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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. One aspect of such transition processes that is emphasized in transition management is learning about user behaviour and preferences. However, while earlier research on sustainable mobility acknowledges the importance of refuelling infrastructure, the question of how to unroll such an infrastructure and the role of user practices and user behaviour largely remains unanswered. In this paper we present an agent-based model to study the process of development from niche to market for hydrogen vehicles. We thereby focus on the role of users in this process and support our model by empirical data. Within this model the effects of different strategies for hydrogen infrastructure development on hydrogen vehicle fleet penetration are studied. More specifically, diffusion patterns for hydrogen vehicles are created through the interactions of consumers, refuelling stations and technological learning. The main result is that social network effects do influence the technological trajectory of hydrogen vehicles and thus should be taken into account by infrastructure developers and policymakers.

1. Introduction

While sustainable technologies are necessary to achieve the goal of a more sustainable society, market forces alone cannot be relied upon to ensure the diffusion of such technologies. This especially holds for technologies that require a change in infrastructure due to the associated high and irreversible investments. In the Netherlands a transition policy framework is in place to guide the transition to a more sustainable society based on the model of transition management [1,2]. This paper focuses on the transition to sustainable mobility where hydrogen-based transport is seen as a promising option[1] [3].

One of the challenges for transition management is to connect the short term steps of policy to the long term goals of transitions [1]. Transition management addresses this challenge through the stimulation of strategic experiments with promising technologies. This approach has led to an increased understanding of the behavioural and institutional changes that are necessary for a sustainable transport system [4]. A recent analysis of the Dutch energy transition [5] indicated that it is difficult to move from a (protected) technological niche to the growth phase of development [6] and revealed a need among stakeholders to increase the scale of experimentation in order to stimulate further technological learning and learning about user needs. However, as the build of costly hydrogen infrastructure is required for such large scale experiments insight is necessary regarding the aspects of this technological transition that determine the patterns of hydrogen vehicle diffusion and that need to be addressed in future strategic experiments.

One aspect of such transition processes that is emphasized in transition management is learning about user behaviour and preferences [2,3]. However, while earlier research on sustainable mobility based on technology roadmaps and forecasting

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[1] www.energietransitie.nl.

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methods [7–10] acknowledges the importance of refuelling infrastructure, the question of how to unroll such an infrastructure and the role of user practices and user behaviour 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 and move beyond the technological niche? Previous research indicates that these are questions that need to be considered before making large investments in a refuelling infrastructure and thus are useful inputs for transition policy. In this paper we therefore aim to gain insight in to the process of development from niche to market for hydrogen vehicles and in particular in the role of users in this process. The main research question of the paper is:

> *What is the relation between initial refuelling infrastructure availability and the expected diffusion pattern of hydrogen vehicles and how are these patterns influenced by different forms of user behaviour?*

The transition to a hydrogen-based transport system requires the buildup 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 [7]. This is often referred to as the chicken-and-egg problem of infrastructure development. However, the buildup 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.

In earlier research refuelling availability is found to be an important decision factor for car buyers [11,12], 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 [13–15]. 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. We thereby focus on light duty vehicles for personal mobility. The diffusion of (successful) innovations often follows an S-shaped curve [16]. 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 [17]. 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 [10]. 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 [15] 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. 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 [16] 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