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Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices

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A B S T R A C T

A large body of transport sector-focused research recognizes the complexity of human behavior in relation to mobility. Yet, global integrated assessment models (IAMs), which are widely used to evaluate the costs, potentials, and consequences of different greenhouse gas emission trajectories over the medium-to-long term, typically represent behavior and the end use of energy as a simple rational choice between available alternatives, even though abundant empirical evidence shows that real-world decision making is more complex and less routinely rational. This paper demonstrates the value of incorporating certain features of consumer behavior in IAMs, focusing on light-duty vehicle (LDV) purchase decisions. An innovative model formulation is developed to represent heterogeneous consumer groups with varying preferences for vehicle novelty, range, refueling/recharging availability, and variety. The formulation is then implemented in the transport module of MESSAGE-Transport, a global IAM, although it also has the generic flexibility to be applied in energy-economy models with varying set-ups. Comparison of conventional and 'behaviorally-realistic' model runs with respect to vehicle purchase decisions shows that consumer preferences may slow down the transition to alternative fuel (low-carbon) vehicles. Consequently, stronger price-based incentives and/or non-price based measures may be needed to transform the global fleet of passenger vehicles, at least in the initial market phases of novel alternatives. Otherwise, the mitigation burden borne by other transport sub-sectors and other energy sectors could be higher than previously estimated. More generally, capturing behavioral features of energy consumers in global IAMs increases their usefulness to policy makers by allowing a more realistic assessment of a more diverse suite of policies.

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Introduction & motivation

The future direction of the world's energy and transport systems, and in particular society's ability to mitigate climate change and overcome a variety of other sustainable development challenges, hinges critically on both technological and socio-behavioral factors. These factors, many of which are associated with large uncertainties, have been studied in detail by diverse research communities employing a variety of methodological approaches: from engineers to natural scientists to social scientists. Somewhere in the middle of these communities sit modelers, drawing, in an interdisciplinary way, on the thinking of individual disciplines. Models come in all shapes and sizes: some, for instance, focus only on the transport sector in a particular country whereas others cover the energy-economic system of the entire world. Many models are forward-looking and therefore are used for medium-to-long-term scenario analyses, with an eye toward informing energy, transport, and sustainable development policy; some of these models consider both technological and socio-behavioral elements in developing their scenarios. Bridging the gap between these dimensions has historically presented a challenge (Turnheim et al., 2015; Avineri, 2012). This paper attempts to make progress by using transport sector-focused behavioral research to enhance the state-of-the-art of energy-economic and integrated assessment models.

Global integrated assessment and energy-economy models in brief

Models of the global energy-economy are widely used to evaluate the costs, potentials, and consequences of different greenhouse gas emission trajectories over the medium-to-long term. These models are increasingly coupled to atmospheric, land use, agricultural, forestry and other sectoral models: hence, 'integrated assessment models' (IAMs). Representation of the global energy-economy within IAMs is inevitably – and often intentionally – stylized, simplified, and selective. Their purpose is to derive robust insights – qualitative and quantitative – on the systemic consequences of socio-economic development and technology and policy choices (Krey, 2014).

Krey (2014) distinguishes IAMs along three main dimensions: (i) the 'mathematical solution concepts' – optimization or simulation, partial or general equilibrium, limited or perfect foresight; (ii) system boundaries – sectoral, regional, temporal; and (iii) the level of detail or heterogeneity – technological, spatial (urban/rural), income. Meanwhile, Sathaye and Shukla (2013) summarize the eight main sources of variation across model structures and assumptions that yield differences in results. These include energy demand drivers, resource costs and technology performance parameters, endogenous technological change, and solution algorithms (e.g., intertemporal optimization, myopic with recursive dynamics). (Details for a sample of global IAMs are provided in the Supplementary Material).

IAMs also differ in their representation of energy end-user or consumer behavior. This 'behavioral realism' of models has not, heretofore, been meaningfully discussed in the literature. The objectives of this paper are: (i) to review relevant empirical literature on the behavioral characteristics of energy end-use; (ii) to assess the ways in which IAMs currently endogenize or reproduce key features of human behavior; and (iii) to develop and test a novel IAM formulation for representing heterogeneous consumer groups with varying preferences. Throughout, the focus is on light-duty vehicles and consumers' purchase decisions.

Why behavioral realism in IAMs is important

Climate change mitigation scenarios and the IAMs that generate them are increasingly being designed to be more 'realistic' by incorporating features observed in the real world. Such real-world features include delays in concerted global mitigation action (e.g., Riahi et al. (2015)), fragmented policy approaches (e.g., Tavoni et al. (2013)), and the absence from mitigation portfolios (either for political or social reasons) of specific low-carbon technologies or resources, such as nuclear power or biofuels (Riahi et al., 2012; Kriegler et al., 2014; Krey et al., 2014). Such features are for the most part modeled using exogenous assumptions that are consistent with the overarching scenario narrative.

Another important feature of the 'real world' relates to human behavior. IAMs generally represent the behavior of consumers or energy end-users in a stylized way through simplified economic relationships: energy demand as a function of price, technology investments to minimize levelized costs, and so on. (The same basic arguments apply equally to producers or firms (e.g., Laitner et al. (2003)), but the emphasis in this paper is on energy consumers.)

With their necessary levels of aggregation, IAMs do not represent individual interacting decision makers, but rather 'representative agents' that describe aggregate behavior at the mean (Conlisk, 1996; Laitner et al., 2000). Representative agents act 'as if' they were perfectly rational. Rational choice implies: (i) decision makers with known and fixed preferences; (ii) utility-maximizing decisions; and (iii) perfect information about all decision alternatives and their attributes. As Laitner et al. (2000) argue: "the crucial question is whether the behavior that is actually carried out by the economic agents has different consequences for economic modeling of climate policy than the 'as if' presumption of maximisation" (p. 19).

A cursory review of the evidence suggests this is indeed the case. Behaviorally-realistic models of many different forms show the important influence of behavioral assumptions on policy-relevant outcomes in the energy economy (e.g., Rivers and Jaccard (2006), Sun and Tesfatsion (2007)). In addition, a mass of empirical evidence has accumulated on behavioral influences on energy use, end-use technology adoption, and resulting emissions (e.g., Lutzenhiser (1993), Ayres et al.

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