Radical Technology Development by Incumbent Firms

Daimler's efforts to develop Fuel Cell technology in historical perspective

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Abstract

This paper discusses how an established industry as the automotive industry has reacted to the emergence of a radical technology, the fuel cell, with opportunities to answer several environmental concerns. Given that established firms (incumbents) are likely to respond conservative to radical technologies, the automotive industry forms an outstanding case given the large investments it has spent on developing fuel cell vehicles. In this paper a detailed look is taken at one car manufacturer, which was the first to commit serious resources to FC technology: DaimlerBenz/Chrysler. The development of the FC program will be discussed historically in four periods, each distinct with respect to the position and viability of fuel cell vehicles (FCV). The paper draws conclusions concerning the R&D process of technology diffusion within Daimler, the identification of milestones, and assessment of driving forces. It is concluded that Daimler's activities form a serious ambition to bring FCV to commercial production. Broad environmental concerns are the most important driver for this ambition, together with remarkable technical progress of FC technology, and Daimler's strategic position as the industry leader.

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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 is thought to 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). Established firms are often looked upon to take up the technological challenge, due to their financial opportunities. However, innovation studies show that leading firms are seldom inclined to invest in radically new technologies either due to organizational inertia (Utterback 1994), resources dependency in fixed assets (Abernathy and Utterback 1990) or incorrect market appreciation (Christensen 1997). Established firms tend to prefer incremental changes to their current technology, over the development of radically new technology requiring a whole new set of competencies, with all the risks involved.
The auto industry from this standpoint provides an interesting case. Under increasing regulatory pressure the large car manufacturers are increasingly developing alternatives to the internal combustion engine (ICE). Electric Vehicles (EV), Hybrid Electric Vehicles (HEV), hydrogen fueled ICEs and Fuel Cell Vehicles (FCV) provide answers to environmental concerns in the auto industry, but also require a new set of competences, and ultimately put the future of the ICE on the line. Of these technologies the FCV currently seems the most promising technology to propel the future car. The auto industry thus seems increasingly committed to new technologies, which in the end would make the established technology (ICE) obsolete. The automotive industry therefore provides an interesting case studying the driving forces for this changing attitude towards investing in radical technology. It could provide insight in the circumstances by which established firms might be more likely to invest in technological breakthroughs.

The technological focus of this paper will be on fuel cell technology. A Fuel Cell (FC) is an electrochemical device that converts hydrogen and oxygen into electricity and water in a chemical process. Although there are several different types of fuel cells the one used for automotive use is called the Proton Exchange Membrane (PEM). The electricity drives the car via an electric motor, thereby replacing the internal combustion engine. The FCV has the potential of providing an answer to environmental concerns as oil depletion (use of hydrogen), local emissions (a hydrogen fueled FCV is emission free), global warming (no CO2 is emitted) and a high energy efficiency (in theory fuel cells provide higher efficiency than the combustion process).[1]

Hundreds of millions of dollars are spent by car manufacturers on FCV. The question then becomes why radical technology as the Fuel Cell (FC) is pursued by the automotive firms. Are there specific circumstances under which radical technology are likely to be adopted by incumbents? Is it largely motivated from regulatory standards, or are other factors in play? And how does this process of technology adoption take place within an established firm? In order to understand the adoption of FC technology by the automotive industry and assess the future prospects of this technology it is required to unravel in detail the technology-strategy process by which individual car companies have dealt with FC technology. This paper fits in a larger research project to assess and understand differences between individual car companies with respect to FC technology.

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[1] The environmental benefits of FCV over ICE driven vehicles is not undisputed, especially with regard to energy efficiency (Höhlein 1998). Its benefits are largely dependent on the way hydrogen is produced: using fossil fuels for hydrogen production, CO2 and other emissions are still produced, whereas oil depletions remains an issue. If hydrogen is to be produced by for instance photovoltaic power, then the environmental benefits become more realistic. It is safe to say that FCV have a long term environmental opportunity when sustainable hydrogen production is achieved (Plante & Van den Hoed 2000).

This paper takes a detailed look at one car manufacturer, which was the first to commit serious resources to FC technology: DaimlerBenz (since 1998 DaimlerChrysler). The development of the FC program will be discussed historically in four periods (before 1990, 1990-1996, 1997-1999, 2000-2001). Each period is distinct with respect to the position and viability of fuel cell vehicles (FCV). The objective of the paper is to draw conclusions on the R&D process of technology diffusion within a company, such as identifying milestones and driving forces, characterizing Daimler's technology strategy with respect to FC technology and assessing the prospects for FC technology from Daimler's point of view.
The data originate from the Business and Industry database, year reports, Fuel Cell databases (www.fuelcells.org), supplemented with 4 interviews with Daimler employees related to the FC program.
A similar analysis will be carried out for major competitors of Daimler. Together these analyses allow to draw conclusions how an industry as a whole has reacted to the emergence of FC technology, and how such technological adoptions could be fostered by policy makers.

2 The search for alternatives (before 1990)

During the late 1970s and 1980s a great deal of research within Daimler's research labs has been reserved for a broad investigation of alternative fuel systems and propulsion technologies. The exploration of alternatives for the ICE falls together with increasing pressure on the automotive industry due to their polluting nature. The 1970s forms one of the first periods of increased environmental consciousness; the first regulation on emissions standards are set (by California, 1966), followed by regulation in the US federal government (Clean Air Act, 1970), and somewhat later European and Japanese regulations. The increased pressure compels the automotive industry to react, leading to research explorations to alternatives. Alternatives include electric vehicles, hydrogen fueled ICEs, FC technologies (as well as alternative fuels like gas, methanol, bio fuels). FC technology related research can be traced back to the 1980s.

In the1980s Daimler-Benz buys several leading research companies from the periphery of the automotive industry with the objective of strengthening the technological competence of Daimler. Examples include the AEG, strong in electronic technology, and the aerospace related company Dornier. Around these competencies Daimler creates a central research department of about thousand employees, with a mixture of knowledge in a range of automotive relevant areas. This research department is responsible for basic research.

Daimler's has been active in battery and hybrid electric vehicles since the late 1970s. Since 1987 DaimlerBenz subsidiary AEG has been developing the sodium-nickel chloride (ZEBRA) battery in a major joint venture with Anglo-American Ltd. The ZEBRA batteries are demonstrated in several prototypes. ZEBRA battery powered A-Class cars are considered a candidate for meeting DaimlerBenz's ZEV obligations in 2003. A decision to establish a facility for its production is stalled.
However, during the development phase of EVs Daimler becomes convinced it is not a suitable alternative for ICE powered vehicles, and research funds are reduced between 1994-1998. Until this day EV related research continues, to keep in contact with current events, but also because FC technology requires EV technology (for instance electric motor, control technology). In interviews Daimler executives mention that electric motors can be labeled as relatively 'developed' technology, which does not leave much room for margins. Electric motors will most probably be bought as commodity products in the future, might they become popular.

Another technology studied in the 1980s is the hydrogen-fueled internal combustion engine. Since 1975 Daimler has explored hydrogen fueled ICE (instead of the common gasoline-ICE), and between 1984 and 1988 Daimler road tests several prototypes, making Daimler a frontrunner in this technology. Five passenger cars and five delivery cars are tested and run more than 250,000km within Berlin (see figure 1). In the end of the 1980s Daimler scale down their activities in this field. Barriers mentioned by Daimler executives include low efficiency (boil off), remain of (Nox) emissions, but mostly the storage problems of hydrogen.

Figure 1 Hydrogen fueled ICE vehicles demonstrated in 1984

A last alternative for the ICE forms the fuel cell. In 1985 Daimler acquires a stake in Dornier GmbH, a German aircraft and aerospace company. Dornier has expertise in FC technology, due to their development of a FC-based power requirement for the Hermes satellite shuttle program (1987-1992). Dornier develops several FC systems, including a PEM-based system. With the stake in Dornier, Daimler provides itself FC knowledge. In 1991-1992 a project team is set up in which FC technology for vehicle propulsion purposes was explored. The project team consists of between 15 and 25 researchers, most of them originating from Dornier. Around 1990 contacts with leading FC manufacturer Ballard in Canada starts.

Daimler's choice for FC technology is based on a long-term vision of developing a propulsion technology that would be able to reduce concerns about fossil fuel resources and climate change, while alleviating automotive emissions. Compliance to future regulations concerning fuel economy and exhaust emissions are of an immediate concern to Daimler, whose large-sized Mercedes-Benz are particularly exposed to such regulations (Steinemann, 1999).

3 FC Exploration phase (1990 – 1996)

The period between 1990 and 1996 can be characterized as the exploration phase for FC technology. A small group of between 20-50 researchers, mainly originating from the Dornier group working on the satellite program, explored the possibilities of using FC for propulsion purposes. This takes place in basic research centers in Ulm, Friedrichshaben, Konstanz and Frankfurt.

The objective of the group is to build a working prototype, for which they use a Mercedes van (see figure 2). During this period FCs might have been produced within Daimler, however the FCs used in the van originate from partner Ballard. Contacts with Ballard stem from around 1990, and in 1993 Daimler and Ballard sign a 4 year-$15-million contract in which Ballard agrees to supply Daimler with their FCs. The contract is not exclusive, while Ballard was also in contact with Daimler's competitors, including General Motors, Nissan, Toyota, Volkswagen, Mazda, Yamaha, Volvo and Honda. The agreement was followed by a $2,3M contract in August 1996.

The van, named the NECAR 1 (New Electric CAR, also referring to the nearby river Necar), is demonstrated in the beginning of 1994 for a technical board. Based on the model Daimler makes their first public announcement of their interest and research efforts in FC technology in the end of 1994. This event creates widespread attention for FCs in the automotive industry.

Figure 2 NECAR 1 and NECAR II

The FC system of the NECAR 1 provides 50kW of power, using hydrogen as a fuel. The hydrogen is stored as compressed gas. Although the system works, the FC system comprised all of the van except the driver’s seat. If Daimler is to invest more in FC technology there would have to be dramatic reductions of weight and size of the FC system. Meanwhile a second vehicle prototype is built.

The second FCV prototype is based on the V-Class. The main thrust is to minimize the size of the FC system, in which Daimler succeeds with great success. The NECAR II model is demonstrated in May 1996. It is the first fully functional light duty passenger vehicle to be powered by a FC: passengers don't see anything of the FC system, and no passenger space was lost (only luggage space). It is powered by hydrogen, and has a maximum speed of approximately 120 kilometers. Given the complexity the NECAR II is considered to be an impressive engineering achievement. The system is still too heavy but it is operational.
Hydrogen however is not seen as an option for the short term. Methanol is given preference over gasoline, as methanol is easier to reform into hydrogen rich gas. According to Daimler executives this decision was made between 1995-1996.

Daimler’s management acknowledges the dramatic progress of FC systems with regard to efficiency, weight and costs. It is decided to increase its FC efforts. In the beginning of 1997 management and key technical activities are centralized in Nabern, the former facilities of DASA close to Stuttgart, in the so-called ‘FC house’. Around 75 staff are engaged in methanol fuel processor development and integration of subsystems into FC power plants, with a focus on configurations for mass manufacturing. The ‘FC house’ can call on the entire capabilities of DaimlerBenz including the corporate research groups and vehicle testing facilities as well as the engineering expertise and facilities of Mercedes-Benz (Maruo 1998).

More important than the centralization of research efforts is that the FC project is founded as a strategic project: not as a research project, but as a ‘car development’ project. The consequence is a change of objectives. Whereas in basic research the objective is to build a working prototype, the task in car development is to build a car, which can be manufactured, in mass and which can be sold. Over the next 2 years every part of the FC engine will be developed to the point where processes for mass-production are established and engine performance and cost can be estimated with confidence (Maruo 1998)

This next level of product development shows the increased commitment Daimler had for FCV. Kalhammer (1998) concludes that within Daimler there is a fundamental belief that FCs are better suited for very rapid, low cost manufacturing than ICE.

Alternative technologies
In this period Daimler's choice of FC vehicles in favor of hydrogen fueled ICEs (H2-ICE) and EVs becomes increasingly clear. Programs on the latter technologies are scaled down, and get little to no press coverage. FC technology is the main bet of Daimler of achieving environmental breakthroughs. According to Trezona (World Fuel Cell Council, interview, 2001):

> *"…Daimler has always been active in discussing their environmental responsibility. Possibly this is related to German culture, where environmental issues are part of a larger societal debate. Looking at company statements through the years, senior executives have systematically expressed concern over issues such as toxicity, CO_2 and diminishing oil reserves for years: it is a recurrent theme of their corporate pronouncements."*

After relatively disappointing results with EV and H2-ICE, DaimlerBenz is said to have become convinced that FC technology is the only option for a sustainable transportation system around 1990 (Trezona, WFCC, interview, 2001). Since this period EV and H2-ICE programs have always been modest within DaimlerBenz.

4 FC development towards mass production (1997 – 1999)

With the decision to build a car ready for mass-production the character of Daimler's activities related to the FCV changes. Whereas in earlier years research was carried relatively in silence and within the Daimler complex (with few partners), the project takes a more outward approach. Apart from the technical developments in this period, Daimler's partnerships, the networking forming, and Daimler's market development of FC will be discussed. Also the merger with Chrysler and the influence on their respective FC programs requires attention.

Technical developments
Between 1997 and the end of 1999 DaimlerBenz and Chrysler showcase a series of FC based vehicles.

Passenger cars
At the Frankfurt Auto Show in October 1997 Daimler demonstrates the **NECAR 3**, based on it's a-Class passenger vehicle (see figure 3). The vehicle is the world's first to be fuelled by methanol, which is converted to a hydrogen rich gas by a steam reformer and CO selective oxidizer. The FC system is developed by Ballard and has a power output of 50kW, comparable to an ICE of a small to mid-sized car. The NECAR 3 has a range of 400km on a full tank (11 gallons of methanol). The size of the FC system has been reduced dramatically but still compromises the passenger space.

The NECAR 3 is the result of Daimler's research and engineering efforts to produce a mass-manufacturable methanol reformer. Designing for manufacturability is integral in the methanol reformer development. Most of Daimler's efforts are directed to this fuel problem, as hydrogen is not seen as a viable option for passenger cars in the short to mid-long term. Meanwhile Daimler has teamed up with Shell to explore the possibilities to extract hydrogen from gasoline, in a gasoline reformer (see partnerships). FC development is not carried out in-house, but takes place at Ballard with which they officially partner since 1997.

Although impressive progress is shown with the NECAR 3, a range of problems remains to be solved. From a technical perspective the balance of plant is a main barrier. Given that the system requires high atmospheric conditions (3 atmosphere) compressor-expander technology is developed. Apart from pressure handling, also the humidification and thermal control of the system are complex and require years of development. Another problem relates to ‘cold start’; the methanol reformer requires high temperatures, so a start up time of the motor has to be taken in consideration. A technical option is to add a battery (making it a hybrid) so that the car drives on batteries in the first minutes. Kalhammer (1998) suggests that sufficient knowledge on this hybridisation would be available at Daimler.
The FC system including reformer is commonly characterized as a small chemical plant under the hood of the car. Kalhammer (1999) concludes that the NECAR 3 is more of a rolling test bed, than a prototype.

March 1999 Daimler (now merged with Chrysler to DaimlerChrysler) unveils its **NECAR 4,** its fourth-generation FC vehicle in Washington, DC (see figure 3). NECAR 4's 70- kilowatt FC, manufactured by Ballard Power Systems, runs on stored liquid hydrogen, unlike the NECAR 3. Daimler announces that it will continue pursuing hydrogen and methanol as the fuel for future FCV (and not gasoline). The range of the NECAR 4 is close to 440 kilometres. Its drive train is developed and produced by EcoStar Electric Drive Systems, a company that was formed out of the 1997 alliance between DaimlerChrysler, Ford and Ballard (see alliance).

Figure 3 Necar 3 and Necar 4

After the merger with Chrysler, the FC department within Chrysler continues showcasing their research developments. In March 1999 DaimlerChrysler unveiled a new FC based vehicle based on the **Jeep Commander**. The engine is a FC/battery hybrid designed to utilize gasoline as fuel. Until this time Chrysler has been particular by not focusing on hydrogen or methanol, and pursuing the gasoline option together with ADL.

All in all the research and engineering efforts of DaimlerChrysler in the period 1997-1999 has made the FCV a more realistic future alternative for the ICE. The 3rd and 4th generation FCV by Daimler show considerable progress with respect to power density, space requirements and technical characteristics. Daimler and Ballard receive a great amount of patents for the research efforts. Daimler’s patents are mostly related to the methanol reforming process, typical for their fuel strategy. Patents related to FCs are mostly issued to Ballard. Whereas the FCV is catching up with the ICE on technical merits the cost aspects remain undiscussed in this stage of development.

Concerning fuel choice Daimler believes most in either hydrogen or methanol. With the Chrysler merger know-how concerning gasoline reforming was added to the consortium. However, after the merger Chrysler decided to suspend their FC activities with regard to gasoline, and switch to methanol. Chrysler called the gasoline-fuelled FCV Jeep Commander a developmental dead end. Furthermore it would continue working on a working methanol hybrid FC system in the Commander by the summer of 2000. The argument for the shift includes the problems of converting gasoline to hydrogen (see 'merger').

The shift from gasoline to methanol was not entirely based on Chrysler conviction. The FC director within Chrysler, Borroni-Bird, was a fierce protagonist of a fuel available to consumers now. After the merger and the decision to cancel the gasoline-conversion efforts, Borroni-Bird decided to move to General Motors, where he is currently in charge with a similar program (Moltavelli, 2000). Unlike Daimler, GM sees more opportunities for the gasoline path.

Although announced demonstration of the NECAR 5 does not occur in 1999, and is revealed in 2000. Also scheduled for late 1999 is a go-no go decision concerning building up manufacturing capabilities. This would be an important sign of commitment from Daimler with regards to FCV and their commercialisation. In late 1999 however no public announcement was made concerning manufacturing plans. Nonetheless Dr Panik, director of the FC House in Nabern, claims production ready cars will be available in 2004.

> *"Not only will we have a production ready car, but DaimlerChrysler will also have production itself, as many as forty thousand FC cars that first year. We have a schedule and we are sticking to it." (Dr. Panik, in Moltavelli, 2000)*

> "*In FCs we want to be on top. It's a competition driven international race, and the company that is first to production will get to make the rules" (Mr. Ebner, board of DaimlerChrysler, in Moltavelli, 2000)*

FC Buses
Parallel to the FCV, Daimler is active in developing buses powered by FCs. May 26, 1997 Daimler Benz unveils a FC bus that runs on condensed hydrogen and has a range of 250km (see figure 4). The bus is tested in-use beginning June 1997 in Stuttgart. Several reports and institutes have argued for the advantages of using buses as the initial market for FC use. The space requirements make FC systems more realistic in buses. Furthermore buses make use of few fuelling stations, opening the possibility of starting with a non-current fuel (hydrogen or methanol) without the requirements of an extensive fuelling infrastructure.

Figure 4 FC bus by Daimler: the NEBUS

Also Daimler and Ballard are active in setting up pilot projects. Plans start for piloting buses in Chicago and in Vancouver, and are under negotiation in California and other states in the end of 1997. In 1998 several of Daimler FC buses, named the NEBUS, start testing in among others Mexico City and in Oslo, Norway. In Norway Daimler teams up with Hydro Gaz, a subsidiary of Norsk Hydro, which provides the hydrogen used by the NEBUS. Norsk Hydro has worked with DaimlerChrysler on the development of the NEBUS.

In the end of 1998 DaimlerChrysler head of the FC house Ferdinand Panik predicts ‘about nine units a year would be tested in urban areas through 2003’. Several bus operators have by then announced plans to deploy FC buses in then near future (for instance Hamburg, North America, Mexico and Czech Republic). Daimler intends to start selling the NEBUS worldwide in 2004.

Partnership (ref. Ballard annual reports)
With the decision to pursue FC technology more dramatically, Daimler decides to become a strategic shareholder in Ballard Power Systems in the beginning of 1997. Daimler purchases 25% minority interest in Ballard by investing $400M. Ballard Power Systems will continue to develop, manufacture and supply FCs for the alliance, as well as for other automakers.
Also two joint venture companies are established. First of all DBB FC Systems has the mission to develop and manufacture transportation FC systems. Second, Ballard Automotive has the mission to market automotive FCs and FC systems to car, bus, and truck manufacturers globally.

In December 1997 Ford announces to join the alliance between DaimlerBenz and Ballard. Ford acquires 15% interest in Ballard Power Systems, reducing Daimler’s interest to 20%. Furthermore it acquires a 22% interest in DBB FC Engines, and Ford becomes a partner in the marketing collaboration Ballard Automotive.

Another joint venture is established (in August 1998): EcoStar Electric Drive Systems Co. The new company, launched by Ford, will develop electric drive trains for FCVs. Ford is majority owner with 62%; Ballard Power Systems and DaimlerChrysler participate with 21% and 17% respectively (see figure 5). The company intends to have FC drive trains commercially available in 2004.

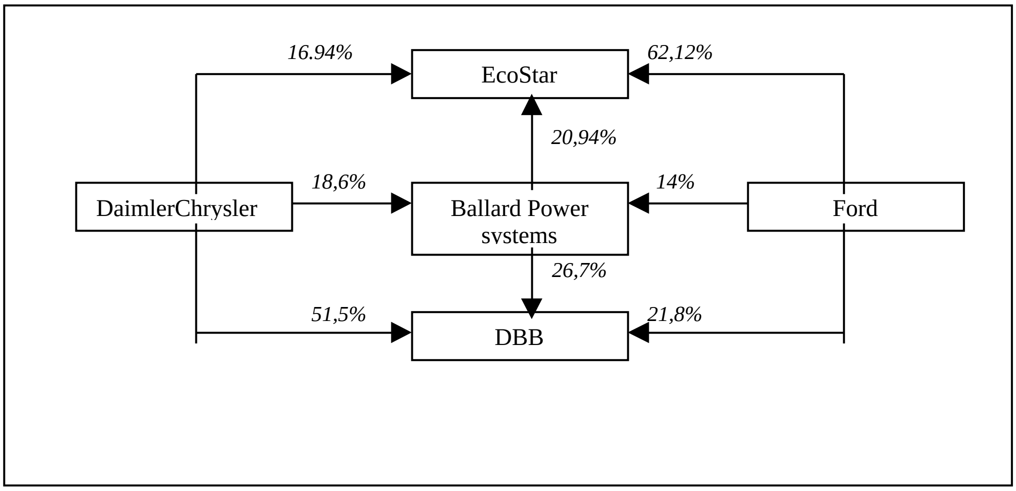

Figure 5 The FC Alliance between DaimlerChrysler, Ford and Ballard (December 1997)

Network

Apart from the technical efforts of DaimlerBenz/Chrysler in the period 1997-1999 a clear broadening of the horizon can be discerned. Daimler is increasingly engaged in FC-discussions with other partners, either in the oil industry, other automotive companies, suppliers and governmental organisations. What follows is an overview of Daimler's networking efforts.

Oil Companies

In August 1998 Shell and DBB FC Engines start two collaborative research projects. The first is to study the opportunities of developing a hydrogen infrastructure. The second is a research-collaboration with Daimler to study the viability and future opportunities of gasoline reforming. Shell brings in its Catalytic Partial Oxidation (CPO)-technology, which converts liquid fuels into a hydrogen rich gas. The technology is best suited for converting gasoline into hydrogen.

As mentioned Daimler prefers methanol and hydrogen for technical reasons. Methanol can be converted into hydrogen more easily than gasoline, making it a more suitable fuel for short-term usage in FCVs. After a 18-month collaboration the project is suspended. Executives mention that Daimler did not want to rule out the possibility of gasoline reforming. However the Shell collaboration has shown the shortcomings of the conversion technology, which requires years of intensive research. This prospect does not fit Daimler's plans to start commercialising FCV in the near future. According to Kalhammer (1998) methanol reforming is 4-8 years closer to commercialisation than gasoline reforming.

Apart from Shell, Daimler discusses infrastructure issues with the oil industry continually among which British Petroleum, Texaco and Exxon. In the end of 1999 discussions start with Nippon Mitsubishi, leading to a joint project studying the future requirements for FCV-fuels, among which methanol.

Automotive companies: Chrysler merger

In May 1998 Daimler-Benz and Chrysler merge. Although the merger is formally equal, Daimler heads the new company whilst several Daimler top executives move to Chrysler for a major reorganization. Industry experts as well as Daimler executives acknowledge that the merger is more of a 'friendly takeover' (economist, August 5, 2000). This relation has influence on the continuation of the FC project within Chrysler, as mentioned before.

Chrysler had been running a modest FC program, compared to Daimler, GM, Ford and Toyota. According to Kalhammer (1999) there was no strong commitment to FC technology. Its strategy was to initially buy all key FC components and systems. In case a mass market would develop, it planned to acquire FC engine technology appropriately. In 1998 Chrysler had expressed that commercialisation of FC vehicles would be possible around 2015. Chrysler worked together with Delphi Automotive systems.

Chrysler had differing viewpoints with respect to two technical aspects of a future FCV. First of all the fuel: it was the only auto manufacturer preferring gasoline over hydrogen or methanol. Their collaboration with ADL provided them with cutting edge conversion technology for gasoline to hydrogen. However this technology was far from commercialisation. A second technical difference concerned the hybridisation of a FCV, meaning the use of batteries parallel to FCs. The FC would only provide the acceleration power, keeping the amount of required (expensive) FC low.

After the merger Post Merger Teams were responsible for streamlining and bringing together research within both firms. Given Daimler's lead in FC technology, Daimler's preferences for methanol/hydrogen over gasoline was chose. The gasoline-conversion program within Chrysler was stopped. Head of Chrysler’s FC program, Mr. Borroni-Bird, subsequently moved to General Motors.

Governmental programs
Daimler also becomes more active in setting up projects with governments to discuss FC issues.

- **Hydrogen infrastructure in Iceland**. In 1998 Ballard, Daimler- Benz, and the government of Iceland sign an agreement to begin pilot production of hydrogen and to deliver several FC-powered buses to Iceland's Industry and Fuel Ministry. The agreement is part of a project to create the first hydrogen infrastructure in the world, in Iceland. Daimler will provide FC based buses and vehicles. Also Shell is involved by developing the required hydrogen infrastructure. Iceland provides an opportunity for Daimler to deliver and test the first series of FCV and FC buses.
- **Start of California FC Partnership**. DaimlerChrysler is one of the founding members of the Californian FC Partnership (CFCP), set up in April 1999. Partners are the California's Air Resources Board (CARB), the California Energy Commission, Ford Motor Company, Ballard Power Systems and the oil companies ARCO, Shell and Texaco. The cooperation has since been extended to include a number of new partners such as Honda, Hyundai, Nissan, Volkswagen, International Fuel Cells, the US DOE, the US DOT and the South Coast Air Quality Management District.
  The partnership will put a fleet of up to 50 FC vehicles on the road between 2000 and 2003. The oil companies involved in the deal - Atlantic Richfield, Shell Oil and Texaco - will work on development of alternative fuels and fuelling infrastructure. Methanol and hydrogen will be tested along with other fuels. Ford and DaimlerChrysler will each provide 5 FC passenger cars by 2001, fuelled with hydrogen. The fleet will include about 25 buses. Similar to the Iceland project the CFCP provides the opportunity of delivering and testing FC prototypes. Also it forms a platform for Daimler to discuss infrastructure and FC-technical issues with automotive partners and the oil industry. Lastly the partnership includes discussing FCV and infrastructure related issues with one of the leading regulators in the world concerning vehicle emissions, the CARB.

5 Commercialization of FCV (2000-2001)

5.1 FC project

Between 1999 and 2001 DaimlerChrysler’s activities in FC technology increase continually. In the beginning of 1999 nearly 300 people work on FC vehicles; by 2001 the FC program comprises approximately 500-600 people. The FC program is carried out by the former DBB FC House, now called XCELLSIS FC Engines. XCELLSIS has its head office in Nabern, Germany, but is also located in Vancouver and San Diego. In Nabern 400 employees mainly work on reforming technology of methanol. Main technical hurdles are the ‘cold start’, dynamic aspects during acceleration and breaking, and reliability issues. Vancouver is mainly concentrated on bus systems; San Diego deals with hydrogen systems. The Vancouver and San Diego teams have around 100 people in their program. The majority owned XCELLSIS (former FC House) form the main activities to develop FC vehicles.

Investments
According to Kalhammer DaimlerBenz will have spent around $1B on FC technology until the end of 2000. At the Hanover Fair in June 2001 CEO Schrempp announces DaimlerChrysler will spend around $1B for commercializing FC technology in the coming years. In spring 2001 the United States FC Council (USFCC) report Daimler’s FC-investment plans of $1,4B in the coming four years (USFCC, 2001).

Despite hard times at DaimlerChrysler in 2000-2001 with large cost-cutting operations, the FC program is preserved. Top management acknowledges the importance of keeping a start-up organization motivated and providing it with sufficient and continued funds.

Commercialisation

During this period the commercialisation of FCV take shape. Although Daimler has claimed market introduction of FCV in 2004, more specialized market information is announced. In February 2000 DaimlerChrysler sets a target price for its first fuel-cell-powered passenger car-around $18,054 at current exchange rates. The car will be a version of the Mercedes-Benz A class, with a few thousand expected to be introduced in 2004. At a Tokyo symposium, DaimlerChrysler states that FCV will account for up to 25 percent of the global market by 2020.

Professor Klaus-Dieter Vöhringer, member of the DaimlerChrysler Board of Management with responsibility for research and technology, predicts the FC will be introduced into vehicles in several stages:

> *"In 2002, DaimlerChrysler will deliver the first city buses with FCs, followed in 2004 by the first passenger cars. Up to that time, the vehicles from the first production phase will be using liquid or gaseous hydrogen as a fuel. However these fuels are unlikely to see widespread use because of the high cost of the infrastructure. Nevertheless, we'll be operating test fleets in several regions of the world to gain experience with daily use of FCs."*

Nevertheless there are several uncertainties:

- fuel infrastructure: Daimler’s choice for methanol is not shared by the industry as well as by a majority of the oil industry. Daimler is faced with a major hurdle, which is key to the success of FC vehicles.
- Technical problems: FC vehicles pose complex technological problems to the engineers, and the 2004 deadline seems to come slightly early for commercial passenger vehicles.
- DaimlerChrysler’s financial situation: DaimlerChrysler’s financial results are a major concern. A major reorganization within Chrysler leads to great losses, which make stock markets question the merger between the two. Daimler’s shares shrink by 50% during this period, and Daimler is heavily under fire to start cutting costs and reorganize. CEO Schrempp predicts Chrysler will start making profits in 2003.

The bus program

In May 2000 DaimlerChrysler announces its plans to build 20 to 30 FC city buses within the next three years and sell them to transport operating companies in Europe and abroad. The FC "Citaros" are expected to be delivered by the end of 2002, at a price of US$1.2 million each. The buses will run on compressed gaseous hydrogen, with a top speed of 50 mph (80 kmph) and a range of 186 miles (300 km). In April 2001 the first FC bus is sold to several European cities for test trials. Furthermore, in February 2001 Daimler delivers its first FC vehicle other than a bus, the Mercedes-Benz Sprinter to Germany’s Versand Service.

Figure 6 The Citaro FC bus, and the Mercedes-Benz FC-Sprinter

In the end of 2001 questions remain concerning the reality of commercial FC vehicles on the short term. Daimler continues to emphasize its commitment to FC technology, despite the technical, infrastructural and financial setbacks.

Alternatives for FCV: EV development

In October 2000 DaimlerChrysler purchases Global Electric Motor Cars (GEM), the largest producer in the US of electric vehicles. With the purchase DaimlerChrysler becomes the first major automaker to sell Neighbourhood Electric Vehicles (NEV) in the US. According to DaimlerChrysler’s press release ‘marketing NEVs is part of DaimlerChrysler’s continuing effort to develop, produce and sell the world’s most environmentally friendly vehicles.’ The purchase of GEM also fits with DaimlerChrysler’s ZEV requirements in 2004.

5.2 Technical progress and choices

Technical progress

November 2000 DaimlerChrysler presents the NECAR 5, the latest version of the New Electric Car, in Berlin. The NECAR 5 runs on methanol, unlike its predecessor, the NECAR 4, which runs on hydrogen. Daimler claims that the FC drive system has shrunk to such an extent that it does not require more space than a conventional drive system. The FC system fits in the sandwich construction in the floor of the A-Class.

Figure 7 Necar 5 and the Jeep Commander 2

Also in Berlin DaimlerChrysler unveils the Jeep Commander 2 FC concept vehicle, running on hydrogen reformed on-board from methanol. The vehicle is a FC/battery hybrid concept, with a nickel-metal-hydride battery to provide supplemental energy during acceleration, and for cold starts. The battery also captures energy from regenerative breaking. The Jeep shows Chrysler’s choice to pursue and study the possibilities of hybridisation.

In November 2000 XCellsis announces the production start of new model FC engine, the P5, in 2002 with hundreds a year. This is an important step for the development of FC vehicles, as this means the propulsion unit for FC vehicles is on the market.

Meanwhile Daimler experiments with other FC types and alternative functionalities.

- Following BMW, in January 2000 Daimler presents a FC used as an auxiliary power unit (APU). The APU is responsible for energy requirements on board of the vehicle other than propulsion. A FC APU permits higher voltage necessary for the increased energy requirements within the car. The FC would replace the current battery.
- In November 2000 DaimlerChrysler unveils a Ballard Direct Methanol FC (DMFC) prototype at DaimlerChrysler's Innovation Symposium in Stuttgart, Germany. The 3kW FC powers a small one-person demonstration cart. The cart demonstrates Daimler’s studies to alternatives to the PEM FC. The DM FC is seen as an important successor of the PEM FC.

Testing

During this period Daimler increases its efforts to test FC vehicles and to get hydrogen powered FC vehicles accepted by national agencies for road testing. DaimlerChrysler's NECAR 4 FC vehicle is operated daily for three weeks shuttling flight crews, airport employees and other visitors at the Munich Airport. In August 2001 DaimlerChrysler teams up with Hermes Versand Service, a Hamburg-based delivery company, to run a two-year field test on a FC vehicle. The hydrogen-powered Mercedes-Benz Sprinter van will go into operation in the Stuttgart metropolitan area before being transferred to Hamburg.

Lastly field test agreements are signed with the Singapore government (June 2001) and the Japanese Ministry for Infrastructure and Transport (April 2001) to allow Daimler to conduct FC vehicle road tests.

Fuel preference

As mentioned earlier Daimler prefers to pursue methanol for passenger cars and hydrogen for fleet operated vehicles. Methanol is a midterm solution in order to bring in place a hydrogen infrastructure. More importantly is its choice to NOT pursue gasoline, as competitors GM and Toyota are doing. Environmental concerns seem to play an important role in the fuel discussion. CEO Schrempp (November 2001, www.daimlerchrysler.com):

> *"Which energy will ultimately shape our mobility and therefore our life is now the key question. We must continue to make mobility more environmentally sound and lower emissions. The demand for energy continues to grow and at the same time the supply of fossil fuels is limited. We'll be able to use petroleum for many years yet, but perhaps not at today's prices.”*

5.3 Coalition building

The continuation and building of coalitions remains an important part of the activities DaimlerChrysler carries out in order to keep FC technology in the race. Most striking is the amount of collaborations with oil companies and fuel suppliers. Furthermore Daimler’s increased activities in the East (Mitsubishi and Mazda) form an indication of Daimler’s efforts to put FC technology on the map in Japan.

The Allianz

In November 2000 Ballard Power Systems, DaimlerChrysler and Ford Motor Company sign an agreement in which Ballard acquires the interests of DaimlerChrysler and Ford in XCELLSIS GmbH and EcoStar Electric Drive Systems, LLC. This transaction increases DaimlerChrysler and Ford's commitment to, and reliance on, Ballard as their exclusive FC engine supplier.

Car industry

Mitsubishi

In March 2000 Daimler acquires a 34% stake in Mitsubishi Motor Corporation, which as many Japanese car manufacturers has serious financial concerns. The motivation is to strengthen DaimlerChrysler's plans for small cars.

Mitsubishi has a moderate program on FC technology together with former mother company Mitsubishi Heavy Industries Ltd, in which they research and develop FCs in house. Mitsubishi and Mitsubishi Heavy Industries signed an agreement in 1998 under which they would jointly introduce a FC car by 2005. Daimler thus acquires access to Mitsubishi's FC program.

Although several news reports suggest collaboration in the field of FC technology Daimler executives claim that Mitsubishi will continue its own FC program. Daimler will continue to rely on Ballard FC stacks, which it claims are still the most competitive in the field.

Daimler does admit discussing FC issues with Mitsubishi and Mitsubishi Heavy Industries given their specific areas of expertise. In December 2000 Mitsubishi enters into a strategic alliance with Methanex Corp and Misui & Co., to promote the use of methanol in Japan as the fuel of choice for FC vehicle applications. Given that a majority of car manufacturers have by then switched to gasoline as the preferred fuel, Mitsubishi's commitment to methanol provides support for Daimler's strategy.

Mazda

In April 2000 Mazda Motor Corp. announces to join DaimlerChrysler Japan Holding Ltd. and Nippon Mitsubishi Oil Co. Ltd. in a project to develop FCVs with government subsidies. 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 (US $9.3 million) and is expected to receive between 200 and 300 million yen (between US$1.8 and 2.8 million) worth of subsidies from Japan's Ministry of International Trade and Industry.

Oil industry/ fuel issues

Methanol

Apart from the above mentioned collaborations with Mitsubishi (and Mitsubishi Heavy Industries) and Mazda (with Nippon Mitsubishi Oil), Daimler continues to set up projects with other fuel providers. In September 2000 DaimlerChrysler AG, British Petroleum, BASF, Methanex, Statoil and XCELLSIS enter into a co-operation agreement to evaluate the introduction of methanol FCV. The goal is to establish a joint position after examining any health, safety, environmental and infrastructure issues associated with the use and introduction of methanol FCV.

Gasoline

In February 2000 Shell and DaimlerChrysler discontinue their research collaboration on reforming technology of gasoline to hydrogen. After the 18-month collaboration DaimlerChrysler concludes that the technology is not far enough developed to be introduced on the mid-long term (2004-2008). Daimler prefers the methanol path.

Shell, claiming that its reformer technology is competitive, will continue to develop it although no specific partners are mentioned. Shell and DaimlerChrysler will continue their joint projects in Iceland and CFCP.

Hydrogen
Since 1999 BP Amoco and DaimlerChrysler join forces to take part in a US5 million joint venture to bring hydrogen FC buses to London. BP will fund the cost of developing the hydrogen fuel infrastructure and Daimler will provide three hydrogen-powered Citaro buses in 2003.

Government related
DaimlerChrysler continues its projects with governments to bring FC vehicles to market. Most are related to the bus program together with individual cities. Also DaimlerChrysler is heavily involved in the Californian FC Partnership (CFCP) to develop prototypes. In November 2000 XCELLSIS joins the CFCP.

In January 2000 Daimler withdraws from the climate coalition, an oil and automotive industry platform to discuss the effects of the effects of CO2 on climate conditions. In general the climate coalition is seen as a platform to counter environmentalists' views that CO2 should be reduced dramatically. Daimler's withdrawal, second major car manufacturer after Ford, gives an indication of their position on environmental issues.

6 Findings

This paper gives a detailed picture of Daimler's activities in FC technology, and thereby provides the raw data for analysis of its R&D process.

Stages in FC technology development at Daimler
First of all the data show the different stages of FC-research and -development. Since the start of FC related activities five stages can be discerned distinct with respect to organization, financial commitments, objectives and status of the technology. Table 1 gives an overview.
Between 1987 and 1992 FC knowledge was built up within Daimler's partner Dornier. At this point in time FC technology was not yet related to vehicle applications. Vehicle applications became relevant in 1991. The progress in FC technology had become apparent to such an extent that Daimler set up a team to build a prototype with FC technology. Central objective was to assess whether it was possible to actually build a FCV. With the technical objectives achieved, from 1994 to 1996 Daimler dedicated the FC program to test the viability of a FCV: would it make sense to make a fuel cell vehicle?, and also Where are the main technical hurdles and can we overcome them? A major step was taken in the beginning of 1997 when Daimler decided to set up the FC House, making the FC program a 'car development program'. This got the project out of the research realm, into 'development' with a clear objective of developing a mass-producible car. Since 2000 Daimler is more actively involved in paving the way towards commercialization, parallel to its developmental program. Central in this strategy is coalition building, network formation, and testing programs.
A transition from 'research object' to a 'commercially attractive technology' has thus taken place in a period of 10-12 years. Daimler has predicted that at least three more years (2004) are necessary to produce several hundreds of passenger cars. For large-scale production and commercialization a timeline of 2008-2010 is mentioned. Given the amount of hurdles to be taken this is by no means an accurate estimation. It can be questioned, as several industry experts do, whether commercial, large-scale produced FCVs will ever see the day.

FC program size
During the development period the FC program was expanded dramatically, from a mere 15-25 employees in 1990 to between 500 and 600 in the beginning of 2002. Its budget increased correspondingly from thousands of dollars to hundreds of millions of dollars a year. In the coming four years time DaimlerChrysler will invest between $1-1.4B

on FC technology. With a yearly R&D budget of $8.9B (1999) FC investments are between 3-5% percent of the total R&D budget of DaimlerChrysler. It can thus be concluded that the FC project is more than window dressing or a way to enhance the Daimler image in the public domain, which has been suggested by critical observers. This might have been the case in the early years of development (1990-1996), but in recent years strategic value has overruled the value of public image of FC technology; the investments are just too vast. Given the amount of resources spent and the size of the FC program it can only be concluded that DaimlerChrysler is making serious efforts to prepare FCV for commercial production.

Table 1 R&D phases within Daimler with respect to FC technology

	$/year	**employees**	**Internal/external**	**partners**	**Objectives**
1987-1992	> $ 0,5M	15-25	Internal/subsidiariy	-	Non automotive
1991-1993	$ 1-3M	25-40	Internal	FC manufacturers Government programs	Exploring technical working of FC
1994-1996	$ 10-30M	40-80	Internal + external links	FC manufacturers Government programs Suppliers of FC components	Studying viability of technical system
1997-1999	$50-200M	100-300	Start of external partners	FC manufacturers Car manufacturers Suppliers of FC components Governmental agencies	Mass production objective
2000-2002	$ 300-450M	300-600	Building external network	FC manufacturers Car manufacturers Oil industry Government agencies Suppliers of FC components	Commercialization objective, incl: Network building, infrastructure focus, etc.

Network

Prominent in Daimler's activities are the efforts to build a network of suppliers, oil manufacturers, government agencies, institutes, and build coalitions with car manufacturers. Figure 8 maps several of the more important partners Daimler collaborates with. It gives a good indication how the type of partners have changed throughout the years.

Where technical problems were the most crucial in the early years, collaborations mainly were sought with FC manufacturers like Ballard, some in the chemical industry and with specialized suppliers.

With the set up of the FC program a more coherent strategy was set up, focusing on partners in the car industry (Ford, Mitsubishi, Mazda). Only in later stages infrastructure issues were discussed intensively with a range of oil industry representatives, leading to several projects (e.g. Shell, BP, Statoil, Methanex).

The development of FCV clearly is by no means to be solved by one company only; it requires a range of partners on the supply side as well as on the infrastructure side for successful introduction. The collaborations with the oil industry in 1998 seem to indicate an urgency to deal with this 'infrastructure-hurdle', and suggest that hurdles to the technical system of FCVs were until that time more prominent. In that case the oil industry collaborations are another indicator of belief in the technical viability of the FC system and accordingly of vehicles with FC technology.

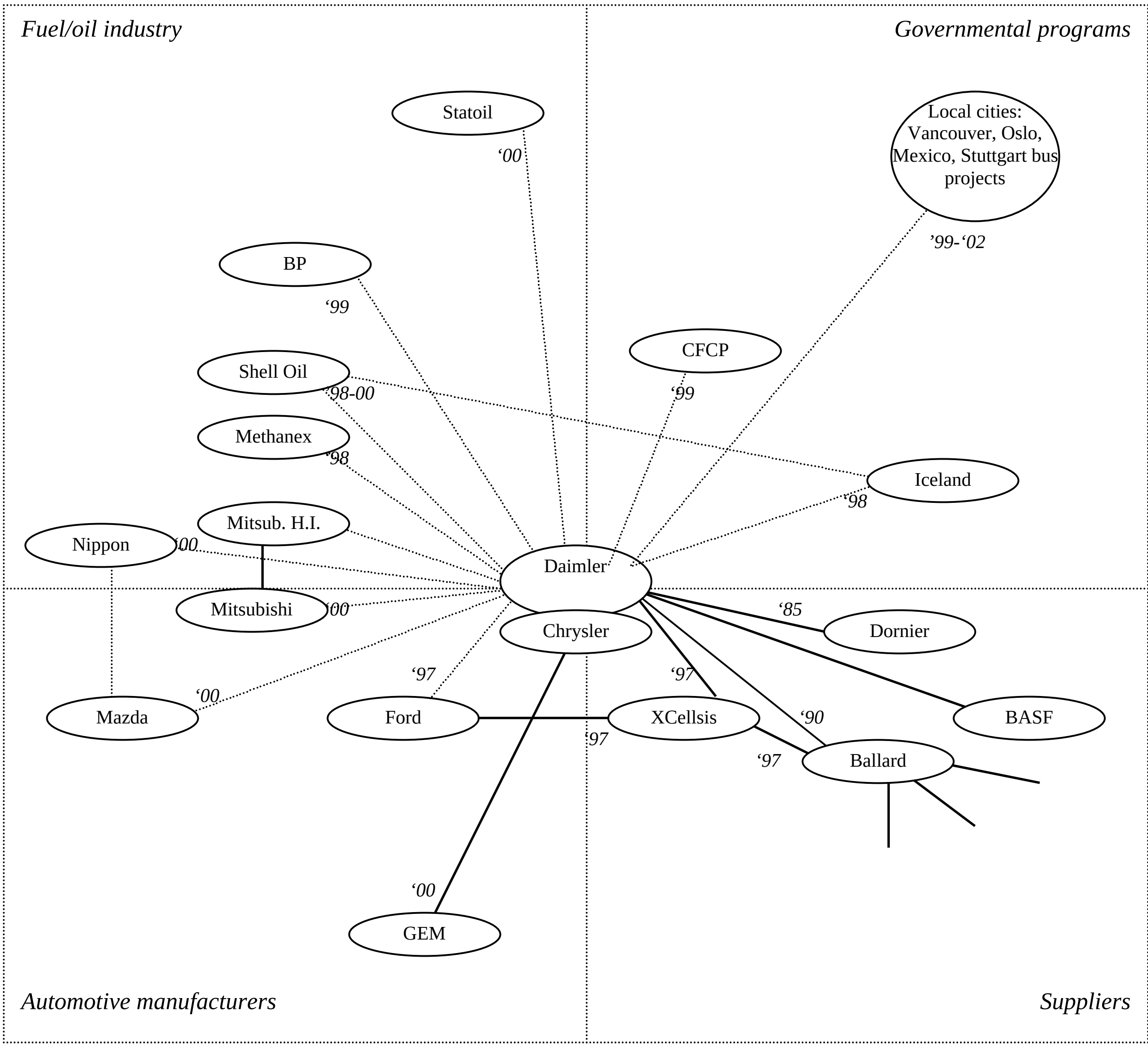

Figure 8 Daimler's network around FC technology

Milestones

The first milestone was the demonstration of the NECAR1 in 1993 for Daimler's technical board. It showed the technical viability of FCV and the advancements made by Ballard in recent years. It showed that FC technology might provide opportunities on the long term. Upon this demonstration Daimler's board decided to continue its program towards passenger car application.

A second major milestone was its successor the Necar 2, which showcased the progress made with FC technology in terms of space and efficiency. The technical progress shown was impressive and indicated the possibility for steep learning curves in FCV. After Necar 2 the board decided to start the FC house. Possibly this was the most important step given that FC technology was taken up as a 'car development program' with the specific objective of developing a mass-producible car. Daimler was the first to do so.

The next milestone was the alliance formation with Ballard, and later with Ford in 1997. It ensured Daimler's leading position in FC technology (through Ballard) and provided support from the number-two car manufacturer in the world (Ford). The alliance would form a strong backbone for further development.

The end of the collaboration with Shell can be considered a milestone as well, namely the decision *not* to pursue gasoline. Collaborating with Shell had a function of justifying Daimler's preference to methanol over gasoline. Shell was not able to convince Daimler. On the other hand Daimler had possibly hoped to convince Shell of the methanol path, in which they in turn did not succeed. The termination of the collaboration in the beginning of 2000 left Daimler with a problem: it lacked a strong partner in the oil industry and was linked only to minor players as Statoil and Methanex. Since this period Daimler has been very active in convincing partners in the automotive industry (Mitsubishi, Mazda), oil industry (BP), and government agencies to jointly develop a methanol infrastructure.
A last milestone mentioned was the showcase of the Necar 5. This methanol fueled passenger car had no restrictions in terms of space for the passengers with all technology hidden in the sandwich construction of the A-Class. This showed the unprecedented engineering achievement reached in the last 10 years of development.

Motives

How can Daimler's investments in FC technology be explained? The data suggest that Daimler's early involvement in FC technology can be explained by a combination of factors. First of all Daimler had early access to PEM FC knowledge through subsidiary Dornier, which also had contacts with leading FC manufacturer Ballard. As a result it had an increased sensitivity (absorptive capacity) to the progress made in FC technology in the beginning of the 1990s). Second Daimler's had longstanding efforts to study alternatives to the ICE, including hydrogen burning, electric vehicles and fuel cell technology. This provided Daimler with a detailed understanding of the pros and cons of the technological alternatives, arguably being better informed than its competitors. Lastly Daimler's had recent experiences with hydrogen projects (including storage technology), central to the development of FCVs. It seems that the threshold for Daimler to engage in FC technology was lower than its competitors.

But why then did the program of Daimler continue growing throughout uncertain technical prospects, financial problems of the company and competitive strategies towards other alternatives (EV, HEV, H2-ICE)? Downsizing of technology-programs is quite common, and has happened in the past with EV and H2-ICE programs. What is it with FC technology to keep it going, and in this pace?

Environmental regulation

A popular view is that environmental regulation, and especially the Zero Emission Vehicle (ZEV) standards in California have played a crucial role in the attractiveness of FCVs. However, Van den Hoed and Bovee (2001) have already suggested that Californian regulation has not been the main driver. Main argument is that Daimler was not affected by the ZEV regulation given its 'intermediate volume manufacturer' status in California, which had much less stringent standards to conform to than 'large volume manufacturers'. Furthermore Daimler is developing the FC system on the A-Class platform, a car not sold in California.
A more likely driver than this *specific* regulation is the *general* concern over environmental problems. Daimler's longstanding efforts of developing cleaner alternatives in the 1970s and 1980s are evidence of Daimler's commitment to environmental concerns, and also in relation to FC technology environmental benefits are consistently mentioned. Industry experts, Daimler's statements and the interviews at DaimlerChrysler suggest that environmental concerns are taken very seriously and form the backbone for innovative research like FC technology.

Technological progress

Apart from regulatory pressures several milestones demonstrate remarkable technical progress of the FC system, with regard to efficiency, platinum loading, size, weight, viability of methanol reforming and a range of other technical hurdles. The NECAR prototypes have played an important role in communicating these advancements. Both the NECAR 1 and 2 played crucial roles in convincing the technical board of the opportunities of FCV. In later stages the NECAR 4 and 5 were crucial to show the enormous progress in terms of size and weight. Without the advancements it is highly unlikely the FC program would have grown the way it did. The FC program has benefited largely from the merits of the technology itself.

Strategic positioning
The third important driver for Daimler seems to be the strategic position it has achieved with respect to FC technology. Being the first with FC-prototypes, and the first to have a strategic alliance with leaders Ballard and Ford gave Daimler a head start and a strong competitive advantage over competitors. Although the fruits of being technological leader are uncertain, there are opportunities: 'innovative' and 'green' public image for Daimler, appropriating technology (e.g. patents), and being able to set the industry standards. Although this may have played a role in the mid-nineties we have argued that the current investment levels are probably too high to justify mere public image building. Furthermore the current lack of strong oil partner is precarious for DaimlerChrysler in order to build an infrastructure. Lastly competitors GM and Toyota have made rapid advancements also in relation to FC technology; Daimler's leading role is challenged. Thus the driver of strategic positioning seems to be losing ground for DaimlerChrysler.

7 Conclusions

In a detailed description of Daimler's FC-activities, the transition from a 'research object' to a 'commercially attractive technology' has been presented historically via five distinct phases. Concerning this R&D process we conclude the following.
First, the size of the program and the structured development of a network around the technology provide strong evidence that DaimlerChrysler is making serious efforts to prepare FCV for commercial production.
Second, the experience with hydrogen experiments, the extensive research programs on ICE-alternatives, and the early access to FC-knowledge (via Dornier) have lowered the threshold for Daimler and increased its sensitivity to FC advancements, and have made Daimler a likely candidate to be the industry leader with regard to FC technology in the beginning of the 1990s.
Third, broad environmental concerns over oil depletion, emissions and global warming seem the strongest driver for the continuous commitment to the FC program. These general concerns have played a stronger role than specific regulation such as the ZEV-standards in California.
Fourth, apart from regulatory pressures the technical advancements achieved with FC systems, and the strategic (leading) position Daimler had, were drivers for the growth of the FC program within Daimler. Especially the strategic positioning is losing ground as a major driver given the challenged position as technological leader by competitors.
Fifth, the efforts to develop a network of relevant partners on the supply side, infrastructure side, and with competitors indicates the importance for successful development of the technology.

Literature

Abernathy W.J. and J.M. Utterback, *Patterns of Industrial Innovation*. Technology Review, vol. 80, no. 7, June-July 1978, PP. 2-9, 1978

Christensen, C. M., *The innovator's dilemma: when new technologies cause great firms to fail.* HBS, Boston, 1997

Economist, *The DaimlerChrysler emulsion*, August 5, 2000

Fussler, C. & James, P., *Driving eco-innovation: a breakthrough discipline for innovation and sustainability*, London, 1996

Van den Hoed, R. and Bovee, M., '*Responding to stringent environmental regulation; the case of the automotive industry*', Paper for the seventh annual Eco-Management and Auditing Conference, Nijmegen, June 21-22, 2001

Höhlein, B., *Vergleichende Analyse von Pkw-Antrieben der Zukunft mit verbrennungsmotoren oder Brennstoffzellen-Systemen*, VDI Berichte, München, 1998

Jansen, L. and Ph. J. Vergragt, *Sustainable Development: A challenge for technology; Proposal for the interdepartmental research program Sustainable Technology Development*, Leidschendam, 1992.

Kalhammer F.R. et al., *Status and Prospects of Fuel Cells as Automotive Engines; A Report of the Fuel Cell Technical Advisory Panel*. California, July 1998

Maruo, K., S*trategic Alliances for the Development of Fuel Cell Vehicles*. KFB Rapport 1998: 37. Goteborg, December 1998

Moltavelli, J., *Forward Drive, the race to build "clean" cars for the future*, Sierra Club Books, San Fransisco, 2000

Northeast Advanced Vehicle Consortium (NAVC) and M.J. Bradley and Associates (2000), *Future Wheels; Interviews with 44 Global Experts on the Future of FCs for Transportation and FC Infrastructure and a FC Primer*, Boston

Plante, M. & R. van den Hoed, *Environmental Performance of Fuel Cell Vehicles*, *Identifying underlying variables for explaining heterogeneous outcomes*, Report for Kathalys, 2000

Shnayerson, M., *The Car That Could; The inside story of GM's revolutionary electric vehicle*. New York, 1996

Steinemann, P.P.. *R&D Strategies for New Automotive Technologies: Insights from Fuel Cells*. A paper for the International Motor Vehicle Program, Boston, 1999

United States FC Council (USFCC), *Status Report*, Spring 2001

Utterback, J.M., *Mastering the Dynamics of Innovation*. HBS press, 1994

Weizsäcker, E.U. von, A. Lovins and H. Lovins, *Factor Four; Doubling Wealth, halving Resource Use: The new report tot the club of Rome*. Earthscan Publications Ltd, London, 1997

Weterings, R. & Opschoor, J., *Towards environmental performance indicators based on the notion of environmental space*. RMNO publication nr. 96. Rijswijk, 1994.

www.fuelcells.org
www.evworld.org
www.ballard.com
www.daimlerchrysler.com