Technological Forecasting & Social Change xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

A system dynamics based market agent model simulating future powertrain technology transition: Scenarios in the EU light duty vehicle road transport sector

Guzay Pasaoglu [a,b,*], Gillian Harrison [a], Lee Jones [c], Andrew Hill [c], Alexandre Beaudet [c,d], Christian Thiel [a]

[a] *European Commission, Directorate-General Joint Research Centre, Institute for Energy and Transport, Westerduinweg 3, NL-1755 LE Petten, The Netherlands* [1]
[b] *Istanbul Technical University, Institute of Energy, Istanbul, Turkey*
[c] *Ventana Systems, United Kingdom*
[d] *Imperial Centre for Energy Policy and Technology, United Kingdom*

ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form 9 November 2015
Accepted 27 November 2015
Available online xxxx

Keywords:
EU road transport sector
System dynamics simulation
Alternative fuel vehicles
Alternative fuel infrastructure
Hybrid and electric vehicles
Hydrogen and fuel cell vehicles

ABSTRACT

The study presents an extensive System Dynamics simulation model, running up to 2050, employing an agent-based approach and incorporating major factors that influence the technology transition in the EU light duty vehicle road transport sector. The model aims at better understanding and analysing market trends. It is a comprehensive representation of EU powertrain technology transition, at member state level, and includes interactions and feedbacks between major stakeholders influencing the evolution of the market shares. The model seeks to integrate a wider range of market, industry and technology dynamics compared to other known models to date. Five scenarios are conducted to explore the dynamics of the powertrain transitions under different oil prices, GDP growth, learning rates, purchase subsidies and EU emission targets. The findings illustrate that the developed model is able to give strategic insights to authorities, manufacturers and infrastructure providers regarding their respective decisions, policies and challenges in relation to medium and long-term trends in the EU road transport sector.

1. Introduction

The goal of the European Union's (EU) sustainable transport policy is to ensure that the transport system meets the economic, social and environmental needs of society (EU, 2011). Road transport plays an important role in this context and it covers a significant proportion of the European transport needs as described in detail in Pasaoglu et al. (2012). Due to factors such as globalisation, changing customer needs and economic and environmental pressures, the European road transport sector is continually undergoing transformations, including technology transitions. Within wider carbon reduction targets, the EC set out in the White Paper on Transport a target of reducing transport GHG emissions by 60% of 1990 level by 2050 (EU, 2011). Recent European policy initiatives targeting the decarbonisation of road transport, which contributes about a fifth of total EU emissions (EEA, 2014a), are directed towards (i) enforcing CO_2 reductions on a fleet level for all vehicles (EC, 2009d, 2011b, 2014b; EC, 2009a, EC, 2011a), (ii) reducing the carbon intensity of the fuel mix and energy supply (EC, 2009b, EC, 2009a), (iii) supporting research, development and demonstration (R, D & D) (Zubaryeva and Thiel, 2013; EEA, 2014a) and promotion (EC, 2009c) of alternative technologies, (iv) the provision of consumer information on fuel efficiency and CO_2 emissions (EC, 1999) and (v) fostering the deployment of the infrastructure necessary for alternatively fuelled vehicles (EU, 2014).

These actions are supplemented by demand-side measures in the Member States, such as scrappage schemes and reduction of taxes on low CO_2 cars to stimulate alternative vehicle purchases by customers. Many EU countries have already taken individual initiatives to introduce electric vehicle (EV)[2] technologies, and have launched pilot projects to show their technical feasibility, as well as incentive schemes to promote the deployment of an electrical driven fleet and associated infrastructure. Due to these initiatives, the expectation is that the adoption of alternative fuels and powertrains will accelerate in the EU road transport sector and that consequently CO_2 emissions and fuel dependency will be reduced as illustrated by Pasaoglu et al. (2012). However, there is no common agreed penetration rate projection for alternative vehicles in Europe (Howey, 2012). Although the market penetration rate[3] of new propulsion technologies (alternative fuels and powertrains) will mainly depend on their cost competitiveness vis-à-vis conventional

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* Corresponding author at: European Commission, Directorate-General Joint Research Centre, Institute for Energy and Transport, Westerduinweg 3, NL-1755 LE Petten, The Netherlands.
E-mail address: guzaypasaoglu@gmail.com (G. Pasaoglu).

[1] The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

[2] In this paper, the term EV covers those vehicles employing a full electric powertrain (Plug-in Hybrid Electric Vehicles, Battery Electric Vehicles or Fuel Cell Vehicles).

[3] The share in the annual new vehicle sales.

http://dx.doi.org/10.1016/j.techfore.2015.11.028
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Please cite this article as: Pasaoglu, G., et al., A system dynamics based market agent model simulating future powertrain technology transition: Scenarios in the EU light duty vehicle..., Technol. Forecast. Soc. Change (2015), http://dx.doi.org/10.1016/j.techfore.2015.11.028

vehicles, there are other factors which may influence the deployment of alternative vehicles, such as infrastructure availability, consumer awareness, technological features (range, speed, safety, fuel consumption, emissions, technology maturity etc.), after-sale service availability and government support. Consequently, the market viability and the future market penetration of these technologies remain highly uncertain. Therefore, it is of critical importance to base technology transition expectations on a solid foundation, taking into account the main drivers and parameters influencing the transition.

The aim of the study is to contribute to the understanding of such transitions by providing an extensive system dynamics (SD) model, incorporating the major market agents' decisions, activities and their feedback and interaction with each other. The model is designed to assist in analysing likely technology transitions involving future technologies in the EU light duty road transport sector. In the current environment, where private firms, powertrains and fuel types are competing among each other and authorities define regulations and policies in order to reduce greenhouse gas emissions and ensure sustainable transport, traditional modelling and analytical tools for long-term planning are becoming less relevant. In particular, models need to take into account the fact that market trends do not depend on any single decision makers' actions, but rather on actions, interactions and feedback mechanisms involving multiple decision makers, including consumers, manufacturers, infrastructure providers and authorities. As alternative vehicles have different infrastructural needs, drawbacks and advantages, time series based approaches, which are used for sales forecasting and infrastructural planning of conventional vehicles, are not appropriate to analyse the transition to new powertrains in the road transport sector. The limitations of traditional optimization and forecasting approaches are that they are inherently prescriptive, linear, and mechanistic, while ignoring important feedbacks and overly relying on non-behavioural mechanisms (Pasaoglu Kilanc and Or, 2008). However, in markets where private agents, technologies and products are competing with each other, the need is shifted from planning to designing strategy, requiring complementary modelling approaches such as agent-based models, system dynamics (SD) and game theory. In this paper, instead of concentrating on the details of each part of the extensive model, the main modules, agent roles and interactions with each other, which are the most important for the long-term development of technology transitions are presented. To demonstrate the potential use of the developed model, findings obtained from analysis of several scenarios are given at the end.

2. The main contribution of the study and developed model

2.1. General characteristics of the model and main contributions of the study

In the light duty road transport sector, combined forces of supply and demand conditions, rather than the historic costs, demand and trends of the passenger car market, will determine the deployment of new powertrain types, infrastructural investments and customer preferences. In such an environment, future developments are difficult to predict as all of the relevant factors highly interact and directly influence each other. Manufacturer and infrastructure provider investment decisions mainly depend on their cash flow expectations while user powertrain preferences and authorities' policies (incentives, penalties, and taxes) greatly influence these expectations. The SD approach has been regularly applied to study the diffusion of innovations and new technologies (Valente, 1993; Sterman, 2000; Rogers, 2003; Shepherd, 2014). Although automotive technology transitions have been traditionally analysed using diffusion or choice modelling, these lack the unique dynamic interaction and feedback mechanisms that can be captured in SD (Harrison and Shepherd, 2014). Many studies have therefore used SD to analyse possible future scenarios of technology transition in the automotive sector (Richardson et al., 1999; Janssen et al., 2006; Bosshardt et al., 2007; Struben and Sterman, 2008; Meyer and Winebrake, 2009; Kohler et al., 2010; Ulli-Beer et al., 2010; Walther et al., 2010; Kwon, 2012; Rodrigues et al., 2012; Shepherd et al., 2012; Gomez et al., 2013; Harrison and Shepherd, 2014), and overviews can be found in Harrison and Shepherd (2014) and Shepherd (2014). In particular, Struben and Sterman (2008) developed a behavioural dynamics model that explores the transition from conventional vehicles to alternative fuel vehicles (AFVs) and uses basic technology diffusion concepts. Although their model incorporates feedback from the development of fuelling infrastructure, the main focus of their model is on the behavioural dynamics incorporating word-of-mouth knowledge transmission among consumers, social exposure, and the willingness of consumers to consider AFVs. However, most studies refer to the interaction between one particular alternative energy option and the infrastructure required to support it (e.g., focusing on only hydrogen fuel cell vehicles), or are limited to country-specific case studies. On the other hand, the Astra model, a SD based model, provides simulations of scenarios concerning energy scarcity, high oil prices, technological investments in the EU transport sector and application of measures included in European transport policy (Fiorello et al., 2010; Schade and Krail, 2010). However, the Astra model lacks the agent-based approach. Going deeper into each individual market agent's individual decisions and their interaction with each other is essential as aggregate flow equations usually assume global homogeneous mixing, but the topology of the interaction network can lead to significant deviations from predicted aggregate behaviour (Bonabeau, 2012).

In order to fill the abovementioned gap in the literature, we developed an extensive SD simulation model, employing an agent-based approach and incorporating all the aforementioned factors influencing the technology transition in the EU light duty road transport sector in order to better understand and analyse the market trends in the future vehicle market. The developed model is a comprehensive representation of the light duty vehicle fleet evolution in Europe, at EU member state level, and includes major interactions and feedbacks between the relevant agents (Users, Manufacturers, Infrastructure Providers and Authorities) influencing the evolution of the powertrain market shares in each of the 28 member states. Assumptions and equations regarding regions outside the EU are treated as the rest of the world (RoW) in order to decrease model complexity. The model can make simulations between 1995 and 2050, incremented into annual periods. To our knowledge, the model seeks to integrate a wider range of market, industry and technology dynamics compared to other modelling exercises that have been attempted to date. Furthermore, the model not only addresses the competition between the incumbent technology and new technologies, but also the competition among alternative vehicle types. This approach is aligned with the actual complexity of the automotive sector, which is characterised by multiple players with often conflicting incentives. Naturally, it is worth to state that the model remains a simplified representation of reality and should therefore be used with caution; mainly as a means of exploring "what if" scenarios under various conditions.

2.2. Model architecture

There are over 1500 parameters (equations or data input) leading to 700,000 elements in the developed model, given the number and combination of subscripts modelled (Table 1) and the model scope, but the essence is simple; the behaviour of and interaction between market agents governs the evolution of the powertrain mix. This has been captured in a very high-level overview causal loop diagram (CLD)[4] in Fig. 1. For example, at the core of the model and CLD overview, "sales" exist. Sales of vehicles within any one year determine changes in the fleet

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[4] Causal loop diagrams are a powerful tool to qualitatively map the feedback processes of complex systems. They provide a high- level means of conceptualising models in terms of their feedback loop structure (Wolstenholme, 1999).

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