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Changing minds about electric cars: An empirically grounded agent-based modeling approach

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ABSTRACT

The diffusion of electric vehicles (EVs) is considered an effective policy strategy to meet greenhouse gas reduction targets. For large-scale adoption, however, demand-side oriented policy measures are required, based on consumers' transport needs, values and social norms. We introduce an empirically grounded, spatially explicit, agent-based model, *InnoMind* (*Inno*vation diffusion driven by changing *Minds*), to simulate the effects of policy interventions and social influence on consumers' transport mode preferences. The agents in this model represent individual consumers. They are calibrated based on empirically derived attributes and characteristics of survey respondents. We model agent decision-making with artificial neural networks that account for the role of emotions in information processing. We present simulations of 4 scenarios for the diffusion of EVs in the city of Berlin, Germany (3 policy scenarios and 1 base case). The results illustrate the varying effectiveness of measures in different market segments and the need for appropriate policies tailored to the heterogeneous needs of different travelers. Moreover, the simulations suggest that introducing an exclusive zone for EVs in the city would accelerate the early-phase diffusion of EVs more effectively than financial incentives only.

1 . Introduction

Electric vehicles (EVs — plug-in hybrid and battery electric vehicles) are seen as a promising technology to reduce carbon emissions and achieve the transition to more sustainable transport. Comprehensive investment in research and development, e.g. in battery technology, is essential to achieve these goals, but technological development alone will not ensure the large-scale diffusion of such innovations. For successful dissemination of new technologies it is also necessary to address the demand side (e.g. Ozaki and Sevastyanova, 2011; Schuitema et al., 2013; ran et al., 2012). To this end, we have developed an agent-based model of consumer perceptions and decisions related to innovation adoption in sustainable transport.

While focused on EVs as a technological innovation, our model also helps to answer questions about broader social innovations; i.e., changes in habits and behavioral patterns related to transport. In particular, increasing the use of public transport, bicycles, and car sharing is considered by some as the more important challenge when it comes to organizing the societal transition to more sustainable transport (e.g., Graham-Rowe et al., 2011; Kemp and Rotmans, 2004; Köhler et al., 2009; Nykvist and Whitmarsh, 2008). Even more than technology adoption, large-scale changes in behavioral patterns depend on the decisions of individual consumers. Numerous studies in psychology have addressed environmental decision-making at the level of individual minds (e.g., Bamberg, 2006; Collins, 2005; Fujii, 2007; Hunecke et al., 2001; Klöckner and Blöbaum, 2010; Steg, 2005; Van der Werff et al., 2013), but these studies often neglect the complex interactions with

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broader societal development and the role of other peoples' experiences and decisions when individuals make decisions.

Agent-based models (ABMs) are considered promising tools to study multi-level interactions between individual behaviors and social dynamics (e.g., Bonabeau, 2002; Epstein and Axtell, 1996; Helbing, 2012). Phenomena at the group or societal level (e.g., innovation diffusion) are treated as emerging from multiple interactions of relatively simple behaviors or decisions at the individual level (e.g., changing attitudes). ABMs have become increasingly popular in studies of innovation diffusion in general and research on environmental innovations like alternative fuel vehicles in particular (e.g., Brown, 2013; Eppstein et al., 2011; Higgins et al., 2012; Shafiei et al., 2012; Sullivan et al., 2009; Tran, 2012a,b; Zhang et al., 2011).

This work answers recent calls for more psychologically realistic models of decision-making in ABMs of innovation and social contagion (Kiesling et al., 2011; Sobkowicz, 2009; Squazzoni et al., 2013; Sun, 2012). Previous models have formalized social contagion and innovation diffusion based on simplistic rules. Many such models are inspired by epidemiological models, in which agents adopt decisions of others simply if they exceed some previously defined threshold (e.g., Deffuant et al., 2000; Deffuant, 2006; Faber et al., 2010; Hegselmann and Krause, 2002). Some work on the incorporation of psychological more plausible rules of decision-making has been developed (e.g., Jager et al., 2000; Schwarz and Ernst, 2009; Zhang and Nuttall, 2011), mainly following the theoretical framework of the Theory of Planned Behavior (Ajzen, 1991; Fishbein and Ajzen, 2010). However, these approaches fail to consider the importance of human emotions in the diffusion process.

In an attempt to overcome some of these limitations of agent-based models of innovation diffusion, the decision and communication mechanisms implemented in our novel *InnoMind* model (for *Inno*vation diffusion driven by changing *Minds*) are based on recent advances in understanding the role of emotion in human decision-making and communication. InnoMind is a multi-agent extension of Thagard's (2006) HOTCO model (for "HOT COherence"), according to which agents make decisions by maximizing the coherence of their current beliefs and emotions. InnoMind agents are susceptible to beliefs of other agents as well as further external influences (e.g. political measures), as they can adopt new beliefs and emotions (i.e. learn). As a consequence, they may change transport mode decisions over time.

In contrast to previous simulation models of EV diffusion, which mainly have considered rational factors of adoption decisions – such as costs, time and driving range – our model accounts additionally for essential psychological factors influencing the individual intention to adopt EVs (cf. Schuitema et al., 2013). Moreover, as recommended in a recent review of EV-diffusion simulation models (Al-Alawi and Bradley, 2013), our agent-based modeling approach extends previous work by rigorously grounding simulated mental representations of agents and the parameterization of social influence in empirical work.

The contribution of the present research is thus threefold: (1) We provide a novel theoretical framework for modeling innovation diffusion based on cutting-edge cognitive science. (2) We show how rich empirical data can be integrated into such a theoretically motivated multi-agent decision model. (3) We demonstrate how this approach can inform strategic decisions related to EV diffusion, where data for classical analysis (e.g., discrete choice models) is not available yet. In particular, we evaluate the effectiveness of various policy interventions designed to enhance the acceptability of and future uptake of EVs separately for different consumer groups.

The novel ABM, which we describe in the following sections, explains how patterns of belief change and innovation diffusion in social systems emerge from psychological processes such as attitudes, values, emotions, social norms, and identity (e.g. Fishbein and Ajzen, 2010; Gigerenzer and Goldstein, 1996; Homer-Dixon et al., 2013; Kahnemann, 2011; Loewenstein et al., 2001; Mehrabian and de Wetter, 1987; Thagard and Kroon, 2006; Thagard, 2006). The model demonstrates how the current structure of mental representations, psychological needs, and social values creates path dependencies and constraints on future possibilities for social change and transport transitions. Based on state-of-the-art theorizing in cognitive science, and grounded in empirical data from focus groups, a representative survey, and a vignette experiment (Wolf et al., forthcoming-a,b), the ABM can be used to generate psychologically plausible scenarios for innovation adoption. As a case study, we have focused on the city of Berlin, one of the four regions in Germany under the federal government's "Showcase of Electric Vehicles" initiative (NPE, 2012).

The remainder of this paper is structured as follows. Section 2 deals with the model architecture. We explain mechanisms for individual decision-making based on emotional coherence (Section 2.1), for the flows of information based on homophily in social networks (Section 2.2), and for the change of mental representations based on the communication of facts and emotions (Section 2.3). Section 2.4 summarizes the overall algorithm of our model. Section 3 describes the results of the model validation (Section 3.1), a baseline diffusion scenario for different types of consumers (Section 3.2), and simulations of policy scenarios related to the dissemination of EVs (Section 3.3). Finally, in Section 4, we summarize key findings, discuss limitations and practical implications, and provide suggestions for future research.

2 . The agent-based model: design and methods

In this section, we describe our theory of innovation adoption and its implementation in an agent-based model. This theory follows a more general multi-level approach to the study of belief change in complex social systems (Homer-Dixon et al., 2013). We think that peoples' individual decisions about transport result from maximizing the satisfaction of constraints given by their mental representations, which include emotions, needs, priorities, possible actions, and knowledge about the extent to which the different actions facilitate the needs. This mechanism is called emotional coherence and modeled with localist neural networks capable of processing emotions (Thagard, 2006). The adoption of innovation occurs when people change their mental representations as a result of obtaining new information through communication with others or media campaigns, but this is constrained by the compatibility of the new information with the existing mental representations. The model has a mechanism for specifying which two agents communicate with each other at any time

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