Prototyping Hydrogen Futures
Measuring the Automotive Industry's Expectations of Hydrogen Technologies

DRAFT VERSION – DO NOT CIRCULATIE WITHOUT PERMISSION

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Abstract
In this paper we ask the question what hydrogen prototypes tell us about the expectations car manufacturers hold and to what extent these expectations diverged or converged over time. Expectations are considered to stimulate, steer and coordinate technological development. In order to be influential, expectations must be shared and collective. Prototypes and demonstration vehicles are an important means for communicating expectations of hydrogen as fuel of the future and its enabling technologies. This makes for an excellent indicator of manufacturers’ expectations. To analyse this we perform a measurement in which we include the temporal dimension and try to show to what extent car manufacturers converge or diverge on the indicators over time. For this we compiled a database of 224 prototypes of personal cars running on hydrogen. The database describes: the car’s manufacturer, year of construction, type of drivetrain, fuel cell type and manufacturer, type and capacity of its hydrogen storage system.

We conclude that there is convergence towards two configurations: 1) internal combustion engine with liquid storage and 2) Battery/H$_2$FC hybrid with high pressure storage. Given the increasing numbers of hydrogen prototypes, we conclude that car manufacturers communicate a generally shared belief in hydrogen as one of the alternatives of the future. However the rise of Battery/H$_2$ hybrids, suggests that the automotive industry anticipates a long transition phase.
1 Introduction

While oil prices are rising and the climate problem is high on international agendas, pressure is mounting on the automotive industry to develop clean and affordable alternatives to the ubiquitous gasoline car. One of these alternatives is the hydrogen car. Since the first hydrogen car was constructed in 1807 inventors and car makers have experimented with this technology. Still, no commercial hydrogen vehicle is available today and no one can tell for sure whether there will ever be one. However, car manufacturers make us believe that they are working hard on this and that they consider this to be one very serious contender in the race for the fuel of the future (van den Hoed 2005). For the long term, after the end of the fossil era, battery electric vehicles (BEV’s) seem to be the main competitors.

The outcome of this competition is tough to predict, but we can state that a number of factors have their influence. Of course, a lot depends on technological achievements in terms of (well-to-wheel) energy efficiencies, cost price reductions, consumer preferences, path dependencies in the automotive industry, etc. Another factor that could be seen as a driver for development is the set of expectations of the future potential of both hydrogen and battery vehicles. Without positive expectations of their potential, no one would be interested in investing the billions of dollars that are necessary for their development. In this sense, the competition between the two options is not only a competition on future markets, but also a competition on current expectations. From the sociology of technological expectations (Van Lente 1993; Borup et al. 2006), we take that expectations are most valuable when they are collectively shared by many actors and organizations. Therefore, for the future of hydrogen as energy carrier in transportation, it is useful to be surrounded by a set of shared and coherent expectations. Expectations are generated and communicated in many ways and by many different actors. In the case of hydrogen, and emerging technological systems in general, expectations on different levels are important (Bakker and van Lente 2008). While we focus on expectations of hydrogen as fuel of the future in personal cars, expectations are also of importance on the level of grand visions such as that of the ‘hydrogen economy’ down to the level of, for instance, expectations of new materials for hydrogen storage. Expectations are raised by many, and held by even more, actors and organizations. One particularly interesting group of actors in the case of hydrogen vehicles is the automotive industry itself. The manufacturers are often seen as the most important organizations in terms of shaping the future of the mobility. Therefore it is highly interesting to see what futures try to convey and how they frame the future of hydrogen in their industry. A very powerful means of communicating their notions of the future are prototypes and demonstration models of ‘cars of the future’. As said, whether expectations are influential in the shaping of the future depends on their collectivity. This brings us to our question here: does the automotive industry convey shared and coherent expectations of hydrogen? To answer this question, we present a historical analysis of the prototypes developed in terms of their technological configurations. To substantiate this analysis we also show, in a qualitative manner, what statements are made by the four most active manufacturers to accompany their prototypes.

1 Although one could discuss the exact typologies of ‘futuristic car models’, we will use ‘prototypes’ in this paper to denote them, in our methodology section the different typologies will be discussed and we will sketch the delineation of our research. Also prototypes according to Betz2003, feasibility, functional, engineering, and manufacturing prototypes
2 Framework

Innovation in the automotive industry towards zero emission vehicles has been studied through patent analyses (Pilkington et al. 2002; Frenken et al. 2004; Hekkert and van den Hoed 2004; van den Hoed 2004; Oltra and Saint Jean forthcoming). Patents are then considered to be solid indicators of the industry's R&D activities. However, in terms of aligning and guiding the industry and its wider context, for instance governmental regulation and future customers, towards the development of the ZEV of the future, patents do not have the same communicative strength as prototypes have. In our framework we combine notions on prototypes with the sociology of expectations and the selection of technological variation. Nonetheless to do justice to earlier patents analyses we make a comparison between those and our findings.

2.1 Dimensions of prototyping

We consider prototypes as means for the industry to explore alternative propulsion systems and at the same time communicate the results of their efforts to the outside world (figure 1).

Thereby prototypes are both a reflection of actual R&D within the company and a means of sharing expectations of future developments. These are by no means necessarily true expectations, or plain and naïve reflections of R&D activities, held within the industry or individual companies. They can also be rather strategic messages put forward in order to, for instance, convince outsiders of their good intentions concerning environmentally friendly cars. They can even be means to influence policy making when it comes to convincing regulating bodies that the automotive industry will come up with ZEV’s without stringent market policies such as the well known Californian ZEV regulation (CARB 2008). These two dimensions of the prototypes’ message, true expectations and strategic communication, are depicted in figure 2. There is no such thing as a fully naïve, non-strategic, prototype that only serves the company’s internal research trajectory. Also there will be no solely strategic prototype that has no relation whatsoever with the actual future vision and research trajectories of the company.
This implies that every firm that works on hydrogen prototype development holds some positive expectations of hydrogen. This does not necessarily mean that the company believes hydrogen will be fuel of the future, but rather that it believes that it should at least be prepared, in terms of knowledge and capabilities, in case hydrogen does turn out to become the fuel of the future. In innovation processes, companies tend to explore more than one option at a time and thus also in terms of developing prototypes of possible future products (Stirling 1998). This exploration can be either close to the existing markets and products, incremental, but for hydrogen vehicles one can safely state that this is a form of radical innovation and therefore radical exploration. Radical exploration has a high degree of uncertainty. Reducing uncertainty, on the firm level in terms of not missing out on future markets, can be achieved through exploration of multiple alternative futures. Efforts towards exploitation will only be taken when the explored technologies match the aspiration levels set by the company (Greve 2007).

In that sense, the fact that a manufacturer has developed one or more hydrogen prototypes only indicates that is exploring this option. Not that is fixed, or locked-in, on this one specific path.

From the perspective of the technological expectations framework, the question whether the industry is telling its ‘true story’ or whether their expectations are true or false is rather irrelevant. What matters is that expectations, when they are shared and held collectively, are performative in the sense that they stimulate, steer and coordinate efforts by involved actors (Van Lente 1993; van Lente and Rip 1998; Borup et al. 2006). Thus not only the manufacturers themselves, but also governments, consumers, fuel companies, car parts suppliers, etc. The efforts made by this multitude of actors are necessary to develop the new technological system required for hydrogen in mobility. This system involves not only the cars and their different enabling technologies, but also the future (consumer) market, large scale hydrogen production and a distribution infrastructure. To get this radically new technological system off the ground, expectations are raised (and maintained) on all conceivable levels in the system. In the case of hydrogen, an image is created in numerous roadmaps, forecasting studies, vision reports and other future scenarios (McDowall and Eames 2006), of a system that consists of four basic elements from production to end use. These elements are prospectively filled with specific enabling technologies that make up the hydrogen energy system (Bakker and van Lente 2008), figure 3. What stands out of this prospective chain of technologies is the ambiguous
story it tells. On the hand this is portrayed as a highly flexible chain in which many technologies and hydrogen energy pathways can be fitted. On the other hand it is a chain made of weak links that are far from ready for market introduction. Apparently, no one knows what the hydrogen energy system will look like because at this point no single configuration makes sense? This dilemma, a flexible vs a clear and unified story, could be one of the reasons why so many are ambiguous when it comes to the future of hydrogen. In the hydrogen literature, utopian storytelling (Rifkin 2002) is done at the same time as the impossibility of any hydrogen energy system is declared (Romm 2004; Bossel 2006).

Figure 3. The prospective chain of hydrogen technologies

From the perspective of hydrogen’s competition with the BEV, it would be more attractive to have a clear vision of the future of the hydrogen vehicle. Our question is therefore whether the automotive industry tells a unified and clear story about their hydrogen vision or whether they are just a confusing (or should we say flexible?) as the wide-ranging technological scenarios?

2.2 Prototypes as arenas of expectations

In order to study the dynamics of variety, we need one more conceptual ingredient. Expectations of certain technological varieties are put forward in arenas, as we propose to call them (Bakker and van Lente 2008). An arena of expectations is a locus where expectations are voiced and tested, where they are confronted with experience, knowledge, and interests. The ongoing processes of variation and selection of systemic technologies are not just bilateral interactions but a collective social process over time engaging a lot of different actors and organizations. The loci for these multi-actor interactions are scientific conferences, journals, wider media, committees, research councils, and also prototypes of vehicles. Within arenas of expectations battles of expectations take place, ‘trials of strength’ (Latour 1987) and are fed with past experiences with comparable technologies, and with facts and forces of the social and economical context. Therefore the accumulation of knowledge and failures, expectations and disappointments, hopes and fears become relevant in arenas. In figure 4 we summarize how in arenas, expectations are fed and maintained by enactors and used and assessed by selectors.
Figure 4 shows, on the left side, how enactors feed and maintain expectations in the arena. They have to do this in order to receive a mandate for further work on improving their technology. This mandate is granted because technology selectors are convinced of the future potential of the technology, that is, for the time being. At stake, thus, is the robustness of the expectations in the arenas; too much contestation harms the mandate for the enactor community. The drawback of robust expectations, however, is that they may constrain the enactor community not to deviate from their promising approach.

On the right side of the arenas are the selectors, who are informed (but also constrained) by expectations and who make assessments and pick their winners, in whatever phase of the selection process. As a result, some options are favoured or at least not contested by selectors, others are seen as not viable, or not yet. The results of the selector’s decision making process feeds back into the arenas and influence the ongoing struggle for mandate.

Note that there may be multiple arenas, at various levels of aggregation. Highly detailed expectations of materials or techniques may be tested in different arenas than, say, expectations about the hydrogen energy system as a whole. Specific expectations will circulate in specialized scientific committees, where the merits of the ‘hydrogen economy’ will figure in public debates on sustainable energy. Here though, we focus on the prototypes arena.

To answer our question, we focus on the elements of (on-board) storage of hydrogen and its end-use in the vehicle’s drivetrain. Here a number of technological varieties are used by different manufacturers and in different prototypes. Manufacturers explore enabling technologies on the basis of both their technological capacities as well as the vision of the manufacturer. An interesting example of a manufacturer’s technological choices can be found in an article from GM (von Helmolt and Eberle 2007). The most prominent example of this last issue is the, rather diverging, preference of BMW to use a combination of liquid hydrogen storage and an internal combustion engine. One could expect the technological varieties to converge towards a unified and, in the future, dominant design (Abernathy and Utterback 1978) of the hydrogen vehicle. In terms of expectations this would provide the clear story the hydrogen vision needs in order to be convincing. On the other hand, manufacturers might as well keep on using their own, differing, technologies. This convergence-divergence dimension of expectations can be measured in a static and a dynamic
fashion. The static measurement only indicates whether car manufacturers at a certain moment in time share a number of expectations indicated by their usage of specific enabling technologies and their accompanying statements. However, we choose to perform a dynamic measurement in which we include the temporal dimension. Thereby we try to show to what extent car manufacturers converge or diverge on the indicators (technologies used and their accompanying statements) over time.

3 Methodology

For the quantitative analysis we compiled a database of 224 prototypes of hydrogen cars. This data was gathered through an online search, using mainly websites dedicated to hydrogen vehicles, car manufacturers' websites and general car news sites. This search was supported by already existing overviews. Buses, trucks, and utility vehicles were not included in the database. Several technological specifications were included in the database. For the purpose of this analysis we included the type of drivetrain, type of fuel cell (if used in the vehicle) and the hydrogen storage method. These specifications were then plotted on a time line, showing either convergence (towards a dominant design) or divergence over time.

This type of search method does not necessarily generate all prototypes ever built, and for some prototypes not all data is available. This could be the result of secretiveness on the side of manufacturers. But since most manufacturers obviously want the world to know about their efforts, they share most of the information, certainly for the more recent models. For the more historic prototypes some data is probably missing because information in general was not as available as it is today. Still, we hold that the database is adequate for our purposes and is certainly accurate for the last ten years in which the majority of models were produced.

For the qualitative analysis we gathered data from manufacturers' press releases (accompanying the prototypes) and more general communication on their hydrogen vision. This was however limited to the four most active, in terms of hydrogen prototypes, in the industry: BMW, Ford, Toyota and Honda. This data was analysed for statements on 1) technological choices made in their prototypes and 2) the wider hydrogen visions put forward by the manufacturers.

4 Quantitative analysis

While the first hydrogen car was developed in 1807, equipped with a single piston combustion engine, serious development of hydrogen vehicles started only in the mid 1970’s. In those days most hydrogen vehicles were existing models, adapted or retrofitted to run on hydrogen. Only recently have manufacturers begun to develop dedicated hydrogen vehicles of which the whole design is based on its hydrogen drivetrain. The number of prototypes developed shows a steady growth up to the mid 1990’s. From the end of the 1990’s however, the number of prototypes developed each years increases dramatically. All major car companies are involved from there onwards. The cumulative prototype production increases from 32 in 1997 up to 224 in 2008 (figure 5).

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2 www.netinform.net/h2/, www.hydrogencarsnow.com, visited in may/june 2008
4 We consider the words drivetrain and powertrain as synonyms, both referring to the configuration of technologies used to power the vehicle.
The bulk of prototypes are developed by the incumbent firms in the automotive industries (figure 6). 18% of the prototypes were built by universities or as part of research networks. This suggests at least that the automotive industry responds to questions about future mobility concepts. Universities and other research organisations fulfil mostly the role of (enabling) technology enactors. They are most active in research on parts of the prospective hydrogen chain such as fuel cells and hydrogen storage materials.

4.1 Drivetrain

From the database we take that there are three main variations for the drivetrain. These are: 1) the hydrogen fuel cell (FC) as main energy source, 2) the internal combustion engine (ICE) and 3) a primary battery (or super capacitor) supported by a FC as so-called range extender. While the fuel cell is often seen as one of the main drivers for hydrogen as fuel of the future (because of its high efficiency), the battery electric vehicle with the hydrogen range extender appears to more popular (figure 7) than the pure FC car. However we must note here that the distinction between these
two variations is rather arbitrary. A prototype that primarily runs on its FC will always be equipped with a battery or capacitor as buffer for the electricity generated by the FC. The battery is then used during acceleration for instance. Also, it can be used as a storage medium for energy restored by a regenerative braking system. In our database we comply with the information provided by our source and if available from the manufacturer itself. This preference for a primary battery might indicate that the automotive industry takes the BEV very serious, but at the same time acknowledges their main limitation, the inability to recharge fast enough. The ICE is applied throughout the years by a limited number of companies, most notably by BMW. Deviant options like on-board methanol reformers and bivalent ICE's that can handle both gasoline and hydrogen are not used any more in the last seven years. In that sense there seems to be convergence towards three types of drivetrain. When one adds up all the battery/capacitor and FC combinations, this drive train is highly dominant.

Figure 7. Cumulative numbers of different types of drivetrain used

### 4.2 Fuel Cells

While a number of fuel cell types are available, the automotive industry chooses the proton exchange membrane (PEM) FC. The reason for this is its low temperature of operation (<100°C), whereas other types operate only at temperatures of 400 degrees and higher. This is thus a clear example of a dominant design, without competition. Although not at the core of this study, it is worthwhile to take a look at who is actually manufacturing the FC's. Dedicated FC producers like Ballard and UTC Power together provide 38% of the FC's used. Car manufacturers themselves have also developed and produced FC's. Most notable here is GM, 12% of all prototypes uses a GM FC. Other FC producing car companies include Honda and Toyota. Both develop FC’s that are used in various other car brands' prototypes.

### 4.3 On-board storage

A particularly intriguing matter is the storage of hydrogen on board the vehicles. While the fuel cell is often seen as a true enabler (creating an opportunity) of the
hydrogen vision, storage is seen as a problematic issue. Because of the low energy density (per volume) of hydrogen as a gas under ambient conditions, it is a challenge to take enough hydrogen on board to allow for an acceptable range without refuelling. The two obvious ways of doing so are pressurising or liquefying the gas. Both require enormous amounts of energy, giving energy losses up to 20% for compression and about 30% for liquefying (Department of Energy 2002). On top of that, gaseous hydrogen under high pressure is considered as a safety hazard. Liquefied hydrogen suffers losses due to so-called boil-off: it is impossible to prevent any hydrogen to evaporate and the resulting gas has to be released. As alternatives to these relatively simple solutions, a number of more innovative and complex solutions have been proposed. Most attention is given to storage in metal hydrides. Here, hydrogen gas is fed to a tank containing a metal powder and is absorbed as hydrogen atoms in the metal’s atomic lattice to form a metal hydride. Using metal hydrides, the hydrogen can be stored with a higher volumetric density than that of liquid hydrogen. The main backdrop however is in the weight of the total storage system, due to the weight of the metal used. Also the rate of the ab- and desorption (increasing refuelling time), and operating temperatures are still problematic. Other competition for gaseous and liquid storage comes from storage in chemical hydrides (bonding the hydrogen to a liquid chemical substance such as ammonia or hydrazine), solid storage in nanomaterials or rather exotic methods such as clathrates (ice-like structures capturing the hydrogen). These solutions however are far from practically usable and seldom used in prototypes.

In the meantime, while research is conducted on the alternatives, the automotive industry uses liquid and gaseous storage systems in their prototypes. Metal hydrides have been used, but it seems that the industry has abandoned them for now. Nonetheless, as can be seen from the research activities in the US and the EU, expectations of metal hydrides are still very much alive (Bakker and van Lente 2008). When looking at the storage methods more closely, there was an initial dominance of liquid hydrogen storage. Since the late 1990's this dominance was taken over by compressed gas. Between 1999 and 2008, 69% of all prototypes produced hold a high-pressure tank. This coincides with the increase in the use of fuel cells, both in pure FC's and the BEV/FC hybrids, in that period. Some companies have experimented with on-board reformers that produce hydrogen from methanol, these cars make up a large part of the 'other' category in figure 8.
The dominance of gaseous storage does not necessarily imply that a dominant technology has emerged. On the one hand, some companies, again most notably BMW, hold on to liquid storage because it enables them to store more, although less efficient, hydrogen. On the other hand, gaseous storage is done at varying pressures. As can be seen in figure 9, the pressures gradually rise, with 350 and 700 bar as competing standards\(^5\). Although the 700 bar tanks hold more gas, allowing for an increase in the vehicles range, they are less energy efficient, more expensive and pose greater safety risks. That is for many manufacturers the reason to stay with the 350 bar tanks, as is demonstrated in the qualitative analysis.

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\(^5\) Some hydrogen filling stations can refuel vehicles at both 350 an 700 bar.
4.4 Preliminary conclusions
From a multitude of variations, two designs come forward as a result of the witnessed convergence of technologies used. It is therefore not one specific combination of technologies that stands out. It is merely two promising configurations over which the automotive industry is divided. The first is the BEV and FC hybrid, with varying balance between the two power sources. This makes use of the PEM FC in combination with gaseous storage (at either 350 or 700 bar). The second is the hydrogen ICE vehicle with liquid hydrogen storage.
Even though this divide is clear to see, within these configurations there is convergence in terms of enabling technologies. Also, for each of the car brands it is clear what their message to the outside world is, no brand is currently working on both configurations. What the exact rationales for their preferences are does not show from the quantitative study. Therefore we will try to explain this in the following qualitative analysis.

5 Qualitative Analysis
As mentioned, not all car manufacturers are included in the qualitative analysis of their technology preferences. For this, four manufacturers, Ford, BMW, Honda, and Toyota were selected. These are the manufacturers that are closest to market and are involved in large scale tests and demonstrations projects. Both BWM and Honda are currently involved in supplying vehicles to selected customers for daily-use trials. They are therefore given most attention here.

5.1 BMW
In the development of its hydrogen vehicles, with the Hydrogen 7 as the latest result, BMW has shown a preference for ICE's and liquid storage. BMW says to be convinced of hydrogen as the future fuel, as opposed to BEV's. Hydrogen allows them to continue to produce large, powerful and luxurious cars. Their slogan on this issue is:

“We stop emissions. Not emotions.”

In a 2008 press release BMW calls hydrogen the most logical energy carrier of the future for the following three reasons;

“In BMW's view, hydrogen is the most logical energy carrier of the future for...”

www.bmw.com
three reasons. First, it has no carbon and therefore hydrogen combustion generates no CO2, HC's and other pollutants. Second, it can be produced using renewable, clean technologies like solar, wind, geothermal, and bioprocesses. Lastly, it can be produced in stable areas of the globe as necessary for energy security. Although today's hydrogen is mainly derived from natural gas, hydrogen can and will be "green" from renewable and clean sources in the future. Unlike batteries, which will likely also play an important role in future transportation, hydrogen vehicles can be refuelled rather quickly for long trips, don’t require power lines across the landscape, and hydrogen can be generated and stored 24/7 when wind is greatest or demand for electricity is low.7"

These reasons show why BMW is so interested in seeing hydrogen succeed. BMW however also believes electric hybrids and FC technology cannot offer the BMW feeling and see them as intermediary technologies on the way to hydrogen cars. BMW does however actively take part in research into FC technology, but it mentions, like most other car manufacturers, that it feels this is only necessary to keep up with the competition. They have however, in the past, applied FC’s as an auxiliary power unit for other applications in the car.

Besides the bivalent Hydrogen 7, BMW is has now developed a mono-fuel version of the Hydrogen 7, this is a virtually emission free vehicle. According to BMW:

“It demonstrates BMW’s support for a hydrogen infrastructure by producing an ICE that produces truly near-zero emissions”

All this makes BMW one of the very few companies that really seem to commit itself to a hydrogen, and not an electric, future with a central role for the ICE. All hydrogen vehicles built by BMW use an ICE. This is due to BMW’s strong association with large, high performance, luxury sedans. Another large luxury car manufacturer involved in the development of hydrogen vehicles, Mercedes, takes a different approach. They develop small hydrogen vehicles and show high expectations of the FC instead of the ICE.

5.2 Honda

Honda has a dream: “Environmentally Responsible Mobility9”, so it states. This has focused their interest on a completely emission free vehicle, a FC vehicle running on clean hydrogen. Honda’s hydrogen flagship, the FCX clarity is dubbed a “dedicated platform hydrogen FC vehicle”10, this means that the vehicle is specifically designed to run on hydrogen. This in contrast to many other hydrogen prototypes that are existing models, retrofitted with a hydrogen drivetrain.

The FCX Clarity has recently gone into production, some hundreds of vehicles, and will be leased to customers to in Japan and the US. From the selection procedure of potential FCX Clarity customers it becomes clear that Honda is cautious about the slow growth of infrastructure. And they admit that hydrogen vehicles do not yet comply with their future vision, considering the current ways of producing hydrogen. But according to Honda’s calculations, the FC vehicle can reduce carbon dioxide emissions by half compared to a similar gasoline vehicle. In the US, where most electricity is produced using coal, it is even outperforming a BEV car in that respect.

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8 BMW press release 04/14/2008
10 Honda press release 05/20/2008
Honda says it has specifically chosen a 350 bar gas tank to prioritise efficiency over range. To enhance efficiency, the company focuses on further development of the FC stack. The FC used in the FCX Clarity is 65% smaller than the previous FC and they have reduced the total weight of the drivetrain by 45%. The vehicle contains the new and improved Honda V-Flow FC and an improved lithium ion battery. The car is powered directly from the FC leaving the battery to be charged by regenerative braking system.

According to Honda the FCX Clarity is a production-ready vehicle and it was engineered to be built on a conventional assembly line. The company tries to address the problem of hydrogen availability with its “Home Energy System”, a natural gas reformer that users will operate themselves at home. The price however remains a problem. The lease price of $600 per month is not a reflection of the actual costs of the vehicle. It is mainly the FC that causes the high production costs. Nonetheless, Honda US's CEO Tetsutuo Iwamura states that:

"The FCX Clarity is a shining symbol of the progress we've made with FC vehicles and of our belief in the promise of this technology".

Similar to BMW, Honda follows one pre-set path towards their hydrogen car of the future. It is currently the only manufacturer that has a FC vehicle in (limited) production. Thereby it positions itself as one of the strongest believers of the hydrogen vision. Furthermore Honda has chosen to develop a FC vehicle instead of a hydrogen ICE, it has done so from the beginning of its hydrogen efforts. Every Honda hydrogen prototype is and was equipped with a fuel cell.

5.3 Ford

In contrast to BMW and Honda, Ford is simultaneously pursuing alternatives mobility futures in more than one direction. Besides that, Ford stresses energy security issues over environmental considerations. In some statements the latter are even fully absent. Still, hydrogen makes a substantial part of the company’s efforts to develop alternatives to the gasoline car. Compared to the development of (gasoline) hybrid vehicles, hydrogen remains an option for the long-term future. Ford feels that large-scale adoption of hydrogen will not take off until a refuelling infrastructure is present.

The company’s hydrogen research concerns both ICE\textsuperscript{12} and (BEV hybrid) FC vehicles. The most recent development in FC vehicles is the HySeries Drive, a BEV/FC hybrid, with the FC as range extender. According to Ford statements this configuration:

“reduces the size, weight, cost and complexity of a conventional system by more than 50%.” and “It also promises to more than double the lifetime of the FC stack”.

This was implemented in two concept vehicles, the Ford Flexible Series Edge and the Ford Airstream.

Overall Ford seems convinced that vehicle-based technology is not the biggest problem, but rather the lack of a suitable infrastructure. It tries to contribute to a solution by its participation in several projects in which hydrogen fuelling stations are built. Five fuelling stations are the result of these efforts. For now, Ford’s efforts are really focussed on other pathways such as hybrid vehicles, ethanol, clean diesel and refinements to gasoline-fuelled engines and advanced transmissions.

\textsuperscript{11} Honda press release: ‘Honda Debuts All-New FCX Clarity Advanced Fuel Cell Vehicle’, 11/14/2008
\textsuperscript{12} Partial Ford subsidiary Mazda is on a unique path, namely the hydrogen rotary (Wankel) engine. This engine was used in Mazda's older models and now gets a new chance as hydrogen engine. The company claims that this engine type is even more suited for hydrogen than for regular gasoline.
5.4 **Toyota**

Toyota has made a point of keeping fuel cell development and production in-house from its first FC model in 1992. Since then Toyota has made significant improvements and now claims to be performance leader in vehicular FC's worldwide. In 2005 Toyota even stated that it will reduce the vehicular FC price from $1 million to $50k by 2015 and they further promised develop hydrogen production systems to power commercial fleets and work with partners and government to set up a network of at least 1000 fuelling stations.

Having said all this, earlier this year Toyota and partner GM cast doubts about the viability of hydrogen FC's for mass market production in the near future. They stated that FC's are too expensive and that battery technology will allow electric cars to drive up to 300 miles. GM vice chairman Bob Lutz was quoted saying:

"If we get lithium-ion to 300 miles, then you need to ask yourself, Why do you need FC's?" and "We are nowhere [near] where we need to be on the costs curve [for fuel-cell vehicles]."

These thoughts were then backed by Toyota President Katsuaki Watanabe, stating that costs for FC's remain high and the infrastructure needed to distribute hydrogen is far off.

The various hydrogen vehicles produced by Toyota show their dedication to in-house development. Toyota spent at least 4 years in research before producing their first FC vehicle, powered by its own FC. In terms of raising expectations it is intriguing to observe Toyota making a strong start in FC technology and voicing such high and confident expectations of a bright future for the technology only to move away from it several years later. These developments are likely to come from Toyota's strong position in gasoline/battery hybrid technology. Toyota's knowledge in FC technology is not put to waste however, as other car manufacturers such as Daihatsu use Toyota FC's in their vehicles.

6 **Conclusions & Discussion**

From our quantitative analysis we conclude that there are two hydrogen configurations that have emerged from 40 years of prototype building. Within these two configurations there has been significant convergence of the enabling technologies used. Our qualitative analysis shows that the four most active manufacturers are diverged in their hydrogen beliefs. While BMW and Honda have both set their own courses, Ford has no clear path towards a hydrogen future and Toyota openly shares its pessimism. In terms of expectations this is of course not a convincing story for the new technological system. Nonetheless, the signs given by BMW and Honda can be interpreted in a positive manner. This goes for BMW in the sense that it states that it does not believe in an electric future. And Honda's activities are also promising even though it endorses a battery-electric transition phase.

The very fact that most prototypes in our database are indeed hinting at this, BEV/FC hybrid, gives us an idea of a likely future in which the battery vehicle (with hydrogen range extender) acts at least as a transitional technology. None of the manufacturers will however state when they plan on introducing these vehicles onto the market or start mass production.

In our framework we proposed that prototypes can be interpreted as arenas of expectations. This implies that there are enactors and selectors active in the variation and selection game. Prototype manufacturers have an ambivalent role in this game,

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being enactors (often as developer of enabling technologies) and selectors (choosing from multiple variations) at the same time. Other actors and organizations can be defined more clearly as being either enactors or selectors.

Table 1. actor groups and the information they take from prototypes

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<tr>
<td>Consumers</td>
<td>current technological capabilities and hints of future options</td>
</tr>
</tbody>
</table>

In table 1 we attempt to distinguish between the two types of actors and what type of information they can get from the hydrogen prototypes. Research communities working on enabling technologies and suppliers in the vehicles’ value chain are the most obvious enactors. They can take valuable information from the prototypes about what criteria the manufacturers take into account and what preferences they have. On the other hand, selectors such as governments and regulating bodies get an impression of the efforts made by the automotive industry to develop hydrogen vehicles. This information can be useful to assess whether further stimulation is necessary and whether regulation is needed. Consumers are not selectors in the strict sense that they can actually select a hydrogen vehicle for their own use. But already they get an idea of hydrogen’s potential as fuel of the future. In terms of market success, the cultural meaning of hydrogen vehicles is already constructed by the prototypes and manufacturers do take into account what consumers will want in the future. BMW’s ICE vision is again the most striking example of this.

All actor groups mentioned here have more sources of information and it is not our claim that they are informed and motivated by prototypes alone. Nonetheless, prototypes are important for the exchange of hydrogen expectations simply because of their visibility.

References