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Applying engineering and fleet detail to represent passenger vehicle transport in a computable general equilibrium model

Valerie J. Karplus *, Sergey Paltsev, Mustafa Babiker, John M. Reilly

MIT Joint Program on the Science and Policy of Global Change, 400 Main Street, Building E19, Cambridge, MA 02139, USA

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ABSTRACT

A well-known challenge in computable general equilibrium (CGE) models is to maintain correspondence between the forecasted economic and physical quantities over time. Maintaining such a correspondence is necessary to understand how economic forecasts reflect, and are constrained by, relationships within the underlying physical system. This work develops a method for projecting global demand for passenger vehicle transport, retaining supplemental physical accounting for vehicle stock, fuel use, and greenhouse gas (GHG) emissions. This method is implemented in the MIT Emissions Prediction and Policy Analysis Version 5 (EPPA5) model and includes several advances over previous approaches. First, the relationship between per-capita income and demand for passenger vehicle transport services (in vehicle-miles traveled, or VMT) is based on econometric estimates and modeled using quasi-homothetic preferences. Second, the passenger vehicle transport sector is structured to capture opportunities to reduce fleet-level gasoline use through the application of vehicle efficiency or alternative fuel vehicle technologies, introduction of alternative fuels, or reduction in demand for VMT. Third, alternative fuel vehicles (AFVs) are represented in the EPPA model. Fixed costs as well as learning effects that could influence the rate of AFV introduction are captured explicitly. This model development lays the foundation for assessing policies that differentiate based on vehicle age and efficiency, alter the relative prices of fuels, or focus on promoting specific advanced vehicle or fuel technologies.

1. Introduction

Computable general equilibrium (CGE) models are widely used to understand the impact of policy constraints on energy use, the environment, and economic welfare at a national or global level (U.S. CCSP, 2007; Weyant, 1999). However, for certain research questions, results from these models do not capture accurately the relationships in the underlying physical system. These relationships include links between income and demand for services provided by energy-intensive durable goods, as well as the richness of opportunities for technological or behavioral change in response to policy.

Maintaining dual accounting of physical and economic variables is particularly important when modeling consumer durable goods such as passenger vehicles. Vehicles are an example of a complex multi-attribute consumer product with a long lifetime. Consumer preferences across attributes – such as horsepower and fuel economy in the case of vehicles – involve engineering trade-offs at the vehicle level. For instance, over the past several decades, fuel efficiency gains have been offset by a shift toward larger, more powerful vehicles in some regions, offsetting improvements in on-road fuel economy (An and DeCicco, 2007; Knittel, 2009). As policymakers consider how to most cost-effectively regulate the air, climate, and security externalities associated with vehicle use, macroeconomic forecasting models that capture the range of technological and behavioral responses to regulation will become increasingly important.

The goal of this work is to develop a new method of projecting physical demand for services from passenger vehicles in a recursive-dynamic CGE model. This new method is applied to the MIT Emissions Prediction and Policy Analysis Version 5 (EPPA5) model, a CGE model of the global economy (Babiker et al., 2001; Paltsev et al., 2005, 2010). The method captures the richness of the technological response at an appropriate level of detail, without sacrificing sectoral and regional coverage or the ability to capture the macroeconomic feedbacks that make this modeling system advantageous over other approaches.

The text is organized as follows. Section 2 describes current practices for representing energy-intensive consumption at the household level in CGE models, including the representation of durable goods, and the rationale for a new approach. Section 3 presents the new approach, divided into three parts. Section 3.1 explains how the relationship between income and demand for vehicle services was parameterized using econometric information and implemented using the well-established Stone–Geary (quasi-homothetic) preference system. Section 3.2 describes how vehicle engineering and fleet detail were used to parameterize the

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* Corresponding author at: MIT Joint Program on the Science and Policy of Global Change, 400 Main Street, Building E19, Room 429p, Cambridge, MA 02142, USA. Tel.: +1 617 715 5430; fax: +1 617 253 9845.
E-mail address: vkarplus@mit.edu (V.J. Karplus).

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structure of the passenger vehicle transport sector and opportunities for fleet-level fuel efficiency improvement. Section 3.3 describes the representation of alternative fuel vehicles. Section 4 describes the impact of model developments on forecasts of gasoline use, greenhouse gas (GHG) emissions, and household consumption. Section 5 offers conclusions and directions for future work.

2. Bottom-up technology in top-down models: Issues and previous work

2.1. Background on the CGE modeling approach

The CGE model structure is based on the circular flow of the economy in which households supply labor and capital to firms that produce goods and services, which are in turn purchased by households. The CGE model has its origins principally in neoclassical modeling developments and invokes microeconomic principles (Arrow and Debreu, 1954; Shoven and Whalley, 1984). Based on their endowments and preferences, one or more representative agents maximize utility subject to a budget constraint, while producers maximize profits, with production functions specified as constant returns-to-scale. A vector of prices and quantities for which demand equals supply (market clearance), household income equals expenditures (income balance), and the profits of firms are driven to zero (zero profit) comprises an equilibrium solution. The basis for CGE model calibration is typically National Income and Product Account data, which is used to develop a Social Accounting Matrix (SAM) that captures economic flows across all sectors in a single model benchmark year. The SAM has its origins in traditional input–output (I/O) analysis (Leontief, 1937).

In the structure of a CGE model, elasticities of substitution represent the willingness or ability of households and firms to substitute among inputs to production or consumption in response to changes in input costs. The elasticity values are typically based on econometric evidence or other methods as appropriate (Arndt et al., 2002; Balistreri et al., 2003; Zhang and Verikios, 2006). Most CGE models also include some form of capital stock accounting, either using a putty-clay representation (Lau et al., 2002; Phelps, 1963) or a sector-specific capital vintaging structure (Paltsev et al., 2005).

2.2. A literature review on approaches to modeling energy-intensive durable goods

A perennial challenge in the CGE modeling community has been how to forecast both expenditures and physical quantities consistently. Expenditure shares and elasticities are parameterized based on physical quantities, prices, and abatement costs in the benchmark year and are expressed in value terms. Expressing a quantity in value terms means that the benchmark year quantity is defined as the price multiplied by the quantity in that year and prices are normalized to unity. In future model years, however, pinning down the relationship between spending, goods purchased, as well as the impact on demand for efficiency-improving technologies can be difficult, since it requires assumptions about how these relationships will evolve over time. An example of the introduction of thermodynamic efficiency in CGE models can be found in McFarland et al. (2004).

The problems that arise from imprecise physical accounting can be particularly pronounced in the case of complex, quality-differentiated consumer durable goods because forecasted expenditures must capture changes in demand for the service itself. The relationship between expenditures and service demand may change due to a variety of factors, including diversification of expenditures toward or away from the service of interest or changes in the attributes of the good that provides the services. Omitting such factors can produce misguided forecasts because the attributes of durable goods are defined in the benchmark year, and unless otherwise specified change only due to price-driven substitution among inputs. The total energy requirement may also be misestimated because tradeoffs between fuel economy and other product attributes are often not well specified. Functional attributes can be energy saving—i.e. technology that decreases fuel consumption per mile, or energy intensive—i.e. technology that increases fuel consumption per mile, or possibly have no net effect on fuel consumption at all. Forecasting energy requirements is difficult when the model does not resolve how income and input costs (including fuel cost) affect demand for vehicle services and product attributes, and its relationship to household spending.

Before describing the approach developed in this work, I briefly review the range of modeling approaches used to assess the impact of policy on consumption of energy-intensive durable goods. In developing models for energy and environmental policy analysis, researchers have tried various strategies to address the problem of how to simultaneously forecast physical and economic variables. One approach is to focus on the detailed physical system while holding exogenous macroeconomic variables (including in some instances prices) fixed, and forecast energy use (and technology adoption) using a cost minimization algorithm that takes policy, if imposed, as a constraint. By definition many macroeconomic models – including partial and general equilibrium models – encompass more than one market and capture the price changes that result from inter-market interactions. These models often sacrifice technological detail in the interest of generalizable insights and computational tractability, representing production and consumption activities in a deliberately simplified and aggregated fashion. Without additional structure it is impossible to determine, for instance, how demand for vehicle use responds to changes in the vehicle and fuel components of travel cost since these models only forecast the value of services provided.

One approach designed to preserve bottom-up technological detail without sacrificing macroeconomic feedbacks involves the coupling of highly aggregated macroeconomic models with detailed models of the physical system. An example for transport is the analysis by Schafer and Jacoby (2006), which coupled a top-down (CGE) model with a bottom-up (MARKAL) model and a mode share forecasting model to evaluate the impact of climate policy on transportation mode shares and technology adoption. Other examples of this approach have been implemented for the electric power sector (Sue Wing, 2006) and for aggregated production and consumption activities in models (Messner and Schrattenholzer, 2000).

Still other models provide a system of fleet and fuel use accounting that forecasts the impact of individual technology scenarios (which are an input to the model). These scenarios may be carefully designed to achieve compliance with a particular policy target but do not typically capture the economic response. Models in this category include the Sloan Automotive Lab U.S. Fleet Model as well as the International Energy Agency's global fleet model (Bandivadekar et al., 2008; Fulton and Eads, 2004).

However, all of these approaches – and the CGE approaches in particular – are not generally capable of tracking both the economic and physical variables simultaneously and consistently within a single model framework. Few existing CGE models treat passenger vehicle transport explicitly in household consumption.

2.3. A strategy for modeling passenger vehicle transport in a CGE framework

We develop a model of passenger vehicle transport that introduces constraints on forecasts of economic and physical variables by implementing a technology-rich model structure and parameter calibration. The new model developments can be grouped into three categories, and are shown graphically in Fig. 1.

First, the model captures how expenditures on passenger vehicle transport will change with per capita income, as consumers increase their vehicle holdings and travel more miles according to their travel needs. The income elasticity of demand for VMT has been shown to