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Initial infrastructure development strategies for the transition to sustainable mobility

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Abstract

Within the Dutch transition policy framework, the transition to hydrogen-based transport is seen as a promising option towards a sustainable transport system. This transition requires the build-up of a hydrogen infrastructure as a certain level of refuelling infrastructure is necessary before (even the most innovative or environmentally friendly) consumers will substitute their conventional car for a hydrogen vehicle (Dunn 2002). This is often referred to as the chicken-and-egg problem of infrastructure development. However, the build-up of infrastructure is costly and irreversible and it is therefore important for policymakers to gain insight in the minimally required levels of initial infrastructure that will still set off the transition. In this paper we therefore present a diffusion model for the analysis of the effects of different strategies for hydrogen infrastructure development on hydrogen vehicle fleet penetration. Within the simulation model, diffusion patterns for hydrogen vehicles were created through the interactions of consumers, refuelling stations and technological learning. We compare our results to the benchmark patterns derived from the hydrogen roadmap. The strategies for initial infrastructure development differ with respect to the placement (urban or nationwide) and the number of initial refuelling stations. Simulation results indicate that when taking social learning between consumers into account, diffusion is generally lower than in the benchmark patterns. Furthermore, simulation results indicate that a nationwide deployment strategy generally leads to faster diffusion of hydrogen vehicles than a strategy focused on urban areas. These demand side aspects of the transition to sustainable mobility are considered especially important in the Netherlands since besides the high cost associated with infrastructure investment the Netherlands do not have a domestic car industry so that policy measures will most likely focus on infrastructure and consumers. Increased insights in the relation between infrastructure development strategies and hydrogen vehicle diffusion are thus necessary to further manage the transition to sustainable mobility.

1 Introduction

Within the Dutch transition policy framework, the transition to hydrogen-based transport is seen as a promising option towards a sustainable transport system. This transition requires the build-up of a hydrogen infrastructure as a certain level of refuelling infrastructure is necessary before (even the most innovative or environmentally friendly) consumers will substitute their conventional car for a hydrogen vehicle (Dunn 2002). This is often referred to as the chicken-and-egg problem of infrastructure development. However, the build-up of infrastructure is costly and often irreversible and it is therefore important for policymakers to gain insight in the minimally required levels of initial infrastructure that will still set off the transition.

Transition management, the process of governing the transition to a more sustainable society, acknowledges that the different stakeholder groups need to be actively involved in this process of change (Kemp and Rotmans 2004, Rotmans et al, 2001). This approach has led to an increased understanding of the behavioural and institutional changes that are necessary for a sustainable transport system. The necessary changes in infrastructure however are mostly regarded from a purely technological point of view leaving out the role of user practices and user behaviours within the transition. While earlier research based on technology roadmapping and forecasting methods (Phaal et al. 2004; Martin and Johnston 1998; Watts and Porter 1997; HyWays 2008, Dunn 2002) thus acknowledges the importance of refuelling infrastructure, the question of how to unroll such an infrastructure largely remains unanswered. Which stations should be first movers in supplying hydrogen: urban, highway or small town stations? How many of these first stations are needed to create a critical mass? Previous research indicates that these are questions that need to be considered to effectively manage the transition to sustainable mobility and before making large investments in a refuelling infrastructure.

In earlier research refuelling availability is found to be an important decision factor for car buyers (Bunch, Bradley, Golob, Kitamura, and Occhiuzzo, 1993; O'Garra, Mourato, and Pearson, 2005) which indicates that the number of hydrogen fuel stations influences the likeliness of hydrogen car adoption. Additionally, refuelling behaviour is found to be concentrated near car owners' home and work locations, indicating an influence of hydrogen fuel station location on hydrogen car adoption (Kitamura and Sperling, 1987; Melaina, 2003; Sperling and Kitamura, 1986). Therefore our hypothesis is that for hydrogen car adoption, the number and location of available refuelling stations influences its diffusion pattern.

The goal of this paper is to further investigate this relation, by simulating hydrogen car diffusion patterns for different initial refuelling infrastructure availability strategies. The following research question is answered:

What is the relation between initial refuelling infrastructure availability and the expected diffusion pattern of hydrogen vehicles in the Netherlands?

We thereby focus on light duty vehicles for personal mobility. The diffusion of (successful) innovations often follows an S-shaped curve (Rogers, 2003). Initial diffusion is slow when there are only a few adopters. As more and more consumers learn about the innovation and decide to adopt the S-shaped curve of diffusion takes off. Rogers states that processes that have entered this take-off phase often become self-sustaining and are difficult to stop or reverse. The exact shape of the innovation diffusion curve is innovation specific and depends on the innovation itself, the size and type of the early adopter group and the speed of the diffusion. The diffusion curve is thus the outcome of non-trivial interactions between social, economic, behavioural and technical characteristics of the innovation and of the adopters (Frenken 2006). For hydrogen, one of these factors is the initial infrastructure build up strategy that is chosen as different early user groups (or early adopters) may indicate different preferred infrastructure roll-out strategies.

Agent based modelling allows us to model these complex interactions and thus create the S-curve "from the bottom up". A simulation model with both fuel stations and consumers is constructed to measure hydrogen diffusion over time. Eight initial refuelling infrastructure build up strategies are tested, with variations in the number and location of refuelling stations offering hydrogen at the time of hydrogen car market introduction. The model is built with the Dutch passenger car market in mind, but is designed such that it can easily be adjusted to other nations or regions. The model uses available data from earlier studies and forecasts concerning the transition to a hydrogen-based transport system such as HyWays (2008). However in this research we explicitly study how the S-curve of diffusion is constructed from the underlying processes rather than use the S-curve as an input to our model. More specifically, we study the impact of different initial infrastructure development strategies on the shape of the S-curve by modelling different social interaction processes. Cantono and Silverberg (2008) also consider the role of social processes in relation to the innovation diffusion curve and illustrate that agent based modelling can provide useful insights for policymakers. In this paper we focus explicitly on the possible initial infrastructure strategies. This aspect of the transition is considered especially important in the Netherlands since besides the high cost associated with infrastructure investment the Netherlands do not have a domestic car industry so that policy measures will most likely focus on infrastructure and demand side issues. Increased insights in the relation between infrastructure development strategies and hydrogen vehicle diffusion are thus necessary to further manage the transition to sustainable mobility.

The paper will proceed as follows. Section 2 discusses the theory on the diffusion of innovations. Section 3 then relates this theoretical framework to the existing knowledge regarding the adoption and diffusion of (alternative fuel) vehicles in general and hydrogen vehicles in particular. The model is then described in Section 4 together. Section 5 continues with a benchmark diffusion pattern based on existing scenarios. A description and analysis of our model results is then given in Section 6 followed by conclusions and recommendations for infrastructure developers in Section 7.

2 Theoretical framework: the diffusion of innovations

We follow the model of Rogers (2003) to model the adoption decision of consumers. Rogers states that the diffusion of innovations is mainly determined by the attributes of the innovation and by how these attributes are valued by potential adopters. More specifically, potential adopters base their decision whether or not to adopt an innovation on five perceived innovation attributes: relative advantage, compatibility, complexity, trialability and observability. Relative advantage is the perceived added value an innovation brings as compared to the current (incumbent) technology. It is positively related to the adoption rate. Compatibility is the degree to which an innovation fits to past experiences and existing values and needs. The more compatible an innovation is perceived to be, the higher is its adoption rate. Complexity addresses the difficulty of understanding an innovation. If an innovation is perceived as more complex, it is less likely to be adopted. The trialability is the extent to which an innovation is easily experimented with prior to definitive adoption, and is positively related to the adoption rate. Finally, observability concerns the visibility of an innovation when in use. Innovations that are highly visible are more likely to have a high adoption rate (Rogers, 2003).

The innovation attributes listed above are thus not measured objectively, but as perceived by potential adopters. These perceptions are heterogeneous throughout the population: individual adopters all have their own specific selection criteria on which they decide to accept or reject an innovation. Rogers identified five adopter innovativeness categories, ranking from high to low innovativeness: innovators, early adopters, early majority, late majority and laggards. Rogers suggests the following group sizes for the different adopter categories (Rogers, 2003, p. 281): 2.5% innovators, 13.5% early adopters, 34% early majority, 34% late majority and 16% laggards. As a general rule, more innovative adopters are relatively earlier in adopting new products and ideas than less innovative adopters. That is, innovators and early adopters play an important role in the initial diffusion of a technology but for widespread diffusion it is also important that the product appeals to consumers that belong to the early and late majority. Initial diffusion is thus slow when there are only a few adopters, the innovators. As more and more consumers learn about the innovation and decide to adopt, the S-shaped curve of diffusion takes off.

Two important processes influence the perceived innovation attributes by consumers: social learning and technological learning. Social learning in this case refers to the process in which consumers learn about the innovation from (observing) other consumers. Technological learning refers to the increasing returns to adoption that technologies are able to realize with increased diffusion (Arrow 1962, Arthur 1989). Technological learning is often represented by a progress ratio (PR) that can be defined as the fraction to which the costs are reduced for each doubling in the number of adopters (Junginger 2005).

Social learning is the process where consumers learn about the technology by observing the adoption decisions of other consumers (e.g., Ellison and Fudenberg 1993). The size and shape of the resulting diffusion curve depend not only on technological learning but also on the way this process of social learning unfolds. That is, it depends on the structure of the social network between consumers. Different types of social network structures are distinguished within the literature. A local network is a network where consumers only exchange information with their immediate neighbours, whereas in a complete network information concerning the innovation is available to all consumers. Finally, in a small world network (Watts and Strogatz, 1998) consumers mostly look to their immediate neighbours for information also have some links to consumers outside their immediate neighbourhood. Many real world networks exhibit small world properties (Watts 2003).

In summary, the adoption decision of a consumer depends on the innovativeness of the consumer and the perceived attributes of the innovation. The way innovation attributes are perceived by different consumers over time depends on social and technological learning processes. The next section describes how this model was applied to the case of hydrogen infrastructure development.

3 The diffusion of hydrogen vehicles

When considering hydrogen infrastructure development two types of adopters are of importance. The first adopter group consists of the end consumers that have to decide whether or not to purchase a hydrogen vehicle. The second group consists of the refuelling stations that have to decide whether or not to adopt hydrogen, i.e. add hydrogen to their product range. In this paper we assume some fuel stations will initially add hydrogen to their product range while the rest of the fuel stations will base their adoption decision on the number of hydrogen vehicles in their vicinity. Below we will discuss the model for hydrogen vehicle adoption by consumers in more detail by discussing the perceived innovation attributes relative advantage, compatibility, complexity, trialability and observability in the case of hydrogen vehicles as described in the literature.

Relative advantage is determined by the advantage of buying a hydrogen car as opposed to a conventional car. Past research shows that purchase price, fuel costs and refuelling range between stops are the three most important car properties taken into consideration in car buying decisions (Bunch et al., 1993; O'Garra et al., 2005). Fuel cost and refuelling range are assumed to be comparable to conventional cars once hydrogen cars become available to consumers (HyWays 2008). However, existing estimates assume an initially high price for hydrogen cars compared to conventional cars, which drops as more hydrogen cars are produced, due to learning effects in technology development (HyWays, 2008; Schwoon, 2006). These dynamics of the hydrogen car purchase price and the car price consumers are willing to pay is modelled similar to Cantono and Silverberg (2008). An initial hydrogen car price is taken, together with a standard learning curve, under the assumption that the more people adopt the new technology, the lower the production costs are due to large-scale production possibilities and the lower the purchase prices will be. Alberth (2008) shows that experience (cumulative production) is a more effective explanatory variable than time for forecasting technology costs.

Each consumer in our model has a personal reservation price, which is the maximum price she is willing to pay when buying a car. The consumer will thus not consider buying a hydrogen vehicle when the current hydrogen car price p_t is above her reservation price. Current hydrogen car price p_t at a given time t is modelled as:

$$p_t = p_0 \left(\frac{N_0}{N_{t-1}} \right)^{\alpha},$$

The initial price p_0 decreases as the cumulative number of hydrogen car adopters N_{t-1} increases in relation to the initial number of adopters N_0. The speed of the price decrease is determined by the learning ability α. This learning ability α is determined by the Progress Ratio (PR):

$$PR = 2^{-\alpha}$$

This progress ratio is defined as the fraction to which the costs are reduced for each doubling in the number of adopters.

Compatibility is the degree to which hydrogen car adoption requires consumers to alter their behaviour in using a car. Possible areas of incompatibility described in the literature on alternative fuel vehicle adoption are (1) daily use, (2) service and repair availability and (3) hydrogen fuel availability (Flynn, 2002; HyWays, 2008; Melaina, 2003; Zhao and Melaina, 2006). In daily use, hydrogen cars are expected to be very similar to conventional fuel cars, apart from minor changes resulting from differences in engine design (no gear change needed) and refuelling operation (different fuel dispenser). These changes are in this research not expected to be of major importance in hydrogen car adoption decisions. Service and repair availability is a possible compatibility issue, as car mechanics have been trained specifically to service vehicles with low-pressure liquid fuel tanks and internal combustion engines (P. C. Flynn, 2002). Both of these components are possibly replaced by other technologies in hydrogen cars (HyWays, 2008). The main potential compatibility issue for hydrogen car adoption however is the availability of refuelling infrastructure. Refuelling availability is found to be an important decision factor for car buyers (Bunch et al., 1993; O'Garra et al., 2005). Most car owners currently expect to be able to refuel their car at every refuelling station encountered during travelling (P. C. Flynn, 2002). A limited availability of hydrogen fuel stations requires car drivers to more accurately plan their trip routes than with a conventional car, which decreases hydrogen car compatibility. Furthermore, if no fuel station would be available at all within reasonable distance from a consumer’s home, it is safe to say that hydrogen car adoption is not an option, as refuelling behaviour is concentrated around people’s home and work locations (Kitamura and Sperling, 1987). Compatibility is expected to increase with increased hydrogen fuel availability.

Complexity Although in terms of operation hydrogen vehicles are very similar to conventional cars. There are some concerns about the perceived safety of hydrogen technology. In particular, hydrogen storage and its flammability are issues that are currently not widely approved to be as safe as for conventional car fuels. These concerns are expected to be largely taken away once hydrogen technology becomes more familiar to potential adopters (R. Flynn, Bellaby, and Ricci, 2006). This familiarity increases as more people in a potential adopter's social environment have already adopted hydrogen cars. Perceived complexity is expected to decrease with the number of adopter's in a consumer's social network.

Trialability is the ability to try out a hydrogen car before buying it. Test driving is common practice at most car dealers, and will thus be possible immediately after hydrogen cars become commercially available. This being said, trying out a hydrogen car is expected to become easier as more people in a potential adopter's social environment already drive in hydrogen cars. Trialability is thus expected to be positively related to previous adoption in a consumer's social environment.

Observability is both high and low for hydrogen cars. In exterior design, hydrogen cars do not differ from conventional fuel cars. While this is positively related to compatibility, this implicates a low observability in terms of visibility of the physical product to others. In a more social sense, a high observability is expected, as cars are a topic people talk about to others within their social network. Observability is therefore expected to increase with more previous adoption in a consumer's social environment.

Based on the literature review described above we thus find that relative advantage is mainly determined by the hydrogen car purchase price (subject to technological learning) in relation to the purchase price of conventional cars and the reservation price of the consumer. Compatibility is mainly determined by hydrogen fuel availability in the neighbourhood of the consumer. Complexity, trialability and observability are determined through social learning processes.

4 Model description

This section describes the simulation model that was created based on the theoretical model described above. In an agent-based simulation model, decision behaviour is simulated by creating populations of agents (Epstein and Axtell 1996; Alkemade and Castaldi 2005; Schwarz and Ernst, in press). An agent-based model consists of agents, rules and environments. In our model the agents are consumers and refuelling stations. The rules are the mechanisms by which the consumers and fuel stations decide whether or not to adopt hydrogen. The environment in which the agents reside is a simplified representation of the Netherlands. Below we will first discuss each model element in more detail and then we will discuss the different initial infrastructure development strategies that were simulated.

4.1 Model elements

The environment is a simplified square grid version of the Netherlands (Figure 1). We distinguish between a densely populated urban area and a rural area with a lower population density. The urban area is represented by an area in the mid-west of the simulation world, where a consumer is placed on every cell. In the rural area, consumers are placed on every other cell using a checkerboard pattern. Total grid size is 400 by 400 cells (of which 200 by 200 cells for the urban area), giving a total consumer population of 100,000 (40% urban, 60% rural).

Apart from consumers, refuelling stations are also located on the grid. With roughly 4,000 fuel stations (Bovag/Rai, 2007) and 8 million passenger cars (CBS, 2003), the Dutch station-to-car ratio is around 1 : 2,000. This ratio is used in the simulation model, resulting in a total of 50 fuel stations on 100,000 consumers. Fuel station location assignment is in line with the population distribution, meaning that

40% of the fuel stations are located in the urban area and 60% percent in the rural area. Fuel station locations are randomly assigned given these constraints.

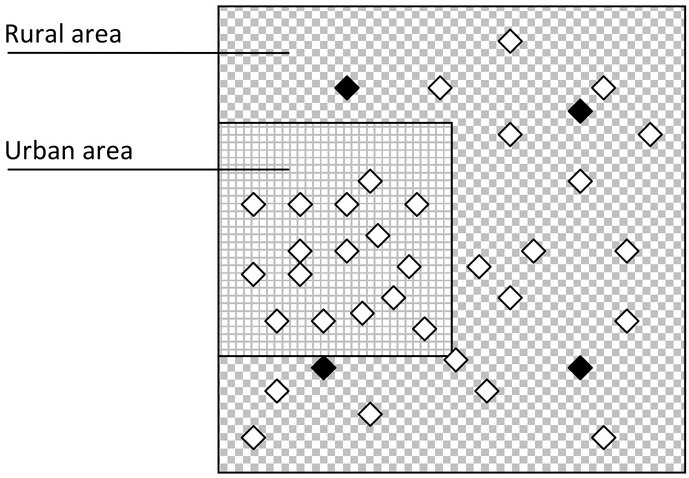

Figure 1. Schematic representation of the model environment with consumers (white squares) and fuel stations (diamonds). This example includes 4 hydrogen stations (shown in black).

Agents - consumers. Consumers differ with respect to their reservation price and their innovativeness and are randomly assigned to available grid positions with a maximum of 1 consumer per grid cell. As described above, the decision of a consumer to adopt a hydrogen vehicle depends on (a) her level of innovativeness, (b) her reservation price and on the perceived attributes of hydrogen vehicle technology determined by (c) technological learning, (d) social learning processes, and (e) fuel availability:

a. Innovativeness. Five adopter categories are distinguished. Following Rogers adopter innovativeness is drawn from a normal population distribution which leads to the following categories (Rogers, 2003, p. 281): 2.5% innovators (I = 5), 13.5% early adopters (I = 4), 34% early majority (I = 3), 34% late majority (I = 2) and 16% laggards (I = 1).

b. Reservation price. As described above we use current hydrogen vehicle price as an indicator for the *relative advantage* of hydrogen cars over conventional cars. At the time of market introduction, we assume that only a very small part of the consumer population is willing to pay the initial hydrogen car price. The initial hydrogen car price p_0 is given in relation to conventional car prices. For conventional cars, an average used car price of 1 is assumed and an average new car price of 2. Hydrogen cars are assumed to be initially available only in the high-end segment of the new car market. The initial hydrogen car price is expected to be 4, which is twice the new conventional car price and thus four times the average used car purchase price. These estimates are based on Dutch car statistics (Bovag/Rai, 2007; CBS, 2003) in combination with future hydrogen car production price estimates (HyWays, 2008). Given that used car sales are about 4 times larger than new car sales (CBS, 2003), the overall average conventional car purchase price in our model is 1.2. The mean of the reservation price distribution in the simulation model should correspond to this value. Additional requirements are that about 80 percent of people are willing to pay a car price around 1 (average used car price), and about 20 percent are willing to pay a price closer to 2 (average new car price). A lognormal distribution $\theta \approx \exp N(\mu,\sigma)$ with μ = 0 and σ = 0.7 for the consumer reservation price meets these requirements sufficiently.

c. Technological learning. With respect to the effect of technological learning on price, HyWays (2008) estimates progress rate values between 0.98 in the modest learning and 0.80 in the fast learning scenario, also depending on the technology in consideration (hydrogen tank, fuel cell system). IEA (2005) uses progress rate values for fuel cell vehicles between 0.78 in the optimistic and 0.85 the pessimistic case. Both HyWays and IEA only consider the new car production price and do not take the used car market into account. Our simulation model does consider used cars as used car sales are expected to become a major part of sales within the scope of our simulation. Used cars are on average less expensive than new cars which accelerates the decrease in the minimum price at which hydrogen cars are available to consumers in relation to the HyWays estimates. This is implemented in the simulation model by setting the default value of progress rate to 0.80, which is on the high end of the HyWays range.

d. Social learning. Finally social learning is used as an indicator for perceived complexity, trialability and observability. We investigate three types of social network structures: global, local and small world. In the local social network structure, each consumer is connected to her eight nearest neighbours on the grid (see Figure 2 for an example). The small world network is similar to the local structure, but with 10% of all the nearest neighbour links (calculated over the population as a whole) replaced by a link to a random neighbour anywhere on the grid. Finally, in the global network structure, each consumer is connected to all other consumers on the grid and thus not geographically limited in her social behaviour.

   An individual consumer's social network influence depends on her personal innovativeness. In correspondence to the theoretical framework, the simulation model assumes this social network influence to increase with a decrease of innovativeness. This is implemented by giving each consumer a minimum neighbour adoption threshold, based on the adopter group she is in. A higher threshold value means more neighbours must have already adopted hydrogen before the consumer is willing to adopt hydrogen herself. The threshold value for each adopter group is calculated using the adopter groups which are more innovative. Each consumer in an adopter group with innovativeness *I* is assigned a threshold value somewhere between a low and high end boundary. The low end is formed by the fraction of consumers with minimum innovativeness *I* + 2, the high end is formed by the fraction of consumers with minimum innovativeness *I* + 1. Innovators thus all have a threshold value of 0, early adopters in the range of 0 - 2.5%, early majority 2.5 - 16%, late majority 16 - 50% and laggards 50 - 84%.

   This is illustrated by an example for the using the centre-right consumer in Figure 2. Suppose this consumer currently has a conventional car and has to make an adoption decision regarding a hydrogen vehicle. She has eight neighbours, of which three have already adopted a hydrogen car. This equals a 37.5 % neighbour adoption rate. If this consumer would be of type innovator, early adopter or early majority, she would adopt a hydrogen car based on social network influences, as her personal threshold value (which lies between 0 and 16%) is always below the actual neighbour adoption rate. Would she be of type late majority, however, chances are that her personal threshold value (which lies between 16 and 50%) is above the current neighbour adoption, leading to rejection of the hydrogen car. Would she be a laggard, she would always reject a hydrogen car, as her personal threshold value (50 to 84%) is never below the actual neighbour adoption.

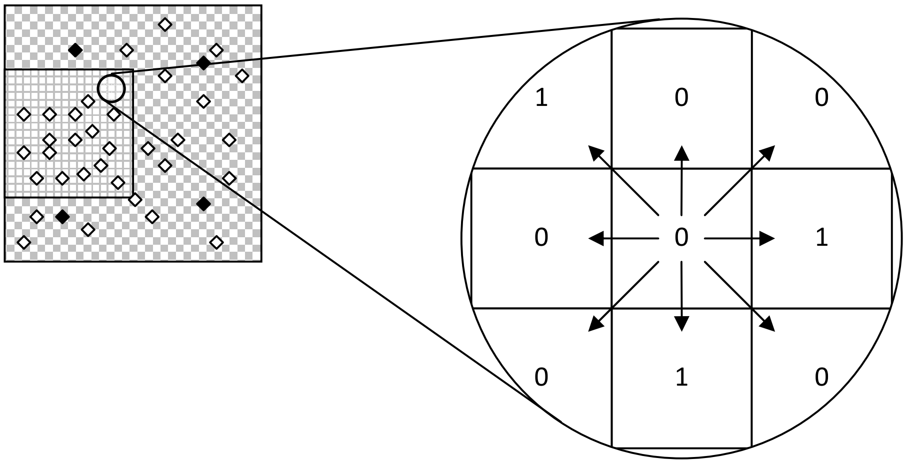

Figure 2. Example of local social network scope for a single consumer in the urban area. The values shown represent each consumer's car type; 0 = conventional, 1 = hydrogen.

e. Fuel availability. As an indicator for perceived compatibility we use fuel availability. A consumer checks hydrogen availability at the nearest 3 refuelling stations from her own grid position (which is considered to be home). If at least one of those stations offers hydrogen, the consumer considers the technology compatible.

Agents - refuelling stations. Each fuel station offers only conventional fuels or conventional fuels plus hydrogen. In making the adoption decision, the refuelling station considers the percentage of consumers within its customer base that have adopted a hydrogen vehicle. When this percentage of adopters exceeds the private threshold value of the refuelling station, the station adds hydrogen to its product range. A lower threshold value implies a more positive attitude towards hydrogen; a higher value implies more risk-averse investment behaviour. Threshold values are assigned randomly between 0 and 20 percent of the station's customer base[1]. Once a fuel station adopts hydrogen, this is considered to be a definitive choice for the rest of the simulation run. This represents the irreversibility and inflexibility of the initial investment costs in installing hydrogen refuelling facilities (Gómez-Ibáñez 2003; Alkemade et al. In press).

Rules - modelling diffusion patterns. In order to get insight in the effects of initial infrastructure strategies on diffusion patterns we run the model described above for a number of 200 time steps, where a time step corresponds to 1 year. This large timeframe is necessary as transitions are generally considered to take decades (Kemp and Rotmans 2004; Elzen et al. 2005). In each time step of the model refuelling stations decide whether or not to add hydrogen to their product mix. For consumers, literature suggests a range of possible average replacement rates. According to Dutch car sale statistics

[1] LPG has never reached a market share above 20% in the Netherlands and yet is widely available at refuelling stations.

(Bovag/Rai, 2007), each year 2.5 million vehicles are sold (new and used), on a total of 7.5 million vehicles. This implies an average car replacement rate of once in three years. On the other end, Schwoon (2006) used once in 8 years for the German situation in his hydrogen adoption model, but only considers new car sales. In this simulation model, an average car replacement rate of once every five years is assumed. This is implemented by giving each consumer a yearly chance of 20 percent to replace her car. Some consumers will buy a car two years in a row, while others might not buy one in ten years time. In this way, individual car replacement behaviour differences are simulated.

4.2 Initial infrastructure strategies

The purpose of the simulation is to test the effects of different initial refuelling infrastructure strategies on the diffusion of hydrogen vehicles. The two main variables in a car refuelling infrastructure are the initial number of stations available and the locations where these initial stations are positioned (Melaina 2003). As for locations, literature suggests two station types to be most suitable as early hydrogen fuel suppliers: urban fuel stations to serve a large number of cars in a small geographic area, and highway stations to facilitate hydrogen refuelling on long-distance trips (HyWays, 2008; Melaina, 2003, Mans et al. 2007). This is implemented in the simulation model by testing two station placement strategies: 'urban', with a focus on population-dense urban areas only, and 'nationwide', spreading the stations over the grid as a whole. The initial hydrogen stations are spread as evenly as possible over the area in which they are placed. This is implemented by dividing the grid into one or more smaller sub-squares, and selecting the fuel station nearest to the centre of each sub-square. See Figure 3 for examples of initial hydrogen station placement.

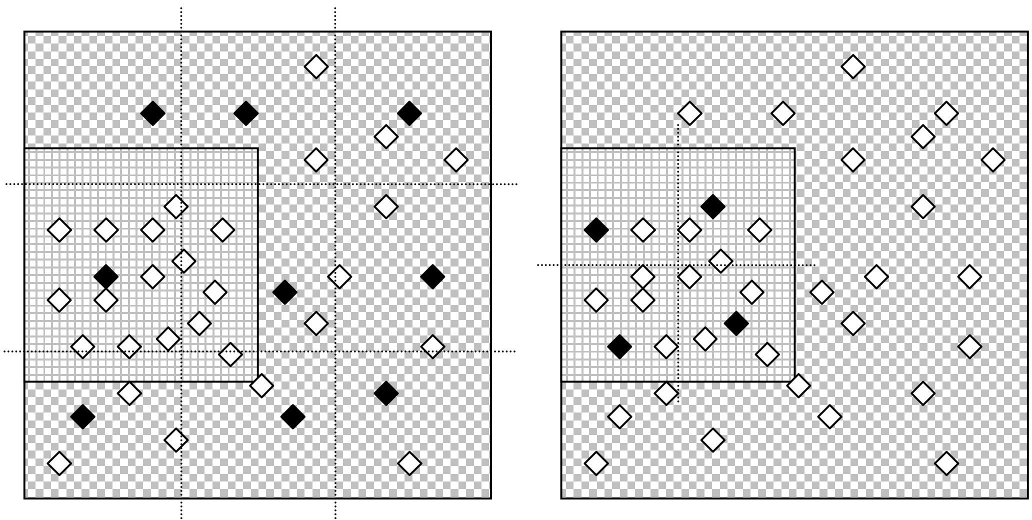

Figure 3. Two examples of initial hydrogen fuel placement onto the grid. Left: 9 initial stations placed with a nationwide infrastructure development strategy. Right: placement of 4 initial stations using an urban strategy.

Concerning the size of the initial fuel infrastructure, literature suggests a minimum of 5 to 20 percent of the fuel stations is needed for widespread hydrogen adoption (HyWays, 2008; Melaina, 2003; Sperling and Kitamura, 1986). Hydrogen diffusion patterns are simulated for a number of 1, 4, 9 and 16 initial fuel stations. This equals 2%, 8%, 18% and 32% hydrogen refuelling availability at the start of the simulation (for 50 refuelling stations). Initial availability of 8% and 18% values are within the literature estimates, while 2% and 32% are below and above these boundaries respectively, allowing us to compare simulation model behaviour to estimates from the literature.

On the consumer side, the number of initial adopters N_o is set to 5 in the simulation model. This value is based on the starting point used in HyWays (2008) from which learning curves can be applied, which is 10,000 cars. As there are currently about 200 million cars in the EU (Eurostat, 2007), this corresponds to 0.005 % of all cars. With 100,000 consumers, this amounts to 5 initial hydrogen car adopters. For further reference, the main simulation model parameter values are listed in Table 1.

Table 1. Overview of main parameters in the simulation model.

Description	Value(s)
Nearest fuel stations considered by consumer for fuel availability	3
Fuel station minimum consumer adoption threshold	0 - 20%
Average yearly consumer car replacement rate	0.20
Initial number of hydrogen car adopters (N_0)	5
Initial hydrogen car market price/conventional car price (p_0)	4
Learning ability (α)	0.30[2]
Initial percentage of fuel stations offering hydrogen	2,8,18,32%
Initial geographical spread of hydrogen fuel stations	urban,wide

5 The benchmark model

In order to compare our simulation results to hydrogen diffusion scenarios described in the literature, we first construct a benchmark S-curve. We model this S-curve using the substitution model of technological change described by Fisher and Pry (1971) where the fraction substituted f (in our case the hydrogen vehicle fleet penetration rate) is calculated by:

$$f = \frac{1}{2}[1 + tanh\, \beta(t - t_h)]$$

Where β is half the annual fractional growth in the early years of diffusion and where t_h is the time at which the diffusion has reached 50% (Fisher and Pry, 1971). HyWays (2008) distinguishes between four scenarios for hydrogen vehicle diffusion that differ with respect to learning (modest learning, fast learning) and policy support (high, very high). Very high policy support scenarios are scenarios were the government stimulates deployment and invests in R&D to increase learning if necessary. Based on the scenarios described in the HyWays roadmap (HyWays, 2008, Figure 2.3) we have created the benchmark curves shown in Figure 4. Table 2 gives an overview of the parameter settings that were used. As we use

[2] Corresponding to a progress rate of 80%

a value for the progress rate that corresponds to the fast learning scenarios in the HyWays roadmap we will compare our simulation results to the S-curves for fast learning.

Table 2. S-curve parameter estimates for the different HyWays scenarios

HyWays Scenario	B	t_h
Very high policy support, fast learning	0.075	28
High policy support, fast learning	0.07	34
High policy support, modest learning	0.04	45
Modest policy support, modest learning	0.06	45

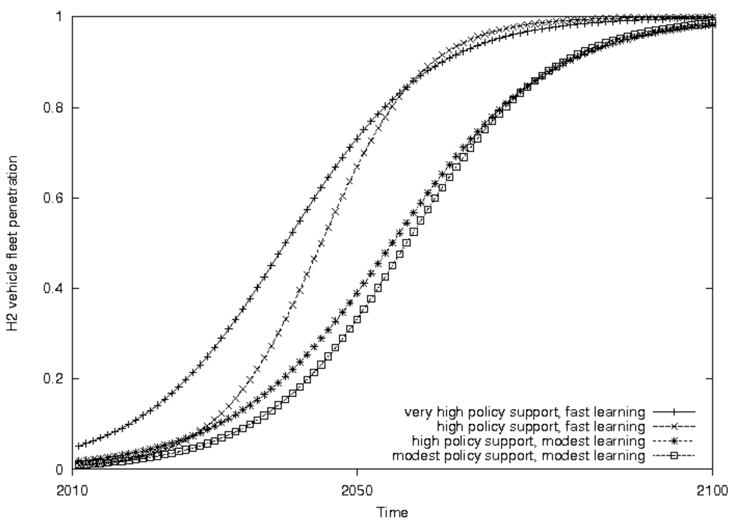

Figure 4. Benchmark curves based on HyWays scenarios.

6 Simulation of hydrogen vehicle diffusion patterns

This section discusses the result of simulation outlined above. We compare our results to the benchmark patterns derived from the hydrogen roadmap. The strategies for initial infrastructure development differ with respect to the placement (urban or nationwide) and the number of initial refuelling stations (2%, 8%, 18%, and 32%) offering hydrogen. Furthermore we analyze the effect of the structure of the social network among consumers on these diffusion patterns. Figure 5 - Figure 8 show the results from our simulations for the 8 and 18% strategies as they are within the range of commonly recommended values. All results shown are averaged over 10 simulation runs.

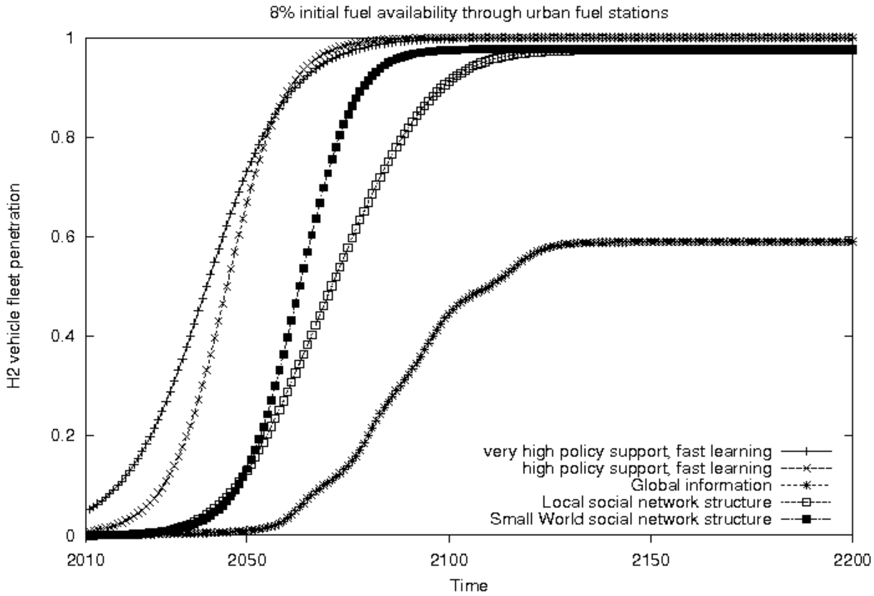

Figure 5. Simulation results for 8% initial fuel availability through urban fuel stations.

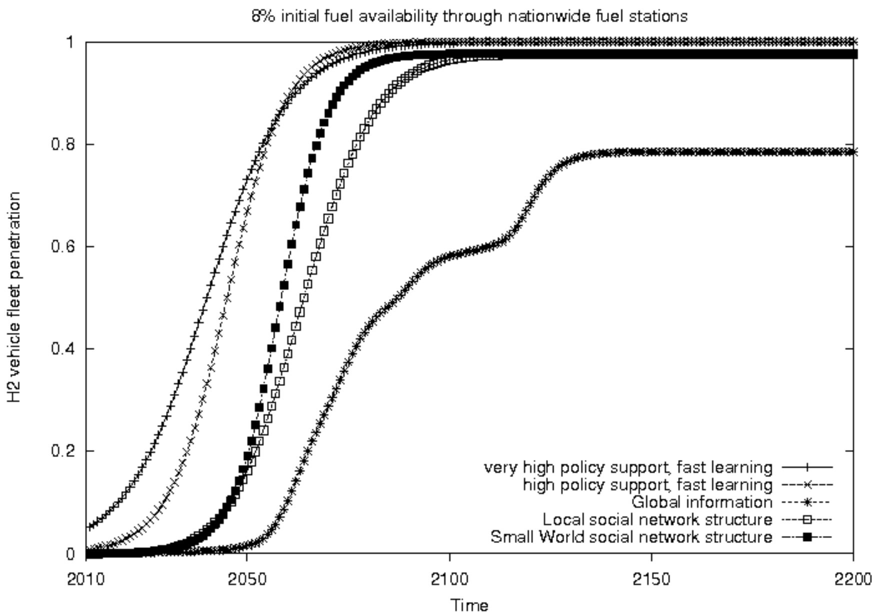

Figure 6. Simulation results for 8% initial fuel availability through nationwide fuel stations.

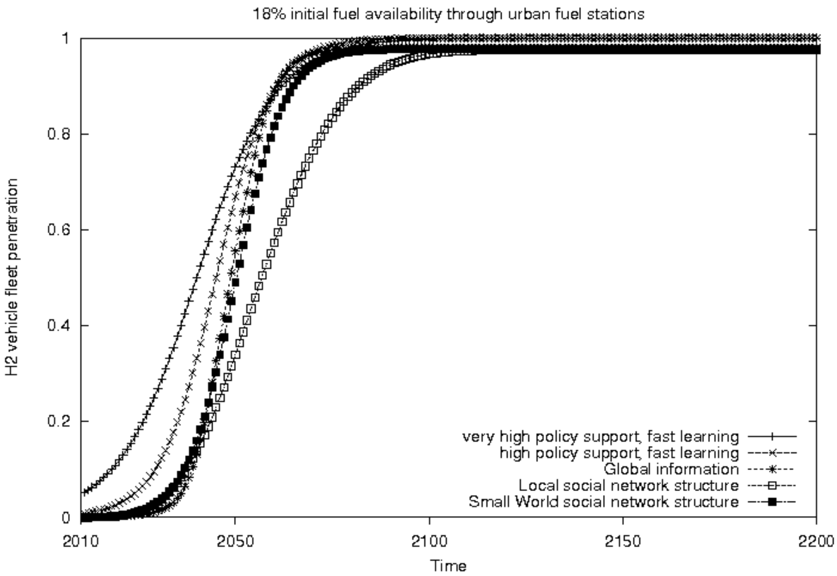

Figure 7. Simulation results for 18% initial fuel availability through urban fuel stations.

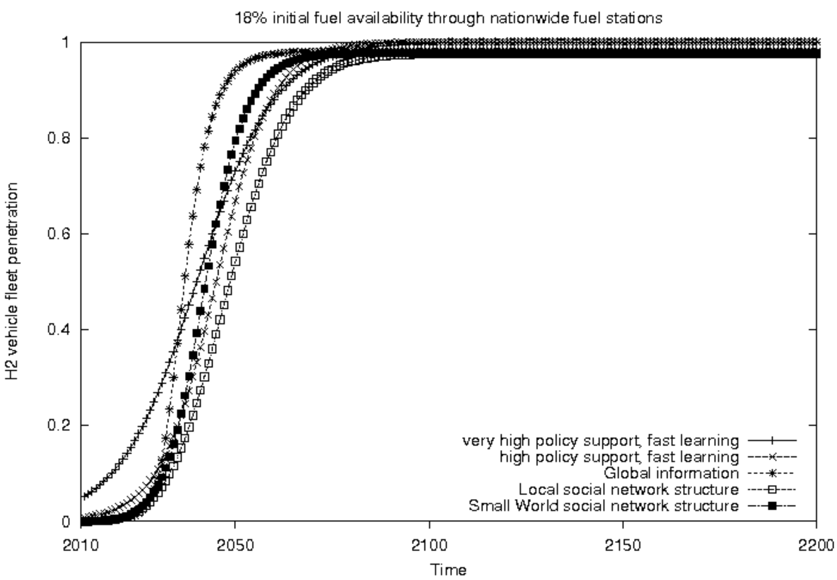

Figure 8. Simulation results for 18% initial fuel availability through nationwide fuel stations.

When we consider the results in Figure 5 - Figure 8, we notice that simulated patterns only match the speed of diffusion of the benchmark pattern when a nationwide initial infrastructure build up strategy is chosen with 18% of refuelling stations offering hydrogen. For the other strategies tested, the main difference between simulation results and the benchmark curves, is the time it takes to reach a critical mass for further self-sustaining diffusion. Once a critical mass has been reached, the diffusion speed (as determined by the steepness of the curve) is similar to the benchmark scenarios for both 8 and 18% hydrogen availability, with the exception of 8% fuel availability with global information.

As for the initial location of hydrogen fuel stations, for both 8 and 18% fuel availability we see that the nationwide deployment strategy leads to a higher rate of diffusion than the urban strategy, regardless of the social network structure (global information, local or small world). This indicates that pursuing maximum geographical coverage with initial stations is more effective as a deployment strategy than focussing on densely populated areas only to try and to reach a maximum number of consumers with each individual station.

With respect to the social network among consumers we see that a small world network generally corresponds to higher diffusion rates than other network structures. An exception is the global information case which performs very well under the conditions of 18% fuel availability in combination with a nationwide deployment strategy (Figure 8). The global information curve however is not smooth and has a lower diffusion after 200 time steps in the case of 8% availability strategies (Figure 5, Figure 6). This indicates that widespread diffusion of hydrogen cars was not been reached in all the individual simulation runs. The local and small world networks show more robust results for lower initial fuel availability.

Below we elaborate on the sensitivity of model results to changes in the parameter values.

Sensitivity analysis of results

In all cases, a nationwide spread of initial hydrogen stations leads to more rapid hydrogen car diffusion than urban focus. At 2 percent initial h2 availability, only local and small world networks show any significant hydrogen car diffusion, albeit in only a small part of the simulation runs. From 18 percent up, all approaches lead to widespread diffusion in all runs.

At lower initial hydrogen fuel availability (2 and 8 percent), local and small world networks show higher diffusion rates than the global network. At higher initial hydrogen fuel availability (18% nationwide and 32 percent both urban and nationwide), the global network shows more rapid diffusion than local and small world. At 8 percent, local and small world networks already produce smooth S-curves, while global network diffusion results vary depending on random initialization factors.

In our base model parameter settings used for the simulation results, each consumer considers the nearest three fuel stations for hydrogen fuel availability ($s = 3$). We tested sensitivity for changes in the value of s ($s = 2$, $s = 4$ and $s = 5$). The results of these tests show that larger s values lead to a more rapid hydrogen car adoption, but only the diffusion take-off speed is affected and not the ultimate diffusion rate reached.

Where changes in the value for s only affect the diffusion speed, changes in learning ability α affect both the diffusion speed and whether or not any widespread diffusion is reached at all. For our main simulation results, a value of $\alpha = 0.3$ was used. Sensitivity tests for α values 0.1, 0.2 and 0.4 show that at $\alpha = 0.1$, practically no hydrogen car diffusion takes places, not even with 32% hydrogen fuel availability. For $\alpha = 0.2$, only the 32% availability strategies show any clearly S-shaped diffusion curves for any of the social network structures. On the other end, at a high level of $\alpha = 0.4$, even some 2% fuel availability simulation runs trigger widespread hydrogen diffusion (but only after a long period of time). The latter is not the case for the base settings with $\alpha = 0.3$. Results are thus very sensitive to learning.

7 Conclusions and policy recommendations

Within the Dutch transition policy framework, the transition to hydrogen-based transport is seen as a promising option towards a sustainable transport system. This transition requires the build-up of a hydrogen infrastructure, as a certain level of refuelling infrastructure is necessary before (even the most innovative or environmentally friendly) consumers will substitute their conventional car for a hydrogen vehicle. However, the build-up of infrastructure is costly and irreversible and it is therefore important for policymakers to gain insight in the minimally required levels of initial infrastructure that will still set off the transition. In this paper we have presented a diffusion model for the analysis of the effects of different strategies for hydrogen infrastructure development on hydrogen vehicle fleet penetration. Within the simulation model, diffusion patterns for hydrogen vehicles were created through the interactions of consumers, refuelling stations and technological learning.

First, model results indicate that in general when social network effects are taken into account diffusion is slower than diffusion in the benchmark patterns based on the HyWays hydrogen roadmap. That is, it takes longer for the system to reach the take-off point at which diffusion becomes self-sustaining. Furthermore, model results indicate that when taking into account these social network effects, quite a large number of initial refuelling stations (18%) is necessary to reach the benchmark diffusion rates.

Second, model results indicate that a nationwide initial infrastructure development strategy is preferable to an urban strategy. In addition simulation results are very sensitive to learning. High progress rates are necessary to achieve diffusion comparable to the benchmark patterns. These results suggest that pursuing maximum geographical coverage with initial stations is more effective as a deployment strategy than focussing on densely populated areas only to try and to reach a maximum number of consumers with each individual station. Furthermore, it might thus be sensible to pursue infrastructure deployment strategies that focus on learning instead of diffusion to reduce the price of hydrogen vehicle technology.

Third, simulation results indicate that the structure of the social network among consumers does influence the resulting diffusion patterns. A small world social network structure seems most favourable to fast diffusion. Although many real world social networks already exhibit small world properties, these properties can become an active part of transition management strategies through the use of change agents. Social network effects should be further investigated and taken into account in creating hydrogen technology deployment scenarios and policies.

In this paper we thus focused explicitly on possible initial strategies for hydrogen infrastructure development. This aspect of the transition is considered especially important in the Netherlands, since besides the high cost associated with infrastructure investment, the Netherlands do not have a domestic car industry, which means policy measures will most likely focus on infrastructure and demand side issues. This paper illustrates the necessity to take the social processes that play a role in the adoption and diffusion of new technologies into account when designing such policy measures.

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