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Introducing Behavioral Change in Transportation into Energy/Economy/Environment Models

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Abstract

Transportation is vital to economic and social development, but at the same time generates undesired consequences on local, regional, and global scales. One of the largest challenges is the mitigation of energy-related carbon dioxide emissions, to which this sector already contributes one-quarter globally and one-third in the United States. Technology measures are the prerequisite for drastically mitigating energy use and all emission species, but they are not sufficient. The resulting need for complementing technology measures with behavioral change policies contrasts sharply with the analyses carried out by virtually all energy / economy / environment (E3) models, given their focus on pure technology-based solutions. This paper addresses the challenges for E3 models to simulate behavioral changes in transportation. A survey of 13 major models concludes that especially hybrid energy models would already be capable of simulating some behavioral change policies, most notably the imposition of the full marginal societal costs of transportation. Another survey of major macroscopic transportation models finds that key specifications required for simulating behavioral change have already been implemented and tested, albeit not necessarily on a global scale. When integrating these key features into E3 models, a wide range of technology and behavioral change policies could be analyzed.

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INTRODUCING BEHAVIORAL CHANGE IN TRANSPORTATION INTO ENERGY/ECONOMY/ENVIRONMENT MODELS*

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Introduction and Scope of the Analysis

Vital to economic and social development, transportation also generates undesired consequences on local, regional, and global scales. Local scale impacts include motor vehicle accidents, which caused about 37,000 traffic deaths in the U.S. in 2008 (U.S. Census Bureau, various years) and more than 1 million traffic deaths worldwide (World Bank, no date). Another local-scale impact is traffic congestion, which has resulted in 4.8 billion hours lost in traffic on U.S. roads alone in 2010, a number that continues to rise; the associated costs of extra time and fuel use was estimated to equal US$(2010) 100 billion (Schrank *et al*., 2011). Meanwhile traffic congestion has spread to air transportation. Data describing U.S. airline operations suggests a continuous increase in air traffic delays (U.S. BTS, 2011). Traffic congestion is highest in the vehicle growth markets, i.e., cities of the developing world, where infrastructure growth lags behind the much more quickly expanding vehicle fleet.

A key regional scale impact is urban air pollution, to which vehicle emissions typically contribute the largest single share (Gorham, 2002). While urban air quality has improved within cities of the industrialized world due to tighter vehicle emission standards and inspection programs, there is still little sign in cities of the developing world. On the contrary, emissions partly released by the transportation sector, are transported over long distances and deposited across national borders. Examples include the transpacific emissions of nitrogen compounds (Fenn *et al*., 2003), black carbon and other substances (Forest Magazine, 2003) in the Western U.S.

The currently most discussed global impact of transportation is the concern about climate change. Burning one kilogram of gasoline, diesel, or jet fuel in an automobile or aircraft engine releases nearly 3.2 kilograms of carbon dioxide (CO_2) into the atmosphere. Already, the atmospheric concentration of CO_2 has increased from a preindustrial level of 280 parts per million by volume (ppmv) in 1800 to about 390 ppmv in 2011. Given the projected increase in human activity, concentration levels will continue to rise, changing the radiative balance of the Earth. The projected implications of the anthropogenic (human-influenced) greenhouse effect are significant. An increase in the mean Earth temperature leads to the thermal expansion of oceans, the melting of the ice shelves, and thus to a sea level rise. It also induces an increase in extreme weather events, such as heat and cold waves, droughts, heavy rains, and tropical storms. Some of these ecosystem alterations form the basis for secondary impacts, including the spread of tropical diseases outside their current latitude band, mass migration of people most affected by climate change, and economic losses. Due to its abundance, CO_2 is the most important contributor to the anthropogenic greenhouse effect. Other GHG emissions, however, can have a stronger warming effect. Other examples of global transportation impacts include high-altitude aircraft nitrogen oxide emissions, which contribute to an increase in the ozone concentration in the upper troposphere and lower stratosphere, enhancing the greenhouse effect. However, at higher altitudes, nitrogen oxide emissions contribute to the destruction of the stratospheric ozone layer, causing surface level UV radiation to increase (IPCC, 1999).

While some of the local and regional impacts, such as traffic accidents and urban/regional air pollution, seem to follow an Environmental Kuznets Curve, other impacts, such as anthropogenic climate change do not. In contrast to traffic accidents and urban/regional air pollution, significantly mitigating climate change would require more drastic policy measures. And the success of mitigating GHG emissions will increasingly depend on the transportation sector. As economies develop, value added shifts from agriculture to industry and services. Within services, transportation (moving people to jobs and recreation and goods to markets) takes an ever-increasing economic role. Because each of these economic sectors also consumes energy, a similar shift in importance can be observed in the energy system for energy use and CO_2 emissions. Figure 1 shows these shifts in CO_2 emissions, from the residential sector (for heating, cooling, and running appliances), to the industry sector, and finally to the service sector, of which transportation is by far the single largest energy consumer. Significantly mitigating GHG emissions thus requires addressing the transportation sector.

[Figure 1]

A number of studies have explored the opportunities for and challenges to reducing GHG emissions from transportation. Common to all these studies is the conclusion that technology will play a major role. However, the level of technology optimism and thus the emission reduction potential due to technological change differs. A recent IEA (2009) report concludes that world transport sector GHG emissions could be reduced to well below the 2005 level by 2050. A 30% reduction below 2005 levels could be achieved through a combination of fuel efficiency improvements and alternative fuels, despite the projected increase in passenger-km travelled (PKT) in the two baseline scenarios by 120-180% and an even higher anticipated growth in freight ton-km generated. In combination with behavioral change leading to reduced passenger travel demand and shifts away from road transport toward more energy efficient freight transport modes, the IEA study anticipated even stronger reductions in the order of 40% below 2005 levels. However, the impact resulting from behavioral change is only imposed exogenously and assumed to be caused by "a combination of better urban planning, infrastructure improvements, better public transit systems (including bus rapid transit, light rail, and intercity high-speed rail systems) and policy measures that encourage the use of these modes".

In contrast, Schäfer *et al*. (2009) find that while technological change is central for reducing passenger travel GHG emissions, the limited scalability of second generation biofuels (such as synthetic fuels from cellulosic biomass), long time constants for technological change, and other constraints would almost certainly result in an increase in global GHG emissions by 2050 in the absence of radical behavioral change, even under drastic climate policies. Their baseline scenario projects a 170-300% increase in world PKT by 2050 over 2005 levels, that is, almost a tripling to quadrupling of 2005 levels. Even if assuming a fuel price in excess of US$ 5 per gallon, making most future, advanced hybrid electric vehicles cost-effective over an amortization period of 3-4 years, the combination of drastic technological change (leading to a reduction of energy use per passenger-km by up to half) and alternative fuels (accounting for up to 20% market share in terms of second generation biofuels) would still result in an *in*crease in world passenger transport GHG emissions by 50-150% over the 2005 level. This increase is a composite of two different trends. In the industrialized world, passenger travel GHG emissions can be stabilized at or even slightly reduced below early 2000 levels, but in the developing world with high income and population growth, passenger travel GHG emissions are expected to rise drastically, even in a CO_2-constrained world. Hence, behavioral measures are imperative to further reduce the growth in GHG emissions. Conclusions very similar to those for the industrialized world were derived in a recent European Commission project for the 27 European countries "Technology Opportunities and Strategies toward Climate-Friendly Transport" (Dray *et al*., 2011).

GHG emission mitigation in the transportation sector on a global level has also been studied with energy/economy/environment (E3) models, as used for the IPCC scenario work. The most employed global model is the Global Change Assessment Model (GCAM) at the Pacific Northwest Laboratory. GCAM was used for a number of analyses, including examining the role of advanced vehicle technology to meeting various atmospheric CO_2 concentration levels by the end of the 21st century (Kim *et al*., 2006). That particular study finds that the carbon tax required for achieving a 550 ppm atmospheric CO_2 concentration by the end of the century, rising from US$ 24 per ton of carbon to $375 per ton of carbon by the end of the century, is not sufficiently large to significantly affect transportation demand and technological change in the U.S. transportation sector. This conclusion is consistent with the analysis by Schäfer *et al*. (2009).

The key challenge of behavioral change is how to mitigate the long-term historical trend toward ever more and faster mobility. Realizing a departure from this stable development is challenging, given the strong forces at work. Figure 2a reports the growth trend in per person PKT over GDP per capita for 11 world regions from 1950 to 2005. Here, PKT includes all major modes of transport, i.e., automobiles, low-speed public transportation (buses, urban and slow intercity railways), and high-speed transportation modes (high-speed rail and aircraft). Because people's travel time is limited, the rising demand for mobility needs to be supplied by faster modes of transport (Schäfer *et al*., 2009). Figure 2b depicts the associated shift toward faster modes as per person travel demand rises. Similar systematic trends toward faster modes can be expected in freight transportation, where the rising value of the transported commodities requires faster and more reliable shipments.

[Figures 2a,b]

Given the trends toward ever higher levels of transportation at continuously increasing speeds the question arises whether this development will ultimately be scalable in light of the various environmental impacts described above. Clearly, a departure from the trends observed in Figures 2a,b will be especially difficult within the industrialized world, where incomes are high, transportation-related price elasticities low, and most of the relevant infrastructures already in place. However, more opportunities may exist in developing countries with lower income levels, higher price elasticities, and less infrastructures in place. One possible alternative development of these countries could be to leapfrog many of the undesired transportation externalities described above and move towards a cleaner and potentially less transportation-intensive state, while not giving up accessibility to information, goods, and services. The degree to which such a state can be achieved will ultimately depend on the set of available transportation options and policies put in place to rebalance consumer preferences. As will become clear from the review of E3 models below, analyses of such kind still have to be carried out.

This report explores the opportunities for and the challenges associated with the introduction of behavioral change in E3 models. We continue with exploring the opportunities and challenges associated with green growth in transportation. That section leads to a list of specification requirements to enable E3 models simulating green growth in transportation. In the subsequent section, a survey explores to what extent existing E3 models already satisfy these requirements. Thereafter, standalone transportation models are evaluated to understand which of these models' features could be adopted for further sophistication of the transportation sector in E3 models. After summarizing the results, the conclusions end with recommendations for further research.

Green Growth in Transportation: Opportunities and Challenges

Green growth in transportation can be defined in multiple ways. However, virtually independent of its definition is the requirement for high levels of accessibility at reduced levels of transportation activity. At the same time, there is a strong need for less energy-intensive and cleaner modes that operate at high levels of service quality. Green growth therefore requires the combination of technological and behavioral change to “do more with less”.

While prospects for technological change have been widely discussed (see, e.g., Schäfer *et al*., 2009) and simulated in E3 models (as described in the subsequent section), less attention has been dedicated to opportunities for inducing behavioral change. These include but are not limited to (i) charging travelers the total marginal societal costs of transportation, (ii) making more balanced investments into non-road based infrastructures, and (iii) altering consumer lifestyles such as changing vacation destinations or partially substituting telecommunication means for physical travel.

Because transportation interacts with virtually each economic sector, drastic behavioral change could have economy-wide knock-on effects on even a global scale. Some of these propagating effects can be counterproductive. In particular, reducing the amount of transportation can conflict with fundamental economic interests, especially for developing economies. For example, tourism is a vital component of economic growth in many low-income countries (UNWTO, 2011). Similarly, reducing the amount of goods traded could disproportionally affect lower income countries.

Nevertheless, the opportunities for significant reductions in energy use and associated emissions are large. Figure 3 shows the technical potential associated with mode shifts in freight transportation (Gucwa and Schäfer, 2011). Energy intensity (energy use per ton-km), which is the product of energy use per vehicle-km and the ratio of vehicle-km to ton-km, declines with rising amount of freight carried per vehicle (truck, aircraft, locomotive, or ship), as the increase in energy use per vehicle-km is more than offset by the decline of vehicle-km per ton-km. Basic physics implies that the slope is steepest for railways. Figure 3 shows the enormous opportunities for achieving very low energy intensities if moving (intercity) freight by (especially high-capacity) railways or waterways instead of trucks and aircraft. Exploiting these potentials, however, would require higher shipment speeds (thus sacrificing some of the potential for reducing energy intensity) and reliability of delivery, as with increasing economic development and rising value of an increasing number of transported commodities, these requirements increase and in the past have been satisfied best by trucks and aircraft.

[Figure 3]

The remainder of this section outlines the various policy elements of green growth in transportation and their relationship to wider economy and the resulting challenges. The section concludes with an assessment of the capabilities that are required to incorporate these policy options into existing E3 models.

Internalizing External Costs

The environmental externalities due to transportation can be broken down into those associated with (i) the amount of fuel used and (ii) the distance driven. The first category includes the costs associated with climate change and oil dependence. Small and Van Dender (2007) compare several estimates of automobile travel for the U.S. and the U.K. Their data suggest that fuel use-related damages are in the range of 4-10 US₵ (2005) per liter.[1] The second category of distance-related costs includes traffic congestion, accidents, air and water pollution, and noise. These estimated damages are significantly larger than the fuel use related ones and range between roughly 5 and 30 US₵ (2005) per km (Small and Van Dender, 2007).

[1] These costs are significantly higher than those associated with climate change alone, as a carbon price of US$ 50 per ton of carbon corresponds to only some 3 US₵ per liter of gasoline. Hence, pricing transportation for the full amount of external costs would lead to a significantly larger consumer response.

The societal costs can be compared to the fuel taxes currently in place. Assuming an average vehicle fuel consumption of around 9 liters of gasoline per 100 km, total marginal costs (fuel use and distance related) translate into around US$(2005) 0.5-4 per liter. Figure 4 depicts the gasoline retail price, the percent fuel tax, and the absolute level of fuel taxes for 2010. The retail prices range from a low of US₵ 65 per liter in Mexico to a high of US$ 1.88 per liter in Germany. Most of that variation can be explained by differences in fuel taxes, i.e., US₵ 9 per liter in Mexico versus US$ 1.17 per liter in Germany. The level of fuel tax in Germany and other Western European countries is within the range of the total marginal costs of around US$ 0.5-4 per liter, albeit at the lower end. Yet the general trend toward higher levels of mobility and speeds also exist there.

While the significantly higher fuel taxes in Western Europe do not lead to substantially different travel patterns compared to other world regions, they help explain the different levels in absolute mobility and mode shares in Figures 2a,b. According to Figure 4, the 7-8 times higher fuel taxes result in a gasoline retail price that is about 140% higher compared to that in the U.S. Partly as a result of the significantly higher fuel taxes, the Western Europe region experiences lower levels of mobility and automobile share at a given income level compared to the North America region, of which the U.S. accounts for 90% of the population. The difference in fuel taxes also helps explain the choice of automobiles (not shown in Figure 2). European vehicles are about one segment smaller than their U.S. counterpart, and engine power is only about half as large. Nevertheless, the trend toward larger and more powerful vehicles also exists in Europe (Schäfer *et al*., 2009). This suggests that pricing the societal marginal societal costs is necessary but not necessarily sufficient to radically change travel behavior.

[Figure 4]

It is likely that a larger consumer response in travel behavior could be achieved if charging the distance-dependent costs, which account for the vast majority of external costs, in terms of road user charges. Such a road pricing scheme would discourage consumers from buying more fuel-efficient vehicles while keeping their driving distances virtually unchanged. Although studies estimating the consumer response to changes in travel costs within the U.S. find very low price elasticities in the order of only around 1% in the short term and 6% in the long term (Small and Van Dender, 2007)—a condition that would require very high road pricing charges to induce some consumer response—the price elasticity is likely to be much higher in high-density cities with more travel alternatives. Therefore, the imposition of full societal marginal costs should be complemented by additional measures that provide alternatives to automobile travel, such as investments in public transportation infrastructures along with land-use changes and possibly telecommunication substitutes. These options are briefly discussed in the following.

Infrastructure and Land-Use Policies

Investments in transportation infrastructures can have long-term implications if they determine the use of land and affect the economic viability of competing transportation modes. The suburbanization of the U.S. is no exception. The initial stage of suburbanization during the first two decades of the twentieth century was enabled by electric streetcars—new settlements grew along streetcar lines. During the subsequent stage of suburbanization, the automobile enabled filling the space between the finger-like railcar induced settlements (Jackson, 1985). The resulting lower population density of road-induced suburbs makes it virtually impossible for other modes than private vehicles to serve them economically. Such developments result in essentially locked-in land-use / transportation systems, as residential intensification efforts may be impractical, may face public opposition, and—in case they are feasible—can require several decades to materialize. Partly due to the resulting lack of alternative transportation modes, the U.S. national average price elasticity of automobile kilometers traveled has declined to only around 1% in the short term and 6% in the long term (Small and Van Dender, 2007). Many urban areas in the developing world are currently also undergoing urban sprawl, which is manifested by the more rapid expansion of the urban area in comparison to the respective population (UN, 2010). Although the reasons for sprawl may differ between high and low-income countries, the impact on car dependence is identical.

The impact of comparatively high population densities in combination with public transportation investments on travel patterns is also visible in Figure 2a,b when comparing the Pacific OECD region with Western Europe. The Pacific OECD region is dominated by Japan, which accounts for 85% of the regional population. The comparatively high density of Japanese cities causes total travel per person and automobile use to develop at lower levels than Western Europe at a given income level despite the slightly lower level of fuel taxes (Figure 4). As we will see in the coming sections, virtually all energy/economy/environment (E3) models build on a continuation of these trends of quasi-irreversible early infrastructure policy.

Infrastructure and land-use policies can mitigate such trends toward low population density developments, by encouraging shorter trips and shifts toward public transportation modes. This is evidenced by the successful combined implementation of land-use policies and bus rapid transit systems in Curitiba, Bogota, and other cities of the developing world. However, in the absence of accompanying (market-based) policy measures, infrastructure and land-use planning are no guarantee for a significant change in travel behavior. Careful econometric studies suggest that—in the absence of other policy measures—only drastic changes in land-use can cause a reduction of automobile use (Pickrell, 1999). And even then, many urban design elements can enhance or reduce auto travel, depending on the change in relative costs of driving versus other modes (Boarnet and Crane, 2001).

Lifestyle Changes and Telecommunication Substitutes

The key lifestyle change that could bring about the largest impact on travel is the substitution of physical travel by telecommunication means. In 2008, in the United States, around 24 million employees or about 17% of the employed labor force telecommuted to work at least once a week (WorldatWork, 2009). In addition, internet shopping is on the rise. In the U.S., the value of all merchandise sold online increased from some 30% in 2003 to some 48% in 2009 (U.S. Census Bureau, 2011).

A first-order theoretical potential for substituting travel can be estimated from the evolution of trip making in Figure 5. With rising income and distance traveled per day, the average number of trips per person increases from around 1.5 at low mobility levels (Delhi suburbs in the late 1970s) to more than 4 at very high levels of daily distance traveled (U.S. in 1995). Common to travelers in all parts of the world is that around one trip per person per day is dedicated to the aggregate of work and education, the prerequisite for immediate survival and later wellbeing. With rising income and daily travel distance, more trips are added with regard to personal business (including shopping) and leisure. While the number of trips per person dedicated to these two purposes is below one in low-income countries, personal business-related travel accounted for two trips and leisure for one trip per person per day in the U.S. in 1995. If about half of all work and personal business trips were substituted by electronic means, the total number of trips in high-income countries could be reduced by around 35%. This potential would be significantly smaller in developing economies, already because a significantly higher share of the labor force works in difficult-to-substitute sectors such as agriculture and manufacturing.

[Figure 5]

Importantly, partly exploiting the potential of telecommuting as a substitute for physical travel requires the imposition of a price signal, such as charging the full societal marginal costs of transportation. In the absence of price signals, such as in the past, no convincing evidence exists that telecommunication means would actually substitute travel (Weltevreden, 2007; Schäfer *et al.*, 2009). In fact, Mokhtarian (2004) concludes that if incorporating all determinants of telecommuting, including the willingness and frequencies of those commuters who could telecommute, the commuting patterns and residential locations of those commuters, and the possible substitution of non-work trips for work trips, "telecommuting is likely to reduce only a fraction of 1% of household travel in the US, even well into the future." Hence, instead of being a substitute, in the absence of pricing measures, large-scale use of advanced telecommunication systems could reinforce the trend toward ever-faster modes of travel. In the past, the automobile allowed commuters to move further away from the workplace; the choice of workplace location was always limited, however, by the driving distance to that workplace. In contrast, advanced telecommunication systems could enable a nearly complete decoupling between home and workplace if the frequency of physical commuting can be reduced: living in Paris and working in Washington, DC may thus become practical.

Implications for Energy/Economy/Environment Models

Simulating the above-discussed behavioral change policies requires particular specifications of E3 models. Both the behavioral change policies described above and the required model specifications are shown in Table 1. For virtually every policy, E3 models require an elastic demand specification, which endogenously simulates the consumer and industry response to changes in prices and travel speeds. These price and speed changes can result from internalizing external costs, mode shifts, and the adoption of new transportation technology. In addition, E3 models need to determine the change in mode shares endogenously as a way to simulate the transportation demand response to changes in travel costs and speeds (which can result from any of the three behavioral policies examined here). As will be discussed in more detail below, such consumer response can either be simulated by consumer choice models, nested production functions, or a set of (cross) price elasticities. The third E3 model specification is the separation of urban and intercity transportation. This specification is not necessarily required, although highly desirable to enable differentiating policies, impacts, and infrastructure capacities for these two transportation market segments. A final model specification is accounting for the capacity of the available transportation infrastructure and the consumer response to additions or shortages—a shortage of infrastructure will lead to traffic congestion and lower speeds, which in turn will lead to a shift towards competing transportation modes. Because any of the behavioral change policies will alter travel costs and potentially speeds and thus transportation demand, an iterative procedure will be required to calculate a new equilibrium in most cases.

Table 1 Behavioral change policies and the associated required specifications for simulating behavioral change in transportation within E3 models

Behavioral Change Policies	Required Model Specification
Internalizing external costs	Elastic transportation demand specification Endogenous choice of transportation modes Segmenting urban and intercity transportation if differentiating societal costs (e.g., local air pollution impacts) between urban and intercity transportation
Investments in transportation infrastructure to influence travel behavior	Elastic transportation demand specification Endogenous choice of transportation modes Accounting for infrastructure capacity to simulate traffic congestion and endogenous change in travel speeds Segmenting urban and intercity transportation if differentiating urban and intercity infrastructure
Lifestyle changes and telecommunication substitutes	Elastic transportation demand specification Choice of no (physical) travel Endogenous choice of transportation modes Segmenting urban and intercity transportation

If these specifications are implemented into existing E3 models with a technology assessment focus, a wide range of complementary options for mitigating energy use and the related environmental impact could be studied, along with possible leapfrogging opportunities for emerging economies. The subsequent section puts existing E3 models on the testbed to understand to what extent such required model specifications already exist.

Existing Transportation Sector Representation in Energy Models

Many energy/economy/environment (E3) models already include transportation sector representation in one way or another. This section provides an overview of these models and how that sector is represented.

A Brief Introduction to Energy/Economy/Environment Models

The main objective of E3 models is to formulate internally consistent scenarios of change in the economy, society, technology, access to fuel resources, and other factors affecting future levels of energy use and emissions of GHGs and other types. Typically, these models are run for a reference or baseline scenario with anticipated or no new policies and then rerun with policy interventions to evaluate the change in key output variables. These include GHG emissions and the costs of their abatement at the highest level of aggregation and the adoption of technologies at the most detailed level.

A wide range of E3 models exists. Differences can be attributed to the level of inclusion of economic processes, the degree of technological detail, the number and detail of economic sectors included, the time horizon, geographic scope, and other factors. It is convenient to distinguish E3 models based on the modeling paradigm, that is, bottom-up / systems-engineering models and top-down / macroeconomic models. Although both model families underwent a process of cross-fertilization, basic differences remain. While bottom-up models are technology-explicit but lack a representation of the wider economy, top-down models include an array of macro-economic variables describing the fundamental economic processes, into which energy is only one production factor (in addition to capital, labor, and resources), however, on the cost of technological detail. The effort of combining the strengths of both models then leads to hybrid energy models. Although the distinction between top-down, bottom-up, and hybrid energy models covers nearly all E3 models, it is not exhaustive. We therefore add one more category of "other models".

Bottom-up / Systems Engineering Energy Models

Bottom-up energy models are typically dynamic (linear) optimization, partial-equilibrium models (where key macroeconomic assumptions remain exogenous). Central to these models is the so-called reference energy system (RES), which represents a user-specified sequence of interlinked energy conversion steps of the problem under investigation. The RES can cover the entire energy system and include the conversion chain from fuel resource extraction at the primary energy level to the demand for energy services at the end-use level. For illustrative purposes, Figure 6 depicts a simplified RES. Starting with the extraction of energy resources on the left, various conversion steps provide electricity, heat, along with solid, gaseous, and liquid fuels to the end-use sectors on the right. Typically, several competing technologies are available to be chosen by the model for each combination of energy carrier and conversion step—each dot in Figure 6. These technologies are specified by energy inputs and outputs, conversion efficiency, economic characteristics (investment costs, fix and variable operating costs), economic lifetime, capacity factor, year of technology readiness, and potential market penetration constraints. A mature model may include several thousand technologies in all sectors of the energy system (Loulou *et al*., 2004).

[Figure 6]

Bottom-up models require the user to specify the demand for energy (services) over time, using other models or expert judgment. Some models require the projected demand to be represented by fixed values for each time step. (The demand curve thus represents a vertical straight line in the price-quantity diagram). These models minimize the total cumulative discounted costs over the scenario time horizon. Other models, such as the “Elastic Demand” version of the widely-used MARKAL model, specify end-use demands as a function of other variables such as income and prices, thus generating a demand curve. Hence, while also minimizing total cumulative discounted costs, these models inherently maximize total producer and consumer surplus. Independent of specifying fixed or elastic demand, a bottom-up model computes an energy balance for the defined RES at every time step, while satisfying the respective demand level through the optimum deployment of technologies for each combination of energy carrier and conversion step. The key output of bottom-up models consists of an assessment of the costs for and potential of mitigating energy use and associated emissions, on the basis of the identified optimum set of technologies. The latter is typically shown as a marginal abatement cost-curve, with the cumulative reduction potential by technology shown on the x-axis.

Compared to other types of energy models, bottom-up models tend to estimate comparatively low mitigation costs of energy use and environmental impacts. This can be attributed to a number of factors, including (i) the lack of inclusion of economic processes and feedbacks, such as the rebound effect, (ii) the perfect foresight of future policy interventions and oil price changes that allow the model to make an optimum transition toward more expensive, fuel-saving technologies (by minimizing sunk costs), and (iii) the use of low, social discount rates, which leads to significant opportunities for energy savings and thus GHG emission mitigation, as the current value of future energy savings by improved technology is comparatively large.

Transport Sector Representation. As with all other sectors, the exogenously specified transportation demand is satisfied through an array of conversion technologies. The RES in Figure 6 suggests that in this particular application busses, trucks, railways, ships, and aircraft are propelled with oil-derived liquid fuels, while automobiles can also be fuelled with electricity. Only one generic type of oil products is being considered, which results from either domestic or imported crude oil. After being refined, transported, and distributed, it becomes available for transportation. In contrast, electricity can be produced from a wide range of sources, including natural gas, coal, nuclear, and renewables. Presumably, the model's database includes several alternative technologies for any of these electricity generation alternatives and vehicle technologies.

Table 2 Examples of bottom-up model-based applications with transportation sector representation

Model	Focus	Reference
GET	Assessing fuel choices in the global transportation sector under stringent global CO_2 constraints	Azar *et al*. (2003)
MARKAL (standalone)	Exploring technology opportunities and cost implications for mitigating UK CO_2 emissions	Marsh *et al*. (2002)
TIMES	Exploring technology opportunities and cost implications for mitigating CO_2 emissions in Ireland	Gallachoir *et al*. (2011)

Table 2 summarizes exemplary studies of bottom-up models with transportation sector representation. All studies focused on the optimum deployment of transportation and upstream technologies to mitigate energy use and GHG emissions and did not consider behavioral change policies as specified in Table 1. Typical differences across these models are with regard to assumptions about size and costs of energy resources, techno-economic characteristics of technologies, the imposed change in demand over time, and the geographical scale of the model.

Current-generation bottom-up models experience several limitations with regard to the inclusion of consumer behavior, particularly in transportation. Because mode choice is exclusively determined by user costs, bottom-up models would satisfy transportation demand by the lowest-cost mode of passenger and freight transportation, respectively. To overcome that unrealistic behavior, the exogenous transportation demand is typically specified for each mode independently. Similarly, for automobile travel, bottom-up models would exclusively choose the least-cost technology, e.g., a Toyota Camry over a Mercedes C Class, thus neglecting the many other mode and vehicle attributes consumers value. Therefore, the implicit assumption with regard to vehicle choice is that alternatives only differ in terms of fuel consumption and purchase price, while vehicle size, comfort and safety aspects, and aesthetic appearance are identical. Because an increase in fuel costs would almost certainly induce consumers to also shift towards cheaper and smaller vehicles instead of exclusively purchasing more expensive, same size vehicles with more fuel-saving technology, bottom-up models provide an *upper limit* of technological change.

Top-down / Macroeconomic Models

In contrast to bottom-up models, top-down models simulate the major monetary and monetized material and energy flows within an economy and between regions. Computable general equilibrium (CGE) models, which have become the dominant type of macro-economic energy models, simulate the circular flow of goods and services in the economy, along with the reverse flow of payments. Compared to the partial equilibrium models discussed above, a CGE model seeks an economy-wide equilibrium of the now interdependent sectors. An economic shock in one sector (e.g., a fuel tax in transportation) would propagate through all other sectors through their input/output relationships.

In CGE models, each sector is represented by a (nested) production or utility function, in which the inputs (capital, labor, energy, materials, and resources) contribute to the production of the sector gross output or consumption. The technical ability or willingness of individuals to make tradeoffs among the inputs to both production and consumption is captured by the elasticity of substitution, a key parameter in production and utility functions (Babiker *et al*., 2001). For producers this elasticity reflects the underlying technology, the extent to which labor, capital and energy can be substituted for each other. For consumers, this parameter represents the willingness to substitute one consumption good or service for another one, given a change in relative prices. For example, if gasoline costs increase, consumers may substitute other goods and services for (predominantly leisure) travel, the rate of which is determined by the elasticity of substitution.

The substitution elasticities are important determinants of the cost of policies to control GHG emissions. If a carbon dioxide restriction increases the price of carbon-based fuels, the cost of production will not increase much for an industry that can easily substitute other inputs for energy. Similarly, if consumers are able to shift easily away from the use of energy, their economic well-being (economic welfare) will be affected only slightly. Vice-versa, small substitution elasticities can result in greatly increased mitigation costs. Another important parameter determining the costs of mitigation policies is the so-called autonomous energy efficiency improvement index, or AEEI. In contrast to substitution elasticities, this empirical parameter represents the non price-induced reduction in energy intensity, which can be due to continuous technological progress, structural change in the economy, or other factors. The larger this parameter, the less energy and carbon dioxide will be emitted per unit activity and the lesser the need for mitigation options to satisfy a GHG emission target.

CGE models mainly differ with regard to the level of resolution of the economy and energy system, the way they capture the dynamics of the economy through time, the extent to which production factors are used efficiently, the nesting structure of the sectors, and the functional form / assumed substitution elasticities of the production and utility functions. Common to all models is that they are solved through iteration of a price vector that clears the markets for all goods and services, such that consumer welfare and producer profits are maximized. The resulting estimates of the costs for mitigating energy use and emissions are higher compared to bottom-up models. The more conservative estimates can be attributed to (i) the assumption that current production technologies are efficient, (ii) the inclusion of economic feedbacks such as the rebound effect, and if applicable, (iii) the myopic model structure.

Transport Sector Representation. As with other sectors, the transport sector is represented through production functions. The Schäfer and Jacoby (2005) specification serves as a representative example. Figure 7a illustrates the commercial transportation bundle. Inputs into commercial transportation are value added (the aggregate of capital and labor) and energy (refined oil), the proportions of which are determined by the relative prices and the elasticity of substitution. At the demand side, households can choose between own-supplied transportation and purchased (commercial) transportation (Figure 7b). Personal transportation is the aggregate of the “other industry” sector, which includes manufacturing (the vehicle itself) and services (vehicle maintenance and insurance), and energy (refined oil), the proportions of which are also determined by relative prices and the elasticity of substitution. A higher price for refined oil will change the factor proportions toward lower inputs of refined oil in favor of higher inputs of value added (in commercial transportation) or other industry (in household transportation), depending on the size of the elasticity of substitution. Figure 7b also illustrates that higher oil prices will induce a shift in consumer demand toward non-transportation goods and services, provided they are affected less by an increase in the oil price. This is the main behavioral adjustment related to the transportation sector.

Table 3 summarizes exemplary studies of top-down models with transportation sector applications. Only studies conducted with the MIT EPPA model were identified. This can be attributed in part to the significant effort associated with introducing additional economic sectors into CGE models. However, as with bottom-up studies, these analyses focused on the impact of policy interventions on vehicle adoption and largely neglect behavioral change.

Table 3 Examples of top-down / macro-economic model-based applications with transportation sector representation

Model	Focus	Reference
EPPA	Assessing impact of a biofuel mandate on the composition of the European vehicle fleet	Gitiaux *et al*. (2009)
EPPA	Evaluating commercial potential of plug-in hybrid electric vehicles, their possible contribution to reducing CO_2 emissions, and their implications for electricity and petroleum use in the U.S. and Japan	Karplus *et al*. (2009)

While CGE models offer a more complete picture of the transportation sector and interdependent energy system, the key shortcoming is similar to the bottom-up models: changes in demand are exclusively price-induced. Hence, a reduction in public surface transport user costs would divert travelers from automobiles and aircraft to buses and railways. In reality, the rising value of time pushes travelers to faster modes as their income rises—this important parameter is typically ignored in CGE models. In addition, different transportation modes are often not sufficiently separated—often household vehicles are distinguished from an aggregate of “remaining” transport modes. Enlarging the representation of alternative modes is critical when evaluating behavioral change with regard to mode choice. However, such expansion comes at a significant effort, as all sectors are interconnected and thus these linkages (in terms of input/output tables) would need to be re-estimated along with some of the other key model parameters.

Hybrid Energy Models

Hybrid energy models combine the individual advantages of bottom-up and top-down models, i.e., economic comprehensiveness and technological explicitness, and these models thus lessen the emission mitigation cost bias of either model type. In the past, the most common approach has been to couple a one-sector macroeconomic model with a bottom-up model that can handle the necessary energy sector detail. The most frequently used macroeconomic model has been MACRO, a neoclassical one-sector model of the economy, linked with different bottom-up models, such as ETA (Manne and Richels, 1992), MARKAL (Manne and Wene, 1992), and MESSAGE (Messner and Schrattenholzer, 2000). Other approaches combine existing CGE models with bottom-up models (Schäfer and Jacoby, 2005).

More recently, another stream of hybrid energy models has evolved that link energy demand and supply models, sometimes coupled with a macroeconomic model at different degrees of complexity. While IMACLIM-R and ReMIND contain a sophisticated general equilibrium model (Crassous *et al*., 2006; Luderer *et al*., 2010), other models solve for a partial equilibrium with a very limited representation of the economy: GCAM derives regional GDP growth from exogenously specified regional labor productivity growth and labor force participation (Kim, 2010), whereas PRIMES and CIMS require exogenous projections of GDP per sector (NTUA, 2007; Bataille *et al*., 2009). Important differences also exist among the models with a more sophisticated representation of the macro economy, which are essentially identical to those discussed for CGE models above. Differences also exist with regard to the solution method, i.e., forward looking (ReMIND) or recursive dynamic (all other models with the exception of PRIMES that can be solved either way). Other differences relate to geographical focus, ranging from individual countries such as Canada (CIMS) to the entire globe (GCAM). Common to all representatives of this family of hybrid models is that they are solved by iteration of a price vector for different types of energy to find an economic equilibrium between the demand and supply curves.

Transport Sector Representation. Compared to bottom-up and top-down models, the transport sector representation varies significantly across hybrid energy models. Table 4 summarizes several hybrid model applications with transportation sector representation.

Table 4 Examples of hybrid model applications with transportation sector representation

Model	Focus	Reference
CIMS	Simulation of behavioral responses to technology-focused climate policy in Canada	Horne *et al*. (2005)
GCAM	Exploring the CO_2 emissions mitigation potential of light-duty vehicle technology in 14 world regions	Kyle and Kim (2011)
IMACLIM-R	Estimate costs for stabilizing CO_2 emissions through technological change, among others, in transportation worldwide	Crassous *et al*. (2006)
MARKAL-EPPA	Simulation of transport sector implications and technology dynamics under CO_2 policies in the U.S.	Schäfer and Jacoby (2005)
MARKAL-MACRO	Simulation of technology pathways and economic impacts of climate policy in the U.K.	Pye *et al*. (2007)
PRIMES	Energy Roadmap 2050 – Reducing EU GHG emissions by 80-95% below 1990 levels by 2050	EC(2011)
ReMIND-G	Exploring the “decarbonization” of the global transportation sector under climate policy	Pietzcker *et al*. (2010)

The representation of the transportation sector in hybrid energy models is generally more advanced compared to bottom-up or top-down models. The travel demand models implemented in each hybrid model can reproduce the fundamental dynamics of passenger travel shown in Figures 2a,b. All models also have an elastic demand specification and all hybrid models but the

MARKAL related ones incorporate endogenous mode shifts. CIMS even integrates a discrete choice model for travel and vehicle choice. In addition, IMACLIM-R accounts for transportation infrastructure investments and their impact on travel demand. Thus, jointly, a number of model specifications for taking into account behavioral change in transportation listed in Table 1 are satisfied. However, until today, these models have predominantly only focused on technology solutions. As we will see in the following section on existing stand-alone world-regional/global transportation demand models, some of these models already are complementary to the transportation sector specified in existing E3 models.

Other Models

Although the distinction between bottom-up, top-down, and hybrid models covers most E3 models, it is not exhaustive. Among those models not covered by the above taxonomy are predominantly econometric models. Those are based upon a set of empirical relationships, the coefficients of which were estimated statistically. The Prospective Outlook on Long-term Energy Systems (POLES) model is perhaps the most prominent representative of this type of models (see Appendix for details).

Table 5 summarizes the major characteristics of the E3 models examined above. While all models have been used for technology assessments, several include specifications that allow testing policies that aim at behavioral change. All E3 models but two bottom-up models are capable of estimating change in transportation demand in response to changing transportation costs. In addition, multi-sector CGE models simulate the diversion of consumer demand away from transportation towards other goods and services, as travel costs increase. The capability of simulating endogenous mode shifts also exists for the majority of hybrid energy models. In addition, few hybrid models are already capable of simulating further behavioral change policies, such as the choice of non-physical travel (EPPA, MARKAL-EPPA) and the impact of infrastructure policies on transportation demand (IMACLIM-R). The subsequent section examines standalone macroscopic transportation models to understand whether some features could be adopted in E3 models to enable exploring the full range of behavioral change policies.

Table 5 Main characteristics of existing Energy/Economy/Environment models with transportation sector representation

	Cont. hist. mobility trends	Solution	Equilibrium	Geographic Scope	Technol. Assessments	Elastic transport demand	Endogen. mode choice	Choice no (physical) travel	Segment. urban / intercity	Acctng. for infrastrct. capacities
Bottom-up Models										
GET	X	FL	Partial	11 R	X	—	—	—	—	—
MARKAL Standalone	X	FL	Partial	C + R	X	—	—	—	—	—
MARKAL El. Demand	X	FL	Partial	C + R	X	X [2]	—	—	—	—
TIMES	X	FL	Partial	C + R	X	X [2]	—	—	—	—
Top-Down Models										
EPPA	— [1]	RD	General	16 R	X	X [2]	X [2]	X	—	—
Hybrid Models										
CIMS	X	RD	Partial	Canada	X	X	X [3]	—	X [4]	—
GCAM	X	RD	Partial	14 R	X	X	X	—	—	—
IMACLIM-R	X	RD	General	5 R	X	X	X	X	—	X
MARKAL-EPPA	X	RD	General	U.S.	X	X	—	X	—	—
MARKAL-MACRO	X	FL	General	C + R	X	X	—	—	—	—
PRIMES (EU-27 only)	X	RD/FL	Partial	35 C	X	X	X	—	—	—
ReMIND	X	FL	General	11 R	X	X	X	—	—	—
Econometric Models										
POLES	X	RD	Partial	32C+18 R	X	X	—	—	—	—

Notes: FL: Forward-looking, RD: recursive-dynamic, C: country, R: world region. [1] As a consequence of omitting non-price induced changes to final demand and not because of behavioral change policies. [2] Only price-induced adjustments; transportation demand could also be speed-responsive if using generalized costs instead of economic costs. [3] Only for one study (Horne *et al.*, 2005), otherwise "—" as in MARKAL models. [4] Exogenously imposed shares over time.

Existing World-Regional/Global Transportation Demand Models

After broadly examining the energy/economy/environment (E3) models with transport sector representation, this section focuses on existing transportation demand models. The key question is whether these models contain some of the required model specifications from Table 1 to simulate behavioral change in transportation. These elements could then potentially be integrated into the E3 models discussed above.

International Energy Agency Models

Two world transportation demand models were developed at the International Energy Agency (IEA). The ultimate purpose of both models is the projection of world transportation energy use and GHG emissions. Both models project transportation activity by mode and particularly focus on road transportation.

1996 World Energy Outlook Model. This spreadsheet-type model projects transportation energy use based on projections of per person GDP, population, and transportation prices following a hybrid approach (Wohlgemuth, 1997). For the U.S., Europe, Japan, China, India, the change in vehicle miles travelled for passenger and freight transport modes in relation to the base year values are derived from projections of per person GDP, population, and transportation prices. The associated energy use is then estimated via assumed levels of vehicle occupancy rates and energy intensities. For all other parts of the developing world, transportation energy use is estimated directly from different independent variables or via the vehicle stock, depending on data availability. Underlying the transportation demand projections are scenarios of income and price developments for all countries and regions. While the income and price elasticities for transportation fuel use in most parts of the developing world are based on educated guesses, those of transportation demand in the industrialized world seem to have been estimated. However, no methodological approach was given.

Mobility Model (MoMo) Model. This spreadsheet model projects road transportation demand by mode, energy use, and CO_2 emissions for 22 world regions / countries together forming the world. Based on a 2005 base year, the model projects the stock of 2-3 wheelers, light-duty vehicles, and heavy-duty vehicles depending on income scenarios. The projected fleet of passenger and freight vehicles is multiplied by (i) an annual distance driven to arrive at VKT by mode and by (ii) an average occupancy rate or freight load factor to obtain projections of passenger-km travelled and ton-km generated (Fulton *et al*., 2009). These projections are complemented by direct projections of passenger-km travelled and ton-km generated for railways and aircraft and energy use projections for marine transport (Trigg, 2011). In combination with assumptions about energy intensities and fuel characteristics, transportation energy use and CO_2 emissions are projected. MoMo includes two submodels for projecting (i) vehicle sales based on projected motorization rates, existing vehicle stocks and scrapping rates and (ii) the vehicle purchase prices based on technology costs and learning rates. (Vehicle prices, however, do not seem to influence vehicle sales.)

Both IEA models project the demand for transportation and energy use for each mode separately. Hence, it is impossible to endogenously simulate change in total travel demand and mode shifts in response to changes in travel costs, speeds, etc.

The Schäfer / Victor Model of Global Passenger Travel

This model projects a continuation of the trends shown in Figures 2a,b (Schäfer and Victor, 2000). The underlying rationale is a fixed budget of travel money and time expenditures. A fixed ratio of travel expenditures to income (the travel money budget) causes travel demand to increase in proportion to GDP, provided travel costs are roughly stable. At the same time, a fixed travel time budget requires the rising travel demand to be satisfied by faster modes. In an unconstrained world without diminishing returns to travel, all world-regional trajectories in Figure 2a would need to meet in one hypothetical future “target point”, which is characterized by the exclusive use of the fastest transport mode (aircraft, i.e., 600 km/h) over the entire travel time budget (1.2 hours per person per day), 365 days a year. The respective zero shares for the other modes are shown in terms of the shaded envelope in Figure 2b.

Because the shaded envelopes in Figures 2a,b provide only broad guidance for future levels of travel demand and mode shares, this model projects future levels of travel demand via regressions through the historical regional trajectories and the target point. Future mode shares are estimated via regression equations through the historical mode shares and the target point value for low-speed public transportation modes in combination with balancing equations of total travel time (via modal speeds) and PKT.

The key limitations of this model encompass the exclusion of transport costs and diminishing returns to travel (by means of an income elasticity), variables that are required to model the impact on behavioral change. Nevertheless, the projections of PKT by mode from this model have been inputs into a number of energy models, including Azar *et al*. (2003) and Schäfer and Jacoby (2005), shown in Tables 2 and 5. These studies simulated the required technological change in order to meet a CO_2 emission target, while taking the projected levels of PKT by mode as inputs.

GTrans Model

As with the Schäfer / Victor model, this Global Transportation (GTrans) model—currently under development—incorporates a growth model of total passenger travel and a mode choice model. A first version is operational for the U.S. (Schäfer, 2011). The growth model is a dynamic time series model, with lagged terms of PKT per capita, per person GDP, and average prices (which can be specified as either economic user costs or generalized user costs). Any of the three alternative mode choice models (a multinomial logit, a mixed logit that incorporates the U.S. income distribution, and a nested logit that distinguishes between urban and intercity travel) includes the wage rate and several modal attributes, such as vehicle costs, vehicle speed, and for aircraft the ratio of delay time to total flight time. One key parameter of the choice models is the value of time, i.e., the marginal rate of substitution between money and time. All coefficients are estimated with time series data (1950-2008) of per person GDP, user costs by modes, door-to-door speeds by mode, air traffic delay, and for the mixed logit model, the U.S. income distribution over time (1967-2008). While user costs by mode can be derived directly from consumer expenditure surveys, speeds by mode need to be estimated via general relationships specified with national household travel surveys. Air traffic congestion is taken into account by empirical data from U.S. airlines as an increasing function of arrival delay as a fraction of elapsed flight time over elapsed flight time per year.

Once the coefficients of the choice model are estimated, travel costs, door-to-door speeds, and air traffic delays determine the shares of all transportation modes considered. The weighted average travel costs are input into the demand model, along with projected income levels. Jointly, per person PKT, mode shares, and mode speeds yield the daily per person travel time. The latter is compared to an exogenously specified travel time constraint. Should per person travel time exceed the travel time budget, the value of time coefficient in the mode choice model is being increased and mode shares are recalculated. Because a change in oil price leads to substitutions of capital for energy in transport modes and thus a change in transport user costs and therefore mode shifts, another iteration loop generates an economic equilibrium between total travel, mode choice, and technology adoption.

TREMOVE and Zachariadis Models

TREMOVE is a complex integrated transportation model for policy analysis at local, regional, and European levels (e.g., TML, 2007), which was simplified by Zachariadis (2005). In his model, consumers maximize a nested CES-type utility function subject to a budget constraint. The nested utility function represents a decision tree of choices with regard to (i) work or non-work trips, (ii) whether or not to travel, (iii) if travel occurs, whether it is urban or non-urban, (iv) whether it is short or long-distance in each regime, and (v) whether it occurs during peak or off-peak time. Depending on the spatial characteristics of each trip (urban or non-urban), a secondary decision process distinguishes between private and public modes. This decision tree includes cars of two different sizes, which, in non-urban travel, operate on either motorways or other roads. Similar to passenger travel, a representative firm minimizes a cost function of freight movements or business trips. The resulting quantities at each nest depend on the substitution elasticities of the CES functions and the generalized user costs, that is, the economic costs and monetized time expenditures (NTUA, 2008). The solution of this optimization yields the quantities for each alternative at each nest, e.g., the amount of passenger-km traveled within urban and non-urban travel in the third nest mentioned above. The required substitution elasticities of the CES function are derived from the TREMOVE model. It is not clear, however, how these parameters were estimated for the TREMOVE model.

Simulating Behavioral Change in Transportation with E3 Models

After discussing the current specification of existing E3 models in light of the requirements for simulating behavioral change in transportation and after exploring the respective potential opportunities provided by standalone transportation models, this section discusses how best to integrate these opportunities into E3 models. Table 6 summarizes how the main specifications required to model behavioral change outlined at the beginning of this study are implemented in the various models. The required model capabilities relate to elastic transportation demand, choice of no (physical) travel and thus potential substitution by telecommunication means, endogenous mode shift, accounting for infrastructure capacity, and segmenting urban and intercity transportation. While few E3 models are currently capable of simulating the outcome of individual behavioral change policies, the implementation of relevant features from standalone macroscopic models would allow them to explore the entire range of such policies—in combination with technology assessments.

Table 6 Main characteristics of hybrid Energy/Economy/Environment models with transportation sector representation and standalone macroscopic transportation models

	Geographic Scope	Elastic Transportation Demand	Endogenous Mode Choice Model	Choice of no (physical) travel	Accounting for infrastructure capacity	Segmentation urban / intercity
Hybrid E3 Models						
CIMS	Canada	Price Elasticity	MNL	—	—	Exogenous
GCAM	14 R	Price Elasticity	Logit-type	—	—	—
IMACLIM-R	5 R	CES Function	CES Function	CES Function	Road, Rail, Air	—
MARKAL-EPPA	U.S.	CES Function	—	CES Function	—	—
MARKAL-MACRO	C + R	CES Function	—	—	—	—
PRIMES	35 C	Price Elasticity	Price Elasticity	—	—	—
ReMIND	11 R	CES Function	CES Function	CES Function	—	—
Standalone Models						
IEA Models (Momo)	13C + 9 R	—	—	—	—	—
Schäfer/Victor	11 R	—	Hybrid	—	—	—
GTrans	U.S.[1]	Price Elasticity	MNL,ML,NL	—	Air	NL
TREMOVE/Zachariadis	EC countries	CES Function	CES Function	CES Function	Auto, Truck	CES Function

Notes: C: country, R: world region, MNL: multinomial logit, ML: mixed logit, NL: nested logit; [1] Model is currently being expanded to other parts of the world.

Elastic Transportation Demand

According to Table 6, all hybrid models already account for that fundamental capability. As can be seen, the elastic transportation demand is represented by either CES functions or price elasticities. The type of price elasticity differs by model. In CIMS, price elasticities relate to individual transport modes, whereas those in GCAM and GTrans correspond to overall market elasticities for total passenger travel and total freight transportation, respectively. Yet, all specifications lead to a similar outcome, i.e., the decline in total transportation demand as a result of an increase in total transportation costs. Thereby, the CES function specification is richer, as it also explains the shift in demand away from transportation to specific goods or services. However, for the purpose of modeling the change in transportation demand in response to a change in transportation prices, both approaches are equally valuable.

Endogenous Mode Choice

Table 6 suggests that most hybrid models are capable of simulating mode shifts endogenously. Essentially two different approaches have been pursued, i.e., CES functions and consumer choice models. In order to account for the combined impact of differences in vehicle speed and economic costs on mode choice, a CES production function needs to use generalized user costs instead of economic costs, as implemented in the TREMOVE and Zachariadis models. Although CES functions and consumer choice models can lead to similar outcomes, important differences exist. One difference is associated with analytical simplicity, especially with regard to nested models. While nested CES functions are represented by a product of simple expressions, nested consumer choice models incorporate more complex terms and require a larger database for parameter estimation. (When referring to consumer choice models, in the context of national or world-regional E3 models, reference is typically made to aggregate models, that is, regression equations having the functional form of logit models.)

However, the simplicity of CES functions comes at a cost. The substitution elasticities of CES functions are often based on expert judgment instead of rigorous analytical estimation. Therefore, the Zachariadis model relies on values from the rather complex TREMOVE model which has a similar specification and it is not clear how the TREMOVE substitution elasticities were derived. The simulation results may thus be less reliable. Moreover, consumer choice models can more easily include attributes in addition to transportation costs and speeds, should such data be available. For example, in passenger transport, additional attributes could include air traffic delay and quality of service variables such the operating frequency of public transport modes. In freight transportation, additional attributes could account for the (average) value of the transported commodities or the standard deviation of shipment times over a given distance as a measure of service reliability. But even if including transport costs and average speeds as the only attributes in the utility function, the estimated alternative specific constants take into account the combined effect of all attributes excluded from the utility function, all other factors equal. The compared to CES functions typically resulting larger number of estimated parameters in choice models offers a richer basis for interpretation.

Perhaps surprising, none of the mode choice modeling approaches reviewed here is based on cross-price elasticities, which would be a simple way of simulating mode shifts as a result of price changes. As these elasticities are measured on the basis of modes operating at typical speeds, they inherently take into account the speed differences across modes as well. Such approach would require a comparatively small effort for implementing endogenous mode shifts into E3 models that do still lack that capability, such as the MARKAL family of models.

Choice of no (Physical) Travel

Four models in Table 6, IMACLIM-R, MARKAL-EPPA, ReMIND, and the Zachariadis model account for the option of travelers not to travel at all, which is a prerequisite for simulating the substitution of telecommunication means for physical travel. Figure 7b shows the nesting structure for household travel in MARKAL-EPPA, where transportation is substitutable with non-transportation goods and services in the aggregate consumption bundle. Telecommunication substitutes could be specified as an alternative to physical travel, the combination of both would then be substitutable (with a very small substitution elasticity) with the non-transport bundle. All four models represent this choice via CES functions. Thereby, the simplicity of CES functions has to be balanced with the disadvantages described above. This applies for example to the appropriate choice of the substitution elasticity between telecommuting and physical travel.

Accounting for Infrastructure Capacity

In more disaggregate transportation models, passenger and freight trips are assigned to particular elements of an infrastructure network. Infrastructure investments can then be directed to select congested corridors to achieve the desired improvement. As discussed above, these investments do not need to be dedicated to increase automobile speeds, but can—and in the spirit of green growth—should generally enhance public transportation alternatives. However, irrespective of the desired outcome, a more disaggregate approach is computationally intensive and would considerably increase the complexity and runtime of E3 models. The main challenge arising in this context is then the meaningful inclusion of the spatial distribution of the transportation infrastructure in aggregate E3 models.

According to Table 6, three models incorporate the impact of capacity expansions or constraints on the amount of travel. IMACLIM-R addresses road, rail, and air travel, Zachariadis road travel, and the GTrans model includes a capacity constraint of the air transportation system. IMACLIM-R and GTrans follow a similar approach, namely the adoption of a capacity curve. In GTrans, the air transportation capacity curve is represented by a statistical relationship between the share of arrival delay and elapsed flight time on the one hand and elapsed flight time on the other hand, estimated from annual U.S. data. Absent any capacity increase, rising air travel and thus elapsed flight time, the share of arrival delay and elapsed flight time continues to increase. The resulting decline in travel speed then causes the travel demand growth to decline via higher generalized costs in the total travel demand equation (Schäfer, 2011). IMACLIM-R follows a similar approach by specifying an asymptotic relationship between the average (inverse) vehicle speeds and the percentage capacity utilization level of the respective infrastructure (Crassous *et al.*, 2006c). Hence, investments into capacity expansions reduce the share of utilized capacity and thus result in an increase in mean travel speeds and generate additional travel demand. Conversely, a lack of infrastructure investments results in an increase in traffic congestion and declining speeds. The endogenous mode choice model will then induce a shift to competing transport modes. While the IMACLIM-R approach is elegant, it is not clear how the respective capacity curves were estimated.

In contrast, Zachariadis (2005) relates investments into road infrastructure and parking spaces directly to automobile and truck travel speeds via a factor equation that contains the ratios of travel speeds of any given year to that in the reference year (2000) to the respective ratios of vehicle kilometer traveled, investments into road infrastructure, and parking spaces with the respective elasticities and a multiplicative constant. The elasticities are derived from expert judgment. As with the capacity curve formulation, an increase in road capacity will increase automobile and truck travel speeds, all other factors equal.

Segmenting Urban and Intercity Transport

Unlike any other capability for simulating the outcome of behavioral change policies, none of the reviewed E3 models incorporates the endogenous assignment of transportation to either urban or intercity travel. The two macroscopic transportation models with that capability simulate the split between urban and intercity transport with either CES functions (TREMOVE / Zachariadis) or consumer choice models (GTrans). Essentially the same advantages and disadvantages apply as for endogenous mode shifts and are thus not repeated here. However, a challenge to both approaches indicated in Table 6 is that they account for the user costs and speeds of transportation modes operating in both markets as the only attributes (Schäfer, 2011) or, equivalently, the generalized user cost of travel (Zachariadis, 2005). If passenger-km specific costs of intercity travel are lower than those of urban transportation, their combination with the higher speeds will almost certainly induce a shift away from urban to intercity travel. To avoid a long-term trend to potentially implausibly high shares of intercity transport, the attributes of costs and speeds need to be complemented by aggregate spatial indicators of urban and intercity travel.

An associated challenge is the compilation of (long-term historical) data separating transportation activity into urban and intercity movements. For public road transport, many national statistics already separate out urban bus travel from intercity operations. Similarly, railway travel is often reported as urban, commuter, and intercity markets. Even more straightforward, air traffic would only apply to intercity transport. The key challenge then is to assign the (long-term historical) light-duty vehicle traffic volume to urban and intercity transportation. Among others, this task requires a universal definition of urban and intercity transportation in each part of the world. In the U.S. data set, the distinction is made on the basis of the type of road accommodating the vehicles. This definition is not perfect, as some intercity transportation also evolves on urban roads. In addition, the (long-term historical) light-duty vehicle numbers would need to be split into these two segments, using population statistics that are based on inconsistent cross-country definitions in terms of urban and rural residents. In practice, such (historical) assignment can only be done on the basis of generalized relationships, such as established by Schäfer (2000). Essentially the same challenges apply to freight transportation. While railway, water, and air transportation can be unambiguously assigned to intercity transport, a viable definition of urban versus intercity truck transportation would need to be generalized and the long-term historical truck traffic volume be segmented accordingly.

Conclusions

Green growth in transportation requires the combination of drastic technological and behavioral change leading to the provision of similar levels of accessibility and quality of transportation services while depending on a lesser amount of transportation activities and on a higher share of less energy-intensive modes. In achieving this objective, the required policy measures need to be composed carefully to mitigate undesired ancillary effects. Already, at a given income level, differences in land-use and transportation costs have led to differences in total mobility levels and mode shares. However, more significant changes are necessary to significantly mitigate the undesired externalities of the transportation sector. Most effective would be a combination of measures—marginal social cost pricing, infrastructure and land-use planning, and enhanced use of telecommunication substitutes. The extent to which such policy combinations can mitigate the fundamental dynamics underling the development of our transportation system towards more and faster travel needs to be explored.

The need for complementing technology assessments with behavioral change policies contrasts sharply with the specification and past analyses of most E3 models, although limited-scope assessments would already be possible. Despite the implementation of the transportation sector into a large number of bottom-up, top-down, and hybrid energy models, in nearly all cases, the focus has been on the adoption of low GHG emission vehicle technologies, with consumers choosing among competing technologies based on their cost-effectiveness in most cases. However, the effort for enhancing the opportunities for policy analysis would be comparatively modest. Several E3 models already include specifications that would allow testing a limited number of policies aiming at behavioral change. This applies to especially hybrid energy models, most of which already incorporate an elastic transportation demand specification and endogenous shift between transportation modes. In addition, selected hybrid models also include a representation of the transportation infrastructure capacity that allows simulating the impact of infrastructure investment decisions or the facility to simulate the substitution of telecommunication for travel.

If combined with relevant features of standalone macroscopic transportation models, hybrid E3 models would be capable of simulating a wide range of behavioral change policies. Because different specifications have already been tested in either E3 models or standalone models, the required effort is comparatively modest. The task is then to integrate these features into E3 models and expand the geographic scope from individual countries or regions to the entire globe. This perhaps represents the most challenging part, given the lack of internally consistent socio-economic and transportation databases from which the missing data could be estimated.

Overall, introducing behavioral change in transportation into E3 models is feasible and intellectually rewarding. However, when pursuing holistic approaches to mitigating energy use and emissions, it is indispensable.

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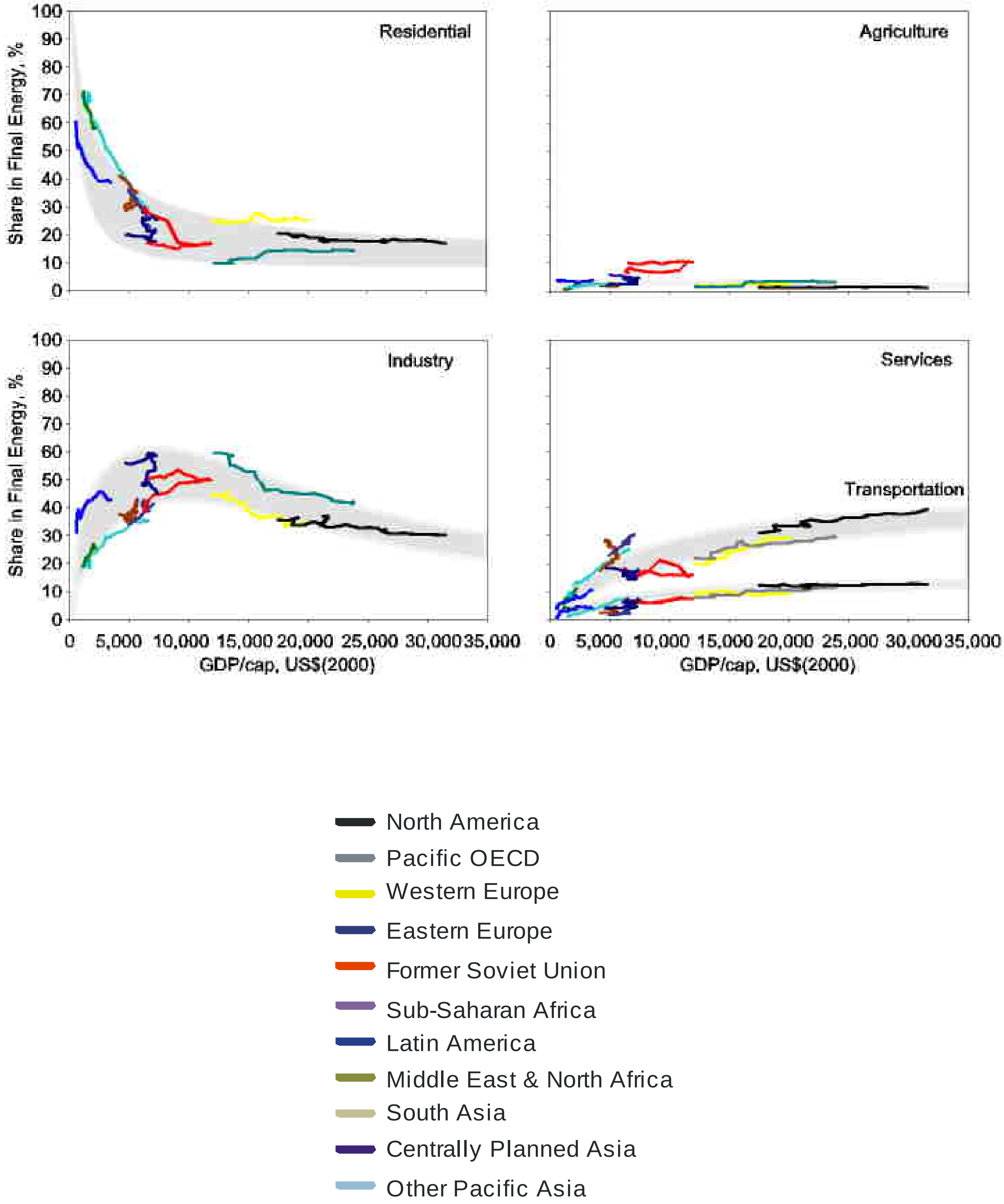

Residential
Agriculture
Industry
Services
Transportation
Share in Final Energy, %
GDP/cap, US$(2000)
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
0
10
20
30
40
50
60
70
80
90
100
North America
Pacific OECD
Western Europe
Eastern Europe
Former Soviet Union
Sub-Saharan Africa
Latin America
Middle East & North Africa
South Asia
Centrally Planned Asia
Other Pacific Asia

Figure 1

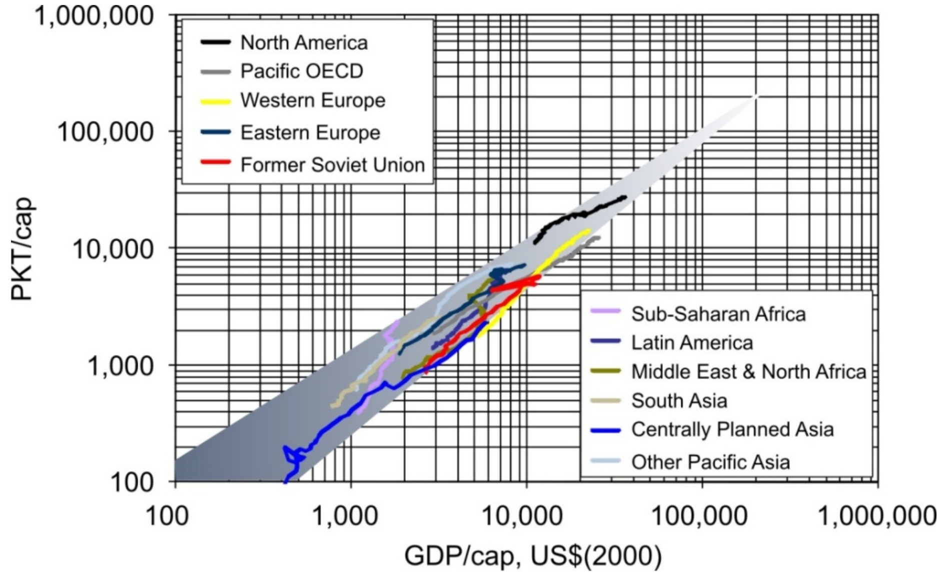
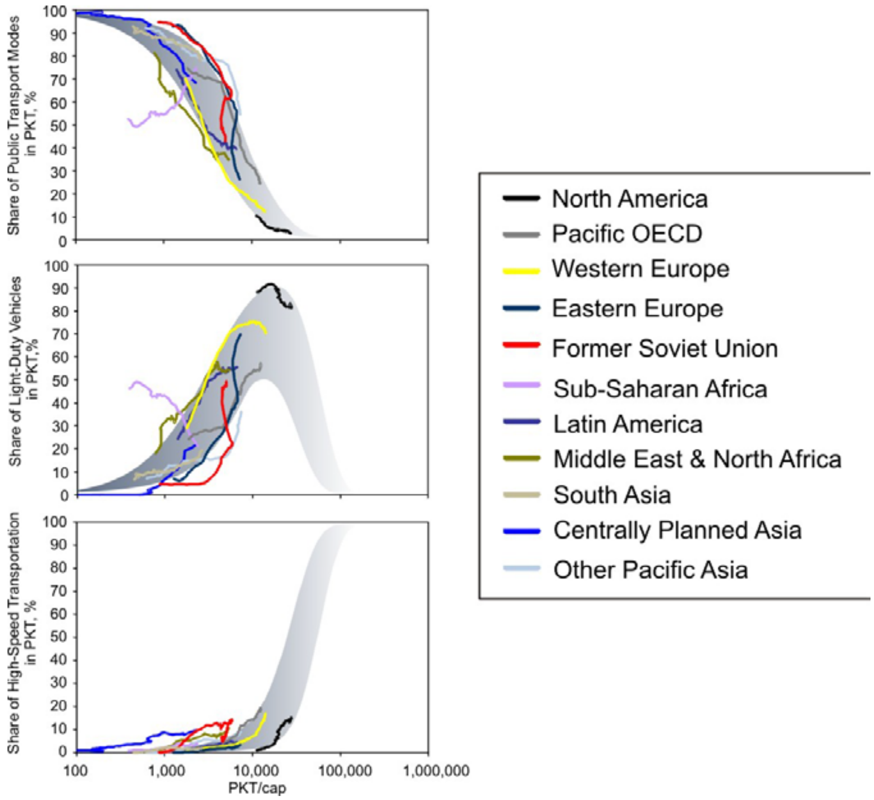

1,000,000
100,000
10,000
1,000
100
PKT/cap
100
1,000
10,000
100,000
1,000,000
GDP/cap, US$(2000)
North America
Pacific OECD
Western Europe
Eastern Europe
Former Soviet Union
Sub-Saharan Africa
Latin America
Middle East & North Africa
South Asia
Centrally Planned Asia
Other Pacific Asia

Figure 2a



Share of Public Transport Modes in PKT, %
Share of Light-Duty Vehicles in PKT,%
Share of High-Speed Transportation in PKT, %
100
90
80
70
60
50
40
30
20
10
0
100
1,000
10,000
100,000
1,000,000
PKT/cap
North America
Pacific OECD
Western Europe
Eastern Europe
Former Soviet Union
Sub-Saharan Africa
Latin America
Middle East & North Africa
South Asia
Centrally Planned Asia
Other Pacific Asia

Figure 2b

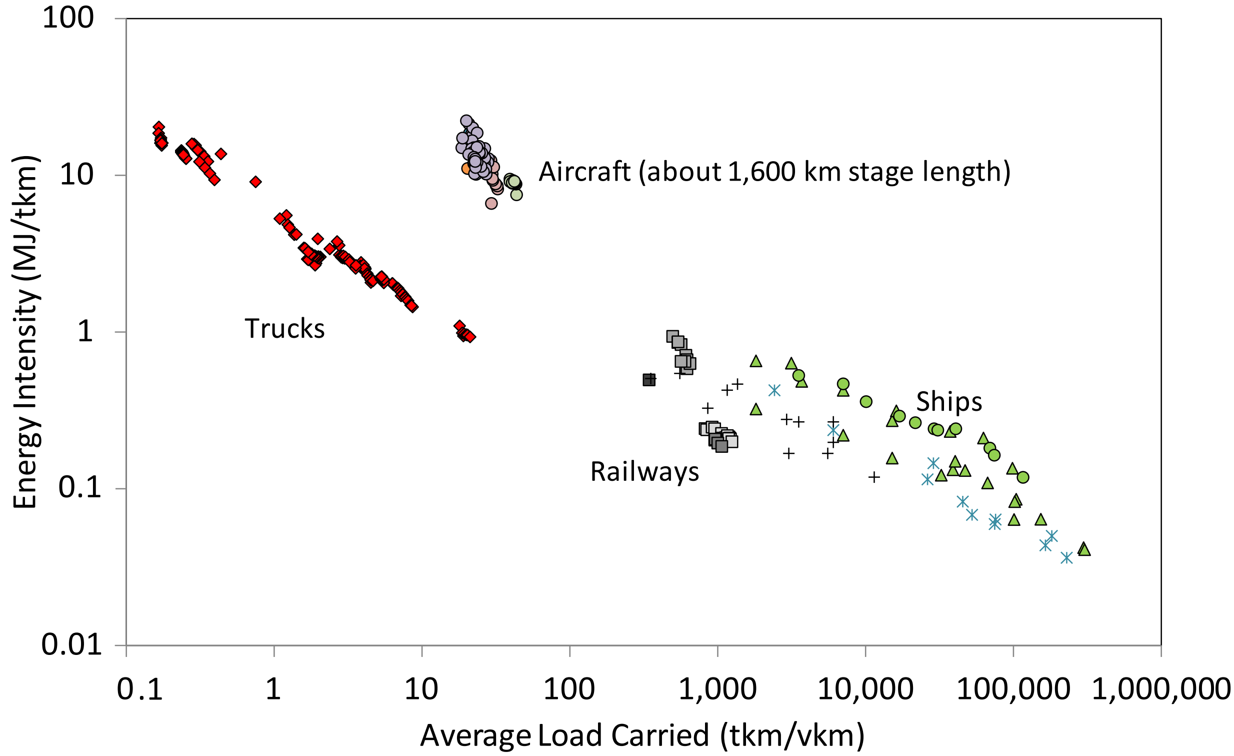
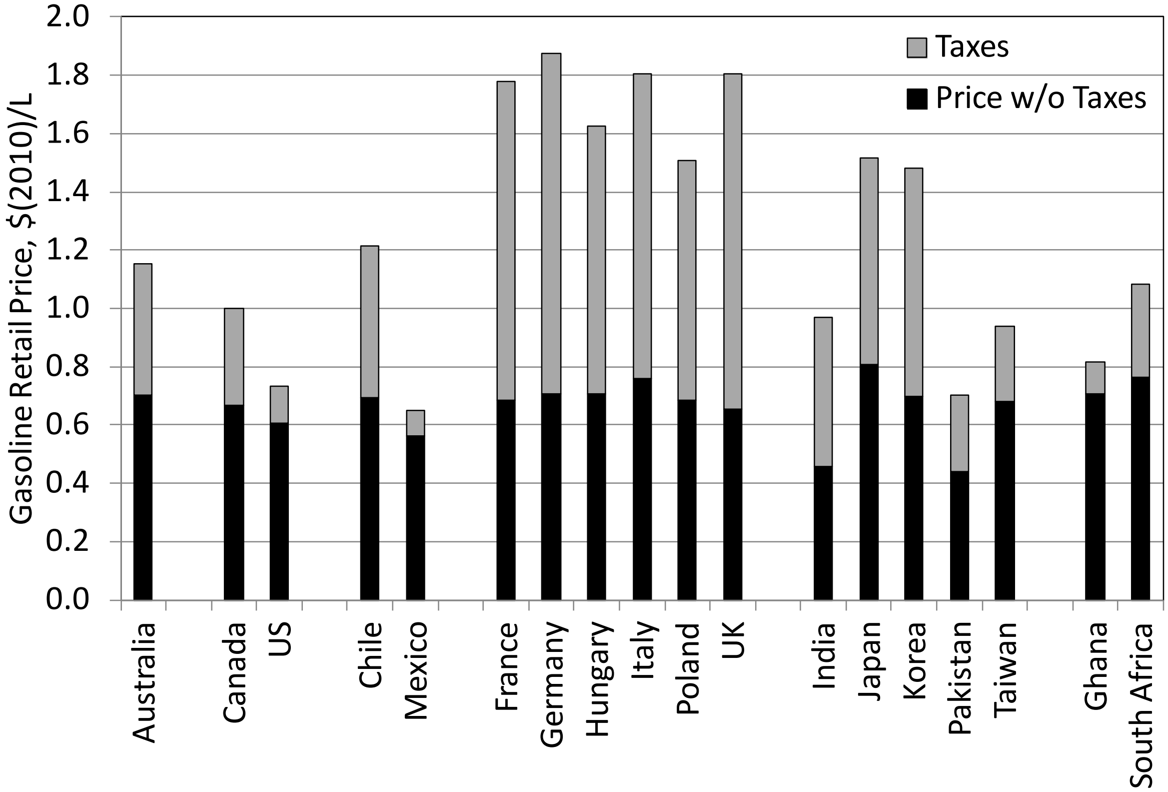
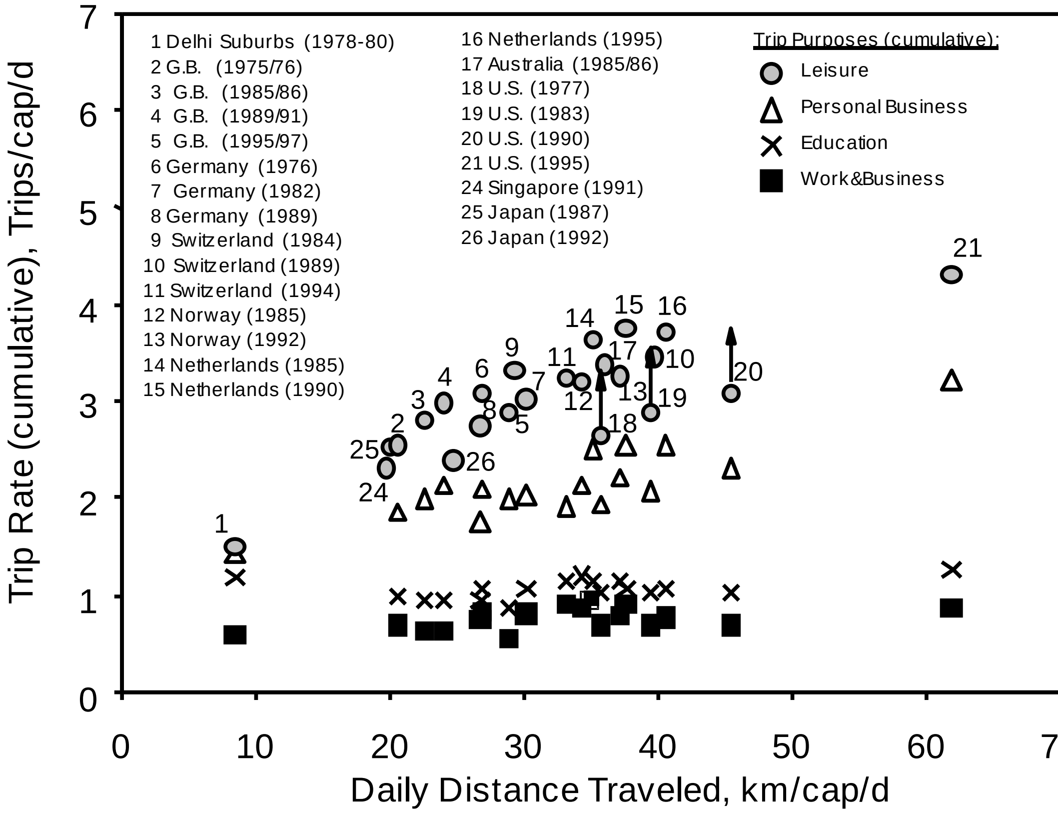

100
10
1
0.1
0.01
Energy Intensity (MJ/tkm)
Aircraft (about 1,600 km stage length)
Trucks
Railways
Ships
0.1
1
10
100
1,000
10,000
100,000
1,000,000
Average Load Carried (tkm/vkm)

Figure 3



2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Gasoline Retail Price, $(2010)/L
Taxes
Price w/o Taxes
Australia
Canada
US
Chile
Mexico
France
Germany
Hungary
Italy
Poland
UK
India
Japan
Korea
Pakistan
Taiwan
Ghana
South Africa

Figure 4



1 Delhi Suburbs (1978-80)
2 G.B. (1975/76)
3 G.B. (1985/86)
4 G.B. (1989/91)
5 G.B. (1995/97)
6 Germany (1976)
7 Germany (1982)
8 Germany (1989)
9 Switzerland (1984)
10 Switzerland (1989)
11 Switzerland (1994)
12 Norway (1985)
13 Norway (1992)
14 Netherlands (1985)
15 Netherlands (1990)
16 Netherlands (1995)
17 Australia (1985/86)
18 U.S. (1977)
19 U.S. (1983)
20 U.S. (1990)
21 U.S. (1995)
24 Singapore (1991)
25 Japan (1987)
26 Japan (1992)
Trip Purposes (cumulative):
Leisure
Personal Business
Education
Work&Business
Trip Rate (cumulative), Trips/cap/d
Daily Distance Traveled, km/cap/d

Figure 5

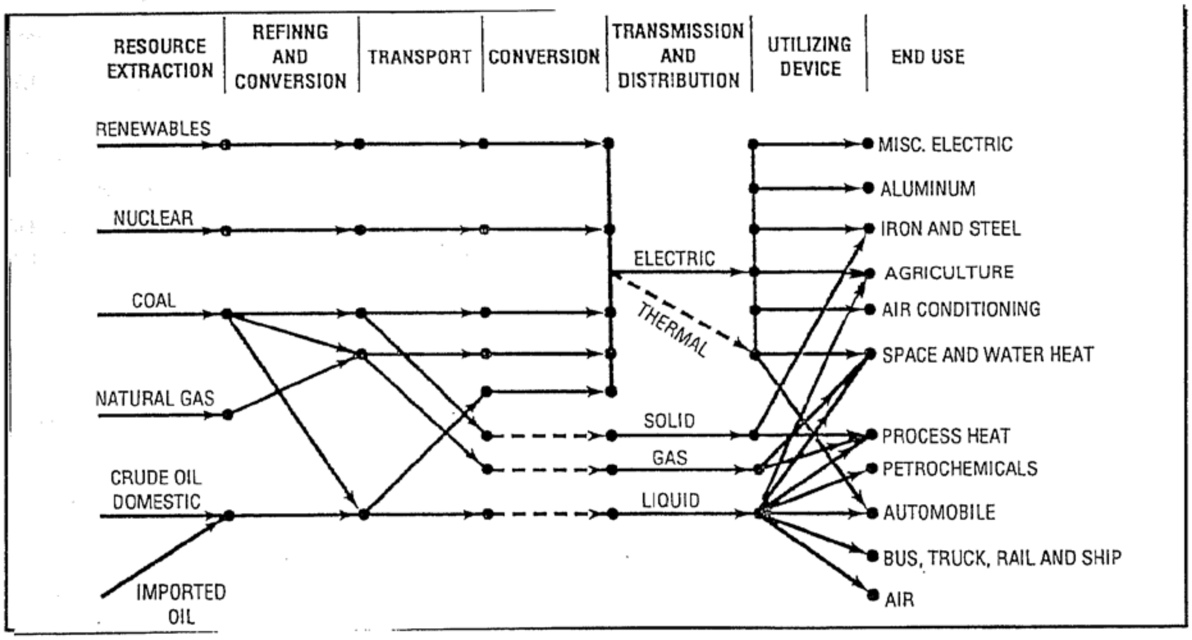
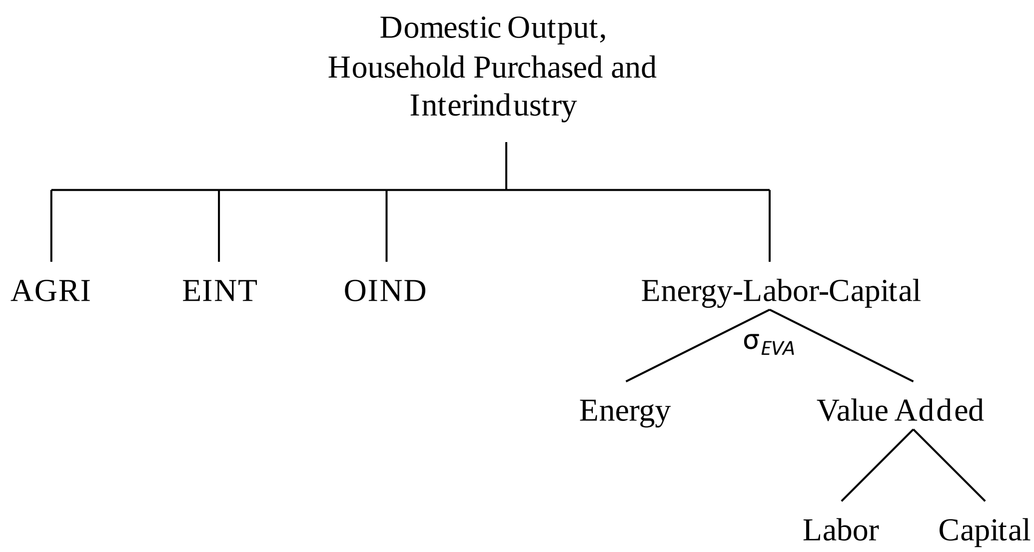

RESOURCE EXTRACTION
REFINNG AND CONVERSION
TRANSPORT
CONVERSION
TRANSMISSION AND DISTRIBUTION
UTILIZING DEVICE
END USE
RENEWABLES
NUCLEAR
COAL
NATURAL GAS
CRUDE OIL DOMESTIC
IMPORTED OIL
ELECTRIC
THERMAL
SOLID
GAS
LIQUID
MISC. ELECTRIC
ALUMINUM
IRON AND STEEL
AGRICULTURE
AIR CONDITIONING
SPACE AND WATER HEAT
PROCESS HEAT
PETROCHEMICALS
AUTOMOBILE
BUS, TRUCK, RAIL AND SHIP
AIR

Figure 6


Domestic Output,
Household Purchased and
Interindustry
AGRI
EINT
OIND
Energy-Labor-Capital
σ_{EVA}
Energy
Value Added
Labor
Capital

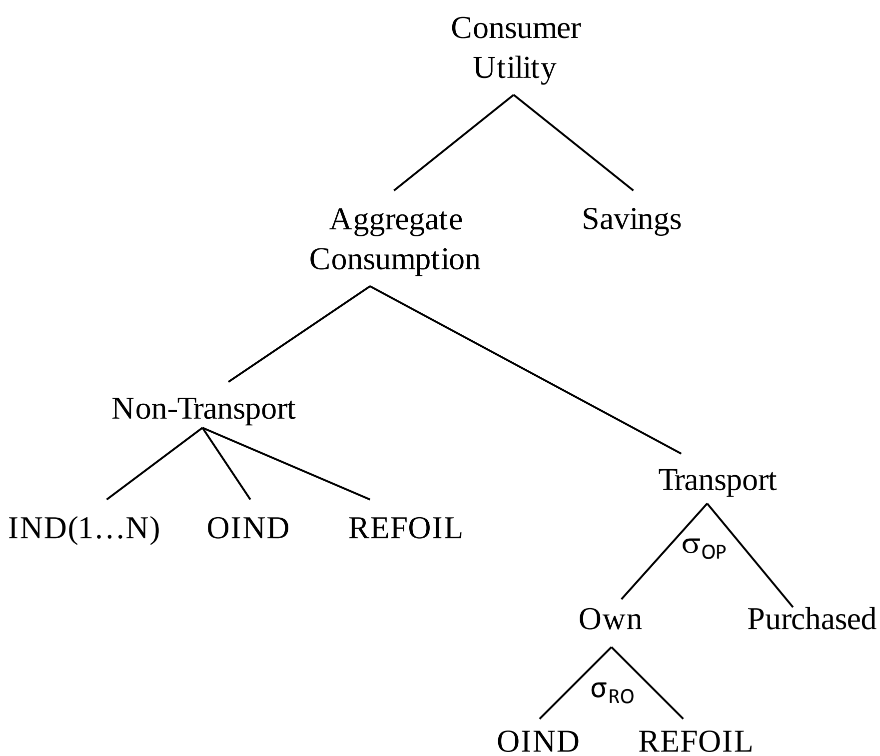

Consumer
Utility
Aggregate
Consumption
Savings
Non-Transport
IND(1…N)
OIND
REFOIL
Transport
σ_{OP}
Own
Purchased
σ_{RO}
OIND
REFOIL

Figure 7a,b

Appendix: Brief description of hybrid and econometric energy models

The Canadian Integrated Modelling System (CIMS), developed at Simon Fraser University, is a simulation model of the Canadian energy economy. It consists of an energy demand model, an energy supply and conversion model, and a macroeconomic model. Starting with an exogenous forecast of the economic activity of and physical outputs from each economic sector, such as passenger-km traveled and freight ton-km generated in the transportation sector, along with a set of prices, the sector submodels track these developments by adjusting the respective capital stock through new purchases, retrofits, and retirements by minimizing financial and intangible expenditures on capital, labour, energy, and emissions charges (Bataille *et al*., 2006). The transportation sector includes passenger transportation, freight transportation, and off-road vehicles. The referenced application of CIMS in Table 4 includes a multinomial logit model of commuting vehicle and fuel choice, estimated with stated preference survey data from a sample of 1,150 Canadians (Horne *et al*., 2005). The demand for freight transportation is linked to the combined value added of the industrial sectors using an econometrically estimated relationship with a cross price elasticity of 0.95 (Bataille and Jaccard, 2004). If the choice of specific technologies and fuels results in different consumer costs (which affect demand), the energy demand model and the energy supply and conversion model are iterated until an equilibrium in prices and demand levels is achieved. In a subsequent step, the macroeconomic model estimates the impact of changing energy prices on the structure of the economy, total economic output, and international trade.

The Global Change Assessment Model (GCAM) model was developed at the Pacific Northwest National Laboratory. It links modules describing global energy, agriculture, land-use, and climate. GCAM calculates equilibriums in each time period in all regional and global markets for energy goods and services, agricultural goods, land, and GHG gas emissions (Kyle and Kim, 2011). It solves for a vector of prices by iteration such that supply and demand for all markets are equal. Its passenger and freight transportation components project aggregate transportation demand for passenger and freight transportation as a function of income and mode-average generalized costs, i.e., the aggregate of travel costs and monetized transportation-related time expenditures. The monetized transportation time expenditures are represented by the ratio of wage rate and vehicle speed (Kim *et al*., 2006; Kyle and Kim, 2011). Therefore, the implicit assumption is a value of time equaling the wage rate. Mode choice is modeled using a logit-type equation where the exponentiated utility terms are substituted by the generalized costs with an exponentiated coefficient and multiplied by another parameter. Hence, an increase in GDP and thus wage rate will increase the costs of low-speed modes more strongly (because of the ratio of wage rate and vehicle speed in the generalized cost term) and the logit-type equation will thus divert travel to faster modes. At the same time, a higher generalized cost will also mitigate the growth in travel demand. The modal composition of freight transportation is modeled similarly.

In IMACLIM-R (IMpact Assessment of CLIMate policies-Recursive version), developed at CIRED, a static economic equilibrium is calculated for each time step. The equilibriums are linked by dynamic relationships describing population growth, fossil fuel resources depletion, and technological change, using prices, investments, and physical flows as inputs to update key model parameters required for calculating the subsequent equilibrium. The model contains 10 economic sectors, including air transport, sea transport, and terrestrial transport, which includes two passenger transport modes, i.e., personal transportation and non-motorized travel (Crassous *et al*., 2006). The model maximizes a utility function which includes household transportation, subject to income and time budget constraints. A nested CES production function (with passenger kilometers traveled as output) then separates out automobiles from public transportation, aircraft, and non-motorized modes. The speed of each road transport mode depends on the available infrastructure, with a shortage of infrastructure supply increasing traffic congestion asymptotically (Crassous *et al*., 2006c). Conversely, infrastructure expansions will increase speeds and thus induce additional travel by attracting traffic from other infrastructures, thus satisfying a key requirement for behavioral change outlined in Table 1. Due to the travel time constraint, a declining speed for a given mode then induces diversion to faster ones, depending on relative speeds and costs. In contrast, the demand for freight transportation, which includes road and rail, is modeled through fixed input coefficients into the 10 production sectors. Therefore, intermediate (freight) transportation is proportional to economic growth.

The MARKAL-EPPA model soft-links a technology-rich MARKAL model with the MIT EPPA model, described above. Travel demand grows with a fixed income elasticity. Because changes in mode share would exclusively be price-induced, in the absence of a value of time, a mode choice model imposes shifts toward faster passenger transport modes in the EPPA model as travel demand grows (Schäfer and Jacoby, 2005). Simultaneously, a simplified modal shift model assigns the inter-industry transportation output of EPPA into different freight transport modes. Technological change in the MARKAL model determines the time profiles of the substitution elasticities between energy and the capital/labor aggregate.

PRIMES, developed at the Energy/Economy/Environment Laboratory at the National Technical University of Athens, is a dynamic partial equilibrium model, which can be run in a recursive dynamic or forward-looking mode. It simulates market equilibrium for energy supply and demand through iterating a price vector of energy carriers. The supply sectors include a wide range of fossil and renewable fuels, while the demand sectors include a representation of industry, households, services and agriculture, and transportation. Transportation demand is determined as a function of income and the overall price of transport, which, in turn, is determined endogenously (as a function of mode shares and prices per mode). Mode shares are determined as a function of the price per mode and "behavioral and structural parameters" (NTUA, 2008). The model keeps track of capital vintages and their technical and economic characteristics. Technical characteristics of new technologies are chosen based on the lowest expected usage costs. Exogenous variables are GDP by sector, household income, and population size. PRIMES has been linked to other models to increase the comprehensiveness of the economy or specific sectors, such as transportation. A NTUA (2008) description of the PRIMES model implies the integration of a more sophisticated transport model by Zachariadis (2005) by the end of 2009. This combination of models, which would allow examining virtually all of the behavioral change policies discussed in the previous section, is described in the subsequent section.

ReMIND-R, developed at the Potsdam Institute for Climate Impact Research, consists of an interlinked detailed energy systems model, an economic growth model, and a simple climate model. ReMIND is an optimal growth model that simulates optimal development pathways for maximizing an intertemporal global welfare, which is based on nested regional production functions. It includes for a set of detailed energy carriers and conversion technologies. It operates under perfect foresight, which implies that technological options requiring large up-front investments that have long pay-back times are more readily adopted in determining the optimal solution as compared to myopic models, such as IMACLIM-R. The transport sector, which is currently being further developed, is represented by nested CES functions, whereas individual technologies are modeled with linear production functions.

The POLES model is an econometric partial equilibrium model. Its demand module uses exogenously projected economic growth per sector, initial energy prices, and population projections as inputs to project final energy consumption per sector via dynamic statistical models. An exception is the transportation sector, where transportation activity is projected for each mode. Using the age composition of vehicle fleet, final consumption is then translated into final energy demand. The projected levels of final energy demand are then satisfied by the supply module. Because energy supply is also a function of price, the market clearance price for coal, oil, and gas and thus the amount of final energy consumed by fuel are determined iteratively (EC, 2010). New technologies are introduced to satisfy the rising end-use demands and to substitute those technologies that reach end-of-life and are phased out; technology adoption is typically based on a least-cost basis, although more complex portfolio optimization techniques were developed for electricity generation (EC, 2006). Given the exogenously projected GDP levels and the lack of a value added feedback, the POLES model cannot estimate the macroeconomic impacts of mitigation policies.