## Title
FORESEEING THE MARKET FOR HYDROGEN FUEL-CELL VEHICLES: STAKEHOLDERS' PERSPECTIVES AND MODELS OF NEW TECHNOLOGY DIFFUSION

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# Foreseeing the Market for Hydrogen Fuel-Cell Vehicles: Stakeholders' Perspectives and Models of New Technology Diffusion

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# FORESEEING THE MARKET FOR HYDROGEN FUEL-CELL VEHICLES: STAKEHOLDERS' PERSPECTIVES AND MODELS OF NEW TECHNOLOGY DIFFUSION

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## 1. Introduction

The extreme dependency on oil of ground transportation systems across the world—particularly in the United States—has become a weakness in national economies. It engenders environmental degradation, excessive strategic dependency on foreign oil (e.g. California Air Resources Board-California Energy Commission, 2003), pernicious health effects (e.g. Thayer *et al.*, 2003, World Bank, 1998), agricultural losses, and growing contributions to global warming.

These factors have, at different points in time, directed the eyes of policymakers to alternative fuels and new automobile technologies. Oil prices triggered an interest in energy efficiency in the early 1970's, poor air quality led regulatory action to promote methanol and electric vehicles in the early 1990's, and energy dependence and climate change are driving the interest in hybrid electric vehicles (HEVs) and hydrogen in the beginning of the 21st century. Radical transformations have proved, however, more difficult to implement than incremental improvements of standard technologies. Policy processes to move away from a gasoline were often characterized by asymmetric information (the regulated industry dominating the technical debate), regulators' limited understanding of market demand, political unwillingness to internalize externalities, and industry reluctance to depart from the status quo.

The idea of a transportation sector relying on hydrogen as its main fuel has grown since its inception, from little more than a scientific hypothesis to a tangible possibility. As an energy carrier, just like gasoline, hydrogen necessitates a technology to extract usable energy from it. The fuel cell is the technology that most efficiently does this. When used in fuel cells, hydrogen vehicles have no tailpipe emissions while at the same time offer private benefits relative to conventional internal combustion engine vehicles (ICEVs) (e.g. superior vehicle performance.) This potential dual superiority of hydrogen fuel-cell vehicles (FCVs) has made them a favorite in both policymakers and industry camps. However, whether and when the last essential technological breakthroughs will happen is still uncertain.

Whether and when FCVs will be successful in the market is still uncertain and dependent on several factors. These factors include:

a. Technological progress: Despite sustained progress, a series of technological advances are still needed to position the hydrogen-fuel cell combination as a competitive alternative to mainstream alternatives. Areas where research and development (R&D) are currently directed to include on-board hydrogen storage and fuel cell durability.
b. Technology economics: Factors like production learning, production volume, accessibility to hydrogen fuel dispensing stations, the cost of hydrogen fuel, and R&D investment will directly affect the cost of purchasing and operating FCVs. Needless to say, this cost is to be evaluated vis-à-vis the cost associated to the purchase and operation of competing vehicle technologies.
c. Consumer behavior: Ultimately, it will be the consumer who decides the fortune of FCVs in the marketplace. Not only vehicle cost will be relevant, but also perceptions about the

safety of hydrogen, the value proposition of FCVs relative to gasoline vehicles, and social pressures.

d. Regulation and political agendas: While the market will decide long-term diffusion of hydrogen vehicles, the politico-regulatory environment can play a significant role in the initial stages of the diffusion process. The time scale of the diffusion process in question is longer than typical political time scales. Today, the dominant political driver behind hydrogen in the United States is energy security, in the face of spiking oil prices, an unstable Middle East, and sustained increases in oil demand from growing economies. How long this panorama will last is uncertain. Within the next decade, perceptions on the stability in the Middle East may change, internal combustion engines may become significantly more efficient thereby tempering demand, and the OPEC may exercise its power to affect oil price through adjustments in supply. These and other factors can undermine the continuity of the political commitment, necessary to realize a transition away from oil.

Given the uncertainties involved, it is of interest to gain understanding on the potential dynamics of market penetration of FCVs. The contribution of this study is to propose an integration of theoretical frameworks on the diffusion of innovations with data on stakeholders' opinions, to develop estimates of FCVs market-share evolution.

## 2. Methodology

Following literature on technology innovation (Mansfield, 1961; Chow, 1967; Norton and Bass, 1987; Putsis, 1998), we assume that the evolution in market share of new vehicle drivetrains over time follows a logistic trajectory. Typically, such trajectories are mathematically expressed as

$$\ln\left(\frac{n_t}{N-n_t}\right)=\alpha+\beta\left(t-t_0\right).$$

Here, $n_t$ is the fraction of the market that the technology has at a given point in time $t$, $N$ is the (assumed) fraction of the market that the technology can potentially capture, $t_0$ is the point in time when the technology enters the market, and $\alpha$ and $\beta$ are the parameters of the logistic function. This type of curves is characteristic of the family of models of innovation known as *epidemiological*. To see the role of the parameters $\alpha$ and $\beta$ in the shape of the diffusion curves, let us consider the following examples:

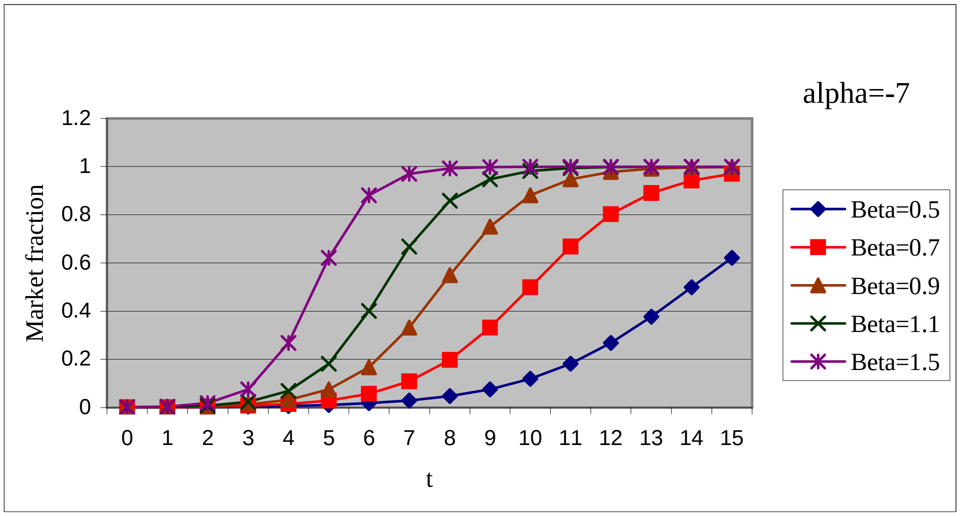

**Figure 1. The role of the parameter beta**

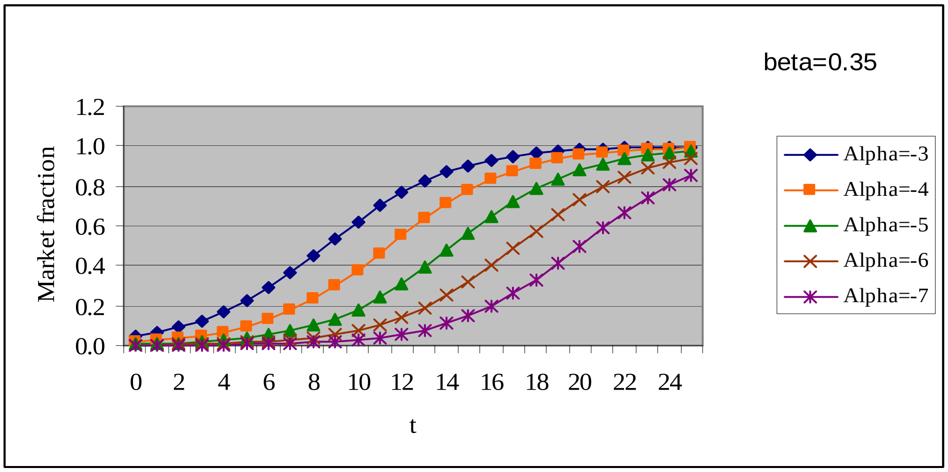

**Figure 2. The role of the parameter alpha**

Figure 1 shows a set of logistic curves for several values of the parameter $\beta$, with a constant value of –7 for the parameter $\alpha$. Figure 2 shows a set of logistic curves when the parameter $\beta$ is kept constant at 0.35 while $\alpha$ takes values between -3 and -7. Essentially, $\alpha$ characterizes the time it takes for a diffusion process to start ramping up. The parameter $\beta$ characterizes the steepness of the central portion of the curve. In the literature on innovation, $\beta$ is known as the speed of diffusion and, in the jargon of epidemiology, it is referred to as the infectiousness of the disease.

According to Kemp (1997), the process of diffusion is affected by three general factors: characteristics of the adopters, characteristics of the socio-economic context, and characteristics of the technology itself and the artifact that uses it. This paper contends that stakeholders' support (and opposition) also plays a significant role in technology diffusion. In epidemiological diffusion models, learning and imitation are considered the principal drivers of the adoption of a technology within a population. These models adopt no behavioral decision-making framework, and thus shed little light into the factors that make people adopt a given technology. Just like in the spread of a disease, the probability of adopting the technology increases with the proportion of the population that has already adopted it (the imitation effect). In this sense, the process of adoption is endogenous to the model. Also, these models require an *ad hoc* specification of the size of the prospective adopters' population.

We will employ here this basic diffusion functional form. It needs to be emphasized however, that improving over this formulation is desirable for more rigorous policy recommendations. One possible improvement would be to let $\beta$ be a function of time like $\beta = Ab^t$, whereby the sign of $b$ determines whether the diffusion curve is positively ($b$ < 1) or negatively ($b$ > 1) skewed (Kemp, 1997). The following plot shows two epidemiological diffusion curves with identical $\alpha$, but different parameters $b$ in the functional form for $\beta$.

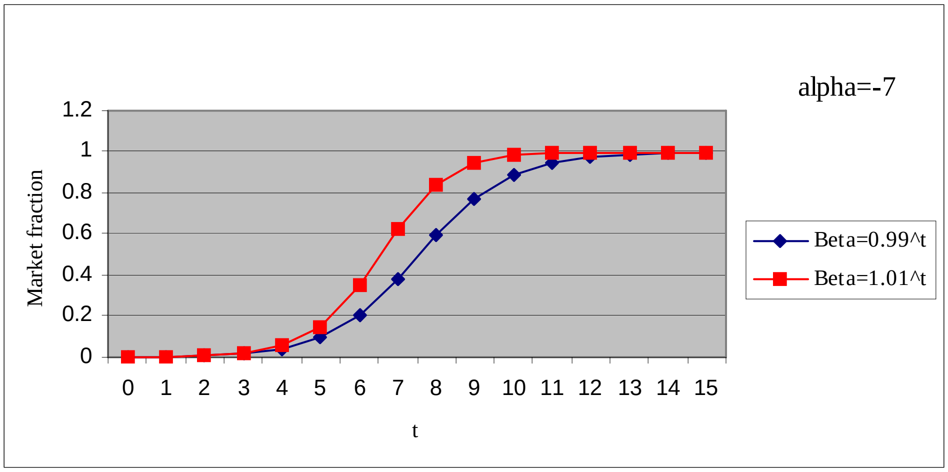

**Figure 3. The role of t-dependent beta parameters**

The expectation is that new drivetrain technologies, like fuel-cell vehicles, if commercially viable, will follow trends with $b$ parameters greater than one. As these technologies are perfected, production learning increases, associated costs go down, the hydrogen refueling infrastructure grows, the products' overall quality improves, customer acceptance will correspondingly increase, and the products will penetrate the market at a faster pace.

## 3. Modeling technologies substitution

It is often assumed, in the modeling of market diffusion curves, that the new technology eventually obtains a 100% of the market. We are interested however in simultaneously study the market evolution of more than one technology which, despite some synergies, will compete with each other. Assuming a constant market size, if FCVs are to gain market share, they will necessarily have to do it at the expense of the share of competing technologies. Previous experiences taught us how crucial it is to understand the potential market share that a new technology can gain, which in turn requires the understanding of the market strength of competing technologies (primarily gasoline internal combustion vehicles.) Thus, our problem involves the modeling of simultaneous diffusion curves—a market substitution problem.

We consider the following scenario: the market of light-duty vehicles is initially composed of only one drivetrain technology: gasoline internal combustion engines. At time $t=0$, gasoline HEVs enter the market, followed by hydrogen-powered FCVs with a time lag $t=t_{0F}$. The penetration of one technology in the market of light-duty vehicles is comes at the expense of market share of a competing technology. In order to obtain a modeling logic for the process of market penetration for the different technologies involved, we consider the following three notions:

- There is a segment of consumers—early adopters—that will tend to adopt new drivetrain technologies first, and this segment is the same for every cleaner technology that enters the vehicle market;.
- The rest of the consumers tend to prefer incremental changes to radical changes when they adopt a cleaner technology.
- In the mature state of these technologies, the value proposition to the average consumer is highest for fuel-cell vehicles, followed by hybrid electric vehicles.

These premises would translate into the following innovation/substitution pattern: before FCV technology achieves a maturity comparable to that of HEVs, conventional ICE vehicles tend to be replaced only by HEVs and HEVs tend to be replaced only by FCVs. At their market introduction, FCVs will be a more exotic, higher-risk vehicle technology than HEVs, and the consumers willing to accept the risk of an early adoption will be the same ones that accepted the risk of early-adopting HEVs. This assertion would probably crumble if FCVs entered the market only a short time after HEVs, so that both technologies entailed comparable perceived risks to the early-adopting market segment—but this scenario will not materialize. The transitional role of HEVs in the sequence of technology adoption just described will probably end once the perceived risk embedded in FCVs (technology reliability, durability, and safety, availability of hydrogen fuel, etc) diminishes to levels comparable to that of HEVs. At that point, an owner of an ICE vehicle shifting to a new technology would consider adopting either an HEV or a FCV. For the purposes of modeling, we adopt the following innovation/substitution pattern: conventional standard internal combustion vehicles are replaced only by hybrid electric vehicles and hybrid electric vehicles are replaced only by fuel-cell vehicles. This assumption is a simplified version of the technology-adoption behavior described above. We will assess the validity of this assumption later in the paper. Mathematically, this technology substitution schedule translates into the following system of equations.

$$\left(\frac{n_t}{N}\right)_{FCV} = \frac{1}{1+\exp\left[-\left(\alpha_{FCV}+\beta_{FCV}\left(t-t_0\right)\right)\right]},$$

$$\left(\frac{n_t}{N}\right)_{HEV} = \frac{1}{1+\exp\left[-\left(\alpha_{HEV}+\beta_{HEV}t\right)\right]} - \left(\frac{n_t}{N}\right)_{FCV},$$

$$\left(\frac{n_t}{N}\right)_{ICEV} = 1-\left(\frac{n_t}{N}\right)_{HEV} - \left(\frac{n_t}{N}\right)_{FCV}.$$

Many studies have generated estimates of the governing parameters of the diffusion curves based on historic data. For new technologies, such data is never available ex ante, though. Precisely the exercise of deciding on values for these parameters and on the relations among them is a key part of this study. We turn to these decisions now.

Table 1 shows data from the Electric Drive Transportation Association, on the numbers of hybrid electric passenger vehicles sold in the United States since the year 2000, along with data from the Department of Energy on the numbers of light-duty vehicles sold in the 2000-2003 period[1] (DOE, 2005).

**Table 1. Progression of electric hybrid new passenger vehicles annual sales**

| Year | Number of new hybrid vehicles sold | Number of new light-duty vehicles sold | Market share of hybrid vehicles |
|---|---|---|---|
| 2000 | 9,367 | 17,234,000 | 0.0005435 |
| 2001 | 20,287 | 17,123,000 | 0.0011848 |
| 2002 | 35,961 | 16,817,000 | 0.0021384 |
| 2003 | 47,525 | 16,548,000 | 0.0028179 |
| 2004 | 83,153 | 16,339,500 | 0.0050891 |

It can be observed that despite the stagnation in the sales of new vehicles, the sales of hybrid electric vehicles have been showing consistent and significant increases. The last column in Table 1 shows the fraction of the market of light-duty vehicles captured by HEVs each year, as the ratio of the second to the third columns. Taking the natural logarithm of the figures in the last column, they can be regressed linearly on the time variable, to obtain estimates of $\alpha$ and $\beta$, the parameters of the epidemiological diffusion curve. We obtain

$$\alpha_{HEV} = -7.915 \ , \ \beta_{HEV} = 0.5359 \, .$$

Both coefficients are significant at the 0.001 level, yielding an adjusted $R^2$ of 0.97. Data on monthly sales would have been preferable so as to increase the observations, but these data were not available. This value of the speed of diffusion is consistent with findings of previous studies (e.g. van den Bulte, 2000.) If the market penetration of HEVs followed a logistic curve characterized by these parameters, HEVs would capture a 50% of the new light-duty vehicle market in approximately in the year 2015. The new-sales projections for the year 2025 made by the Energy Information Administration (EIA) are shown in Table 2. The market shares indicated in Table 2 were calculated assuming that only cars and light-duty trucks of the types shown were sold.

**Table 2. New-vehicle sales projections for the year 2025 (quantities in thousands). Source: EIA (2005)**

| | Cars | | Light-duty trucks | | Total | |
|---|---|---|---|---|---|---|
| | New sales | Percentage | New sales | Percentage | New sales | Market share |
| Gasoline ICE | 1225.486 | 94.46% | 1513.934 | 94.52% | 2739.42 | 94.49% |
| Gasoline HEV | 71.84 | 5.54% | 87.795 | 5.48% | 159.636 | 5.51% |
| Total | 1297.326 | 100.00% | 1601.729 | 100.00% | 2899.056 | 100.00% |

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[1] We use a linear extrapolation of these data to obtain an estimate of sales for 2004, which was not available in the quoted source.

The EIA projects that just 5.5% of the new vehicles sold in 2025 will be gasoline hybrid electric vehicles. A recent market study has forecasted that gasoline hybrids will reach a market share plateau of 3% around the year 2010 (J.D.Power and Associates, 2005). Our parameter values give gasoline HEVs a market share of over 5% in five years, but this market share continues to grow, as we assume that HEVs have the potential to capture 100% of the market. Here is where the understanding of the dynamics of the market for the new technology plays a significant role in eliciting good estimates of market shares. The author does not share J.D.Power's contention that the market for HEVs will stabilize at 3% in 2010 primarily because of a $3,000 to $4,000 excess price tag. It is beyond the scope of this paper to discuss the complex relationship between price and diffusion of innovations—the reader may refer herself, for example, to Bass (1980, 1982), Horsky (1990), Golder and Tellis (1997), and Putsis (1998). Price *is* a very important factor, but so is whether the new product constitutes an improvement over the technology it purports to substitute and consumers like it (Golder and Tellis, 1997). Price may be less of an issue in a strong competitive environment where no major company can afford surrendering the market of HEVs to its competitors, in a regulatory environment where R&D and purchase incentives are provided (as in the Federal Energy Policy Act of 2005), in a political environment where pressures rise to increase fuel economy and reduce greenhouse gas emissions, and in an energy environment where oil prices do not decline significantly. Studies have consistently found that new products sales take off once market penetration has reached approximately 2.5% (Roger, 1983; Golder and Tellis, 1997). In view of these considerations, it seems unlikely that the diffusion of HEVs will stagnate after reaching a 3% market penetration.

We take the year 2000 as the point in time when gasoline HEVs entered the U.S. market. To determine the value of $t_o$ for hydrogen FCVs, we need to address the question of when will these vehicles enter the market. The value of $t_o$ could be estimated from regulatory requirements (for example, the year when zero-emission vehicles are to enter the California market, as required by the Zero-Emission Vehicle regulation.) Alternatively, it could be obtained from stakeholders' estimates.

We obtained such data as part of an online survey that we administered to a wide sample of stakeholders' in the hydrogen policy debate (see Collantes, 2005.) One of the questions in that survey asked our respondents to provide their best estimate of the earliest year when FCVs will enter the showrooms.[2] Another question in the survey asked them for estimates of the year when FCVs would capture 5% of the market for new light-duty vehicles. The former we provided answer options as "before 2010" (coded as 2009), "2010", …, "2030", "later" (coded as 2060), and "never". For the latter we provided answer choices in the form of 5-year intervals: "before 2020" (coded as 2020), "before 2025", …, "before 2050", "later" (coded as 2060), and "never." The response frequencies for each of these questions for respondents based in the United States are shown in Tables 3 and 4.

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[2] The exact wording of the question was "What is your best estimate of the earliest year when production fuel-cell automobile could be ready to enter the automotive showrooms in the country where you are based? Assume no new policy incentives."

**Table 3. Frequencies of estimates of earliest market entrance of fuel-cell vehicles**

| Year | Frequency | Year | Frequency |
|---|---|---|---|
| 2009 | 46 | 2017 | 3 |
| 2010 | 70 | 2018 | 6 |
| 2011 | 3 | 2020 | 44 |
| 2012 | 33 | 2025 | 20 |
| 2013 | 8 | 2030 | 9 |
| 2014 | 4 | Later (2060) | 4 |
| 2015 | 106 | Never | 7 |
| 2016 | 3 | - | - |

**Table 4. Frequencies of estimates of when fuel-cell vehicles capture 5% of new-vehicle market**

| Year | Frequency | Year | Frequency |
|---|---|---|---|
| 2020 | 73 | 2045 | 8 |
| 2025 | 71 | 2050 | 28 |
| 2030 | 63 | Later (2060) | 11 |
| 2035 | 33 | Never | 30 |
| 2040 | 23 | | |

Tables 5 and 6 show the means of these estimates for the US-based subsample, segmented according to the affiliation and expertise of the respondents, respectively. To calculate these values, we exclude “Never” responses.

**Table 5. Respondents’ estimates of the earliest year when FCVs could enter the market and when they will capture 5% of the new-vehicle market, by respondents’ affiliation**

| Respondent association | Market entrance | | | 5% market | | |
|---|---|---|---|---|---|---|
| | N | Mean | Std deviation | N | Mean | Std deviation |
| Entire sample | **359** | **2015.014** | **6.907** | **310** | **2031.032** | **10.608** |
| Auto company | 29 | 2015.448 | 5.103 | 28 | 2033.393 | 16.614 |
| Oil company | 13 | 2022.154[*] | 12.595 | 10 | 2042 | 22.136 |
| Electric utilities | 19 | 2017.211 | 7.060 | 19 | 2047.632[***] | 30.248 |
| Natural gas providers | 8 | 2021.875[***] | 15.788 | 6 | 2031.667 | 5.164 |
| Hydrogen production | 24 | 2015.042 | 10.170 | 22 | 2028.409[****] | 7.136 |
| Hydrogen production equipment | 14 | 2012.571[****] | 3.322 | 14 | 2036.429 | 28.177 |
| Fuel-cell developer | 24 | 2013[****] | 4.890 | 24 | 2033.958 | 23.124 |
| Battery developers | 9 | 2017.111 | 6.333 | 9 | 2054.444[***] | 35.483 |
| Federal government | 20 | 2016.2 | 4.841 | 19 | 2037.368 | 18.736 |
| State government | 29 | 2012.759[****] | 3.5922 | 26 | 2035.577 | 21.741 |
| Local government | 16 | 2013.25 | 5.459 | 16 | 2029.375[****] | 8.732 |
| Regional agency | 15 | 2012.6[****] | 3.203 | 13 | 2026.538[****] | 5.547 |
| Permitting official | 2 | 2009 | 0 | 2 | 2020 | 0 |
| University | 59 | 2014.898 | 7.529 | 47 | 2033.936 | 14.368 |
| National Laboratory | 26 | 2015.889 | 4.136 | 26 | 2041.346[****] | 23.646 |
| Environmental NGO | 22 | 2013.909 | 5.528 | 19 | 2033.947 | 19.831 |
| Health NGO | 3 | 2010 | 0 | 3 | 2038.333 | 12.583 |
| Business NGO | 4 | 2012.25 | 5.188 | 4 | 2043.75 | 37.7215 |
| Media | 9 | 2012[****] | 2.646 | 9 | 2035 | 25.372 |

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[*] Significantly different than the rest of the sample, $p < 0.0001$.

[***] Significantly different than the rest of the sample mean, $p < 0.01$.

[****] Significantly different than the rest of the sample mean, $p < 0.1$.

| **Respondent association** | **Market entrance** | | | **5% market** | | |
|---|---|---|---|---|---|---|
| | **N** | **Mean** | **Std deviation** | **N** | **Mean** | **Std deviation** |
| Consultant | 53 | 2014.472 | 4.870 | 50 | 2037.5 | 21.952 |

**Table 6. Respondents' estimates of the earliest year when FCVs could enter the market and when they will capture 5% of the new-vehicle market, by respondents' area of expertise**

| **Respondent expertise** | **Market entrance** | | | **5% market** | | |
|---|---|---|---|---|---|---|
| | **N** | **Mean** | **Std deviation** | **N** | **Mean** | **Std deviation** |
| Fuel cells | 92 | 2014.011$^{****}$ | 4.8141 | 82 | 2030.732 | 11.225 |
| Automotive | 104 | 2016.712 | 7.773 | 85 | 2033.765$^{***}$ | 10.854 |
| Electric drive | 59 | 2016.339$^{****}$ | 5.941 | 49 | 2035.816$^{**}$ | 13.004 |
| Hydrogen production | 85 | 2014.776 | 7.384 | 74 | 2031.216 | 11.281 |
| Hydrogen storage | 67 | 2014.104 | 5.161 | 59 | 2030.974 | 10.965 |
| Hydrogen fueling | 63 | 2015.032 | 8.014 | 54 | 2030 | 10.640 |
| Lobbying | 62 | 2014.726 | 5.408 | 51 | 2029.706 | 10.267 |
| Policy analysis | 141 | 2016.213$^{***}$ | 8.102 | 118 | 2033.475$^{**}$ | 11.938 |
| Economics | 88 | 2016.784$^{***}$ | 8.703 | 68 | 2033.897$^{***}$ | 11.649 |
| Fossil fuels | 92 | 2016.946$^{***}$ | 9.395 | 75 | 2034.533$^{**}$ | 12.552 |
| Renewable energy | 118 | 2014.839 | 5.539 | 97 | 2031.34 | 11.445 |
| Other energy | 72 | 2015.028 | 5.604 | 58 | 2032.931$^{****}$ | 11.510 |
| Politics | 85 | 2015.659 | 8.664 | 73 | 2032.603$^{****}$ | 11.964 |
| Environmental analysis | 126 | 2014.944 | 6.400 | 106 | 2032.972$^{***}$ | 11.015 |
| Transportation planning | 104 | 2016.510$^{***}$ | 8.855 | 94 | 2033.617$^{***}$ | 11.321 |
| Public transit | 31 | 2013.742 | 3.521 | 26 | 2030.385 | 11.655 |
| Law | 13 | 2011.462$^{****}$ | 2.875 | 8 | 2024.375$^{****}$ | 4.173 |
| Market research | 45 | 2014.111 | 5.310 | 40 | 2030.375 | 9.961 |
| Codes and standards | 34 | 2014.735 | 9.555 | 29 | 2026.034$^{***}$ | 7.948 |

One interesting result is that the mean of the estimates on the earliest introduction of FCVs given by respondents from auto companies or fuel cell developers did not differ significantly compared to the mean of the whole sample. Furthermore, we observed significant variation in the responses given for this estimate by respondents in the same auto company. Also interesting is the relative skepticism of the oil and natural gas companies, as represented in our sample.

These expert opinions can help us generate estimates of the parameters of diffusion curves that in some way reflect the perspectives of key stakeholders. The question now becomes which of these opinions is more relevant. Since the market production of FCVs is so tightly dependent on the timing of the necessary technological breakthroughs, one argument could be to pay particular attention to the opinions of experts in the corresponding fields. The two key areas where technological breakthroughs are most necessary are on-board hydrogen storage and fuel cells. The mean of the estimates for the earliest market introduction of FCVs for experts in the former and latter areas are 2014.104 and 2014.011 respectively. The author believes that these figures, which also similar to the mean of the estimates given by respondents in auto companies (2015.448), are reasonable estimates for modeling purposes. In this study, we will then adopt 2014 as the year when FCVs will most likely enter the market. Based on these data, we adopt $t_{0F} = 9$ as an optimistic value (remember that 2016 is an estimate of the *earliest* that FCVs could enter the market.)

The overall mean of the estimates for the year when FCVs will capture 5% of the new light-duty vehicle market is 2031.032. For respondents with auto companies however this mean is 2033.393, while respondents whose expertise is automotive technology and market reearch have means of 2033.765 and 2030.375 respectively. These means are conservative estimates.[3] Again, different analysts would probably make different choices from among these estimates to use in a model. The author will use the automakers' mean—2033—because it is probably the best educated subsample to provide this kind of estimate, and also because it is consistent with, and in fact exceeds the expectations of federal and state government, as represented in our sample.

Stakeholders' opinions are not static though: they will evolve over time as they obtain better information. Recognizing this fact, we plan to administer our survey on a yearly basis. As we gather new data, we will update our estimates of the technologies substitution schedule. At the same time, we will learn more about the factors that help determine changes in stakeholders' opinions.

Van den Bulte (2000) found that innovations that require a large investments in complementary infrastructure (for instance, color TV sets) diffuse faster than other products after they capture 5% of the market. This kind of durable good will be adopted by consumers slowly at the beginning because the new technology may yield only marginal benefits until the necessary infrastructure is in place. A 5% of the market will be captured only if the technology offers a real value proposition and sufficient investments on infrastructure are made. In turn, the investments in infrastructure will be made if a market exists for the new technology. All this seems to indicate that if new technologies that need significant investments in complementary infrastructure do capture a 5% of the market, it is because they have all the potential to capture a much larger fraction of the market. For example, cell phones were launched in 1983, they reached a 5% market penetration in seven years, and in the next six years they captured an additional 22.8% (Van den Bulte, 2000). This finding is relevant to our study in two ways. First, the initial diffusion of FCVs will be contingent on the deployment of a hydrogen (or methanol) distribution and dispensing infrastructure. Second, and consistent with Golder and Tellis (1997) and Rogers (1983), sales of FCVs are expected to take off after an initial threshold of market penetration (2.5 to 5%) is reached.

Based on the preceding considerations, we argue that the diffusion speed of FCVs, after the initial 5% of the market is captured, would resemble that shown thus far by HEVs. We then adopt $\beta_{FCV} = \beta_{HEV} = 0.5359$. This value, combined with our estimates for the year of market introduction of FCVs and the year when they reach a 5% of the new-vehicle market, help us obtain an estimate of the parameter $\alpha$ for the diffusion curve of this technology. Using these values in the logistic-curve functional form, we obtain

$$\ln(0.05) = \alpha + 0.5359(33 - 9),$$

From here, $\alpha_{FCV} = -15.857$. Table 7 summarizes the values of all the parameters adopted for the example presented hereto.

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[3] For example, a response indicating that FCVs would capture 5% of the market after 2020 but before 2025, was coded as 2025.

**Table 7. Values of the problem parameters used in the example**

| Parameter | Hybrid electric vehicles | Fuel-cell vehicles |
|---|---|---|
| $\alpha$ | -7.915 | -15.857 |
| $\beta$ | 0.5359 | 0.5359 |
| $t_0$ | 0 | 9 years |

Adopting a policy time horizon of 50 years, we present in Figure 4 the dynamics of innovation and substitution of the involved technologies: gasoline internal combustion engine vehicles, hybrid electric vehicles, and fuel-cell vehicles.

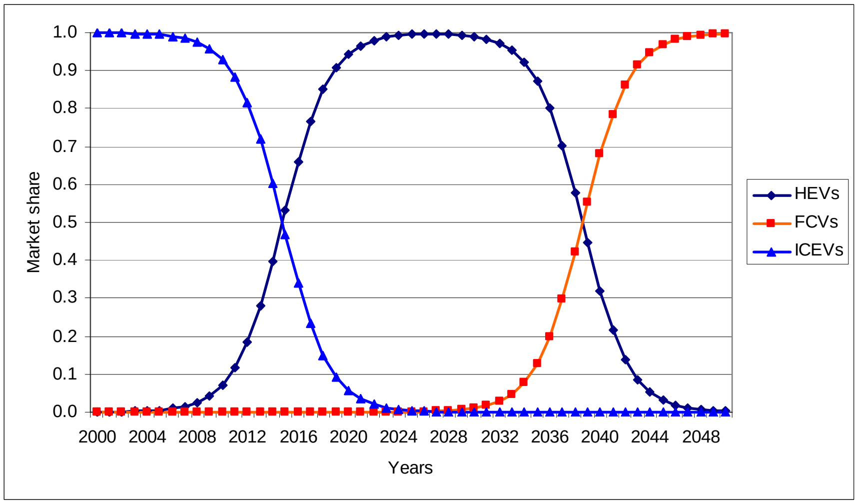

**Figure 4. New-vehicle market substitution of competing technologies, ICEVs, HEVs, and FCVs.**

In this figure, the origin of the time axis corresponds with the year 2000—the year when HEVs are taken to enter the US market. Under this configuration, gasoline HEVs would reach a 50% share of the new-vehicle sales 2015 and a 90% in 2019. FCVs meanwhile would capture a 10% of this market in 2035, a 50% in 2039, and a 90% in 2043.

A direct consequence of our innovation assumptions is that the rate at which ICE vehicles exit the market is the same whether FCVs enter the market or not. This is true because the rate of adoption of HEVs is given, its functional form does not change with the market introduction of FCVs, and because owners of ICE vehicles will buy an HEV before buying a FCV.

How do our results compare to previous studies on the diffusion of FCVs? Thomas (2003) adopted diffusion curves such that gasoline HEVs reach a 50% market share of new sales by the year 2020 and FCVs a 50% market penetration as early as 2035. For the purpose of comparison, we include in Figure 5 the scenarios postulated by the Board of Energy and Environmental Systems of the National Academy of Engineering (2004), and in Figure 6 the scenarios postulated in Mintz et al. (2002).

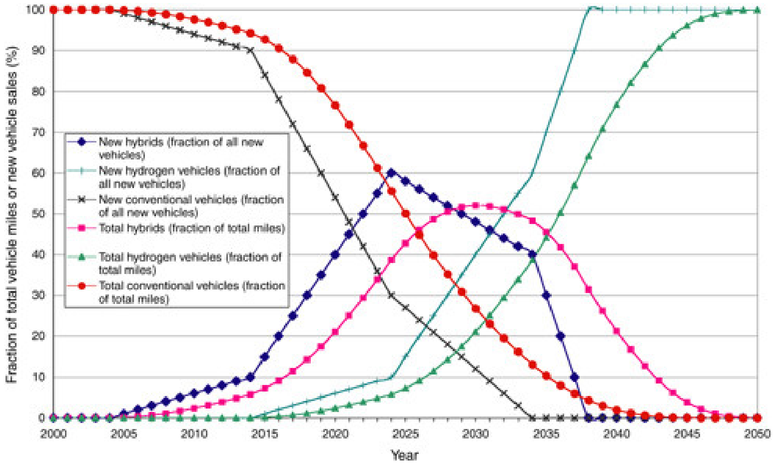

**Figure 5. Market substitution scenarios postulated by the National Academy of Engineering. Source: NAE (2004)**

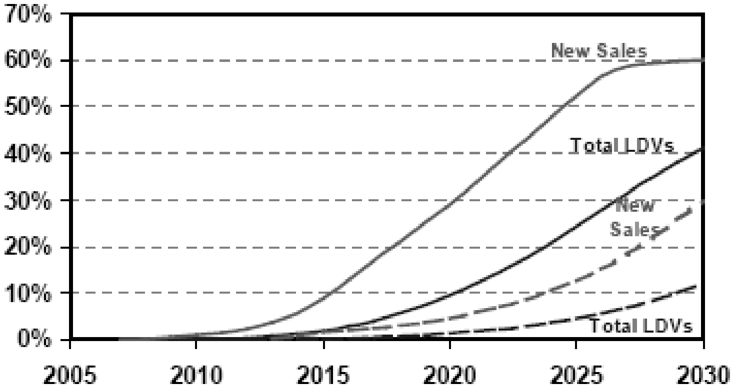

**Figure 6. Optimistic and pessimistic diffusion of FCVs (LDVs). Source: Mintz, et al. (2002)**

The FCVs new-vehicles penetration scenarios submitted by the National Academy of Engineering are optimistic compared to the technology substitution schedule submitted in this paper, particularly in the early stages. Because this study uses linear approximations, hydrogen vehicles reach a 10% market penetration by the year 2024, and a 50% by around 2032. NAE (2004) also submits that HEVs will reach a maximum market share of 60% approximately in 2024, while according to our results this technology eventually secures a 100% of the new-vehicle market. The optimistic scenario submitted in Mintz et al. (2002), suggesting a 10% new-vehicle market penetration by 2015 is certainly unrealistic. Their pessimistic scenario, suggesting a 10% market share by 2024 is very optimistic compared to our results.

For a qualitative evaluation of the potential societal benefits of the market substitution schemes we submitted, we present in Figure 7 the technology schedule for the *entire* vehicle stock.

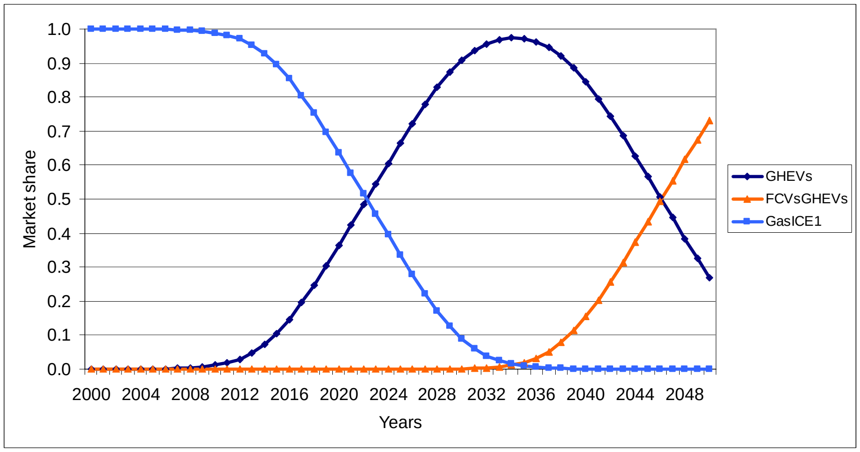

**Figure 7. Time evolution of the total vehicle-stock technology composition.**

To estimate the technology schedule in Figure 7, we assumed that annual sales of new vehicles are 6% of the vehicle stock. We based this assumption on a 1% increase on the estimate that could be obtained from EIA (1994.) We also assume that hybrid and fuel-cell vehicles retire after 15 years. The National Academy of Engineering suggests that hydrogen vehicles would constitute a 10% of the total fleet by 2027, while in Mintz et al.'s pessimistic scenario that level is reached around 2029. Both estimates are optimistic compared to ours.

Under our technology substitution schedule, only 2% of the vehicles in the roads would potentially be zero-emission by 2035. In other words, if this scenario materializes, the adoption of FCVs would result in a mere 2% maximum reduction in annual *per-mile* tailpipe emissions from on-road personal vehicles in 30 years. This result suggests that a sensible policy to reduce oil consumption, greenhouse gas emissions and air pollution needs to consider at least one of the following: a) A continuous regulation of emissions from gasoline vehicles; b) A set of strong incentives to accelerate innovation in and the market introduction of FCVs.

## 4. Conclusions and future research

In this paper we incorporated the expert opinions of key stakeholders in the estimation of the parameters characterizing the diffusion of a new technology. We focused on the case of fuel-cell vehicles, looking at the market-share dynamics in the presence of competing vehicle technologies. We built upon previous work on the diffusion of innovations and used data we obtained from a survey of stakeholders of the hydrogen policy process.

Our results are based on the following structural assumptions: a) market penetrations follow a logistic trajectory, b) consumers tend to prefer more incremental innovations and a typical consumer will adopt a hybrid electric vehicle before adopting a fuel-cell vehicle, c) HEVs and FCVs both have the potential to capture 100% of the market. Our results also depend on our choices in terms of the opinion of which stakeholder groups may be more relevant to generate estimates of diffusion parameters. While we explained the rationale behind our choices, other analysts may have different preferences. Data was provided so that they can generate their own estimates.

This paper also purports to recognize the importance of stakeholders in shaping the market introduction of new vehicle technologies. Traditionally, studies on innovation have used historical data on other technologies to generate estimates of the diffusion parameters of a new technology. This study looks at these studies for general guidance, but relies on expert opinions to generate parameter estimates. The methodology is also very flexible in that it can be adapted to different problems and to different policymakers' preferences.

Our results on the market diffusion of fuel-cell vehicles are in general less optimistic than projections made by other scholars and governmental bodies (e.g. Mintz et al., 2002; NAE, 2004). In particular, we find that the time to take off in sales may be longer than generally believed. A slower diffusion during the initial stages is consistent with previous studies of technologies that require significant capital investments in complementary infrastructures. At the same time, our results are optimistic about the market penetration of HEVs, relative to studies based on other approaches. Greene et al. (2004) for example, concluded that HEVs would capture a 7.1% of the light-duty vehicle market by 2008, and a 14.9% by 2012. They predict, however, that "[b]ecause of their higher costs the combined market share of diesels and hybrids is likely to be limited to half or less than half of all light-duty vehicles even in the long-run, unless policy and market conditions change significantly in their favor. Such changes are not unlikely, given continuing concerns about energy security and global climate change" (p. 55.) We believe that not only these two concerns, but also rapidly increasing global demand for oil and changing consumer perceptions of HEVs, are very likely to generate policy and market incentives for the development of markets for HEVs beyond the levels predicted in Greene et al. (2004).

The time scales involved in this initial stage of market introduction should be of special interest to policymakers who wish to promote FCVs. Government could shorten, to some degree, the time to sales take off by reducing the price effect (with purchase and research incentives) and by reducing uncertainties about the availability of the complementary infrastructure (providing financial mechanisms for the deployment of a hydrogen refueling infrastructure.)

The model, as presented in this paper, gives no *explicit* consideration to the potential effect of regulation and policy in the dynamics of technology innovation. It could be argued, however, that the regulatory perspectives are implicit in the expectations of government officials in our sample. Respondents with regional agencies had mean estimates of 2012.6 and 2026.5 for the years of FCVs earliest market introduction and 5% market penetration respectively, both statistically significantly different ($p < 0.1$) than the rest of the sample. Using these values would yield an estimated earlier market penetration, which could be more reflective of policymakers' expectations.

Generating estimates of the schedule of technologies substitution is the first step in our research agenda. A mathematical integration of the set of diffusion curves can help yield estimates of the associated societal benefits in terms of reductions in greenhouse gas emissions, criteria pollutant emissions, and oil consumption. Research in this area is currently underway.

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