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Paths to the adoption of electric vehicles: An evolutionary game theoretical approach

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ABSTRACT

Electric vehicles (EVs) are a viable alternative to internal combustion engine (ICE) vehicles, with the potential to alleviate the negative externalities stemming from the present ICE-based transportation sector. Notwithstanding, the current prevalence of ICE creates a lock-in state that averts the adoption of alternative and environmental friendly technologies, bringing forth a social dilemma. Here we investigate the feasibility of escaping the present lock-in state by studying possible incentive mechanisms involving, simultaneously, governments (public), companies (private) and consumers (civil). Resorting to evolutionary game theory (EGT), we develop a theoretical model grounded on the strategic interactions between players from the different sectors, whose co-evolving choices influence (and are influenced by) different policies and social incentives. Our findings suggest that i) public regulation is necessary but not sufficient for guaranteeing full EV adoption; ii) public-civil synergies are essential; iii) demand for EVs preceding supply is most efficient, providing companies with the needed incentives to counterweigh infrastructure investments; and iv) full adoption of EVs requires coordination between the three sectors to emerge, particularly when changes are initiated by the public sector.

1. Introduction

The contemporary means of transportation are mostly based on fossil fuels, thus constituting a chief source of air pollution and harmful environmental emissions (Colvile et al., 2001; Egbue and Long, 2012; Grazi et al., 2008; Hoen et al., 2014). Changing to less polluting energy based transport technologies acquired recently a renewed focus, of which the transition from internal combustion engines (ICE) to electric vehicles (EVs) provides a paradigmatic example.

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EVs are nowadays perceived as a solution to reduce environmental problems emerging from the road transport sector (Thiel et al., 2010). As in the past, the snag is, however, that *status quo* reflects the widespread dominance of ICE vehicles, which poses a coordination dilemma to alternative technologies (such as EVs) that remains unsolved to date.

Originating in the late XIX century, the automobile industry witnessed then a competition among several engine alternatives. From steam-powered vehicles to electric and gasoline, all were, at some point, a potential dominant technology (Anderson and Anderson 2010). In time, the gasoline vehicle prevailed and the industry grew into today's global scenario.

The ensuing success of the ICE car surpassed the technological domain and has since then reached deep into almost all domains of society. At the forefront of this societal conquest lies the continual technological development of the transportation sector (Barret, 1996; Bruegmann, 2006). In time, this self-reinforcing process has led the world, through positive feedbacks and path-interdependences (Cowan and Hultén, 1996), to a lock-in state where the ICE engine constitutes the prevailing technology and any beneficial alternative has proved difficult to massively diffuse into the market. This state originated a *social trap* where seeking short-term benefits (e.g. accessibility and avoiding costs of changing the paradigm) generate negative collective externalities (e.g. air pollution) that seriously affect long-term wellbeing. This scenario, together with problems inherent to the EVs, leads to the following 6 obstacles, identified as the main impediments to full adoption of EVs (Egbue and Long, 2012; Giffi et al., 2011; USEPA, 1996): 1) battery range and degradation, 2) higher purchasing costs, 3) limited charging infrastructure and fairly long recharging time, 4) perceived risks, 5) running costs and 6) the evolution of technology. Battery range and planning of charging infrastructures are complex problems still the focus of on-going research (Chen et al., 2016; Lee and Han, 2017; Montoya et al., 2017; Zhang et al., 2017). Besides these barriers, adherence to EVs faces yet deeper issues related with individual and social perceptions regarding environmental prospects (Lorenzoni et al., 2007). These comprise lack of knowledge, uncertainty and skepticism (in technology and scientific outputs), delayed effects in time, reluctance to change lifestyles, personal control issues, lack of political action, free-rider effects, social norms and expectations (Lorenzoni et al., 2007). All together, these perceptions create a "behavioral gap" in environmental consumerism that translates into a mismatch between pro-environmental attitudes of consumers and their willingness to engage in pro-environmental behavior, including buying products and services that minimize the impact on the environment (Gifford et al., 2011; Gupta and Ogden, 2006; Moons and De Pelsmacker, 2012; Schuitema et al., 2013; Steg, 2005; Wu et al., 2010; Zhang et al., 2013).

These technological and social barriers lead, in fact, to a tragedy of the commons type scenario, in which a public good (environmental quality), built upon social cooperation (here through EVs adoption), is endangered by the temptation to free ride (individual gain seeking) (Hardin, 1968; Levin, 2000). The complexity inherent to this type of social dilemma usually requires multi-level and multi-sectorial responses towards coordination into avoiding the non-cooperative state since, at this time, it is not clear whether surpassing technological barriers is sufficient to adopt new products, thus attaining new equilibrium states. This is particularly relevant given the way that individuals discount the future, being unable to incur immediate costs to trigger future benefits (Levin, 2012; Van Lange et al., 2013). Several forecasting models try to understand and predict the impact of EVs adoption on market shares (Glerum et al., 2014; Jensen et al., 2017; Plötz et al., 2014), where it becomes clear the role of the above barriers on consumers' choices. Here we adopt a different approach, including not only the behavior of the demand side but also how this behavior might impact, and be impacted by, the supply side and the public sector (the ultimate player in promoting policies to deal with collective social problems).

The interrelation between societal sectors that exhibit multiple (and potentially diverging) interests produces an incentive landscape that is often challenging to analyze in a systematic way, despite its pervasiveness (Encarnação et al., 2016; Santos et al., 2016). Furthermore, individual preferences across different sectors are dynamically intertwined, as they are influenced by the actions performed, in a given moment, by the representatives of all other sectors. This multi-sectorial and frequency dependent nature of incentives, typically disregarded in conventional forecasting models, falls naturally in the framework of ecological modeling, where situations involving multiple species such as predator-prey dynamics or symbiotic interactions are well-known. In this way, the methods used in theoretical ecology can be employed to better understand the co-evolution of behaviors in socio-economic systems (May et al., 2008; Skyrms, 1996) such as the present one underlying EVs adoption. Evolutionary game theory (EGT) (Hofbauer and Sigmund, 1998; Smith, 1982; Weibull, 1995) constitutes, in this context, the mathematical framework of choice that builds on the idea of strategic interaction present in classical game theory (GT), yet relaxing the rationality assumptions often made there. By resorting to EGT, we explore here the similarities between the principles that govern strategy adoption and peer-influence in social systems and those governing trait evolution through natural selection: successful behaviors (similar to genes) spread faster within populations. This is apparent in the case of innovation diffusion (Rogers, 2003) in which embracing new products is both a combination of spontaneous exploration (mutations or adoption by innovators) and success imitation (social learning or adoption by imitators). In the specific case of EVs, it is likely that the adoption of this technology follows the same principles of multi-sectorial frequency dependence, exploration and peer-influence: governmental subsidies, shared infrastructure costs, technological investment or environmental activism (to name a few) are mechanisms whose implementation depends on the engagement of individuals from particular sectors, and which, if effective, may drive the will of other sectors. These feedback loops, in turn, may steer early adoption and social contagion processes that – similarly to other technological innovations – may determine the disengagement of ICE vehicles and the overall adoption of EVs (Mercure et al., 2014).

Overall, our contribution to transportation research literature is in applying an *analytical framework, based on a population dynamics EGT model*, to explore the possibility of escaping the aforementioned lock-in state, where strong interdependencies among, public, private and civil players are present.