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Technology Detail in a Multi-Sector CGE Model: Transport Under Climate Policy

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Andreas Schafer and Henry D. Jacoby[†]

Abstract

A set of three analytical models is used to study the imbedding of specific transport technologies within a multi-sector, multi-region evaluation of constraints on greenhouse emissions. Key parameters of a computable general equilibrium (CGE) model are set to mimic the behavior of a model of modal splits and a MARKAL model of household and industry transport activities. In simulation mode, the CGE model provides key economic data to an analysis of the details of transport technology under policy restraint. Results focus on the penetration of new automobile technologies into the vehicle market.

Contents

1. TECHNOLOGY CHOICE AND MARKET INTERACTION

Simultaneous consideration of global market interaction and specific technology detail has long been a challenge to economic analysis of energy and environmental issues. Economic-market (top-down) models, with their array of intersecting markets, provide a consistent macroeconomic framework within which energy-economy-environment interactions can be examined. Because these models are designed to take account of the myriad interactions among sectors of an economy, and among countries through international trade, they cannot at the same time incorporate detailed specifications of particular technologies and devices that underlie the sector-level projections. To study technology-specific questions, analysts have applied engineering-process (bottom-up) models. Often formulated in a linear or non-linear programming framework, these models can incorporate the details of specific technologies and their costs. However, just as

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technological detail must be sacrificed in more aggregated economic-market models, engineering process models must simplify the representation of the wider economy in which technologies compete. In general, they take as exogenous both the levels of demand for energy services and the relative prices of fuels and other input factors, ignoring important feedbacks within the economic system.

The ultimate facility for analysis, of course, would be an all-encompassing model with full technology detail incorporated within a multi-nation, multi-sector general market equilibrium representation of the macro-economy. Unfortunately, because of constraints imposed by available computer algorithms, missing data, and limited human capacity to interpret results, such an approach would be overwhelming in its complexity. Analysts have thus tried to gain the joint advantage of these two methods by combining them. Böhringer (1998) and McFarland, Herzog and Reilly (2002) incorporate engineering-process representations of energy supply directly into general equilibrium models. Use of this approach for analysis of the transport technologies would face substantial barriers, as will be made evident in the discussion to follow. The most common approach, however, has been to couple a simple macro-economic sector, producing a single non-energy good, to an engineering process model that can handle the necessary energy sector detail—*e.g.*, Global 2100 (Manne and Richels, 1992) and MESSAGE-MACRO (Messner and Schrattenholzer, 2000). Despite the contributions made by these latter efforts, they are of limited use for analysis of a large energy- and emissions-intensive sector like transportation. Because they do not incorporate a multi-sector description of the economy, they cannot consider how transportation interacts with other sectors. Also, with only a single non-energy good, they can only roughly approximate the effect of international trade on the costs of goods, and therefore on the costs of labor, capital, and energy that feed into analysis of transportation technology. Finally, they are limited in their capacity to explore policy proposals that apply different forms of control or levels of stringency across the sectors of an economy.

In this research, we extend these earlier efforts by means of a loose coupling of a model of transport technology detail with a multi-sector, multi-region computable general equilibrium (CGE) model of the international economy. The parameters that determine substitution possibilities within the CGE structure are set at levels consistent with an engineering-process representation of transport technology, and a further calibration procedure is used to ensure consistency between the two models. It thus becomes possible to identify a set of specific technologies within the transport sector that are consistent with a particular general equilibrium simulation of climate policy. Also, in the process of constraining the CGE to be consistent with the engineering-process model, important insights are gained about potential errors in the selection of elasticity values in the CGE context, and about the shortcomings for policy analysis of the technology representation in engineering models.

The approach is summarized in **Figure 1**, which shows the two main steps involved. Parameter changes to achieve consistency among the models are shown by unshaded arrows in
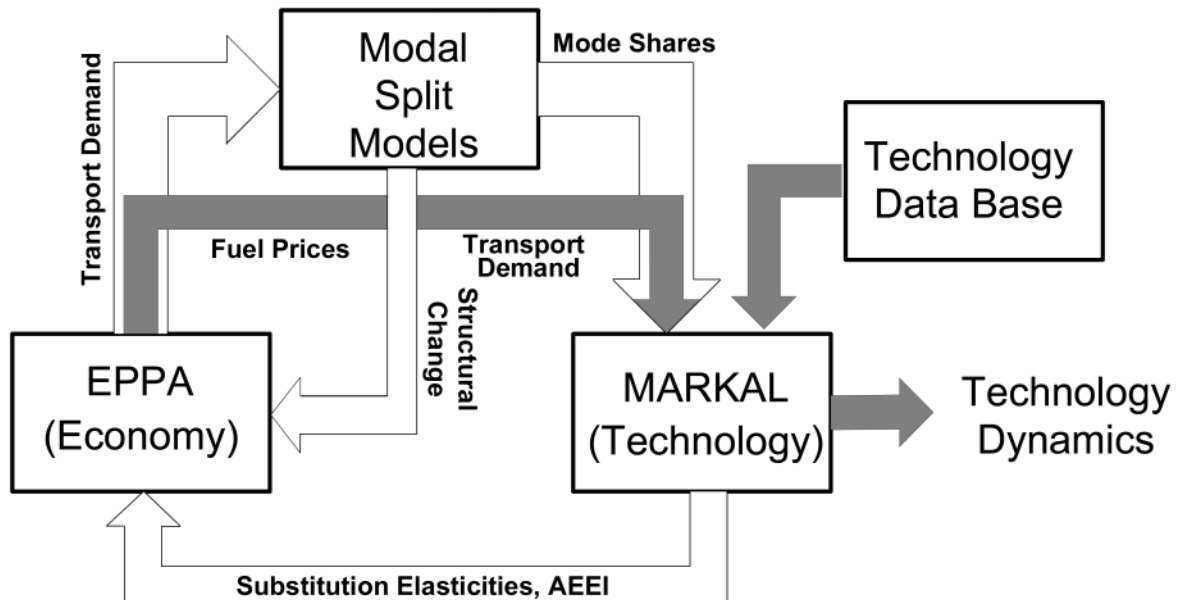
Figure 1. Linked model systems, consisting of the Emission Prediction and Policy Analysis (EPPA) model, the modal split models of passenger and freight transport, and the systems-engineering MARKAL model.

the figure. Shaded arrows show the simulation of reference and policy cases. The MIT Emissions Prediction and Policy Analysis (EPPA) model, described below, is used to produce a multi-sector, multi-region simulation of economic growth, technical change, and emissions. A MARKAL or engineering-process type model of the transport sector is used to analyze particular technologies that can meet the various transportation demands within the economy, given estimates of overall economic activity, associated transport demand, and the relative prices of fuel and other inputs. A third model, of modal splits in transportation, is applied to connect the aggregate transport sector of the EPPA model to the technology detail of MARKAL.

In this application the needed inter-model calibration is essentially one-way. That is, the maintained hypothesis is that the MARKAL model and the model of modal splits contain the correct representation of transport technology, its change over time and its response to various incentives. (Based on the results, this hypothesis is questionable, as discussed in Section 5.) These sector details are below the aggregation level of the CGE structure, and EPPA parameters are adjusted so that its transport sector mimics this sub-scale behavior. Thus, as shown in the figure, modal splits are imposed from the separate model of this process, and substitution elasticities are adjusted to mimic the MARKAL behavior. (Base-year EPPA conditions determine the interest rate used in MARKAL's technology costing, discussed below.) Finally, not shown in the figure is an overall calibration step using a key technology variable (the AEEI) in the EPPA model as an instrument. Convergence between the models is defined in terms of the total energy use in the transport sector.

Then, in the simulation stage sectoral level results from the EPPA model, including economic parameters (prices, taxes) and sector-level transportation demands, are fed to the MARKAL model.

Emissions control policies are applied at the level of the EPPA model, which determines the allocation of the task among sectors (or among nations under emissions trading) along with the resulting adjustments in transport demand and key input prices. The MARKAL results then provide a picture of the specific adjustments in transport technology that are consistent with the economy-wide adaptation to climate policy. The procedure has the flavor of earlier model developments, such as Global 2100 and MESSAGE-MACRO, but it differs from them in the introduction of sectoral detail in the representation of the macro economy. The formulation developed here will allow a more complete representation of feedbacks within the economic system, and permit study of climate policies that impose different levels of restriction among sectors.

Not surprisingly, a number of problems arise in attempting a loose coupling of models with such different structures. The EPPA and MARKAL models are based on different data sets: EPPA is constructed on a social accounting matrix stated in value terms, whereas MARKAL is built up from physical flows. Despite efforts by the groups who prepare these data sets, substantial problems remain in gaining consistency. Also, the two models have different underlying analytical structures. A key task in this research, therefore, is to investigate whether models of this form can be productively linked to meet the requirements introduced above, and whether informative results can be drawn from the exercise.

We begin our exploration of these questions in Section 2 with a description of EPPA and MARKAL. Section 3 discusses the Modal Splits model and subscale adjustments to EPPA parameters. The overall calibration step is summarized in Section 4. Section 5 presents an application of the resulting three-model system, and includes a discussion of modeling issues that are highlighted by the results. Conclusions and suggestions of follow-on work are provided in Section 6.

2. THE CGE AND ENGINEERING PROCESS MODELS

2.1 The EPPA Model of Emissions and Policy Cost

The version of the EPPA model used in this study is a recursive-dynamic, multi-regional general equilibrium model of the world economy (Babiker *et al*., 2001). This model is built on the GTAP4-E energy-economy data set (Hertel, 1997), and the calculations shown here apply the GTAP4-E version of this information resource. The base year of the model is 1995, and it is solved in 5-year time steps. Although the model is capable of analysis encompassing all greenhouse gases, for purposes of simplicity in method development, the calculations shown here focus on the most important gas, CO_2.[1]

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[1] Also associated with the transport sector are emissions of N_2O and black carbon from fossil fuel combustion and HFCs from auto air conditioning. Motor vehicles also are a major source of gases important to the atmospheric chemistry of the greenhouse effect, including CO, NO_X and NMVOCs (Reilly, Jacoby and Prinn, 2002).

Model Structure, and Sector/Regional Aggregation. The GTAP4-E database identifies 22 sectors and 45 nations or regions. For this research, the model is aggregated into 12 regions as shown in **Table 1**. The production side of the economy is aggregated into nine sectors, four producing non-energy goods and services and five producing various forms of energy. In addition, two future energy supply or "backstop" sectors are included. The data set used here involves one modification of GTAP4-E. GTAP does not identify a separate transportation sector, but rather combines transport with trade margins. Neither does it include a separate category for private automobile services within the household sector. Following procedures developed by Babiker *et al*. (2000) corrections have been made to yield a transport-only sector on the production side and to disaggregate transportation services consumed by the household sector into own-produced and purchased components.

The model's equilibrium framework is based on final demands for goods and services in each region, arising from a representative agent. Final demands are subject to an income balance constraint with fixed marginal propensity to save. Investment is savings-driven, and capital is accumulated subject to vintaging and depreciation. Household consumption in each region is financed from factor incomes and recycled carbon tax revenue. Other taxes apply to energy demand and factor income, and international trade, and the proceeds are used to finance an exogenously grown level of public provision.

Energy goods and other commodities are traded in world markets. Crude oil is imported and exported as a homogeneous product subject to tariffs and export taxes. All other goods, including

Table 1. Dimensions of the EPPA Model

Model Sectors	Name		
Production		**Countries and Regions**	
Non-Energy		***Annex B***	
1. Agriculture	AGRI	United States	USA
2. Energy-Intensive Industries	EINT	Japan	JPN
3. Other Industries and Services	OIND	European Union	EEC
4. Transportation	TRAN	Other OECD	OOE
Energy		Former Soviet Union	FSU
5. Crude Oil	OIL	Central European Associates	EET
6. Natural Gas	GAS		
7. Refined Oil	REFOIL		
8. Coal	COAL	***Non-Annex B***	
9. Electricity	ELEC	Brazil	BRA
Future Energy Supply		China	CHN
10. Carbon Liquids		India	IND
11. Carbon-Free Electric		Energy Exporting Countries	EEX
		Dynamic Asian Economies	DAE
Household	H	Rest of World	ROW
Own Transportation	HO		
Purchased transportation	HP		
Other goods and services			

energy products such as coal and natural gas are modeled as differentiated products, with an explicit representation of bilateral trade flows. Energy products are sold at prices that differ between industrial customers and final consumers.

National emissions reduction targets are assumed to apply to a 1990 baseline of fossil carbon emissions, and to be achieved by a reduction in fossil fuel burning. In fact, implications of any reduction commitment will depend on the treatment of non-CO_2 gases, and carbon sinks, in any international agreement. Depending on the region, the inclusion of all gases and sinks, in the baseline and in the control regime, yields an average control cost that is 20% to 35% lower than that estimated from a carbon-only analysis (Reilly *et al.*, 1999; Reilly, Jacoby and Prinn, 2002). Were the analysis below extended to all gases and carbon sinks, both the welfare effects of any restriction policy and the effects on introduction of new technologies would be reduced, because less stringent restrictions on fossil fuel emissions here regarding the joint use of top-down and bottom-up would not be affected by such an extension.

Transportation in the Household and Industry Sectors. Transportation, as other sectors, is modeled as a nest of constant elasticity of substitution (CES) functions (Babiker *et al.*, 2001). The structure of household transport is shown in **Figure 2**. Aggregate household consumption is divided between transport and goods that are the outputs of the non-transport EPPA sectors. Household transport demand, D_H, then is made up of two components: household-own (D_{HO}) and household-purchased (D_{HP}). Own transport includes the services of privately owned vehicles; purchased transport, supplied by the transport industry sector, includes travel by air, bus and train—a category dominated by air transport. In the original EPPA model, the mode choice between own and purchased transport is determined by an elasticity σ_{OP}.
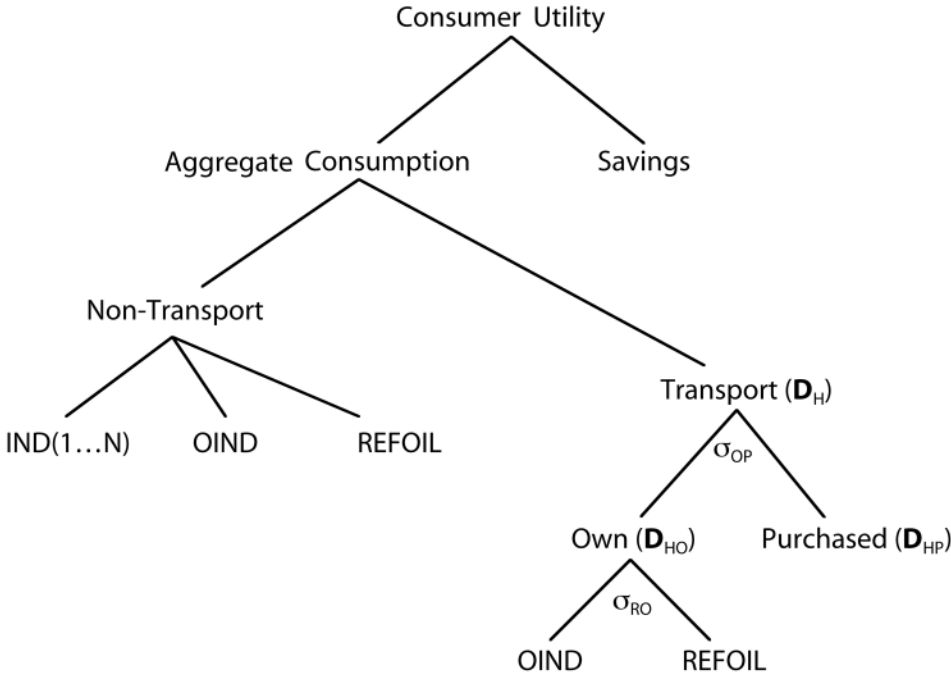
Figure 2. Structure of transportation within the household sector.

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As shown in Figure 2, own transport is modeled as requiring inputs of vehicle manufacture and services from the Other Industries and Services (OIND) sector and fuel from the Refined Oil (REFOIL) sector. Thus another key elasticity is σ_{RO}, which determines the substitutability of OIND for REFOIL in supplying this service. In the original EPPA model, this parameter is constant over time.

Two aspects of transport system structure are considered in the linkage with the MARKAL and Modal Splits models, each of which involves phenomena beneath the level of detail of the EPPA model. One is the shift from private vehicles to air in passenger transport, which will involve replacing σ_{OP} with a time-dependent function. The other is a re-estimation of σ_{RO} based on detailed data on technology change in the private automobile. These changes are discussed in Section 3.

Figure 3 shows the structure of the sector that produces transport within the US economy, supplying both inter-industry demand ($\mathbf{D}_I$) and air, bus, rail transport purchased by households ($\mathbf{D}_{HP}$). Here the key substitution is between energy and value added (labor and capital) in the production of these services, as indicated by the elasticity σ_{EVA}. This last parameter also is re-estimated based on detailed representations from MARKAL, as discussed in Section 3.

2.2 The MARKAL Model of Transport Technology

Model Structure. MARKAL (MARKet ALlocation) is a bottom-up, dynamic linear optimization model (Kypreos, 1996). First developed in the 1970s, the model has undergone continuing refinement and extension, coordinated by the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency. Central to MARKAL is the so-called reference energy system (RES), which represents a user-specified network of energy technologies. The RES can cover the entire energy system and range from fuel extraction to processing, transmission and distribution, storage, and demand for energy services at the end-use level. The model generates that supply structure within the domain of the RES that minimizes total discounted cumulative costs. It does this by choosing the best mix of fuels (here only oil) and technologies out of the associated database. The key output of MARKAL for our purposes is the technology dynamics, *i.e.*, the specific technologies (specified in the database) that would be used at every time step to satisfy the projected demand while meeting a constraint such a CO_2 emissions target (*e.g.,* Kypreos, 1996).
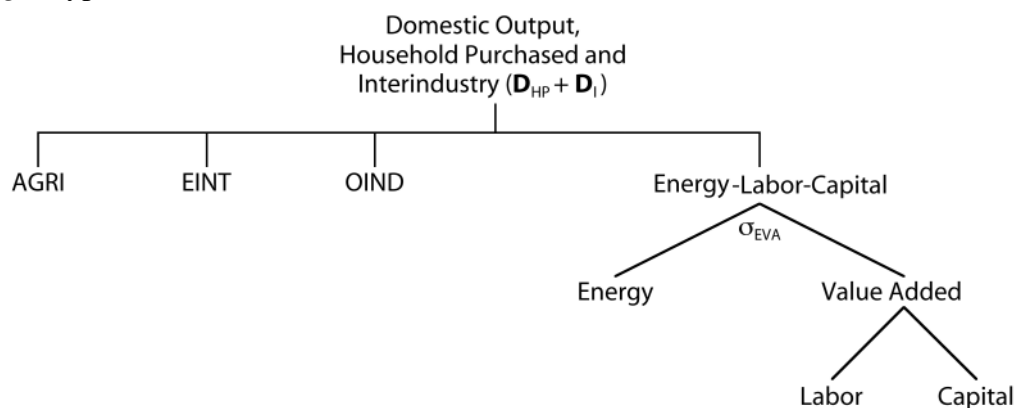
Figure 3. Structure of production within the transport industry sector.
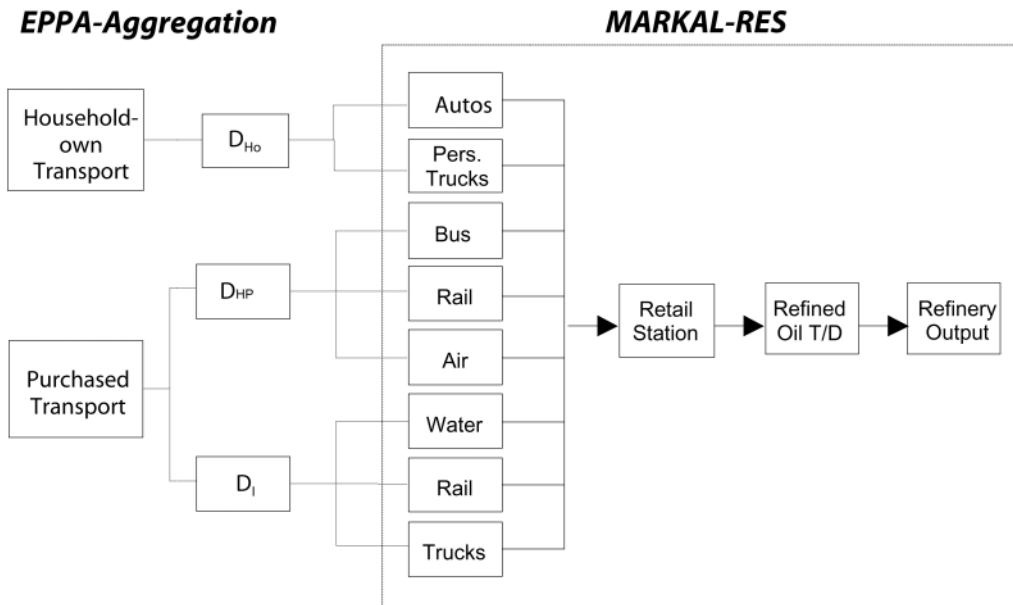
Figure 4. MARKAL Reference Energy System and associated EPPA sector aggregation.

Figure 4 reports the reference energy system developed for this application. The fuel efficiencies of the individual transport technologies (passenger aircraft, passenger railways, buses, automobiles, personal trucks, inland waterways, freight railways, and freight trucks) convert the demand for energy services into energy use, which is then augmented by losses in each of the components of the fuel delivery system, i.e., gasoline retail stations and transmission/ distribution. The calculated refinery output must ultimately be consistent with EPPA transport sector energy use, as discussed in the calibration section below.

Technologies are specified that can be used to meet the demands placed on transport sub-sectors. Due to their significant energy use and greenhouse gas emissions, and flexibility in technology choice, automobiles, personal trucks, and various types of freight trucks are represented by multiple, competing technologies in the technology database. By contrast, the menu of aircraft technologies is limited (and difficult to obtain), and is represented by only one technology with increasing fuel efficiency over time—as are all other end-use technologies (buses, railways, and barges) due to their low level of energy demand (Buses, passenger railway, freight railways, and internal waterways accounted for only 3.4% of final transport energy use of all modes in 1995.) Each technological option is described by performance and cost characteristics. Among these are the type and amount of energy used to generate one unit of transport, the initial investment cost and equipment lifetime, and fixed and variable operating costs. Costs are stated in dollars per pas-km or ton-km, using an estimate of the number of km per year per unit of transport capacity and a discount rate to convert initial capital cost to a levelized cost over the technology's lifetime.

Technology Specification. For this application, the MARKAL database contains the technological and economic characteristics of current and future technologies, from fuel

production, through transmission and distribution, to end-use. The model is calibrated to the (1995) base year using technology data so that it reproduces the 1995 energy flows reported by the International Energy Agency (IEA, 2000), given the corresponding demand for transportation services. **Table 2** reports the characteristics of the automobile technologies in the MARKAL model's database, which are based on two recent Sierra Research reports (Austin, Dulla and Carlson, 1997, 1999) financed by the automobile industry and the Canadian government.[2] MARKAL can substitute the existing automobile fleet by more fuel efficient but also more expensive vehicle technologies, ranging from zero-cost measures, mainly through reducing driving resistances (ZeroCost) to very high-cost solutions, such as aluminum-intensive hybrid drivetrain automobiles (Hybrid).

For analysis of the tradeoff between vehicle cost and fuel efficiency, MARKAL converts the cost data of Table 2 to an annualized basis, which requires an estimate of the average life of vehicles and a discount rate. That rate should be consistent with the database underlying the EPPA model. Unfortunately, although there is a price of capital services in the EPPA model, the figure is not an appropriate representation of the behavior of the car-buying public.[3] However, the time preference behavior of consumers is reflected in the GTAP cost shares in household transport. Therefore the discount rate was set at that level that would, in the base year, yield the same cost shares in the MARKAL results as appear in the EPPA data. This figure was 33%, which is consistent with other studies of consumer behavior.[4] The procedure resulted to a slightly lower value of 29% for the purchased transportation subsector.

Table 2. Personal Transport Technologies, technology description, fuel use, and retail price. Technology data is derived from Austin, Dulla, and Carlson (1997, 1999).

Name	Characteristics	Fuel Use L/100km	Retail Price US$(95)
95 Flt	Existing fleet in 1995	10.1	18,250
ZeroCost	Improved packaging, engine management, lower drag coefficients	9.3	18,230
LoCost	ZeroCost + Lightweight interior, CVT, high-strength steel unibody	8.0	18,580
PowTrn1	LoCost + higher compression ratio	7.9	18,630
PowTrn2	PowTrn1 + VVLT and cylinder deactivation, electronic power steering, lower parasitic losses	7.3	19,070
Alum	PowTrn2 + aluminum intensive vehicle instead of high-strength steel	6.4	20,240
Hybrid	Alum + ICE hybrid drivetrain, elimination of brake drag	5.0	22,370

[2] Details of the specification of transportation and energy use data applied are available from the authors.

[3] The GTAP data set contains estimates of capital flows in the base year, but no estimate of the national capital stock. For purposes of investment and depreciation accounting such a stock figure is needed, and a discount rate is used in calculating it. Otherwise, the recursive-dynamic version of EPPA (as used here) does not yield a national interest rate.

[4] In combination with a vehicle lifetime of 15 years, an annual discount rate of 33% results in a capital recovery factor of nearly 34% per year. Thus, the extra costs associated with a more fuel-efficient vehicle would be recovered after three years. Such short time horizons are typical for the vehicle market (Greene and Schafer, 2003). Similarly high discount rates were estimated for the air-conditioning market (Hausman, 1979)

The rate of substitution of an existing vehicle fleet by a more fuel-efficient technology is limited by the natural rate of vehicle turnover and the maximum rate of introduction of new technology. The latter in turn depends on the vehicle production capacities, which also were derived from the Sierra Research reports (Austin, Dulla and Carlson, 1997; 1999). The corresponding market penetration constraints were estimated with a vehicle stock model that—based on the number of vehicles, their vintages, lifetime, and other scrappage curve characteristics—simulates the fleet turnover of the U.S. light duty vehicle sector. The resulting market penetration constraints were then input to MARKAL in physical units of pas-km and ton-km.

3. SUB-SCALE ADJUSTMENTS TO EPPA

3.1 Household Transport Shares by Mode

For sub-scale adjustments to the EPPA model, and subsequent simulation of the technology details consistent with EPPA projections, transport demand must be disaggregated to the level of detail needed for analysis of specific technologies. This step is carried out using a Modal Splits model (Schafer and Victor, 2000). The modal split calculations are based on per-capita variables (income and travel demand), which for simplicity we ignore here. (The mode split in industry transport, carried out only at the simulation stage, is discussed in Section 5.1.) Household demand is divided into high-speed modes (air travel and fast trains) and low-speed modes (private vehicles, bus and train). Then, particularly important for the United States, the private vehicle or "own" component is further divided among cars and light trucks (the latter including sport utility vehicles, pick-up trucks, and vans). Within the industry component, total transport demand needs to be distinguished between trucks, rail, and ships (the last mainly associated with international trade), the volume of air freight traffic being negligible. Our focus is on analysis of the single most important component of this sector: the technologies supplying household-own transport.

For an initial calculation used in computing this adjustment to EPPA, and for later joint simulation of the two models, a connection must be made between the two models. Travel demands in EPPA are in value units, whereas the MARKAL model deals with transportation demand in physical terms: passenger-kilometers (pas-km) or ton-kilometers (ton-km). The task is to convert $\mathbf{D_I}$ into D_I and $\mathbf{D_H}$ into D_H, where D_I and D_H indicate demands in physical units. Given base-year measures of passenger and freight demands, $D_I(t = 0)$ and $D_H(t = 0)$, demands for each future period are calculated by a scaling procedure. Note that this procedure assumes that increases in transportation service demands in value terms translate proportionally into pas-km and ton-km.

The model of mode choice in household transport is based on data regarding recent decades of consumer behavior, which shows that people tend on average to dedicate a fixed share of time to travel (*e.g.,* Zahavi, 1981). Although the time spent varies slightly between urban and rural settings, the relationship is remarkably consistent at about 1.1 hours per person per day over a wide range of income levels, at least at the national and regional aggregation used in this analysis. On the assumption that this behavior is likely to remain stable, at least for a few more decades, it

can serve as the basis of a model of future modal splits. This behavioral assumption then needs to be supplemented by information about the structural characteristics of the particular region under study. The share of low-speed public transport (buses and railways) is conditioned by established patterns of urbanization and existing transport infrastructure. Similarly, the share of train transport, forecast over the next few decades, is heavily influenced by the inherited rail system. With initial estimation of these two components, plus estimates of average speed of "own" transport (cars) and high-speed transport (air and fast train), the imposition of a travel time budget can be used to estimate the shares of these last two modes (see Schafer and Victor, 2000).

For incorporation in the EPPA model this information is aggregated into household "own" transportation *via* the private light-duty vehicle, D_{HO}, and household "purchased" transport, D_{HP}, which is a an aggregate of bus, rail and air. It is convenient to introduce this split into the EPPA logic in functional form (rather than as a table of results) so this modal split is fitted by a logistic equation in the growing purchased component, with the own component as a residual. The resulting relationship for the US is presented in **Figure 5**, and the shift from light-duty vehicles to aircraft, as people increase travel under a fixed time budget, is clearly shown. This sub-scale behavior is imposed in the EPPA model by setting the CES elasticity between these two components, D_{OP} in Figure 3, to zero and imposing the modal shift directly through adjustments over time in the share parameters in the CES function.
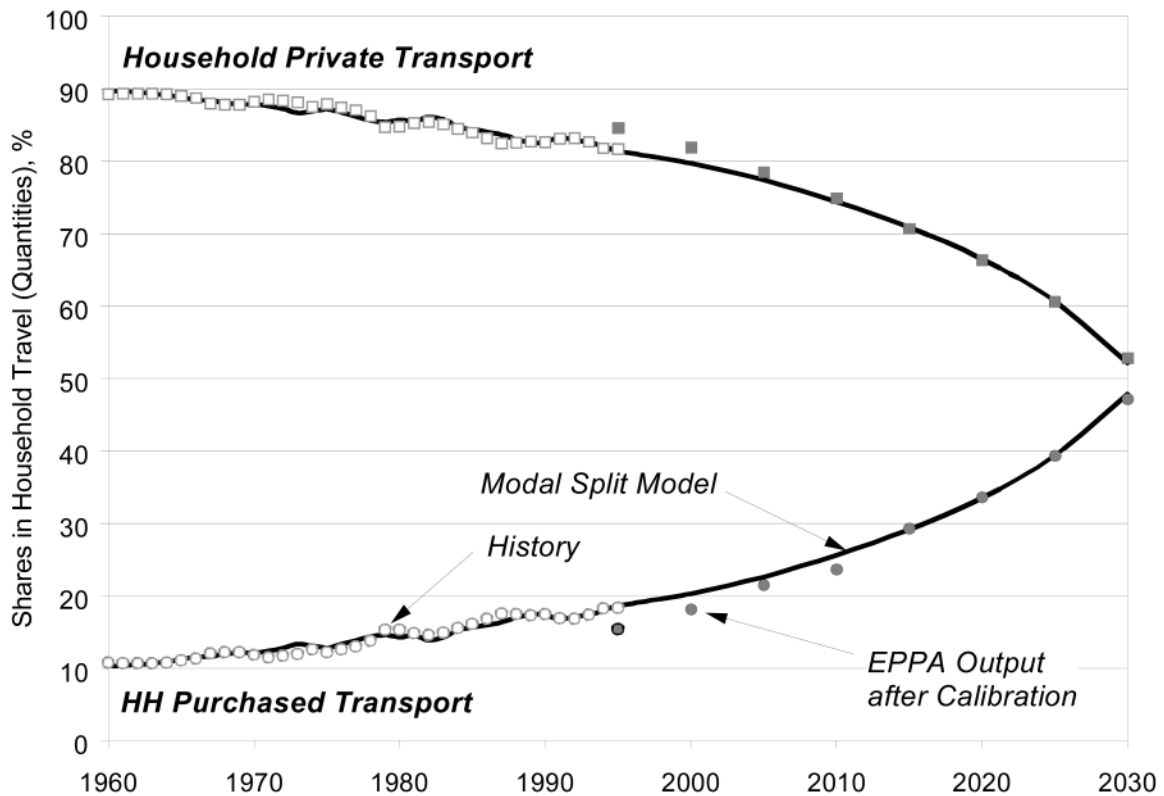
Figure 5. Structural Change in Passenger Transport, Historical Development (1960-1995) and Projections (through 2030).

3.2 Representation of Transport Technology

Household Own Transportation. EPPA does not have a facility for reflecting ways that technology change may influence the ease of substitution of capital and other factors for energy, in response to relative price changes. The MARKAL structure, on the other hand, contains data about various automotive technologies that are expected to become available at various times over the next few decades, and thus this tradeoff is modeled as changing over time. In this circumstance the normal procedure, assuming that the ease of substitution between energy and other inputs (denoted σ_{RO} in Figure 3) is constant over time, would not be consistent with the assumptions underlying the technology description in the MARKAL component of the linked set of models. To reflect this change, the σ_{RO} is adjusted over time in the EPPA model.[5]

The procedure involves the estimation of σ_{RO} as represented in the MARKAL structure for different periods in time. The later the time period the greater the substitution possibilities, because new technical options become available in the interim. To simulate this effect, the MARKAL model is run through 2030, using household-own transportation taken from the EPPA model, computing the penetration of light-duty vehicles and the resulting fuel use. This is done for a range of fuel prices. The higher the fuel price the stronger the penetration of more expensive energy-saving vehicle technologies, and the lower the level of energy use. **Figure 6**A shows the resulting relationship between change in energy use (REFOIL) and inputs from Other Industry Products and Services (OIND) for light-duty vehicles. The data points result from eleven oil price scenarios at seven future points in time. (Because several oil price scenarios result in the same solution, some of the data points overlap at a given year). As a reference point for normalizing energy use and capital services we used a MARKAL model run with constant refined oil prices at US$ 10/GJ (about the 1995 gasoline price). Since cost-effective vehicle substitutions already occur in that scenario, the relationship shown in Figure 6 reports only *price induced* changes of the energy-other industry relationship at different points in time.

CES functions are fitted through the data points for each of the seven future years (from 2005 through 2030), by adjusting σ_{RO} in the D_{HO} branch of the production function shown in Figure 3. The estimated elasticities increase from 0.014 in 2005 to 0.126 at the end of the period. The time profile of the resulting σ_{RO} is fitted by a logistic curve, illustrated in the insert to Figure 6A, for entry into the EPPA model. The relationship in Figure 6A does not exactly follow a CES function. At stronger reductions in energy use, the associated increase in capital services is less than that resulting from a CES function. This inconsistency suggests one area where we cannot expect a perfect match in energy use between the MARKAL and EPPA model.

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[5] Similar adjustments might be made for other sectors in the EPPA model, most productively in electric power, but such additions would lead this CGE framework in the direction of a full multi-sector CGE-bottom-up analysis, which we argued above would be too complex to yield satisfactory results.
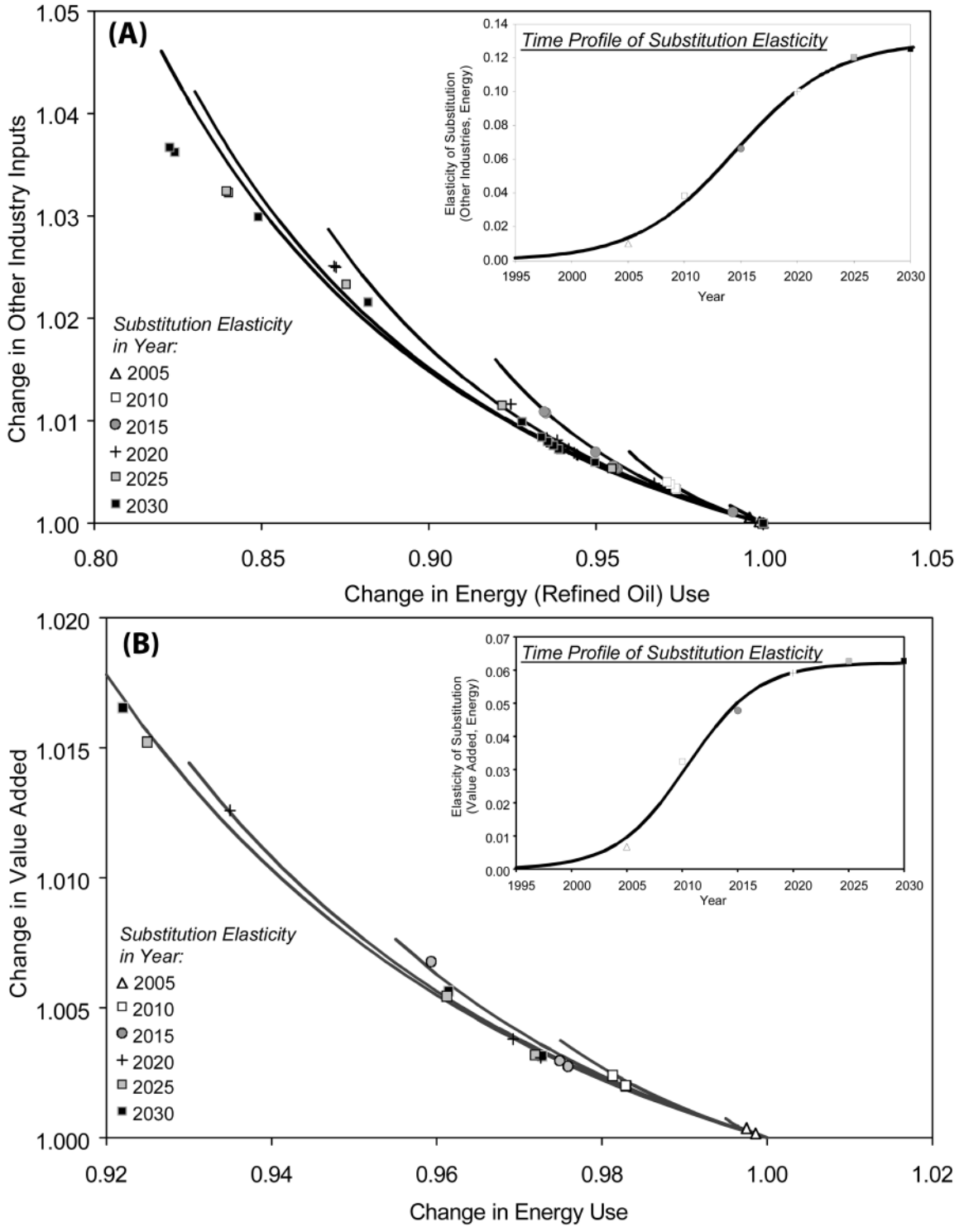
Figure 6. Calibration of substitution elasticties in household own supplied and purchased transportation. The data points result from MARKAL Model simulations, while the continuous CES curves are fitted through the data points of each time step. **(A)** Substitution of "other industry" inputs for light-duty vehicle energy (refined oil) use in household own-supplied transportation. **(B)** Substitution of "value added" for energy (refined oil) use in purchased transportation.

Purchased Transportation. Following a similar approach, the elasticity of substitution between energy and value added in the transport energy sector, σ_{EVA} in Figure 4, was calibrated using a time-dependent function shown in Figure 6B. The 2030 level of the substitution elasticity rises only to 0.062, only half of that in household own transportation. That lower level results from the handling of the purchased transportation subsector in this application, where only freight trucks are represented in detail; all other modes of this subsector are represented by only one technology, each with improving energy efficiency over time (see the discussion on the AEEI below). The substitution elasticity's (constant) value in the original EPPA model was 0.5 for both household own and purchased transport.

4. CALIBRATION USING THE AEEI

Recall that the objective of the multi-model analysis is to develop a picture of the detailed technologies in the transport sector that are consistent with a multi-sector analysis of policies to control CO_2 emissions. For this analysis to be valid, then, the EPPA and MARKAL representations of this sector should give the same pattern of transport energy use for a particular policy. To summarize the model linkage to this point, several steps have been made to seek this consistency:

- The discount rate in MARKAL was set to be roughly consistent with the closest analogy in EPPA.
- The expected change in mode choice in the household sector, as represented in a Modal Splits model, is imposed by an adjustment over time in shares within the CES structure of EPPA.
- Expected change in the technology of cars and light trucks, as represented in the MARKAL model, is imposed in the EPPA model in a time-dependent elasticity of substitution in this part of the CES structure. The technology substitution possibilities in the purchased transport sector are similarly estimated.

Even with these direct connections and adjustments for details of structure, however, further calibration is required. Aside from the dramatic differences in mathematical structure, several factors contribute to the inconsistency. For example, technology change in personal transportation occurs in the MARKAL model even at constant fuel prices, but the representation of this change shows up in EPPA only under the pressure of changing prices. Also, the changing mix of autos and light trucks is not reflected in EPPA.

To correct for these factors, the EPPA model's AEEI parameter for household personal transport is adjusted in calibration runs at constant energy prices. An iterative procedure was followed. In the first iteration, EPPA was run with the modal splits and σ_{RO} and σ_{EVA} values as derived above with no autonomous changes in energy intensity (AEEI = 0), and a constant oil price through 2030. The run yields an estimate of total energy use in household own transportation (D_{HO}) and total purchased transportation (D_{HP} and D_I). These transport demands are input into the MARKAL model as an exogenous demand. The subsequent MARKAL model run (at constant fuel prices) then provides the vehicle technology mix through 2030 and the associated energy use.

The latter was aggregated to household-own and total purchased transport (household purchased plus freight) and compared to the numbers resulting from EPPA. Subsequent iterations of the linked model runs with new AEEIs and the associated EPPA-derived transport demands for household-own, household purchased, and freight transport were then made until a sufficiently close convergence of energy use for the two transportation demand categories was achieved.

The trajectory of the AEEI parameter for the transport sector that is required to yield this convergence is shown in **Figure 7**. As shown there, the AEEI for Household Own transport declines steadily over time. This behavior is the net result of counteracting influences: the penetration of more fuel-efficient vehicles into the fleet, and the substitution from automobiles to more energy-intensive light trucks. For Purchased transport the adjustment starts at a rate that is high in relation to common assumptions about this parameter at higher aggregations (Babiker *et al*., 2001) and falls over time. This behavior also is reasonable, because it reflects the initially high (and exogenously assumed) energy efficiency improvements in especially aircraft technology and endogenous technology substitutions within freight trucks at constant fuel prices especially before 2020.

The reference AEEI applied to this sector in previous studies, where transport was aggregated into Other Industries and Services, was in the neighborhood of 1.0% per year (Babiker *et al*., 2001). In the EPPA version used here, with transport broken out, this parameter was left at 1.0% for purchased transport, but set to zero for the household-own portion. Analysis of uncertainty
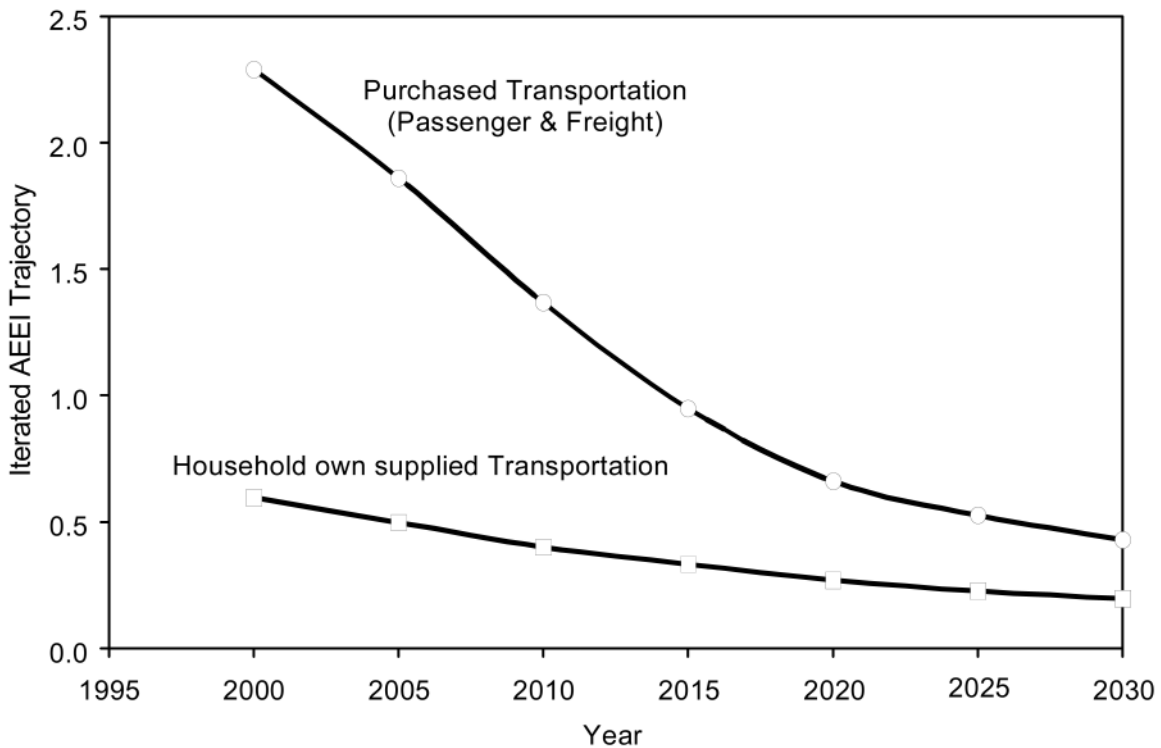
Figure 7. Trajectory of Autonomous Energy Efficiency Improvements (AEEI) for Household-Own (D_{HO}) and Purchased Transport ($D_{HP}+D_I$).
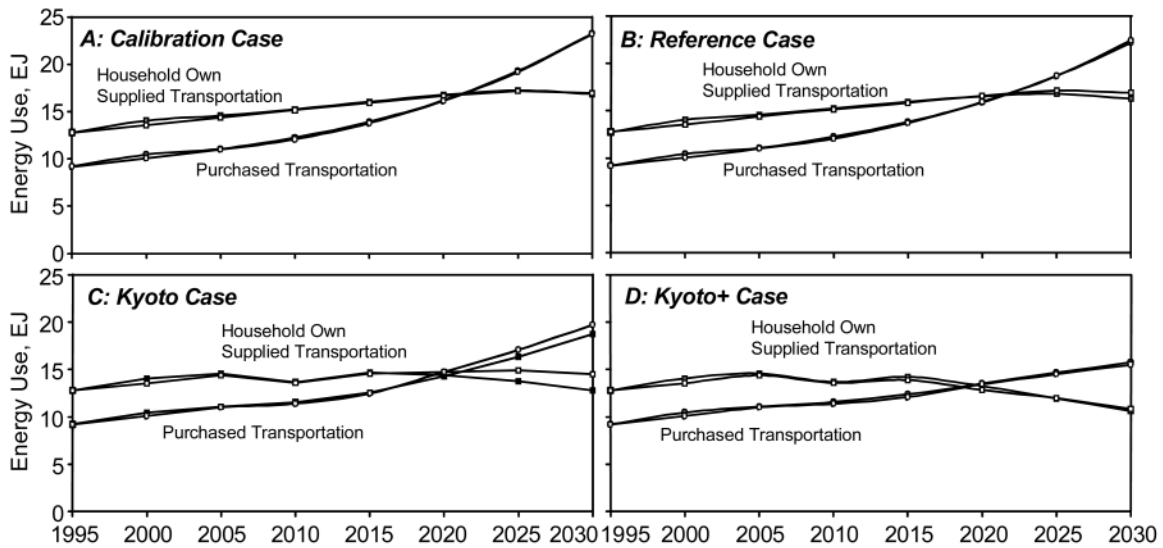
Figure 8. Energy Use in household own supplied and purchased transportation in four cases. EPPA model: black data points, MARKAL: white data points.

in this parameter for the Other Industries and Services aggregate (Webster *et al.*, 2002) indicates a one-sigma bound of about 0.6 to 1.3, so the corrections required here are largely within the level of uncertainty in the EPPA construction. The calibration using the AEEI, which was conducted at constant fuel prices, is shown in **Figure 8**A. This calibration is maintained throughout the remainder of the analysis, even when prices are changing.

5. MULTI-MODEL APPLICATION TO CLIMATE POLICY

5.1 Model Linkage: EPPA Variables to MARKAL

In simulation mode, various policy assumptions are imposed in the multi-sector EPPA model, and resulting economic variables (fuel prices and taxes) and transport demands are passed to the MARKAL model of transport technology, as illustrated in Figure 1. In the adjusted EPPA model, transport demand is represented in three components: an industry demand (D_I) and a household demand divided into own (D_{HO}) and purchased (D_{HP}) components.

For input into the MARKAL model, the division of D_{HP} in the Modal Splits model is maintained between air (and fast train) and bus and train transport. Then, because of important differences in technology within the light-duty vehicle category, D_{HO} is disaggregated into automobiles and light trucks (SUVs, pickup trucks and vans). We have estimated the growing share of light trucks with a logistic curve, increasing from 29% of the light-duty vehicle fleet in 1995 to 47% in 2030, ultimately saturating at 50% in 2050.[6]

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[6] Our current system of models is not yet capable of incorporating the influence of rising fuel prices on the modal shift among types of light-duty vehicles, so sensitivity tests were employed to examine the effect of a possible shift away from light trucks and back toward standard automobiles in a policy scenario. These tests resulted in an energy use in household-own transportation that is only a few percent below the amount in the case with the continuously rising share of light trucks examined here.

Freight transportation is an intermediate demand, driven by inter-industry flows in the EPPA model. As first approximation, we assume mean transport distances to remain constant. The quantities of total freight transportation demand (in ton-km) in each time period are obtained by scaling the EPPA model-derived quantities in value terms. Ideally the split among freight modes would be derived directly from the sectoral flow within the inter-industry matrix. For example, while waterways and railways ship raw materials to energy-intensive industries, heavy trucks typically transport the higher-value goods leaving them. Unfortunately, the rough aggregation of industrial sectors within EPPA does not support a unique allocation of inter-sectoral material flows to the appropriate transport modes. For purposes of testing the linked model, therefore, we have followed a very simple approach. Based on the historical development of the freight modal split from 1970 through 1995, we have extrapolated the declining shares of railways and waterways as a function of ton-km (the latter being closely coupled to GDP). The rising share of truck-based ton-km then is calculated as a residual of the other two modes (the share of airborne ton-km being negligible).

5.2 Assessment of GHG Emissions Targets

As a basis for the analysis we construct a reference run in which oil prices remain at their 1995 level until 2010 when the EPPA resource model is activated. The calculation results in a 40% higher price for refined oil in 2030 compared to 1995, as shown in **Figure 9**. The rising oil
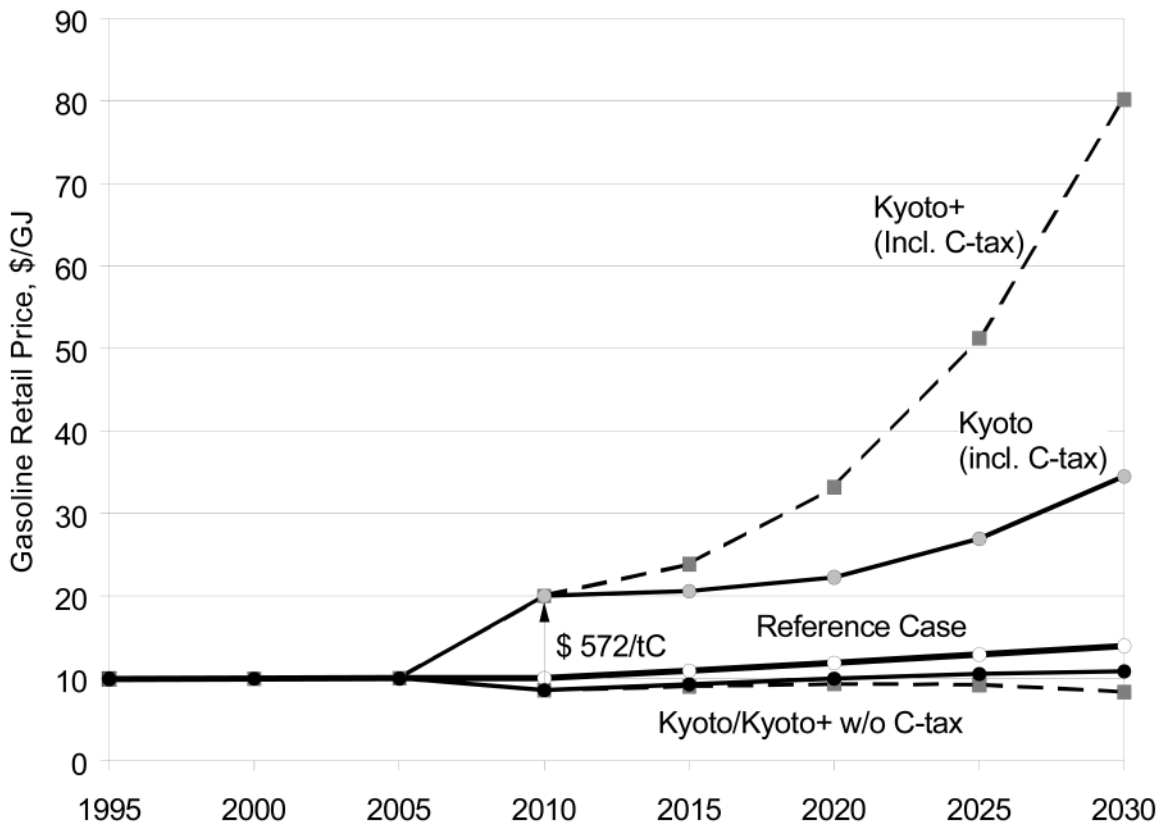
Figure 9. Refined Oil (Gasoline) Price Development.

price slightly reduces the transportation demand compared to the constant-price calibration run, culminating in a loss of 0.3, 2.6, and 0.5% in 2030 for D_{HO}, D_{HP}, and D_I, respectively.

The resulting reference-case subsector energy use for household-own and purchased transportation from both models, EPPA and MARKAL, is shown in Figure 8B. Mainly because of the shift from household own supplied transportation to aircraft (which are included in the purchased transportation sector), energy use of the former stabilizes at about 2020. The associated selection of automobile technology in the calibration run and the reference run with rising oil prices is shown in **Figure 10**A and 10B. (Light trucks—SUVs, pickups and vans—follow a similar pattern.) The combination of capital and fuel savings make the *ZeroCost* technology vehicle cheaper than the 1995 fleet, so it displaces *95 Flt* technology already in a world with constant gasoline prices about US$1.20 per gallon, as seen in the calibration case in Figure 10A. This transition occurs in both the autos and the light trucks. The market penetration constraints imposed on MARKAL ensure that it takes about two mean vehicle lifetimes minus the mean age of the existing fleet or slightly more than 20 years to turn over the *95 Flt* in the calibration case. Note that more advanced vehicle technologies than *ZeroCost* do not enter the market. Essentially the same picture of technology penetration is maintained, when oil prices increase slightly after 2010 in the reference case.
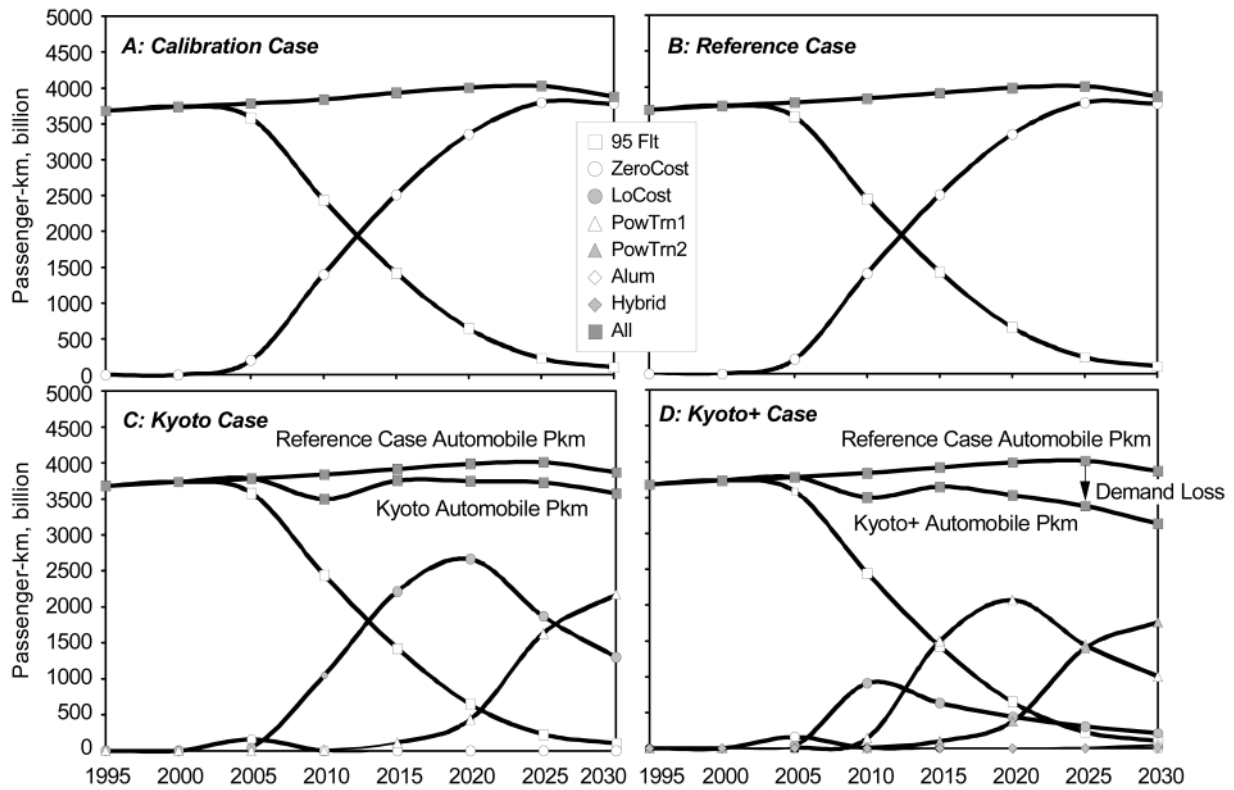
Figure 10. Automobile Technology Dynamics.

We now explore how the transportation sector may adjust to a greenhouse gas emission target, with a focus on automobiles. We consider a scheme that corresponds to the proposed Kyoto protocol target for the US, *i.e.*, a reduction to 7% below 1990 greenhouse gas emissions by 2010. We then maintain the 2010 emission level through 2030. **Table 3** summarizes the percentage change in carbon emissions in each of the end-use sectors (including the carbon associated with electricity use), and electricity generation separately, in this Kyoto-like case, as compared to the reference case. Based on the assumptions mainly with regard to the substitution elasticities and the AEEI in each of the sectors, energy use in transportation declines the least. However, before drawing definitive conclusions about relative sector contributions, more careful analysis would need to be dedicated to the key parameters determining technology change and consumer behavior in the sectors other than transportation.

Under this constraint, total transport demand (household own, household purchased, and freight) is reduced by up to 16% compared to the reference run, in the three transport sub-sectors. That decline occurs because of losses in GDP and higher prices of fuel and capital. The US motor fuel price to the consumer doubles in 2010 and subsequently rises by a factor of 3.5 by 2030 (compared to the 1990 level), as shown in Figure 9. This result compares to the 40% increase in the reference case.[7] The models remain largely consistent in their estimates of total transport energy, even though all AEEI parameters remain the same across all cases. The consistency is especially high for the period through 2020, as shown in Figure 8C.

The MARKAL model, now run with the new, reduced demand and the higher effective fuel price to the consumer—resulting from the lower oil price (and thus price for refined oil) and the fuel-related carbon tax, both from EPPA—provides a significantly different picture of technology substitution. For autos the *ZeroCost* technology begins to displace the 95 Flt in 2005 as before, but subsequently is displaced by the more fuel-efficient *LoCost* technology, as seen in

Table 3. Percent Reduction in Carbon Emissions from the Reference to the Kyoto Case, by Major Sector. All end-use sectors include carbon emissions from electricity generation.

Year	Agriculture	Transport	Energy Intensive Industries	Other Industries and Services	Residential	Total Final Energy Use	Electricity Generation
2010	37	8	36	37	54	31	39
2015	43	8	42	45	54	34	45
2020	48	12	47	51	55	38	50
2025	54	15	52	55	59	42	54
2030	57	18	58	59	65	46	58

[7] Crude oil prices fall somewhat, because the Kyoto reductions are assumed to be met by all Annex B parties. The required carbon penalty to achieve the Kyoto targets (and a more stringent one explored below) are greater than in the EPPA model before the elasticity corrections imposed here. Interpretation of this difference is provided below.

Figure 10C. However, also the *LoCost* design only penetrates into the automobile market until 2020, when it is then beginning to be replaced by the next more fuel-efficient *PowTrn1* technology. For neither vehicle does the Kyoto level of restriction lead to penetration by the Alum or Hybrid vehicles.

We have also examined a scheme in which the 2010 Kyoto target is further tightened by 7% in each subsequent 5-year period, resulting in an economy-wide CO_2 emission reduction of 35% below the 1990 level in 2030. In that Kyoto+ case, the US motor fuel price to the consumer doubles in 2010 and subsequently rises by a factor of 8 (compared to the 1990 level) by 2030. Energy use in household-own and purchased transportation remains consistent between the EPPA and MARKAL model over the entire time horizon (Figure 8D). The loss in GDP and higher prices for capital and fuel result in losses of the demand for automobile travel of nearly 20% in 2030 compared to the reference case (Figure 10D). The same figure shows that—compared to the Kyoto case in Figure 9C—the still more-fuel-efficient *PowTrn2* technology is introduced. Only when reaching the eightfold level of fuel price to the consumer in 2030, *Alum* and *Hybrid* vehicles designs are just being introduced. Figure 9 reports the development of the refined oil price with and without carbon tax for all cases discussed above.

5.3 Interpretation of Differences in Emissions Price

The MARKAL model applied in this experiment contains a reasonable but fixed set of technological options that may be available for application in light duty vehicles over the next few decades. Seeking consistency in the three-model system, the key elasticities in the transport component of the EPPA structure were changed to reflect this opportunity set—making the model "stiffer" in the transport sector's response to carbon prices, and thus requiring higher penalties on the economy as whole. To meet the Kyoto constraint, the calibrated model requires a 2010 carbon price of US$572 compared to US$332 in the original EPPA model.

A stepwise elimination of these calibrations steps can reveal where the increased carbon prices originate. Tightening of the elasticities of substitution between energy and value added in purchased transport (σ_{EVA}), and between REFOIL and OIND in household-own transport (σ_{RO}) have a roughly equivalent effect and are the most important. Together they would raise the emissions price to over US$600. The imposition of the Leontief specification between own and purchased transportation and base year data calibrations (to gain consistency between EPPA and MARKAL quantities) add another small effect. On the other hand, the final calibration procedure, replacing EPPA's AEEI when not calibrated to MARKAL with the pattern in Figure 7, leads prices in the other direction, removing about one-third of the increase that might follow from the elasticity changes alone.

6. CONCLUSIONS AND FURTHER RESEARCH

Several conclusions can be drawn from this set of experiments. It is possible to construct a set of parallel pictures, at macro scale and micro detail while maintaining convergence between the key features of the models. Note that the analysis produced here is not a straight-through forecast of technology development, where analysis of climate policies yields patterns of price change, which in turn determines a unique pace of introduction of new vehicles. The CGE model has been adjusted to mirror, at aggregate level, some of the behavior at what is for it a sub-sector scale. Thus the result is best seen as producing a set of scenarios at different levels of detail that are consistent with one another.

However, to achieve a representation of the transport sector that is consistent with MARKAL the substitution elasticities in the EPPA model had to be substantially tightened. That such a major change was required serves to highlight important questions about the relationship between top-down economic-market models and bottom-up engineering process representations, and the particular assumption about technology evolution. In this analysis, the future evolution of transport technology was ultimately based upon engineering studies. Because such studies (if thoroughly done) can be a reliable source of the technological possibilities in the short term, we believe that the above-described calibration procedure is evidence that the previous EPPA elasticities were too high.

On the other hand, two problems emerge with regard to the MARKAL estimates. First, the representation is with regard to technology alone, and does not reflect other aspect of substitution that are implicit in the elasticity imposed in a CGE model—*e.g*., choices in vehicle weight. Second, uncertainties increase with the time horizon, and over the longer term (20 to 30 years and beyond), the detailed technology characteristics specified in the MARKAL-type database likely are overly constrained by today's understanding. Thus, over longer time horizons the flexibility shown in the parent EPPA model, without the calibration, probably is a better representation of the sector response.

Whatever one's view of these differences, one useful result of a joint model exercise of the type shown here is simultaneously to condition the expert judgment applied in setting parameters of the CES functions that underlie CGE models, and to question whether the particular vehicle types included in a MARKAL-type formulation really capture all the cost-reducing options that may be available over coming decades.

Though the analysis presented here is an experiment in methodology development, it also provides insight into the likely behavior of the transport sector under GHG emission constraint. At a level of emissions restriction consistent with the Kyoto protocol, demand for transportation energy use continues to rise, while energy demand associated with all other goods and services declines. Under a Kyoto target continued in subsequent decades, carbon emissions of personal transport would be reduced by 21%, and those from purchased transport by 16%, compared to

the unconstrained reference scenario in 2030. In personal transport, one-third of the 21% decline results from reduced demand while two-thirds are due to penetration of more fuel-efficient transport technology; light-duty vehicles with reduced driving resistance and improved mechanical drive trains would dominate the vehicle fleet by 2030. Achieving a significant penetration of aluminum intensive and hybrid vehicles by 2030 would require even stronger emissions reductions than shown in the Kyoto+ scenario.

Several areas of future work seem most important. First, additional analysis is needed of the various steps taken to achieve consistency between the two models. The selection of the discount rate to be used in the bottom-up, MARKAL formulation is problematic. Here, data on the factor shares in the GTAP data set were used to impute a consumer discount rate, thought to be appropriate for application in the MARKAL model. A forward-looking version of EPPA, now in development, does contain such an internal discount rate, but important questions remain regarding the relationship of such a national discount rate to the rate appropriate for approximating consumer purchase behavior, in the choice among vehicles of alternative characteristics.

Other aspects of the calibration process also merit additional attention. The method used to calculate the time-dependent substitution elasticity in the transport sector nest seems a useful way to introduce technical change into an EPPA-type formulation. However, this approach deserves further analysis. Also, for this type of application the underlying MARKAL structure needs to be elaborated to better represent emissions-reducing substitution possibilities other than shifts in technology.

Finally, the transport sector, with its detailed structure involving household and industry components and important distinctions among vehicle types, is one of the more complex targets for such treatment. An obvious next step would be the application of a similar approach to the electric power sector. A number of different types of models of electric power system investment choice and operation have been developed, but much remains to be done to construct an analysis where they are run in a consistent manner with a multi-sector, multi-region economic model of the EPPA type.

Acknowledgements

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