a competitive fuel cell program. Their hybrid focus seems to indicate their perception that hybrid-competencies are crucial to future vehicle drives.

6 CONCLUSIONS

This paper has explored recent dynamics in the automotive industry with regard to radical technologies in the light of strong environmental regulation. The literature research combined with two case studies leads to the following conclusions.

First, investments in fuel cell technology by automotive firms have increased considerably over the last ten years. Most major firms have extensive programs exploring the opportunities and barriers for FCVs, which to date has lead to a range of prototypes. Public announcements suggest that the industry leaders are in competition of being first to market. Together with the amount of investments and recent involvement of the oil industry this illustrates the commitment the automotive industry has towards fuel cell technology. Given that fuel cell technology can have a destructive effect on current ICE related competencies, this case give proof of incumbent firms investing considerable research budget on radical technology.

Second, differences in strategies among automotive firms can be discerned with respect to investment levels, technical solutions, and network aspects. Three groups of firms can be separated on investments levels, indicating level of commitment to fuel cell technology. With respect to technical solutions most notable difference include fuel preference and the issue of hybridization. The technical differences suggest that no dominant design for FCVs has emerged as yet.

Third, differences between investment levels can be largely explained by five factors: available resources, external pressure, company culture, competence development, and external networks. External resources and company culture seem necessary requirements for investing in radical technologies like fuel cells; competence development and external networks form explaining factors for technological decisions made. All factors can contribute in understanding company strategy in the development of sustainable technologies.

Further research will be focused on linking the key factors to theoretical notions in technology dynamics, and strategic management. Also it will be tested and further developed in practice in other case studies. In parallel a model will be developed for differences in technical choices among automotive firms, mainly focused on fuel preference.

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LIST OF ABBREVIATIONS

AFV	alternative fuel vehicle
APU	auxiliary power unit
CARB	California air resources board
CFCP	California fuel cell partnership
DMFC	direct methanol fuel cell
DOE	department of energy
DOT	department of transportation
EV	electric vehicle
FCV	fuel cell vehicle
HEV	hybrid electric vehicle
ICE	internal combustion engine
MCFC	molten carbonate fuel cell
NiMH	nickel metal hydride
PEM FC	proton exchange membrane fuel cell
PNGV	partnership for next generation vehicles
SOFC	solid oxide fuel cell
ZEV	zero emission vehicle

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