Managing the Transition to Fuel Cell Vehicles – Policy
Implications of an Agent Based Approach

Malte Schwoon

*International Max Planck Research School on Earth System Modelling, Hamburg, Germany*
*Research Unit Sustainability and Global Change, Centre for Marine and Atmospheric Sciences, Hamburg University, Germany*

Research Unit Sustainability and Global Change
Bundestr. 55, 20146 Hamburg, Germany
Tel: +49 40 42838-4406
Fax: +49 40 42838-7009
E-mail: malte.schwoon@zmaw.de
1. Introduction

The current crude oil based individual transport system is not sustainable for economic and environmental reasons. Oil is a non-renewable resource and even though in the past discoveries of new oil fields and especially improved exhaustion methods have repeatedly extended the statistical reach of oil, there is extensive evidence that we get close to the oil peak (Bentley, 2002). Once the oil peak is reached, resource depletion will be accelerated; and given current demand, prices are likely to increase substantially. An additional (socio-)economic problem is the imbalanced distribution of the world's oil reserves, which are concentrated in the politically instable region of the Middle East. From an environmental point of view, internal combustion engine vehicles (ICEVs) running on gasoline or diesel are major contributors to greenhouse gas (GHG) emissions. They account for more than 20% of total GHG emissions in the US (EPA, 2006) and for about 16% in the EU (EEA, 2006). ICEVs also cause significant local air pollution. Advancements of end of the pipe technologies (3-way-catalytic-converter, diesel particulate filter) have been substantial, but in the past, technological progress has often been compensated at least partly by an increase in the number of cars and/or car use (Friedrich and Bickel, 2001).

Already the oil crises of the 1970s, together with ever increasing emission standards later on, initiated research programs of car manufacturers towards alternative fuel/vehicle concepts. Since the 1990s research focuses on fuel cell vehicles (FCVs) running on hydrogen, with R&D investments in the range of billions of dollars (van den Hoed, 2005). Today, every major car manufacturer has a small fleet of FCVs being tested in daily life situations. Also, some fleet tests of buses and taxis have started and technological problems with respect to onboard hydrogen storage for a sufficient range, reliability of the fuel cell or cold start are basically solved. Together with a positive perception of the technology in the public as being "compact, silent, efficient, and emission-free" (Farrell et al., 2003, p. 1357), FCVs are now a technological option rather than a vision.

A large scale introduction of FCVs would directly solve problems related to local emissions, because FCVs only emit water vapor. Using hydrogen as the main energy carrier in individual transport implies the option to diversify energy sources and thus lower the dependency on crude oil. Early hydrogen demand in the introductory phase would probably be met using

---

1 Before, battery/electric vehicles have received most attention, but technological problems with respect to capacity, recharge speed and weight of the battery seemed unsolvable.
natural gas as the hydrogen source. This would shift GHG emissions (mainly CO\textsubscript{2}) from the vehicle to the fuel production side, with only minor overall emission reductions (at relatively high costs per ton of CO\textsubscript{2} abated; EC-JRC, 2006). But later on, substantial GHG emission reductions could be achieved, if hydrogen generation from fossil fuels is combined with carbon capture and sequestration - once these technologies have proven reliable on a large scale and are accepted by the public - or if hydrogen is directly produced from renewable energy sources like wind power or biomass.\textsuperscript{2}

In this paper, I assume that reduction of local emissions, diversification of energy supply and the long term potential to reduce GHGs are sufficient to let governments consider policies to encourage a significant penetration of FCVs in the car market.\textsuperscript{3} These policies must be pronounced enough to overcome the problem of the missing hydrogen refueling infrastructure, often referred to as the chicken-and-egg problem of hydrogen and fuel cells. Fuel cells are extremely expensive and significant cost reductions are only feasible, if they are produced on a large scale. But car manufacturers are not willing to make substantial investments in product lines as long as missing refueling opportunities prevent consumers from buying. On the other hand, oil companies as the major filling station operators will not set up a hydrogen production/distribution network and hydrogen outlets at the stations without demand generated from FCVs on the road.

There exist a wide range of studies that develop scenarios of the introduction of FCVs for different regions.\textsuperscript{4} In the majority of studies, costs of building up a hydrogen infrastructure are estimated given certain scenarios of the development of the number of FCVs, starting in certain (local, commercial) niche markets before entering the large market of private consumers. The implied assumption is that the government must set up the necessary infrastructure and then there will be a smooth and successful diffusion in the market. But a substantial governmental commitment in setting up refueling infrastructure would be unprecedented and unlikely given budget constraints of public authorities. Policies on emission reductions of the transport sector in the past were either direct regulation, taxes on

\textsuperscript{2} With carbon capture and sequestration even coal might become a reasonable source for hydrogen production, which otherwise would actually imply drastic increases of CO\textsubscript{2} emissions compared to the current system (EC-JRC, 2006). The advantage of coal would not only the much higher amount of resources compared to other fossil fuels, but also its more even distribution over world regions.

\textsuperscript{3} The model presented later is calibrated to the German (compact) car market, but is easily transferable, e.g., to Japan, or the state of California, which have previously introduced strong emission control policies, if necessary without (inter-)national coordination.

polluting (old) technology or tax exemptions for the new technology. Yet, there must be a
direct incentive for consumers to buy the (more costly) FCVs, as the pure existence of
infrastructure is not sufficient. The willingness to pay for "environmental friendliness" of a
car is way below the expected additional costs for the fuel cell (Steinberger-Wilckens, 2003).
Moreover, within car buying decisions, the environmental impact is just one feature in
addition to other characteristic like size, acceleration and also psychological motivations like
status. Thus, joint tax and infrastructure policies are indicated to promote the introduction of
FCVs.

The diffusion problem can be considered extremely complex. There are four (types of) agents
involved: car producers, consumers, fuel suppliers and the government. There are dynamic
interactions between the different types of agents, but producers also affect each other as do
consumers. However, the policy problem of introducing the new technologies remains of
"intermediate range" as defined by Verspagen (this report) and can therefore be approached
with evolutionary methods. In this paper an agent based simulation model based on Schwoon
(2006a, 2006b) is discussed that puts together an existing producer competition model
(Kwasnicki, 1996) with a product adoption model (Janssen and Jager, 2002) in a modular
system. The links between the modules are established in a "natural" way; consumers decide
between the cars offered by the producers and the producers try to meet consumers'
preferences and estimate the demand. Fuel suppliers are represented by a (non-linear) increase
of the number of filling stations with a hydrogen outlet as a reaction to increases in the
number of FCVs on the road. The advantage of modularity and rather simple connections
between the modules are that modeling improvements, as, e.g., a more complex decision
model of fuel suppliers can be implemented "locally", without changing the overall structure
of the model.5

The purpose of the model is to investigate the impacts of different policies on the different
agents and their success in promoting the new technology. Thus, the government is only
represented as the exogenous driver of changing behavior. This allows for normative
interpretations.6 The simulation results presented in this paper suggest that tax/infrastructure

5 The same holds for changes within the modules. For example, implementing cost reductions due to learning by
doing only affect producers decisions. Changes in the consumer module, e.g., a different representation of the
buying decision, would require adjustments also in the demand estimation procedure of the producers, but does
not influence the general structure.
6 A fully specified approach would also include dynamic feedbacks, since the government would evaluate policy
success and, if necessary, make adjustments. In other words, a government module would be required.
policies have strong (asymmetric) impacts on certain groups of agents and lead to concentration in the market. These impacts are so far neglected by scenario studies on infrastructure and fuel cell technology costs.

In this paper I will first argue in section 2 that for the specific problem agent based computational modeling seems to provide additional insights compared to traditional technology adoption models with externalities. In section 3, I will discuss the main features of the model. A selection of results is presented in section 4; and in the concluding section 5, some shortcomings of the specific model and agent based simulations in general are discussed.

2. Traditional analysis of adoption externalities

Katz and Shapiro (1985) state that "(p)ositive consumption externalities arise for a durable good when quality and availability of postpurchase service for the good depend on the experience and size of the service network, which may in turn vary with the number of units of the good that have been sold" (p.424). FCVs are exactly such durable goods. The more FCVs have been sold (i.e. the higher the so called userbase), the more hydrogen filling stations and maintenance facilities will be set up making a FCV more valuable for later adopters.

Katz and Shapiro (1985, 1986) and Farrell and Saloner (1985, 1986) introduce a general theoretical framework to analyze welfare and strategy implications in the presence of adoption externalities. It is applied to show that usually two equilibria exist: an adoption and a non-adoption one. The non-adoption equilibrium can also be interpreted as a lock-in situation, with persistence of the old technology. The adoption equilibrium can only be reached if consumers expect a high enough future userbase, so that they then benefit from being part of that userbase, and it is assumed that firms have some influence on these expectations. But this framework cannot be applied to the case of FCVs, in which consumers, who make buying decisions, consider the compatibility with the current refueling system and not with the future one. Thus, non-adoption would be the only reasonable equilibrium and the result is basically another description of the earlier mentioned chicken-and-egg problem.
The descriptive character of the standard neoclassical framework developed by Katz and Shapiro (1985, 1986) and Farrell and Saloner (1985, 1986) is the main reason why it appears to be inappropriate for FCV diffusion analysis. It lacks normative implications in order to compare different diffusion policies, given that the diffusion of the new technology is preferred, e.g., to reduce environmental impacts. Moreover, it offers a static description of the existence and characteristics of equilibria that does not allow, e.g., predicting the number of users during the transition from the non-adoption to the adoption equilibrium. Yet, a description of the transition process is crucial as for car technologies it might take decades between introduction and full penetration. Another drawback of neoclassical models holds that consumers, producers and also products are assumed to be homogenous. In reality, consumers are heterogeneous not only with respect to preferences for a wide range of car characteristics, but also with respect to refueling needs, i.e. their need for compatibility varies. Car manufacturers are different with respect to their size, profitability and research success. And their products might be similar in a broad sense of functionality, but are certainly not perceived as homogeneous. All these shortcomings of the traditional framework seem to be substantial in the context of a new car technology. Thus, taking them together justifies a departure from an analytically tractable neoclassical framework in favor of an agent based computational model that allows for heterogeneity of agents and normative insights into transition dynamics.8

3. An agent based FCV diffusion model

The downsides of the traditional framework imply the advantages of the agent based modeling approach. Agents can be modeled to represent heterogeneity in characteristics and behavior. The development of "macro" variables (e.g. the penetration rate of the new technology) emerges from dynamic interactions and decision making of agents on the "micro" level. It is assumed that agents are myopic (ruling out strategic long term behavior) due to the complexity of the decision problems. In Schwoon (2006a) there are four different types of

7 Already Katz and Shapiro (1985) identify the missing representation of consumer heterogeneity as a limitation of their approach.
8 Note that this conclusion is not general but refers to the specific FCV diffusion problem. Within the set of assumptions, the traditional framework seems to be appropriate (and has widely applied to) diffusion processes in information technologies (examples are Brynjolfsson and Kemerer; 1992; Gandal 1994; Economides and Himmelberg, 1995). For many these technologies and particularly for software products, switches from the non-adoption to the adoption equilibrium are fast. These products often have a non-zero direct use value without compatibility (that remains if one bets on the wrong horse). This direct utility is usually higher for the new technology. Moreover, the loss associated with choosing the wrong technology with respect to the user base is small compared to the car case.
agents: car producers, consumers, filling station owners and the government. Car producers follow heuristic decision rules, because they are uncertain about hydrogen infrastructure development and own research success. In addition, technology choices and price decisions of the competitors are unknown. These uncertainties together cannot be described by probability distributions, ruling out traditional intertemporal expected profit maximization methods. As stated above, consumers behave myopic in buying the car that maximizes their current utility, because disutility of wrong usebase/infrastructure predictions would be immense.

Figure 1 shows a scheme of the model. An arrow from variable A to variable B should be interpreted as "A is a major determinant of B". In reality, the government can actively influence technological choice by announcing and implementing policies. Their success is then evaluated and if necessary adjustments are made. However, to compare the implications of different (long term) policies, dynamic interactions of the government are not included. Policies simply represent exogenous drivers that follow certain scenarios. The policies investigated include differently scheduled taxes on newly bought conventional cars and investments that increase the share of filling stations with a hydrogen outlet. Policies are introduced around 2010. Therefore, conventional technology refers to already advanced hybrid electric internal combustion engine vehicles (Hy-ICEVs), which perform much better than average current ICEVs with respect to fuel efficiency and local emissions. The model is restricted to the compact car segment, which is a likely segment for the introduction of FCVs on a large scale, because almost all the cars applied in today's small fleet demonstration projects are based on conventional cars of that segment. Within the segment, cars are similar but slightly differentiated between producers according to size, design, chassis or special equipment. If a producer switches from the production of a Hy-ICEV to a FCV all these features remain the same, including characteristics like acceleration, noise etc. Thus, conventional cars and FCVs of the same producer differ only in production costs and fuel availability.

Filling station operators are assumed to react collectively towards changes in the share of FCVs within newly registered cars. If the share reaches a new peak, hydrogen outlets are added, but existing ones are not deconstructed. So the behavior of filling station operators is basically simplified to a positive feedback loop between hydrogen filling stations and the number of FCVs, representing the main source of adoption externalities. Thus, filling station

---

9 For a full description of the model and its calibration see Schwoon (2006a, 2006b).
owners are not represented as optimizing ("software"-) agents like consumers and car producers, whose decision making is sketched in the next two subsections.

3.1. The consumer module

The decision making of the consumer is based on the consumat model introduced by Jager (2000) and applied in the context of environmentally friendly products in Janssen and Jager (2002). The original consumat approach allows for four cognitive strategies of the consumers (repetition, deliberation, imitation, and social comparison). A deliberating consumer compares all the cars from the different producer and takes the one that maximizes his utility function. With respect to cars, this is likely to be the predominant strategy. Repetition and imitation are not included, as they seem to be more appropriate for products that are frequently bought and less expensive. Social comparison refers to a strategy, where consumers evaluate only the utility of the car most of their neighbors drive and compare it with the utility they would get from buying the brand again that they are currently driving. This strategy arises from uncertainty about product characteristics and reduces the decision space to the directly perceivable environment. The impact of consumers doing social comparison is shown in section 4.3.

A consumer evaluates a car according to the utility function

$$U^\text{tot}_{k,t}(c_{i,t}) = \frac{\beta_k U^*_{k,t}(c_{i,t}) + (1-\beta_k)SN_{k,t}(FCV_i)}{(p(c_{j,t})(1+tax_i(1-FCV_i)))^{\bar{H}}} RFE_{k,t}(FCV_i).$$  \hspace{1cm} (1)

$U^\text{tot}_{k,t}(c_{i,t})$ is the total utility consumer $k$ receives from buying car $c_{i,t}$ (from producer $i$) at time $t$. $FCV_i$ is a binary variable that is 1 if the car under consideration is a FCV and 0 for a Hy-ICEV. The first component is direct utility, which measures the difference between car characteristics $(z_{i,j,t})$ and individual preferences $(pref_{k,j,t})$ for the characteristics according to

$$U_{k,t}(c_{i,t}) = 1 - \frac{1}{n_j} \sum_{j=1}^{n_j} |z_{i,j,t} - pref_{k,j,t}|,$$  \hspace{1cm} (2)

10 The equations included here should provide a general notion of how the components of the model shown in Figure 1 translate into a computational framework. For the full system of equations see Schwoon (2006a).
where $n_j$ is the number of characteristics being evaluated. Characteristics and preferences are randomly initialized to vary between 0 and 1. Correspondingly, direct utility also varies between 0 and 1. Producers can change characteristics via R&D. Therefore, the consumer's direct utility can be 1 at the maximum if all characteristics exactly meet his preferences and is limited to zero in the opposite case.

The decision to buy a new technology like a FCV might be affected by the neighbors. The term "neighbors" refers to the social environment (members of the family, colleagues, friends, etc.) that is relevant for the buying decision. If the car under consideration is a FCV then the satisfaction of social needs $SN_{k,t}(1)$, equals the share of neighbors, who already have a FCV (otherwise, $SN_{k,t}(0)$ is computed as the share of neighbors, who still drive conventional cars). But this pressure towards conformity varies from consumer to consumer according to the weight $\beta_k$ (which is positive and does not exceed 1). People with a $\beta_k$ close to 1 decide rather independently of their neighbors (and are therefore likely to be early adopters of the new technology), while others follow the technology choice of their environment.

Utility is normalized by (after-tax) price and the magnitude of the responsiveness of utility towards price changes is represented by the elasticity $\epsilon$. Note that taxes are zero in the case of a FCV. The unusual inclusion of price in the utility function is basically a short cut for not having an explicit budget constraint. Moreover, it allows for a direct trade off between price and fuel availability that has been measured in empirical studies. The impact of fuel availability on utility is represented by a "refueling effect" $RFE_{k,t}(FCV)$, which is defined as

$$RFE_{k,t}(0) = 1 \quad \text{(for Hy-ICEV)} \quad (3a)$$

and

$$RFE_{k,t}(1) = 1 - DP_k \cdot \exp(-\gamma s_{H2,t}) \quad \text{(for FCVs).} \quad (3b)$$

Refueling matters only for FCVs and depends on individual driving patterns of the consumer ($DP_k$) and the share of filling stations that have a hydrogen outlet ($s_{H2,t}$). The driving pattern represents the individual refueling needs. For example the decision might differ for buying a second car. Then, long distant trips with a high "refueling uncertainty" might be done with the conventional first car and the FCV as the second can be regularly fueled at a familiar filling
station, e.g., on a weekly shopping trip.\textsuperscript{11} Driving pattern and fuel availability combined are constructed to be in the range from 0 to 1, so that overall utility of a FCV can actually be 0. Initialization of driving patterns and the parameters $\varepsilon$ and $\gamma$ are jointly calibrated in order to get a price/fuel availability trade off that is in line with the estimates of Bunch et al. (1993) and Greene (1998).

3.2. Heterogeneity of consumers
The description of the consumer module showed three sources of heterogeneity that determine different product choices of consumers. Firstly, consumers have different preferences for certain car characteristics (via $\text{pref}_k$). This is particularly decisive if cars with the same technology are compared. Secondly, consumers are differently influenced by their neighbors on the buying decision (via $\beta_k$), and thirdly they differ in their driving pattern and therefore in their refueling needs (via $\text{DP}_k$). The latter two sources of heterogeneity determine which consumers are most likely to be early adopters of FCVs, namely those with low refueling needs, who decide independently of their neighbors.

3.3. The producer module
The supply side of the model is based on Kwasnicki’s (1996) behavioral model of producers competing in a market of slightly differentiated products. Producers are price setters with limited market power depending on their market share. In each period, the individual producer sets the price that maximizes the following objective function:

$$
\max \ Obj_{i,j} = (1-W_{i,j}) \frac{\text{INC}_{i,j}}{\sum_{i=1}^{n} \text{INC}_{i,j-1}} + W_{i,j} \frac{q'(c_{i,j})}{\sum_{i=1}^{n} q(c_{i,j-1})},
$$

with

$$
W_{i,j} = \exp \left( -\eta \frac{q'(c_{i,\text{FCV},j})}{\sum_{i=1}^{n} q(c_{i,\text{FCV},j-1})} \right).
$$

The objective is a weighted average of expected income $\text{INC}_{i,j}^e$ relative to total income of all producers in the previous period ("expected income share") and expected number of cars sold

\textsuperscript{11} The term driving pattern is used to indicate that it is the actual driving behavior of a consumer that determines his individual refueling needs. However, there might also be a psychological effect that perceived refueling needs are higher than actual refueling needs, but this is not addressed separately.
relative to the total number of cars sold in the car market in the previous period ("expected market share"). The parameter \( \eta \) calibrates the weight \( W_{i,t} \), which is constructed in a way that large producers, i.e. producers with an expected high market share, have a higher preference for income, whereas small producers put more emphasis on market share. The latter can be interpreted as a survival strategy.\(^{12}\)

The maximization is subject to capital constraints. For each price there is a certain expected quantity \( q^e \) and income \( INC^e \) implied. The values are derived following a certain sequence of computations. The sequence is not meant to mimic the order of an actual decision process but reflects how available information is used to make an optimal decision under uncertainty. The sequence can be broken down into five parts which are sketched now.

1. The utility of a car for a consumer depends on his preferences for certain car characteristics, driving patterns, social needs, and the (after-tax) price. It is assumed that the producer can estimate averages of these values at least of his customers (who bought in the previous period), e.g., from after sale questionnaires or maintenance reports. Thus, the producer estimates the expected (average) utility of his car, which is called expected competitiveness. R&D success improves the expected competitiveness, but is subject to some randomness. However, the producer can directly influence the expected competitiveness by setting the price (as the decision variable!).

2. The producer observes the competitiveness of the cars of the competitors and extrapolates a trend from previous development. If the expected competitiveness of the own product exceeds the estimated average competitiveness of all the cars in the market, the producer expects his market share to increase and vice versa.

3. Expected total demand is estimated given expectations on the average price level of the market; and the own price decision affects the expected average price level depending on the market share of the producer. Expected total demand and the expected market share

\(^{12}\) This is not directly implied by equation (5), but follows, because expected market share is deduced from current market share.
derived in the previous step allow the computation of the expected quantity.

4. The expected quantity can only be produced if sufficient capital is available. Capital depreciates over time, but can be increased using retained earnings from previous periods or from lending at the capital market. The individual credit line depends on the amount of existing capital (as collateral) and it is assumed that producing FCVs is more capital intensive than producing Hy-ICEVs.

5. From the expected quantity and the price, the expected income $INC$ is computed as revenue minus variable costs and the value of the objective function can be obtained. As long as the producer has not switched to FCVs, the optimization is done twice, once for Hy-ICEVs and once for FCVs. The switch is made if producing FCVs leads to a higher value of the objective function.

In the case of the production of FCVs, the variable costs in the last step are assumed to decline due to learning by doing (LBD) as in Schwoon (2006b). Learning effects have been observed for a wide range of energy related technologies (Neij, 1997; Mackay and Probert, 1998; Wene, 2000; McDonald and Schrattenholzer, 2001; Neij et al. 2003; Junginger et al., 2005). They are expected to occur also for fuel cell and hydrogen related technologies (Rogner, 1998; Lipman and Sperling, 1999; Tsuchiya and Kobayashi, 2004). LBD leads to a negative relationship between cumulative output and production costs. In the model, LBD is restricted to the fuel cell and hydrogen tanks. Other components and also internal combustion engines show learning effects. But due to the fact that cumulative production already reached billions, they are assumed to be negligibly small.

Implementing LBD in the model requires some refinements of the optimization process, because current production levels affect future costs. Thus, expected (relative share of) income in equation (4) is replaced by its expected net present value computed over a certain decision horizon (with constant quantities and declining costs for FCVs). This generates an inconsistency in that producers create expectations beyond the next period. But this changed optimization only affects the switching decision and not the price decision. It is necessary,
because otherwise with LBD the likelihood of switching increases with the length of the model time step. A longer time step leads to higher production quantities and therefore higher cost reductions. The length of the model time step (three months) is determined by how often prices and production quantities can be adjusted. The decision to switch, though, should incorporate projections over several years.

3.4. **Heterogeneity of producers**
Producers cannot do optimal pricing based on intertemporal expected profit maximization, because the behavior of competitors, R&D success, infrastructure build-up etc. are uncertain and (altogether) do not follow probability distributions. Therefore, a wide range of potential heuristics, i.e. alternative objective functions exists. Kwasnicki and Kwasnicka (1992) show that in a similar setting the above objective function outperforms the majority of alternatives with respect to long term profits. Here, all producers use the same objective function as being the "best one available". However, two sources of heterogeneity between producers remain. The first one is that their products initially have different characteristics and changes due to (individual) R&D success underlie some randomness. The second, more important one is size (in terms of market share). Size determines not only the weight in the objective function, but also market power, credit availability and R&D expenditures (which are positively correlated with R&D success).

3.5. **Connecting modules**
The main connection between producers and consumers is the selling process. After the producers set prices and adjusted their production capacity, the actual total demand in the market (i.e. the number of potential consumers who buy a car) is derived from the actual average price of the cars offered. Buying consumers are chosen, depending on how long they already have their old car. This approximates the behavior that in times of generally increasing prices, consumers tend to drive their old cars longer and in times of decreasing prices more new cars are bought. Consumers evaluate the cars as described in section 3.1 and make their orders. Producers construct only as many cars as consumers order, up to their capacity limit. So there is no excess supply (inventories are omitted). This implies that producers, which overestimated the demand for their products, are penalized by their overinvestment in capacity but not by high variable costs. In the case of excess demand, not all consumers can be satisfied, because a period is not long enough for capacity extensions or price increases. If a consumer cannot get his favorite product, because it is sold out, (s)he will

---

13 Note that expected market share is correlated with current market share.
choose a less preferred product and (s)he can actually end up with nothing and has to wait for the next period.

There are also indirect interactions between producers and consumers. As stated above, producers gather information about the preferences of their customers and target R&D activities accordingly. Consumers’ preferences, on the other hand, are influenced by average car characteristics in the market, representing a marketing effect similar to Valente (1999). Due to the simplistic representation of the fuel suppliers and the government, there is no real connection to the other modules, but rather a direct feedback or respectively an exogenous influence.

3.6. Calibration and scenarios
The model is implemented in the Laboratory for Simulation Development (LSD). Its calibration aims at mimicking some of the main features of the German compact car segment. There are 12 important producers in the segment of compact cars in Germany with market shares exceeding 2% and a dominating producer (Volkswagen) with a market share of about 1/3. To simulate the asymmetric situation initial market shares are drawn randomly from a normal distribution with mean 12/100% and a standard deviation of 10%. For computational reasons 6400 different consumers are modeled. In the control run without any policy about 125 consumers buy each period, i.e. if we assume that each consumer represents about 2,000 similarly behaving ones, we end up at one million sales per year, which corresponds to the size of the compact car segment.

It is assumed that by 2010, 400 fuel stations offer hydrogen (i.e. approximately 3% of the filing stations in Germany). Results are shown only for tax policies or additional "major H\textsubscript{2} program" scenarios, which represent a public infrastructure program that provides 160 additional hydrogen outlets at existing filling stations each year. Two different tax scenarios are implemented and eventually combined with the infrastructure program. One is a "shock tax" with an instantaneous 40% tax in the year 2010 on (newly bought) conventional cars. The tax hits the market so as to directly push FCVs into it. Alternatively a "gradual tax" is used with a quarterly increase of 1% ending up also at 40% in 2020, where agents can smoothly

---

14 LSD is an open source environment for C++ programming. Its main features are discussed in Valente and Andersen (2002) and it is available at http://www.business.aau.dk/lsd/lsd.html.
15 The minimum market share is 2% and the sum of all market shares is scaled to sum up to 100%.
16 2010 is chosen arbitrarily as the starting point of the policies that should move FCVs out of niche applications.
17 This is equal to the "high exogenous H\textsubscript{2}" scenarios in Schwoon (2006a).
adjust to the new circumstances. The scenarios represent extreme cases for demonstrative purpose. The 40% tax level represents not only purchase taxes, but also the net present value of total lifecycle taxes (on ownership, insurance, fuel etc.). Compared to present car taxes in Europe (as listed in Burnham, 2001), 40% is at the low end of current rates.

In the central case, a learning rate of 15% for fuel cell related technologies is assumed. This means that costs decrease by 15% for a doubling of cumulative output. For the simulations here, learning is fully appropriated by the producers, i.e. learning spillovers are neglected (contrary to Schwoon, 2006b). Learning takes place only on the national market, i.e. global learning effects of international producers introducing FCVs in several markets at the same time are ignored. Thus, the results are relevant for a situation, in which a national government decides to push in a solo attempt the introduction of the new technology in a market of comparable size to the German market. An example for such a policy in the history of pollution regulation of cars is the independent introduction of unleaded fuels and the support of 3-way catalytic converters in Germany, preceding most other countries in Western Europe (Westheide, 1987).

4. Results

4.1. Diffusion projections
As a benchmark to compare the success of different policies Figure 2 shows the share of FCVs within all newly registered cars. All figures presented refer to averages of 100 simulation runs using different random initializations. Diffusion comes along with an increase in the share of filling stations with hydrogen outlets (see Figure 3). The shock tax directly forces at least one producer to switch to the production of FCVs. Public infrastructure speeds up diffusion at the beginning, but later on the impact is negligible. The reason is that for a certain share of consumers, refueling remains a critical issue and they are served by a few producers that establish a successful temporary niche.

In the case of the gradual tax, the tax level does not have to reach the full level of 40% before (on average) some producers start producing FCVs. Public infrastructure build-up seems to

---

18 Dutton and Thomas (1984) present data of 100 estimates of learning rates in manufacturing. They find a median learning rate of 19-20%. For a smaller sample of energy technologies, McDonald and Schrattenholzer (2001) report a median of 16-17%, so that 15% is chosen as a rather conservative assumption.

19 The niche is only temporary, because as soon as there is full infrastructure coverage, all producers will switch to FCVs.
have a much more important influence on the diffusion, because, as Figure 3 shows, already about 10% of the filling stations are equipped with hydrogen until the tax reaches a level that forces producers to switch. However, even with a major public infrastructure program, the gradual tax scenario leads to much slower diffusion compared to the shock tax. In the year 2030, 10 years after the gradual tax reached its maximum, the share of FCVs within newly registered cars is 40%, a level reached with the shock tax (without public infrastructure) in less than five years.

The reason why the shock tax leads to faster diffusion can be seen in Figure 4, which shows the number of cars produced relative to the development without a tax. There is a sharp drop in sales due to an increase in after-tax prices in the shock tax case. However, producers, who change production directly due to the shock tax, still include to some degree the relatively high pre-tax production levels into their decision. Thus, they expect comparatively high LBD cost reductions and are therefore more likely to switch. In the gradual tax case, demand goes down steadily, so that if the tax rate reaches levels that make switching considerable, demand is very low. Producers’ expectations about LBD are therefore also low and production of FCVs is postponed. In Figure 5 the relationship between tax scenario and LBD expectations is further illustrated. Sensitivity results are shown for different learning rates (LR). With a rather low learning rate (LR = 10%) only the shock tax leads to diffusion.\textsuperscript{20} The gradual tax signal is not sufficient to stimulate diffusion. With higher learning (LR = 20%) the shock tax generates an instantaneous introduction of the new technology, with more than 50% market share reached within the first year. Even in that case, the gradual tax only leads to a smooth introduction and it takes until 2030 (ten years after the 40% tax level is reached) until every second car sold is an FCV. The strong impact of the learning rate on the speed of diffusion also demonstrates how important knowledge of potential learning processes is. The changes in production (respectively sales) in Figure 4 illustrate that production only recovers after diffusion begins. Thus, a substantial tax that is not sufficient to actually promote switching, because learning effects have been overstated, would be extremely destructive.

\textbf{4.2. Asymmetric impacts on agents}

The production figures are basically a mirror image of the after-tax price development shown in Figure 6. Thus, Figure 4 and Figure 6 together give an impression of how consumers are affected by the tax. Consumers face considerable price increases in every policy scenario.

\textsuperscript{20} 65\% of the observed learning rates presented in McDonald and Schrattenholzer (2001) and 82\% of those presented in Dutton and Thomas (1984) exceed 10\%.
With the shock tax, these increases happen directly after the introduction, but later on price levels are actually lower than in the gradual tax cases. Thus, consumers would be (relatively) better off in the long run. However, consumers would suffer from the drastic price increase right at the beginning and such a policy would therefore be rather difficult to implement. In any case, consumers would benefit from a major infrastructure program via lower car prices. The price effect is due to the generally faster diffusion that implies LBD cost reductions and these cost reductions are at least partly passed on to the consumers.

It might be surprising to see that prices increase at least temporarily by a higher percentage than the tax. This is partly due to the optimization routine of the producers, which focuses on relative income and market share and not absolute, so that they might fully shift the tax burden to the consumers. But another reason is that the large producers have the advantage of predicting demand changes better during changes in the tax rate, as they have a higher influence on average prices. This leads to a noticeable increase in concentration, as one can see from the Herfindahl-index displayed in Figure 7. This index is constructed by summing the square of market shares for all firms and lies between 0 (perfect competition) to 1 (monopoly). The index jumps up from 0.13 to 0.17 for the shock tax. There is a temporary backlash (due to price cuts from small producers in order to survive), but the concentration index remains high afterwards. In the gradual tax cases, there is a steady increase in concentration. In both tax scenarios, the higher concentration, which implies greater market power, leads to higher prices.

This result already suggests that producers are differently affected by the policies, depending on their size. Figure 8 and Figure 9 show the change in the sum of profits of the three largest and three smallest producers relative to the no tax baseline. The profits of the large producers are substantially hit by the shock tax, but then recover very quickly (within about a year) before they actually exceed profits without the tax. The increase in profits then continues, following the development of the concentration discussed above. In the gradual tax cases, profits do not decrease that much, but stay below the level without a tax for almost a decade until the first producers switch to the production of FCVs. Thus, large producers would

---

21 Note that the model neglects the costs of the infrastructure program and a potential use of the tax revenues for infrastructure investments. Thus, the model does not allow a full cost-benefit analysis. However, the development of the after-tax car price is considered to be a good proxy for potential resistance to certain policies.
22 A Herfindahl-index of 0.13 applies to a market in which 7 to 8 firms compete with an equal market share. With 0.17 this number drops to 5-6, thus, the concentration increase is substantial.
23 Note that the possibility of (foreign) entry is ignored.
actually be better off with the shock tax that promotes diffusion immediately and quickly raises their profits above the level without the tax.\textsuperscript{24}

Small producers suffer from any of the policies, but particularly from the shock tax. In that case, the infrastructure program makes them even worse off, which suggests that small producers are the losers especially of those policies that generate fast diffusion of the new technologies. Thus, strong resistance to FCV supporting policies can be expected. On the other hand, large producers additionally win from infrastructure investments. This might actually let them consider side payments to fuel suppliers to support fast infrastructure build-up.

### 4.3. Sensitivity with respect to different buying decisions

Schwoon (2006a) presents a wide range of results from sensitivity analyses, identifying parameters that crucially determine the speed of diffusion. The most important parameters are the price elasticity of consumers, the distribution of weights between individual preferences and social needs in the consumer population, and also the weight between expected income share and market share in the objective of the producers. Here, I only show how the speed of diffusion is affected if some of the consumers do “social comparison” as defined in Janssen and Jager (2002). Applying this different consumer behavior is an example for a change in the consumer module that can be implemented independently of the rest of the model reflecting the advantage of the modular set-up of the simulation model.

Consumers might be uncertain in judging car characteristics or, e.g., operating costs and so on, so they consider themselves unable (or not willing due to information costs) to evaluate all the cars available on the market. In that case, they are assumed to compare only the utility associated with the car that is driven by the majority of their neighbors with the utility from buying the latest version of their old car again. This means that they reduce their decision space to two directly perceivable products.

In the social comparison cases in Figure 10, on average some 50% of the consumers actually do social comparison. The small decision space increases the speed of diffusion at the beginning. Consumers stick to their brand or choose that of their neighbors even if it is now only available as a FCV. But later on this effect of a continuation of previous behavior leads

\textsuperscript{24} Only for an unrealistically high discount rate large producers would be better off with the gradual tax, as it does not imply the drastic profit reduction right after implementation.
to resistance to full diffusion, so that by the year 2030 the share of newly registered FCVs is lower than without social comparison. Note that these results are driven by the fact that producers radically switch to producing the new technology. Thus, consumers sticking to their “old product” might actually be forced to buy a FCV. In a more realistic model that allows producers to offer the same car with different drive trains, social comparison is likely to lead to much slower diffusion in the beginning, because consumers doing social comparison would hardly be exposed to the new technology and, therefore, not consider them at all. They would generally drop out as potential initial adopters, even if, e.g., their individual driving behavior militates in favor of adoption. The number of initial adopters, though, is critical for producers to introduce FCVs. Thus, a large share of consumers doing social comparison might actually prevent a successful introduction of FCVs.

5. Conclusion

In this paper, I described the core features of an agent based computational model that has been developed to understand the dynamics of a policy driven transition to FCVs fueled with hydrogen. The model combines in a modular way an existing producer and consumer model and adds a fuel supplier component. The modules operate relatively independently as they have only a few (but dynamically important) connections. Future improvements or experiments within one of the modules are, therefore, easily implemented. The model is used to evaluate certain tax and infrastructure policy scenarios that enter the model as exogenous drivers. It incorporates several features separating it from neoclassic approaches towards technology adoption in the presence of adoption externalities. Agents are heterogeneous in several characteristics and in behavior. They are myopic and their decisions (as reactions to the policies) are driven by individual interactions with other agents.

The model is specified and calibrated to represent the dynamics of a policy driven introduction of FCVs in the German compact car market. However, the structure can generally applied to new car technologies that require a specific fuel that is rarely available. Results are shown for a shock tax and a gradual tax scenario so as to represent extreme cases. The taxes may or may not be combined with additional public infrastructure investments that increase the share of filling stations that offer the new fuel. The shock tax initiates a diffusion of FCVs in terms of the share of newly registered cars right after the introduction of the tax. With a gradual tax, it takes several years until a tax level is reached that forces producers to
switch to the production of FCVs. But even from that later point in time, diffusion is much slower compared to the shock tax. If the learning rate of fuel cell technologies is rather low, the gradual tax might even be insufficient to stimulate a single producer to switch. However, in the central case parameterization with a learning rate for fuel cell technology of 15% the taxes are able to overcome the chicken-and-egg-problem usually associated with the introduction of FCVs and hydrogen infrastructure.

The different policy scenarios have substantially different impacts on the agents. Consumers are likely to prefer a gradual tax that leads to slowly increasing prices. In any case, they would be in favor of a major infrastructure program, because it promotes faster diffusion and higher learning cost reduction that keep average car prices comparatively low. Both tax scenarios increase concentration in the market. Large producers benefit from higher profits in the medium to long term, particularly in the shock tax case. The benefits are at the expense of small producers, who are likely to oppose any diffusion policy as they would suffer substantial losses. The faster the diffusion, the more profitable are large producers. Therefore, they would also be the winners of a major infrastructure program.

There are two types of modeling issues that limit the validity of the results; model specific simplifications and problems of simulation models in general. Simplifications are necessary to keep the already rather complex model manageable, so that it does not become a "black box", in which too many parameters and behavioral equations tend to obscure results. A major simplification, however, is that producers only have the option to fully switch to the new technology. In reality, producers are more likely to introduce the new technology in certain product lines. Moreover, the model is restricted to a single market segment. But the tax might force consumers, e.g., to switch to cars in a cheaper segment rather than to adopt the new technology. A more realistic model would also call for a more detailed representation of fuel suppliers, including investment decisions with relatively long payback periods. Another drawback is that the consumer model does not allow for a computation of consumer rents\textsuperscript{25}, so that efficiency costs of the tax cannot be investigated. This would be necessary to derive the environmental performance relative to the tax burden (or relative to infrastructure expenditures). The results already indicate that environmental performance of the policies at least over the simulated time period is not straightforwardly computed. The taxes lead to

\textsuperscript{25} The reason is that consumers compare utilities from heterogeneous products and, therefore, do not have a specific willingness to pay that could be used to compute an aggregate demand function. Note that aggregate producer rents are straightforwardly derived.
declines in sales of newly registered cars, suggesting that old cars tend to be driven longer. This might imply adverse environmental effects under the assumption that environmental performance of new cars (FCVs and Hy-ICEVs) is generally higher than that of the average car in the car population.

Apart from the explicit limitations of the model there are problems related to the methodology of simulations as such. The simulations underlie parameter uncertainty together with uncertainty of behavioral assumptions. Uncertainty is particularly large, because the model addresses a very specific technological transition that is unprecedented in history, so that standard calibration/validation cannot be applied. These issues can be summarized as model uncertainties. The only way to deal with it is sensitivity analysis in order to identify those parameters (or behavioral equations) that have the most severe impact on results. In addition to model uncertainty, the model itself generates uncertainty as a simulation of reality, in which decisions are at least partly driven by random events. Random events that drive the results are controlled for by comparing averages over hundreds of simulations. However, the future will not follow an "average path" but will be, so to say, a singular chain of events.

Model uncertainties together with model inherent stochastic developments rule out that simulation results can be interpreted as forecasts. But the model results are the key to understand the main dynamics of a complex technological system. For the introduction of FCVs, lessons learned independently of actual magnitudes are that a high immediate taxation of conventional cars promotes fast diffusion, but at the price of not only declines in sales but also increasing market power of already large producers. In addition, large producers would be the beneficiaries of a major public infrastructure program, whereas small producers would actually suffer. Impacts on consumers and industry performance have been so far ignored by studies that address the costs of switching to hydrogen based individual transport. The introduction of a major tax and/or infrastructure program is likely to face resistance of certain consumer and industry councils. Therefore, a better understanding of transition dynamics helps developing strategies that keep disruptive impacts as small as possible. Identifying the resulting winners and losers of the policies in advance, would also allow for compensation policies that might reduce resistances.
References


Figure 1 Scheme of the model, highlighting the producer and consumer modules
Figure 2 Share of FCVs within the newly registered vehicles for different policy scenarios
Figure 3 Development of the share of filling stations with hydrogen outlet
Figure 4 Change in the sum of all cars sold relative to the development without a tax
Figure 5 Share of FCVs within the newly registered vehicles: Sensitivity to the learning rate
Figure 6 Change in average after-tax price relative to the development without a tax.
Figure 7 Development of the Herfindahl-index after introduction of the tax
Figure 8 Change in the sum of the profits of the three largest producers relative to the development without a tax
Figure 9 Change in the sum of the profits of the three smallest producers relative to the development without a tax
Figure 10 Impact of the share of FCVs within newly registered vehicles if 50% of the consumers do social comparison.