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Fuelling or Charging Expectations? - a historical analysis of hydrogen and battery-electric vehicle prototypes DRAFT PAPER

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Abstract

- DRAFT PAPER - While the gasoline car is clearly the dominant design in the global automotive industry, fierce competition is already going on amongst its potential successors. The most visible contenders, or competing technological paradigms, in this competition are battery electric (BEVs) and hydrogen vehicles. In our paper we study this competition through a historic analysis of prototypes built by the automotive industry. Specific attention in our analysis is given to the development and use of a number of enabling technologies (eg. batteries, fuel cells, hydrogen storage). We show how these technologies resulted in high expectations of one paradigm over the other and successively led to a greater number of prototypes.

Keywords: hydrogen, BEV (battery electric vehicle), demonstration, passenger car

1 Introduction

For years the electric and the hydrogen car have been involved in a race to become the most credible and desirable design of the future. Their competition is based on accounts of technological progress, assumptions about consumer preferences, the availability of resources, diverse criteria for sustainability and so forth. Whatever the deciding factor may be, one thing is certain: both designs are still in the development phase and they are not competing on any consumer market whatsoever. With no commercial products and no real market as selection environment, the competition between the two is mainly a competition based on promises and expectations of future developments.

The competition takes place in diverse arenas, ranging from scientific debate to wider societal discourse. In this paper we focus on a specific arena, namely the arena that is shaped by car manufacturers through their prototyping activities. Prototypes of radical designs are used as R&D tools in a trial and error learning method; technologies are fitted together and tested in the configuration of the prototype. Apart from this internal use of the prototype, the prototypes are also used as communication tools. Manufacturers show off their latest achievements and designs at car shows and in car magazines. By doing so, the prototypes are used as expectations tools to shape expectations with consumers, governments, competitors and so forth.

The message is twofold. On the hand prototypes are used to showcase the potential of the underlying technologies and the futuristic paradigm as such. On the other hand, manufacturers show the world that they are actually working on the (sustainable) car of the future. Both of these messages are important for the manufacturer since it needs to convince outsiders that it is (a) taking it supposed responsibility in producing more environmentally friendly cars and (b) that the route(s) they choose to go for in searching for the car of the future is indeed viable and credible. The outsiders to which they communicate through prototypes are a wide variety of actors and organizations. In figure 1 we list a number of them and in table 1 we sketch the information they take from prototypes.

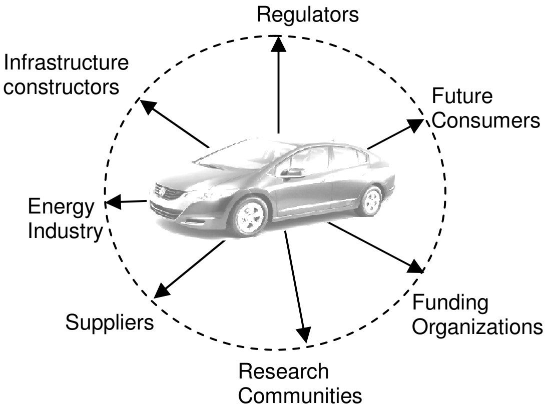

Figure 1: Prototypes as means of communicating expectations

Based on this double notion of prototypes as tools for the internal R&D process and as expectations tools, we propose to use prototypes for our purposes of measuring the development of expectations in the automotive industry on future paradigms for auto mobility. More specifically we will study the interrelation between expectations of the paradigms and expectations of their underlying enabling technologies. Our hypothesis here is that external factors drive the search for new paradigms for personal mobility (i.e. the successor of the gasoline car) and that internal technological developments steer the direction of this search (i.e. either the battery electric or hydrogen vehicle).

Table 1: The information taken from prototypes by different actors

Actors	**Information from prototypes**
Research Organisations	selection criteria from automotive industry
Technology Suppliers	selection criteria and hints of potential future market
Energy industry	hints of potential future market
Governments	efforts made by manufacturers to develop hydrogen vehicles
Funding organizations	selections made by the automotive industry and the criteria used
Consumers	current technological capabilities and hints of future options

First however, we will discuss the two dimensions of prototyping in more detail. After doing so, we will shortly describe the technologies under study and elaborate on our research methodology. The results and analysis of our databases of prototypes of both hydrogen and electric vehicles are then presented and discussed in the final sections of our paper.

2 Prototypes as learning tools

Firms typically tend to explore multiple variations until they pick one of them to exploit on the market. This is the micro-level of evolutionary variation and selection of new technologies in general. This represents the evolutionary model of innovation. The exploration phase is characterised by research and development activities. An important part of these activities is the testing of new concepts, product parts and technological configurations. Tests then are part of a trial and error learning style. Prototypes are, from this perspective, tools for the trial of new (enabling) technologies and configurations thereof. Successful trials then might lead to the continuation of a given R&D trait, failed trials could in turn lead to the killing of the trait.

In the end, as we take from the wide body of literature from innovation science and industrial dynamics, only one design can dominate the market; the dominant design [1-3]. Or, from a more (techno-) sociological perspective, only one paradigm or regime prescribes what a technological design should look like.

A dominant design can be, and has been, conceptualized on many levels of technological hierarchy [4]. That level can be an entire socio-technical system or regime, made up of artefacts and a surrounding set of socio-cognitive rules. But it could also entail the lower levels of subsystems down to technological parts. In our analysis we limit ourselves to one level in particular, namely that of the drivetrain of the car. The drivetrain is made up of the basic components that together make the car move. Today this is a combination of gasoline as energy carrier and the internal combustion engine as means of converting the energy to movement. For the competitors we study, the drivetrain has not yet stabilized in terms of the technologies used. So, while both the electric and hydrogen car are in competition with each other, within these paradigms there is a competition going on between enabling technologies to become or remain part of either of the paradigms. Together, the enabling technologies constitute a design, thus a configuration of technologies used in the drivetrain.

Since prototypes can be regarded as tools for learning, they are in a sense stepping stones towards a new dominant designs. Not all stepping stones should or can be successful, that is some options might prove to satisfy its designers other might fail in that respect. The stepping stones set out a path towards a future design and based on the notion of the dominant design we expect to see convergence towards that design. Convergence is then the narrowing of the search; successive prototypes show less and less diversity up till the point that the optimum design has been found. What the optimum design exactly is and what criteria is should meet might very well differ from firm to firm. For the in-firm use of prototypes we propose the first proposition:

- *There will be convergence of drive train configurations in the prototypes developed by each manufacturer.*

3 Prototypes as expectations tools

Since the hydrogen vs electric competition does not take place in the (consumer) market and cannot be fought out over permance and costs, it is mainly a competition based on expectations of the respective technologies [5]. The second pillar of our conceptual framework builds therefore on the so-called sociology of expectations in science and technology. In the sociology of expectations, expectations are considered [6], to stimulate, steer and coordinate technological development. In order to be influential, expectations must be shared and collective.

As stated in the introduction, the message of the prototype can be twofold. The manufacturing might want to communicate that it is a) taking its supposed responsibility in producing more environmentally friendly cars and (b) that the route(s) it chooses to go in searching for those cars of the future is indeed viable and credible. It is hard, if not impossible to distinguish between the two messages. But, since we are most interested in the routes firms choose and the expectations work they perform this is not too much of a problem.

What then, are those expectations put forward through prototypes? Expectations of technology are in general ideas about future potential of a) the technology itself, thus the future performance potential, b) costs and the reduction thereof, c) market share and users preferences, d) fitness with other technologies and socio-technical systems. In our analysis we will not go further into detail about the different expectations much. The analysis will be limited to the firms' preference for a paradigm and furthermore for the technologies used in the different possible configurations.

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 [6-8]. 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 [9], 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 [5]. 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 versus 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 [10] is done at the same time as the impossibility of any hydrogen energy system is declared [11, 12].

From the perspective of hydrogen in its competition with the BEV, it would be more attractive to have a clear vision of the future of the hydrogen vehicle. In other words: to have the industry tell a unified and clear story about its hydrogen vision instead of a confusing (or should we say flexible?) one such as the wide-ranging technological scenarios that can be found in literature.

4 Emerging Dominant Designs and robust expectations

The two dimensions of prototyping do not interfere with one and other; in fact they reinforce each other. This brings us directly to our second proposition:

- *Convergence in the designs used in prototypes, indicates, and furthermore leads to, convergence of collective expectations of the designs and the enabling technologies*

Once expectations become collective, they become stronger, more powerful and will have more of a performative role. That is, as described, visions of both paradigms are open and rather unarticulated. They are attractive for many actors, but do not require specific action and do not represent one strong option that is truly convincing. Therefore we propose our third proposition:

- *Collective and robust expectations that share a common articulation of an emerging technological paradigm are more performative than open and unarticulated expectations.*

5 Paradigms of the Future: Hydrogen vs Electric

In this section we will provide short descriptions of the most prominent technologies and accompanying beliefs in both paradigms. This should provide enough of a background to engage in the analysis of the paradigms and the technologies used.

5.1 Hydrogen

Hydrogen is seen as a potential fuel for the future because it can be produced, providing there is enough energy available, in endless amounts and does not produce any emissions when used to power a car. Furthermore, hydrogen can be used to power either an ICE or a Fuel Cell, of which the latter is highly efficient in its energy conversion. The energy efficiency and sustainability of hydrogen depends on the technologies and energy sources used.

5.1.1 Energy Conversion

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 convertor, 2) the internal combustion engine (ICE) and 3) a bivalent internal combustion engine that can burn hydrogen as well as gasoline. 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 ICE is still considered by a number of firms, most notably by BMW and Ford.

5.1.2 Storage Methods

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 [13]. 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 has come from methanol as carrier of molecularly bonded hydrogen. The methanol is reformed to gaseous hydrogen and carbon dioxide with an on-board reformer.

Rarer competition 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 currently 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 [5].
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; even though long ranges could be achieved all firms have shifted away from this option in their prototypes.

5.2 Electric

The battery electric vehicle has one major advantage over hydrogen vehicles; it does not require hydrogen. The BEV is a highly energy efficient means of converting (electric) energy to motion. As for the hydrogen car, the exact energy efficiency and sustainability of the vehicles depends on the energy sources used to produce electricity and the type of batteries that are used. Here we consider a number of battery options [14], we leave out the variations of electric engines.
The traditional battery used in cars, the lead-acid battery, are relatively cheap but have a limited specific energy. NiCd batteries have a higher specific energy but are also much more costly than lead-acid batteries. NiMH, the battery used in the Toyota Prius and the Honda Civic Hybrid, scores somewhat higher on both specific energy and specific power than the NiCd battery. The Li-ion battery, rather a collection of varying Li-based batteries, has dramatically higher specific energy than the others (up to 10 times as high). There is still debate however about costs and reliability.
The biggest challenges for pure BEVs seem to be the range on one charge and the time it takes to recharge the batteries. Especially the last issue determines whether or not the car can be recharged on the road or only during long stops or at night.

6 Methodology

For our analysis we compiled a database of prototypes of BEVs and hydrogen vehicles that were developed from 1960s onwards. The data was collected through an online search process. This method has a lot of limitations in terms of tracking all of the prototypes that were constructed. However, for the purposes of our study we hold that this method is efficient and sufficient.
The database describes: the car's manufacturer, year of construction, type of drivetrain, battery or fuel cell type and manufacturer, type and capacity of its hydrogen storage system, and the cars' range. Excluded from both databases are models that are either single-person or (group) transport vehicles.
We plotted these variations on historic timelines to distinguish periods of increased activity and to make visible the use of certain enabling technologies throughout time. Furthermore we analyzed the performance of the prototypes throughout the years in an attempt to explain shits in expectations of both paradigms.

7 Results and analysis

All major car manufacturers work on both hydrogen and electric prototypes. A striking dynamic becomes clear when the numbers of prototypes are plotted on a timeline. In the second half of the 1990s both paradigms grow in population, but then at the end of the 90s electric vehicles disappear of the firms' portfolios and hydrogen almost literally takes off. The hydrogen wave lasts until 2006, then it suddenly stops and electric vehicles reappear on the scene and seem to take over from there onwards. In figure 2 this dynamic is plotted and a three-year-average trend line is added to smooth out some year-to-year discontinuities.
The dynamic of the competition can be explained by a number of arguments:

- Hydrogen has not delivered on its promises and development are therefore stopped
- Electric cars are closer to market, because the technology is less complex and is therefore more suited to deal with growing pressures to produce less polluting vehicles.
- Electric vehicles do not need the intensive infrastructure like hydrogen does and can therefore be marketed more easily to niche markets.
- Battery developments, Li-ion, have taken a flight and this makes the electric car now more a realistic option.

- The success of hybrids has cleared the road for pure electric vehicles, by demonstrating the usability of batteries in the automotive sector and beyond that it helped to shape a future market for electric vehicles.

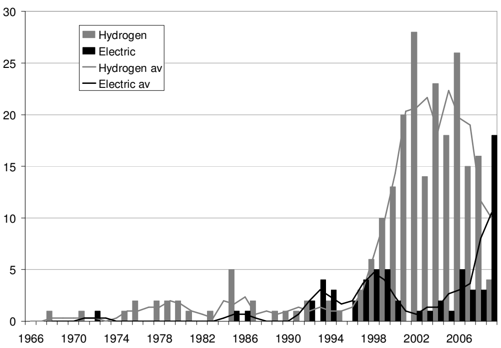

Figure 2: Absolute numbers of hydrogen and battery-electric prototype models as developed per year

In support of the arguments for the BEV being closer to market, is the fact that electric vehicles are developed by the incumbent firms as well as new-entry firms whereas hydrogen prototypes are almost without exception built by the incumbents. This could have several reasons, but it does indicate that battery electric vehicles are closer to market and therefore more interesting for start-up firms. Hydrogen vehicles are, and have been for forty years, further from commercialization and therefore only interesting for large companies that can spend millions, if not billions, on the R&D work needed without direct outlook on returns on investment. Second, battery electric vehicles are perhaps easier to construct, in fact the configuration needs less components (fuel cell, hydrogen storage system). This suggests at least that developing an electric vehicle requires less R&D and is therefore more open to start-ups.

Our propositions however dealt with the role of prototypes in the expectations work performed by the manufacturers, and the dynamics of the paradigms' configurations. To show dynamics of the configurations, we have plotted the configurations used for both hydrogen and pure electric vehicles (figures 3 and 4). In both there is convergence visible. In the case of hydrogen the convergence is towards a fuel cell car powered by gaseous hydrogen. Some manufactures, BMW mostly, do still use combustion engines to convert the hydrogen, but since the end of the '90s this trait was left by most of the manufacturers. As for the fuel cell car, hydrogen storage is done without exception in its gaseous stage since the turn of the millennium. Before, the OEMS experimented with metal hydrides and methanol reformers, but these traits were left completely.

In the case of the battery electric vehicle, during the last five years only Li-ion batteries were used in the prototypes. Even though this is still an expensive option, it does provide the cars with a larger range and is therefore valuable to serve the prototypes' goal of raising expectations.

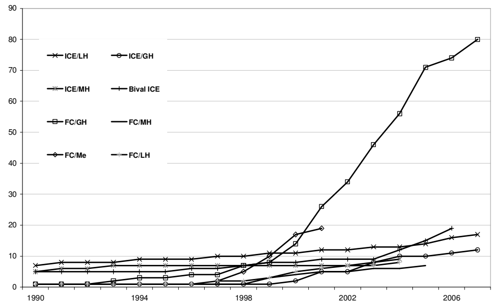

Figure 3: Cumulative numbers of configurations used in hydrogen prototypes

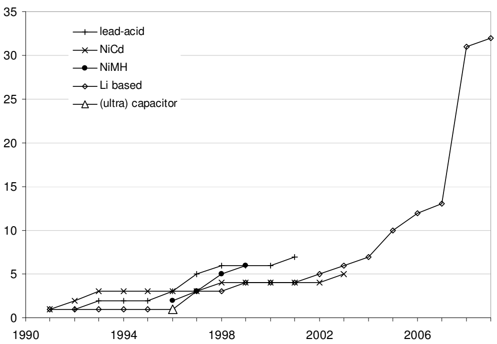

Figure 4: Cumulative numbers of battery types used in battery electric vehicles

When analyzing these dynamics, both paradigms have shown convergence over time in terms of the technologies used, in relation to the role of prototypes as expectations tools, we draw a number of insights:

- The hydrogen vision was indeed articulated to a more singular vision of fuel cells and gaseous storage
- This articulation has not, however, resulted in hydrogen being the stronger paradigm vision than that of the electric vehicle
- The rise of Li based battery systems has clearly contributed to the rise of the electric car paradigm. That is, the use of Li batteries precedes the take-over of battery electric vehicles over hydrogen models.

8 Conclusions & Discussion

From the perspective of hydrogen in its competition with the battery electric vehicle, it would be more attractive to have a clear vision of the future of the hydrogen vehicle. In other words: to have the industry tell a unified and clear story about its hydrogen vision instead of a range of diverging and confusing stories. On the other hand, one strength of hydrogen has always been its flexibility in terms of energy sources, conversion technologies etc as can be seen in the socio-technological scenarios throughout the years. But indeed, the automotive industry has more or less told a unified story of hydrogen through its prototyping efforts; the fuel cell/gaseous hydrogen story. Unfortunately for hydrogen, this story was not convincing enough and now policy makers and the industry itself have turned to the battery electric vehicle to deliver cleaner vehicle solutions. Besides the fast developments of Li batteries, the increased pressure to deliver these solutions on the short term has most probably helped the battery-electric vehicle forward as well. Simply because battery electric vehicles provide the simple solution by leaving out hydrogen as energy carrier.

In this draft paper we claim that the choice of technologies used in the prototypes is a reflection of a manufacturer's R&D efforts and thereby of its expectations. Furthermore, because of their visibility, the prototypes serve an important role in creating collective expectations throughout the automotive industry. Given the increasing number of prototypes of alternative (and zero-emission) vehicles, we conclude that car manufactures share the acknowledged need to develop future technologies. In future work we will study the role of prototypes in more detail by also including measures for performance of the individual prototypes.

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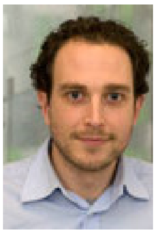

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