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Methodologies for representing the road transport sector in energy system models☆

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ABSTRACT

Energy system models are often used to assess the potential role of hydrogen and electric powertrains for reducing transport CO_2 emissions in the future. In this paper, we review how different energy system models have represented both vehicles and fuel infrastructure in the past and we provide guidelines for their representation in the future. In particular, we identify three key modelling decisions: the degree of car market segmentation, the imposition of market share constraints and the use of lumpy investments to represent infrastructure. We examine each of these decisions in a case study using the UK MARKAL model. While disaggregating the car market principally affects only the transition rate to the optimum mix of technologies, market share constraints can greatly change the optimum mix so should be chosen carefully. In contrast, modelling infrastructure using lumpy investments has little impact on the model results. We identify the development of new methodologies to represent the impact of behavioural change on transport demand as a key challenge for improving energy system models in the future.

1. Introduction

The transport sector is expected to change profoundly over the coming decades as alternative electric and/or hydrogen powertrains are introduced to the market to reduce CO_2 emissions, complementing or replacing the hydrocarbon fuels and internal combustion engine (ICE) designs that have been used since the advent of the passenger car more than 100 years ago [1]. A number of modelling approaches have been used to compare the prospects for, and implications of, various possible future fuels and powertrains. One common approach applies system dynamics modelling to vehicle choice and adoption, and in doing so seeks to explore the relative importance of different behavioural, technical and economic factors in enabling the adoption of different vehicle technologies [2,3]. Another common approach is to compare different vehicle configurations in a static way, developing detailed depictions of the life-cycle environmental and energy impacts, and the total costs of ownership [4–6].

While these studies have provided valuable insights, they share a common weakness, which is that the wider energy system is assumed to be exogenous to the transport sector. The required level of transport decarbonisation is an exogenous assumption in these models and does not account for the relative costs of decarbonising transport and other sectors. Fuel prices and availability are also provided exogenously

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and are assumed to be insensitive to changes in fuel demand. Moreover, some new transport infrastructure, for example hydrogen pipeline networks, might only be economically-viable if they provide energy services to other sectors as well as to the transport sector.

Energy system models, such as MARKAL/TIMES [7] and MESSAGE [8], do not share this weakness. These bottom-up, dynamic, linear programming optimisation models find the cost-optimal decarbonisation pathway within the context of decarbonising the entire economy. They represent the entire energy system from imports and domestic production of fuel resources, through fuel processing and supply and explicit representation of infrastructures, to secondary energy carriers, end-use technologies and energy service demands of the entire economy. Since energy system models determine whole economy decarbonisation pathways, including the transport sector, they are often employed to provide exogenous boundary conditions for the other model types mentioned above. While no single model methodology is capable of fully evaluating the many options for the transport sector in the future, energy system models provide an important and complementary perspective to the other model types. It is therefore important that the transport sector, including fuel supply infrastructures, is appropriately represented in energy system models.

In this paper, we review how different energy system models have represented vehicles and fuel supply infrastructures in the past. We identify key modelling decisions and examine each of these decisions in a case study using the UK MARKAL model. UK MARKAL is an appropriate model for illustrating the methodological issues that we discuss in this paper because it is a mature model that has been the subject of numerous hydrogen-focused papers [9–13]. We concentrate on private cars in this paper as these dominate transport demand and fuel consumption in most countries, but the infrastructure applies to all forms of road transport and the vehicle methodologies apply equally for other types of road vehicle as for cars (but at a different scale). A full description of how to adapt the methodologies presented in this paper for goods vehicles and buses is given in Ref. [14].

1.1. Difficulties representing the transport sector in energy system models

There are a number of methodological difficulties when representing the transport sector in energy system models that we discuss in this paper.

First, non-cost factors are difficult to represent. Consumers take a variety of factors into account when purchasing a vehicle, including cost, size, colour, safety, features and design, while optimisation models such as energy system models account for only cost so would always invest in the cheapest (i.e. smallest) vehicles if given a choice. It is necessary to make assumptions about the impact of non-cost factors on the vehicle fleet in the future. This is particularly important for new low-carbon technologies whose performance (in terms of range, refuelling time, etc.) is worse than that of existing vehicles.

Second, building the required fuel supply infrastructures for electric and particularly for hydrogen powertrains would require huge investments, yet such infrastructures are difficult to represent in energy system models because some of the costs (e.g. for pipelines) are sensitive to the geography of the region/country and the energy throughput can be much lower than the maximum, particularly during transitions to new fuels [15,16]. Spatially-disaggregated infrastructure planning models can be used to examine the development of infrastructure and to provide data for energy system models [17].

Third, it is necessary to ensure that the representations of vehicles and fuel infrastructures in the model are internally-consistent. This means that the costs for all vehicle powertrains and refuelling infrastructure should be calculated in a consistent manner using comparable data sources and with clear assumptions. These data should also reflect the scenario being examined, particularly when other models are used to provide input data to the energy system models; for example, demand forecasts for transport (in total distance rather than energy terms) are sometimes taken from external models (e.g. Ref. [18]) and the assumptions used in these models should be consistent with the assumptions used in the energy system model.

More generally, energy system models have very complicated structures as they examine all parts of the energy economy, so it is necessary to avoid overly disaggregating each sector in order to keep the model and particularly the running time manageable; the modeller aims to minimise model complexity without adversely affecting results [19]. From this perspective, the most appropriate methodology is the least complicated one that produces both realistic overall results and the insights required by the study. Modellers might choose to create two versions of the transport sector: a first for general applications and a second more disaggregated version for studies focusing primarily on the transport sector.

1.2. Outline of this paper

In Sections 2 and 3, we examine previous approaches to representing vehicles and infrastructures, respectively, and we identify implicit assumptions and three key modelling decisions that are often not well documented. We also recommend appropriate methodological approaches for representing vehicles and infrastructures in these sections and we illustrate these in a case study in Section 4, in which we develop a full and consistent representation of transport vehicles and fuel infrastructure in the UK MARKAL energy system model. In Section 5, we examine the three key modelling decisions from Sections 2 and 3 using this revised version of the UK MARKAL model. We finish with a discussion some of the drawbacks with energy system models in Section 6.

2. Representing vehicle technologies in UK MARKAL

Energy system models represent the road transport sector as a simple market of vehicle technologies competing to meet demands on the basis of cost. Exogenous forecasts of car transport demand are identified from the literature, in vehicle kilometres, and the various technologies represented in the model compete to meet that demand over all of the years in