Optimizing U.S. Mitigation Strategies for the Light-Duty Transportation Sector: What We Learn from a Bottom-Up Model

SONIA YEH,*,† ALEX FARRELL,‡ RICHARD PLEVIN,‡ ALAN SANSTAD,§ AND JOHN WEYANT‖

Institute of Transportation Studies, University of California, Davis, California 95616, Energy and Resources Group, University of California, Berkeley, California 94720, Lawrence Berkeley National Laboratory, Berkeley, California 94720, and Department of Management Science and Engineering, Stanford University, Stanford, California 94305

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Few integrated analysis models examine significant U.S. transportation greenhouse gas emission reductions within an integrated energy system. Our analysis, using a bottom-up MARKet ALocation (MARKAL) model, found that stringent system-wide CO_2 reduction targets will be required to achieve significant CO_2 reductions from the transportation sector. Mitigating transportation emission reductions can result in significant changes in personal vehicle technologies, increases in vehicle fuel efficiency, and decreases in overall transportation fuel use. We analyze policy-oriented mitigation strategies and suggest that mitigation policies should be informed by the transitional nature of technology adoptions and the interactions between the mitigation strategies, and the robustness of mitigation strategies to long-term reduction goals, input assumptions, and policy and social factors. More research is needed to help identify robust policies that will achieve the best outcome in the face of uncertainties.

1. Introduction

Transportation of people and goods is an essential part of our economic progress and social interactions. However, the transportation sector produces 32% of the greenhouse gas emissions in the United States, of which more than 97% is from petroleum products. By 2030, the transportation sector's CO_2 emissions are expected to increase by 24% from current levels, which account for nearly 26% of the projected U.S. CO_2 emissions increase by 2030 (*1*).

Numerous states are taking action to reduce greenhouse gas emissions. The Regional Greenhouse Gas Initiative (RGGI) is the first mandatory U.S. cap-and-trade program for CO_2 emissions. However, it only aims to reduce greenhouse gas emissions from power plants. So far, the only legislation that sets mandatory economy-wide greenhouse gas reduction targets in the U.S. is California's Global Warming Solutions Act of 2006 (also known as AB32), which was passed in September 2006. AB32 requires that California reduce its greenhouse gas emissions to the 1990 level by 2020, and 80% below its 1990 level by 2050. In 2007, there were at least a dozen Congressional bills to reduce greenhouse gas emissions, most notably the Climate Stewardship and Innovation Act (McCain−Lieberman Bill, S. 280), the Global Warming Pollution Reduction Act (Sanders−Boxer Bill, S. 309), and the Lieberman−Warner Climate Security Act of 2007 (S. 2191). Several studies that examined the implementation of the proposed cap-and-trade regulations in the U.S. have found that under market mechanisms, reducing total emissions will do little to reduce transportation CO_2 emissions. The EIA analysis on the energy market and economic impacts of S. 280 (*2*) shows that 90% of CO_2 reductions will occur in the power sector, while the transport and industrial sectors will each contribute 4−5%. The report, based on EIA's National Energy Modeling System (NEMS) model, concludes that an overall CO_2 emissions reduction target will induce a slight increase in fuel price, but that the increase will not be large enough to dramatically shift consumer behavior toward more efficient vehicles, demand reductions, or alternative fuel vehicles. Similar results were found in other EIA analyses (*3*) and in an analysis by the U.S. Environmental Protection Agency (*4*).

There are also many separate efforts to reduce greenhouse gas emissions from the transportation sector. These typically aim to achieve at least two of the following three goals: (1) increase independence from imported oil, (2) reduce transportation greenhouse gas emissions, and (3) increase the use of renewable fuels (biofuels in particular). For example, California's AB1493 (Pavley) sets vehicle performance standards and requires a 30% reduction in greenhouse gas (GHG) emissions from new light-duty vehicles by 2016. The Energy Independence and Security Act (H.R. 6), which includes a 36 billion gallon renewable fuel mandate, was passed by Congress and signed by President Bush on December 19, 2007. California's Low Carbon Fuel Standard (LCFS, Executive Order S-1-07) calls for a reduction of at least 10% in the carbon intensity of the state's transportation fuels by 2020. The LCFS regulates emission reductions on a life cycle basis (*5*). Other regulations that adopt life cycle assessment as a basis for regulation include the Energy Independence and Security Act of 2007, the United Kingdom's Renewable Transport Fuel Obligation (RTFO), and the European Commission's Biofuels Directive (2003/30/EC). These regulations focus on inducing the adoption of biofuels.

Given the regulatory activities focused on transportation GHG emissions, most of the U.S. studies examining their reduction potential use either an engineering economics approach that examines the cost of reducing transportation emissions independent of other sectors (*6, 7*), or modeling within an integrated framework that lacks stringent transportation goals (*2*−*4*). Studies that examined the potential of transportation CO_2/GHG emission reductions using engineering economics analyses suggest that the economic impacts of improving energy efficiencies of noncommercial light-duty vehicles will be minor (*6*−*9*). Greene and Schafer (*7*) provided an overview of GHG emissions reduction potentials from the transportation sector and concluded that "a reasonable combination of policy measures should be able to reduce U.S. transportation sector CO_2 emissions by 20 to 25 percent by 2015 and by 45 to 50 percent by 2030 in comparison to a transportation future without any efforts to

* Corresponding author e-mail: slyeh@ucdavis.edu; tel: (530)-754-9000; fax: (530) 752-6572.
† Institute of Transportation Studies, University of California.
‡ Energy and Resources Group, University of California.
§ Lawrence Berkeley National Laboratory.
‖ Stanford University.

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TABLE 1. Description of Scenarios Examined in This Paper

scenario	description	note
reference case	projections of the reference case	travel demand elasticity = −0.1, vehicle technology discount rate = 0.33
10%E, 20%E, 30%E, 40%E, 50%E	10−50% economy-wide cap	travel demand elasticity = −0.3, vehicle technology discount rate = 0.15
10%E&T, 20%E&T, 30%E&T	10−30% economy-wide + transportation cap	
30%E&T_NB	30% economy-wide + transportation cap *without* biofuel mandate after 2015	
30%E&T_NBNC	30% economy-wide + transportation cap *without* biofuel mandate after 2015 and no successful cellulosic ethanol technology	

control carbon emissions." Similar optimism is expressed in the recent McKinsey & Company report (*6*), which concluded that a cluster of transportation technologies including efficiency improvement of vehicles, use of cellulosic biofuels, and hybridization of vehicles could provide 340 megatons of abatement at a cost of less than \$50 per ton (in 2005 dollars) by 2030.

In contrast, Schafer and Jacoby (*10*) use a transportation technology detailed bottom-up model that links to a multisector computable general equilibrium model of the economy, suggesting that an economy-wide CO_2 emission reduction to 35% below the 1990 level in 2030 will double the U.S. motor fuel retail price in 2010 and increase it 8-fold by 2030 (*10*). The study found that the penetration of more efficient vehicles is very sensitive to the consumer discount rate and that even at high fuel prices, the penetration of efficient vehicles will likely remain low through 2030 if no substantial policies are adopted to influence the discount rate. Alternative fuel vehicles or advanced vehicle technologies such as plug-in hybrid vehicles and hydrogen fuel cell vehicles are not included in their study, but they are unlikely to substantively affect the study's results.

This paper examines significant transportation CO_2 emission reduction scenarios in the U.S. using a bottom-up modeling approach within an integrated system model. The integrated system permits an examination of the dynamics of various mitigation strategies in response to supply and demand changes and the potential interactions between sectors of the economy. Mitigation strategies with the potential to achieve significant long-term transportation emission reductions often face significant competition for primary resources with other sectors, including biomass, natural gas, renewables, and coal, and for secondary energy sources such as electricity. Therefore, any significant transportation mitigations will likely affect resource cost and availability to other sectors, which are also likely to face significant CO_2 constraints in the scenario analysis.

In Section 2, we conduct simulations of the mitigation strategies of reducing transportation CO_2 emissions under increasingly stringent economy-wide and/or transportation-specific CO_2 reduction goals as well as policies or social factors that may affect future mitigation pathways. In Section 3, we discuss the dynamics of mitigation strategies to reduce transportation CO_2 emissions. Last, in Section 4, we offer our thoughts on future research in this area.

2. Scenarios of CO_2 Emissions Reduction and Its Impacts

2.1. Model. Our study uses the U.S. EPA national MARKet ALlocation (MARKAL) Model technology database (*11*), modified by the International Resources Group for the Natural Resources Defense Council (NRDC) (*12, 13*), and incorporates a series of transportation updates, including vehicle technology assumptions and improved biofuel characterization (see Supporting Information, referred to as SI hereafter), the new ethanol requirement under the Energy Independence and Security Act (EISA) (we assume biofuel production must reach 36 billion gallons by 2022 and remain at that level until 2050), and the new CAFE standard requiring new vehicle fleet-average efficiency of 35 mpg by 2020. Ethanol can be produced from corn and cellulosic sources and can be blended in gasoline at various levels up to E10 (10% ethanol by volume), or as E85. Previous analysis using

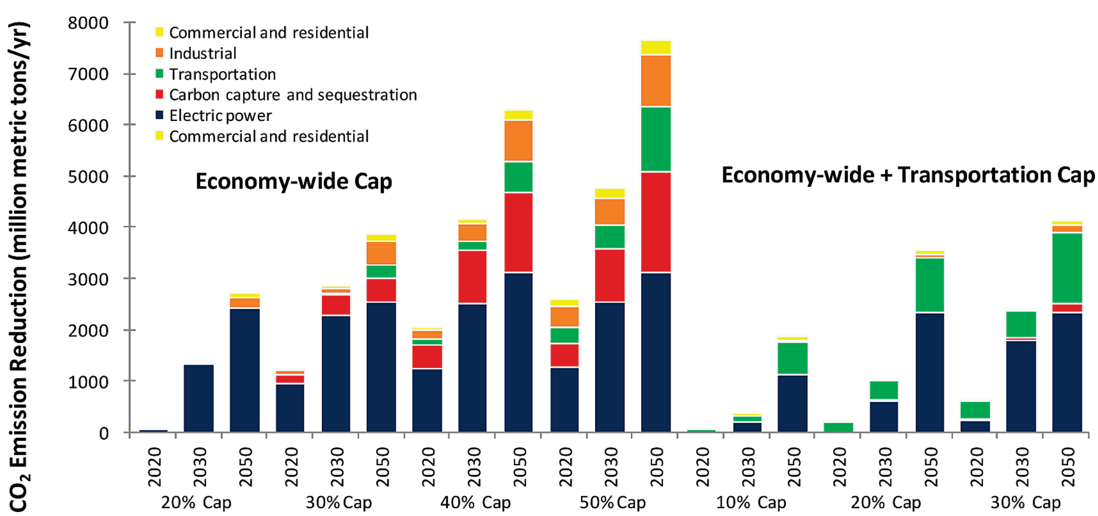

FIGURE 1. Energy-related CO_2 emission reductions in 2020, 2030, and 2050 by sector in the 20−50% economy-wide cumulative CO_2 emission-cap scenarios and in the 10−30% economy-wide and transportation cumulative CO_2 emission-cap scenarios.

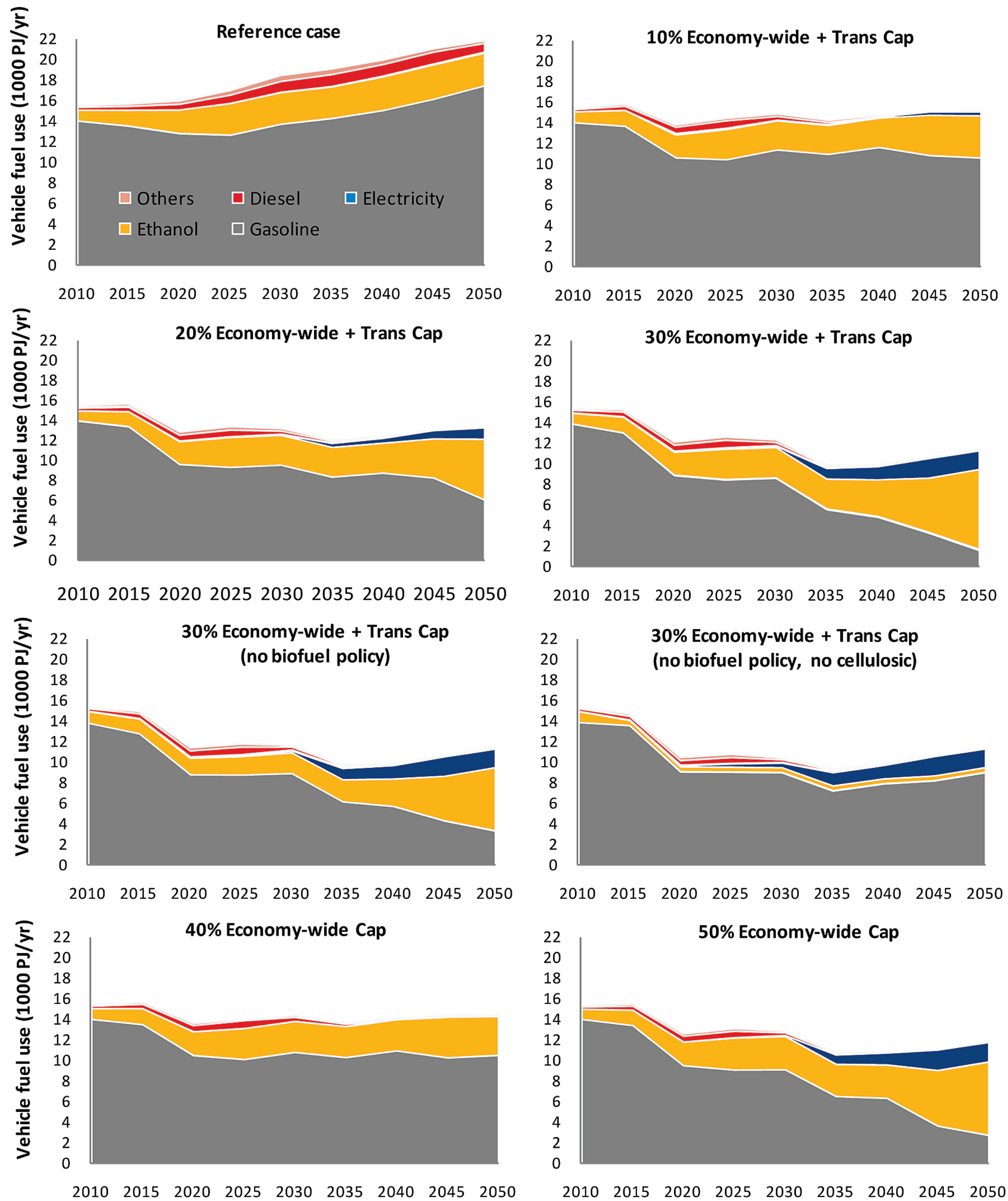

FIGURE 2. Total passenger-vehicle fuel use by type of fuel (1000 PJ/yr).

the U.S. EPA national model database can be found in various publications (*14, 15*). Our current model examines only the emissions of CO_2 gases, which accounted for 84% of total greenhouse gas emissions in 2005 in the United States (*16*). However, for ethanol feedstocks, the considerable N_2O emissions are included as CO_2 equivalents because they can comprise a sizable share of the direct GHG effects of bioenergy crop production. Though our model includes all transportation types, the results presented here focus on mitigation strategies for light-duty vehicles, which account for half of the emissions from the transportation sector.

MARKAL is a bottom-up model that characterizes current and future energy technologies in detail, including variables such as capital cost, operational and maintenance costs, fuel efficiency, emissions, and useful life. MARKAL also accounts for fuel supply, resource potentials, and other user constraints, in identifying the most cost-effective technological pathway to satisfy future end-use demands defined by the modelers (*17*). The MARKAL model assumes rational decision making, with perfect information and perfect foresight, and computes a supply/demand equilibrium where energy demand is price-elastic.

2.2. Emission Reduction Scenarios. Two key sets of scenarios were examined. One set applies economy-wide emission reduction targets (E scenarios), whereas the other set applies the same percentage reduction targets to *both* the transportation sector and the whole economy (E&T scenarios). For the period 2010 to 2050, we examine cumulative emission reduction targets from 10% to 50% economy-wide (E) and from 10% to 30% economy-wide and transportation-only (E&T). Our reference case (also called the “business-as-usual” or “BAU”) incorporates both the new ethanol requirement under EISA and the new CAFE standard. Because of these changes, our reference case has higher

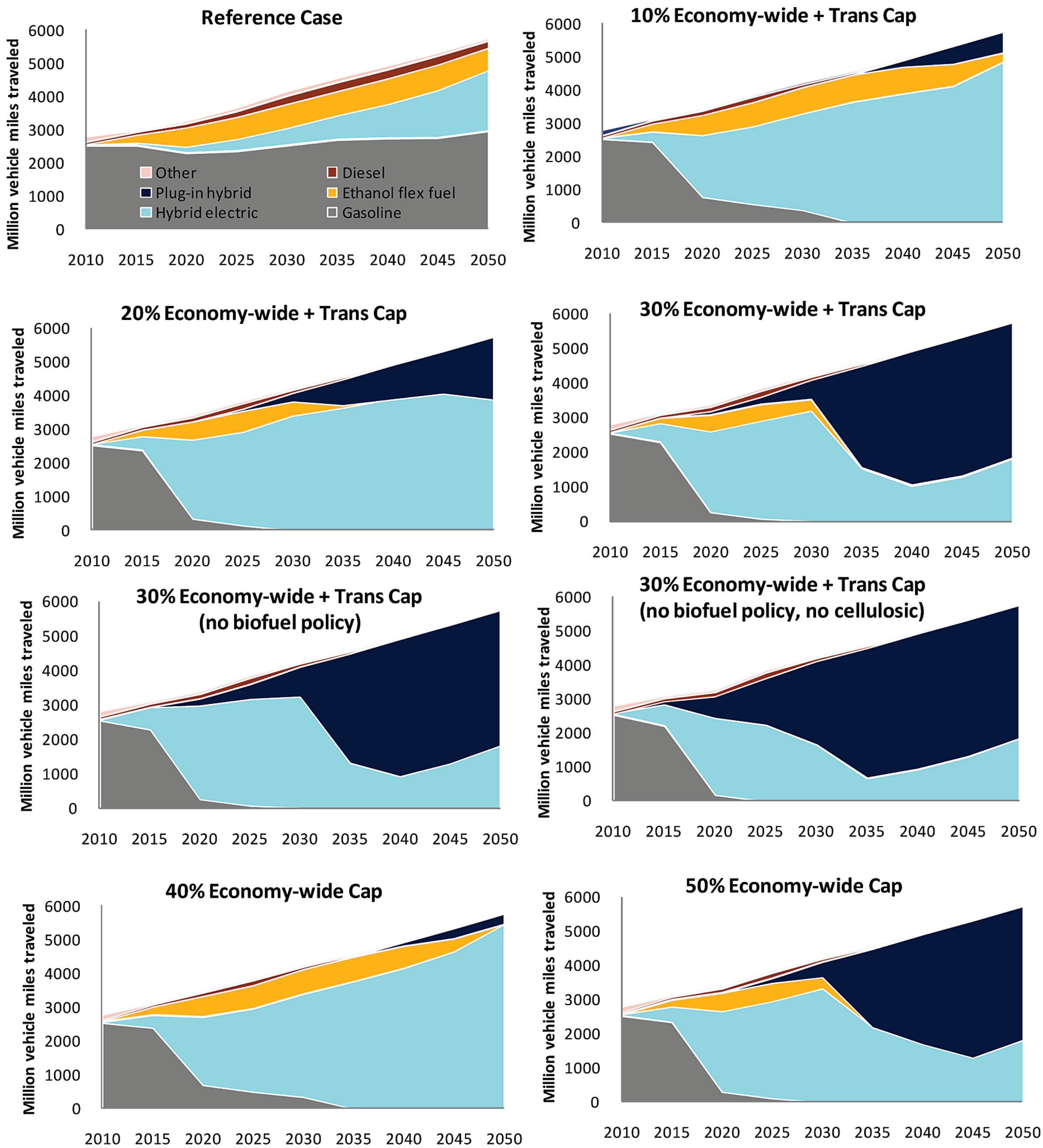

FIGURE 3. Light-duty vehicle penetration profiles (billions of miles per year), 2010–2050.

vehicle efficiency, lower transportation CO_2 emissions, and lower gasoline usage than most BAU projections published prior to early 2008. Therefore, the "cumulative reductions from the reference case" (also referred to as "CO_2 avoided," which represents the amount of total CO_2 emissions "avoided" from a hypothetical reference case) and "caps" examined in this paper reflect emissions-reduction pathways that start from a lower transportation-emissions reference case. We assume travel demand elasticity of −0.1 in the reference case and −0.3 in the policy cases, and apply a discount rate of 33% for transportation technologies in the reference case and 15% in the policy cases. Hough et al. (*18*) showed that the short-run price elasticities of gasoline demand ranged from −0.034 to −0.077 during 2001 to 2006, versus −0.21 to −0.34 for 1975 to 1980, suggesting that U.S. consumers are less responsive to changes in gasoline price in recent decades. A discount rate of 33% is typical for amortization of new vehicles (*19*), and studies showed that lowering discount rate (payback period) can significantly affect technology adoption (*10, 14, 20*). Our policy scenarios' assumption that consumers have higher demand elasticity and lower discount rate toward "clean" vehicle technologies reflects our belief that consumers may be more willing to change their behaviors in the climate-policy scenarios or that corrective policy measures will be implemented to mitigate market failure in the transportation sector.

Table 1 summarizes the scenarios examined in this paper. They intend not to project the future with and without climate policies, but to identify potential mitigation behaviors based on our assumptions of technology costs and resource availability within an integrated energy system, *if* society were to act in the least-cost manner with perfect foresight.

2.3. Modeling Results. Our analysis shows that when economy-wide emission caps are low to moderate (10%−30%E scenarios), the transportation sector contributes a small portion of the overall reductions and the electric sector contributes the majority (Figure 1). This is consistent with other studies (*2, 4*). Our upper-bound economy-wide cu-

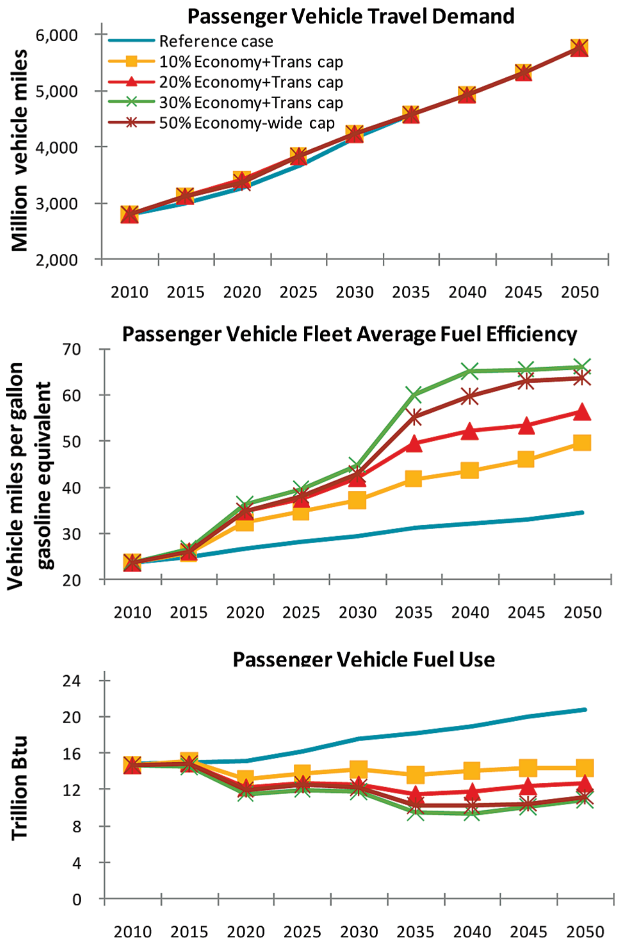

FIGURE 4. Passenger-vehicle travel demand, fuel efficiency, and total fuel use by scenario.

mulative reduction target of 50% is more aggressive than that of S. 280 or S. 2191. The EIA analysis of S. 2191 (*3*) projected the total CO_2 emission reduction in 2030 with no international offsets at 3030 million metric tons CO_2-equiv. This roughly corresponds to our 30%E scenario (2879 million metric tons CO_2 reduction) in 2030. The transportation sector starts to make more substantial reduction contributions at the 40% reduction target and above (7% in the 40%E scenario and 13% in the 50%E scenario between 2010 and 2050, Figure 1).

If the same percentage emission caps (10–30%) apply equally to the full economy and to transportation (E&T scenario), the transportation sector contributes roughly 30% of the overall reductions between 2010 and 2050, while the electric sector contributes 51–66% (Figure 1). Ethanol usage increases from 3.5 billion gallons/yr in 2005 to levels in 2050 of 36.0 billion gallons/yr under the reference case, and to the highest level of 88.4 billion gallons/year under 30%E&T.

Recent studies have shown that there may be adverse land-use consequences associated with biofuel feedstock production in cropland (*21, 22*). The main concern is that biofuel feedstocks that displace food (or any highly inelastic commodity) induce cropland expansion and land conversion elsewhere, releasing large amounts of carbon from the converted ecosystems. Biofuels that induce land use conversion may be greater GHG emitters than gasoline on a life cycle basis, while causing other adverse sustainability impacts. Therefore, there will likely be policies either to limit the use of biofuel produced from arable land or to phase out food-based ethanol. We thus run two additional scenarios: 30%E&T *without* a biofuel mandate after 2015, with a large carbon emission factor from indirect land use change (iLUC) attached to corn-based ethanol (30%E&T_NB) (assuming no carbon emissions from iLUC are assigned to cellulosic ethanol); and 30%E&T_NB without successful (i.e., economically viable at large scale) cellulosic biofuel technology (30%E&T_NBNC). Figure 2 shows that even without a specific mandate for biofuel production, cellulosic ethanol can be a favorable mitigation strategy to achieve significant transportation emission reductions (30%E&T_NB). However, if there is neither a biofuel mandate nor commercially successful cellulosic technology on a large scale (30%E&T_NBNC), more gasoline and electricity, and overall less fuel (6% less than 30%E&T between 2010 and 2050) will be necessary to achieving the required reduction in transportation CO_2 emissions (Figure 2). The total fuel use will be the least for 30%E&T_NBNC, due to the increased adoption of the most efficient vehicles.

Vehicle penetration by type, changes in travel demand, fleet-average fuel efficiencies, and total passenger-vehicle fuel demand are presented in Figures 3 and 4. In all the policy cases that require significant reductions from the transportation sector, gasoline hybrid electric vehicles (HEV) quickly start replacing conventional gasoline vehicles. In 30%E&T, plug-in hybrid electric vehicles (PHEV) are quickly adopted and comprise roughly 68% of the total passenger vehicle fleet in 2050. In 30%E&T_NB and 30%E&T_NBNC, the absence of a biofuel policy results in zero ethanol flex-fuel vehicle penetration and high PHEV adoption. The comparison between 30%E&T and 30%E&T_NB is interesting in that even though biofuels play a key role in reducing transportation CO_2 emissions in both cases, 30%E&T_NB achieves this through gradually mixing E10 in gasoline fuel while 30%E&T will require up to 14.2% of actual vehicle-miles traveled (VMT) by ethanol flex-fuel vehicles in 2030 in order to meet the biofuel volumetric requirement (Figure 3).

Overall, fleet-average vehicle efficiency increases as the stringency of the CO_2 emission caps increases (the 30%E&T scenario gains up to 92.4% in efficiency in 2050 over the reference case), and fuel usage also decreases significantly (up to 48% in 2050 in 30%E&T). In the final equilibriums, the demand levels are similar in all cases (Figure 4, top).

3. Critical Examination of Transportation Mitigation Strategies

3.1. Options to Reduce Transportation Emissions. There are four major categories of mitigation opportunities to reduce GHG emissions from the transportation sector.

Energy Intensity Reduction. Increasing the efficiency of transportation technologies through improvement in vehicle technology or by adopting smaller vehicles.

Fuel Switching. Increasing the share of vehicles using low-GHG fuels such as compressed natural gas, low-GHG ethanol, hydrogen, or electricity.

Lowering the Global Warming Intensity (GWI) of Transportation Fuels. Reducing the GWI (on a life cycle basis) of a particular fuel by (1) making the fuel production process more efficient or reducing upstream emissions; (2) blending low-GWI fuels, such as low-GWI ethanol or biodiesel, into the fuel mix (e.g., E10 or B20); or (3) producing fuel from low-GWI feedstock, such as ethanol from cellulosic materials, or hydrogen from renewable energy sources such as biomass gasification or electrolysis using wind or solar power.

Demand Reduction or Travel-Mode Change. This involves reducing the reliance on personal vehicles, increasing use of more efficient modes of transportation such as mass transit, and better land-use policies that reduce transportation demand (such as smart growth policies that encourage high-density housing and mixed-use residential, retail, and business communities) and improve system efficiency (as by reducing congestion).

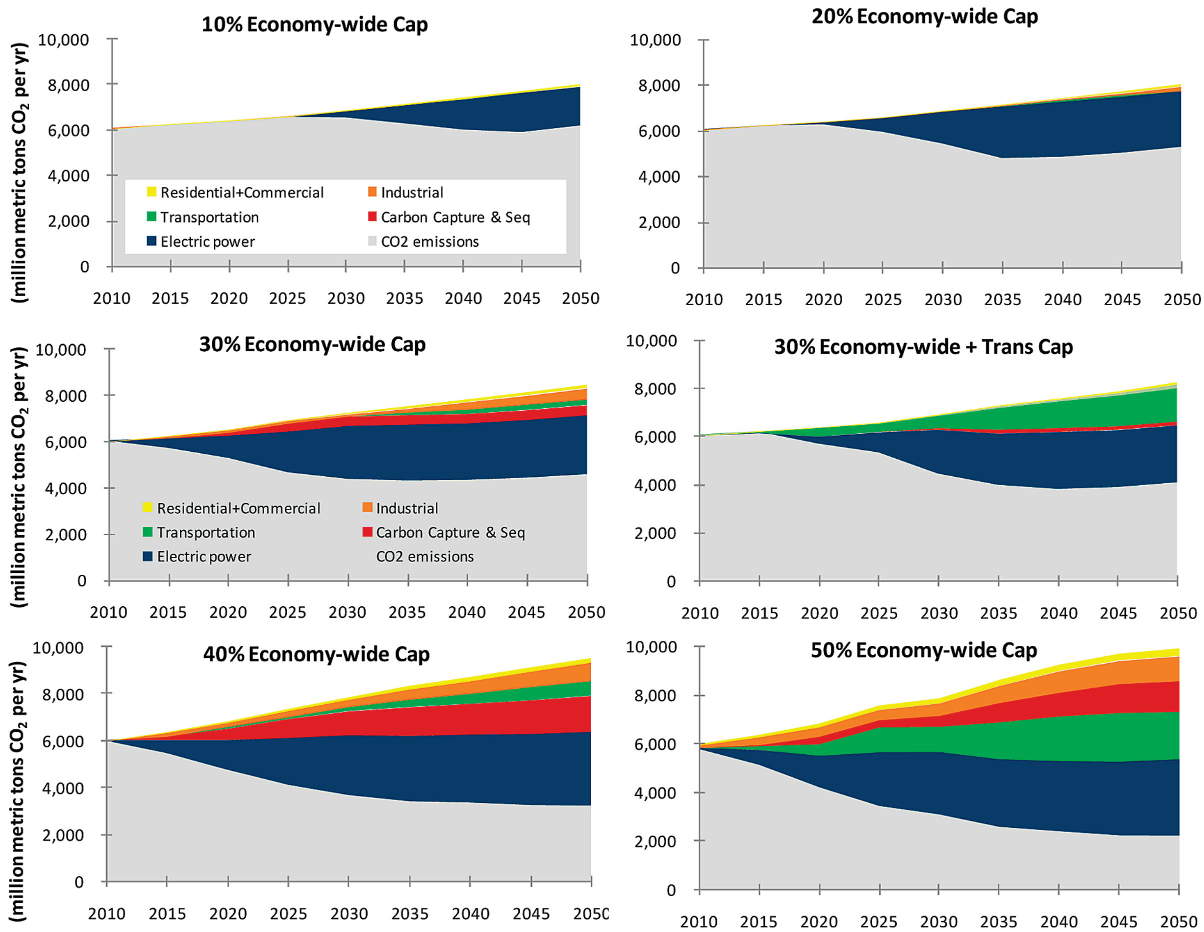

FIGURE 5. CO_2 emission avoided from the reference case by sector. Gray areas show overall CO_2 emissions, and the rest show CO_2 emission reductions by sector.

The analyses discussed in Section 2 account for limited, albeit important, strategies to reduce transportation CO_2 emissions. Our model database does not include mitigation strategies such as improving the efficiency of the fuel production process, upstream emission reduction, or demand reductions by increasing urban density and improving city planning and design, though these options can be incorporated into the model in the future. Nor does it consider limitations of original equipment manufacturers (OEMs) to respond to increased demand in a short time frame, or policies such as taxes or subsidies on a particular type of alternative fuel vehicle. One can also assume higher potential for cellulosic ethanol at lower production cost. Hydrogen fuel cell vehicles (FCVs) do not show penetration in the scenarios we examined. However, hydrogen penetration is sensitive to the cost of fuel cell technology, oil price, and discount rate (*14*). We also do not consider mitigation through the supply of international offsets, which is an element of S. 280 and S. 2191.

3.2. The Concept of Transportation Mitigation Strategies. In 2004, Pacala and Socolow wrote a seminal article in *Science* (*23*) that puts forward the concept of stabilization wedges to solve the climate problem. They pointed out that industrial CO_2 emissions are on a trajectory to double in the next 50 years in the business-as-usual scenario. Solving the climate problem implies keeping emissions at about current levels for the next half-century, and a portfolio of technologies exists today to do so. The authors roughly divide the stabilization triangle, the area between the business-as-usual emissions trajectory and that necessary to achieve stabilization of CO_2 concentration, into seven wedges, each of which reaches 25 GtC by 2054. Fifteen potential wedges were proposed, representing energy efficiency and conservation, fuel shift, carbon capture and sequestration, nuclear power, and carbon sequestration in forests and agricultural soils. Similar research suggests that a portfolio of technologies will be needed to address the variety of technology needs across the world's regions and over time, to achieve an emissions path leading to stabilization at 550 ppm (*24*).

The concept of stabilization wedge, though elegant, provides insufficient information to guide decision making. This is acknowledged by Pacala and Socolow: "*... Interactions among wedges are discussed in the SOM text. Also, our focus is not on costs*" (*23*). Rather, the intention is to examine the "*full-scale examples that are already in the marketplace [and] make a simple case for technological readiness.*"

The U.S. EPA applied the "wedge" concept to the U.S. transportation sector (*25*) and showed that approximately nine U.S. transportation sector wedges, each representing 5,000 MMT CO_2e of cumulative reductions between now and 2050, would be enough to flatten emissions in the sector. However, it also showed that the size of the wedges can be dramatically affected by the choice of scenarios and assumptions. The EPA study recommends adopting a system approach to maximize the utility of the wedges. Below, we critically examine information needed to design effective mitigation strategies and improve the values for policy implementation and decision making.

How We Get There. Figure 5 illustrates U.S. mitigation wedges by sector under the optimization framework. Holding emissions constant to 2050 (constituting an emissions stabilization trajectory) roughly corresponds to our 10% economy-wide cap scenario, and the shape of our 50% economy-wide cap scenario roughly corresponds to the 450

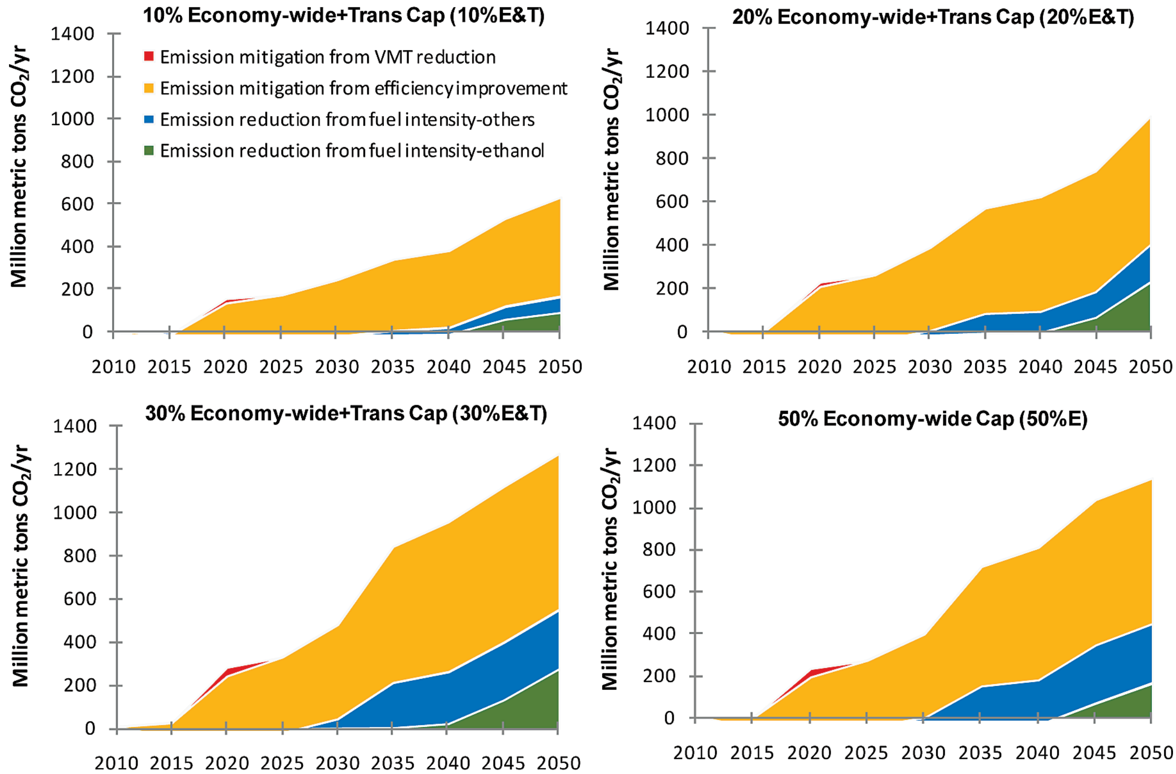

FIGURE 6. Passenger vehicle CO_2 emission reductions from fuel CO_2 intensity reduction, vehicle efficiency improvement, and reduction in vehicle miles traveled. Fuel CO_2 intensity is based on sector-specific emissions and not life-cycle based.

ppm early action wedge (*26, 27*). The projected CO_2 emissions by sector for all scenarios can be found in SI Figure S1. Our model, which solves the least-cost solutions with perfect foresight, suggests that most of the emission reduction will come from the electric sector by fuel switching (increasing use of natural gas, nuclear after 2040, and renewables), adopting more efficient electricity-generating technologies, and employing carbon capture and sequestration (CCS) for the 30% and above economy-wide cap scenarios. The mitigation strategies for the transportation sector include fuel reduction and the adoption of low-GHG fuels (Figure 2), the adoption of advanced vehicle technologies (Figure 3), and increased vehicle efficiency (Figure 4). The contributions of light-duty vehicle CO_2 emission reductions from vehicle efficiency improvement, fuel CO_2 intensity reduction, and vehicle travel demand reduction are shown in Figure 6. The calculation for Figure 6 is described in the Supporting-Information, which also shows the average fuel CO_2 intensity for passenger vehicles by scenario. Overall, we found that in all our scenarios, CO_2 emission reductions are almost entirely contributed by vehicle efficiency improvement and fuel CO_2 intensity reduction (Figure 6). We also found that the switch from gasoline to ethanol and electricity can significantly reduce the average carbon intensity of transportation fuels (SI Figure S4). The fuel CO_2 intensity we refer to is sector-specific CO_2 intensity and not life cycle-based. Therefore, emission reductions in the transportation sector can increase emissions in the other sectors, particularly the electric sector for electricity used to charge PHEVs.

Because ethanol is already included in the reference case due to the biofuel mandate, the use of ethanol does not contribute to fuel CO_2 intensity reduction from the reference case prior to 2040. Our paper only considers two generic types of ethanol: corn ethanol and cellulosic ethanol. Many biofuel production pathways, especially from waste and algae, can contribute to significant further GHG emission reductions (*5, 28*). Similarly, the new CAFE standard is already incorporated in our reference case; therefore, all the efficiency improvement shown in Figure 6 is beyond the requirement of the new CAFE standard.

Nature of the Transition: Smooth, Abrupt, or Transitional. Depending on the dynamics of supply and demand, price equilibrium, and constraints such as the details of the policies, the adoption of an optimized mitigation strategy can be smooth, high-growth (e.g., Figure 3, some of the hybrid and plug-in hybrid mitigation strategies), or transitional (e.g., Figure 3, where some of the ethanol flex-fuel vehicles under the most stringent scenarios are appropriate for short- to medium-term solutions, but might need to be replaced by more advanced vehicle technologies in the long term to achieve higher reductions). Empirical evidence indicates that all these shapes have been observed and that the adoption of alternative fuel vehicles is strongly dependent on payback period and refueling infrastructure, which are influenced by policies and financial incentives (*20*).

Interactions between These Mitigation Strategies: Substitutes or Complements. Pacala and Socolow acknowledged the interactions between wedges and gave an example of the substitution effect: the more the electricity system becomes decarbonized, the less the available savings from greater efficiency of electricity use, and vice versa. Similarly for transportation mitigation strategies, as transportation fuels become increasingly decarbonized through electrification and/or substitutions with low-GHG fuels, less carbon reductions will be available from vehicle efficiency improvement. Reducing vehicle travel demand will have less carbon savings as the average fuel CO_2 intensity is reduced (less gCO_2 reduction per mile). Mitigation strategies can also be complementary. For example, increasing the adoption of plug-in hybrid vehicles can be more effective when transportation fuels are sufficiently decarbonized.

Robustness of the Mitigation Strategies to Various Uncertainties Such As Policy Decisions, the Levels of Caps, or the Modeling Time Horizon. Figures 2, 3, and 4 illustrate that mitigation strategies such as the adoption of HEVs and increasing vehicle efficiency are important in all scenarios, whereas other mitigation strategies are sensitive to the level of CO_2 mitigation policies (e.g., PHEV mitigation), the details of certain policies (e.g., ethanol mitigation), consumer preferences (e.g., demand-reduction mitigation), technology costs (e.g., hydrogen mitigation), and modeling period (e.g., hydrogen mitigation). A hydrogen economy is often predicted to penetrate well before 2050 in most long-term models with a time horizon of 100 years (*29–31*).

The uncertainties of the mitigation strategy in response to policy and social uncertainties, modeling uncertainties, the levels of the emission caps, costs, and consumer behavior, as illustrated in Figures 2, 3, and 4, again confirm that maintaining a portfolio of viable technologies is essential to the success of policies aiming to achieve significant CO_2 emission caps. Recent modeling efforts (e.g., Sanstad et al. (*32*)) that attempt to guide the design of policies to be robust to modeling, parameter, and policy uncertainties may shed light on how to design least-cost policies that will achieve the best outcome in the face of uncertainties, but more rigorous analysis and empirical validation is needed to make these ground-breaking methodologies useful.

4. Discussion

The paper uses a stylized characterization of the U.S. energy system to analyze the role the transportation sector might play under economy-wide CO_2 constraints. We illustrate how mitigation strategies might be utilized to achieve policy goals in reducing transportation CO_2 emissions, and how uncertainties affect implementation pathways under the optimized framework. The results illustrated here are by no means predictive of future outcome of any particular policies.

There are many ways to refine this research. First, there are other strategies for reducing transportation and other sectors' CO_2 emissions. The MARKAL type of bottom-up model is not suited to analyze nontechnology policies such as behavioral changes, land-use policy, smart growth, mass transit, carpooling, or telecommuting. These mitigation options also play important roles in reducing transportation emissions. Second, most analyses of alternative fuels (except for hydrogen fuel, where transport, delivery, and refueling-station costs are examined in detail (*14*)) assume a flat rate for transportation and distribution cost and exclude detailed infrastructure costs such as refueling stations and transport distance. Mitigation strategies involving alternative fuels must take into consideration not only cost, but other social factors and policies that encourage technology adoption. We also do not take into account the social and environmental benefits of reducing CO_2 emissions. More research is needed to help identify robust policies that will achieve the best outcome in the face of uncertainties.

Acknowledgments

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Supporting Information Available

Detailed information on major assumptions in vehicle types, costs, and efficiencies (Section S1) and supplementary modeling results (Section S2). This material is available free of charge via the Internet at http://pubs.acs.org.

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Supporting Information

Optimizing U.S. Transportation Mitigation Strategies: What We Learn from a Bottom-up Model

Sonia Yeh[1], Alex Farrell[2], Richard Plevin[2], Alan Sanstad[3], and John Weyant[4]

[1] Institute of Transportation Studies, University of California, Davis, CA 95616 USA

[2] Energy and Resources Group, University of California, Berkeley, CA 94720 USA

[3] Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA

[4] Department of Management Science and Engineering, Stanford University, Stanford, CA 94305 USA

Corresponding author: Sonia Yeh, email: slyeh@ucdavis.edu, Tel: (530) 754-9000, Fax: (530) 752-6572

Summary: 16 pages, 4 figures, and 6 tables.

Our study uses the EPA national MARKet ALlocation (MARKAL) technology database *(1)*. The model documentation can be downloaded at http://oaspub.epa.gov/eims/eimsapi.dispdetail?deid=150883. The database that we used for this paper was subsequently modified by the International Resources Group for the Natural Resources Defense Council (NRDC) *(2, 3)* and incorporates a series of transportation updates, including the vehicle technology assumptions largely based on the 2007 Annual Energy Outlook *(4)*, improved biomass resource supply curves and biofuel characterization *(5-9)*, and the new ethanol requirement under the Energy Independence and Security Act.

This Supporting Information has two sections. Section S1 describes major assumptions in vehicle types, costs, efficiencies, and emission factors. Section S2 shows additional modeling results not shown in the paper, including projected CO_2 emission for all scenarios, cumulative CO_2 emission reductions, CO_2 mitigation costs, and the calculations for the transportation CO_2 emission mitigations from fuel CO_2 intensity reduction, vehicle efficiency improvement, and reduction in vehicle miles traveled.

Section S1. Key model assumptions

Vehicle costs, efficiency, and emissions

Table S1 lists the assumptions of the cost of light-duty passenger vehicles. The data sources include the Annual Energy Outlook (AEO) 2006 *(10)* and the Annual Energy Outlook (AEO) 2007 *(4)*, with authors' modification based on literature reviews. Empty cells signify that the technologies are assumed to be unavailable for the given years.

Table S1. Cost of light-duty passenger vehicles (thousands of 2000 dollars)

Size	Type	Abbreviation	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Compact	Adv GSL	C.AGSL	19.76	20.68	20.92	21.12	21.27	21.33	21.33	21.33	21.33	21.33
Compact	CNG	C.CNG	24.88	25.81	26.08	26.30	26.48	26.57	26.57	26.57	26.57	26.57
Compact	CNG Flex Fuel	C.CNGX	23.79	24.75	25.03	25.28	25.47	25.59	25.59	25.59	25.59	25.59
Compact	DSL HEV	C.DHEV		24.87	25.17	25.42	25.61	25.69	25.69	25.69	25.69	25.69
Compact	DSL	C.DSL	20.12	20.93	21.08	21.20	21.29	21.32	21.32	21.32	21.32	21.32
Compact	Ethanol Flex Fuel	C.ETHX	19.48	20.67	20.86	21.07	21.20	21.23	21.23	21.23	21.23	21.23
Compact	Fuel Cell - Hydrogen	C.FCH	68.18	60.50	53.84	49.08	44.94	41.80	41.80	41.80	41.80	41.80
Compact	Conventional	C.GSL	18.93	19.85	20.09	20.29	20.44	20.50	20.50	20.50	20.50	20.50
Compact	HEV	C.HEV	22.05	22.11	21.96	21.89	21.96	21.97	21.97	21.97	21.97	21.97
Compact	LPG Flex Fuel	C.LPGX	23.27	24.16	24.47	24.71	24.89	24.97	24.97	24.97	24.97	24.97
Compact	PHEV	C.PHEV			29.75	28.34	26.99	27.07	27.07	27.07	27.07	27.07
Full Size	Adv GSL	F.AGSL	27.42	28.33	28.60	28.82	28.97	29.03	29.03	29.03	29.03	29.03

Full Size	CNG	F.CNG	37.89	38.64	38.88	39.11	39.29	39.39	39.39	39.39	39.39	39.39
Full Size	CNG Flex Fuel	F.CNGX	36.98	37.67	37.95	38.21	38.41	38.51	38.51	38.51	38.51	38.51
Full Size	DSL HEV	F.DHEV			33.10	33.35	33.61	33.83	33.83	33.83	33.83	33.83
Full Size	DSL	F.DSL	26.62	29.15	29.32	29.44	29.50	29.51	29.51	29.51	29.51	29.51
Full Size	Ethanol	F.ETH	26.88	27.81	28.05	28.24	28.37	28.41	28.41	28.41	28.41	28.41
Full Size	Ethanol Flex Fuel	F.ETHX	25.15	27.84	28.11	28.33	28.48	28.53	28.53	28.53	28.53	28.53
Full Size	Fuel Cell - Gasoline	F.FCG		100.39	86.80	76.17	76.00	75.86	75.86	75.86	75.86	75.86
Full Size	Fuel Cell - Hydrogen	F.FCH			63.91	60.41	55.51	51.78	51.78	51.78	51.78	51.78
Full Size	Conventional	F.GSL	26.59	27.51	27.77	27.99	28.14	28.20	28.20	28.20	28.20	28.20
Full Size	HEV	F.HEV	28.21	29.61	29.44	29.56	29.64	29.67	29.67	29.67	29.67	29.67
Full Size	LPG Flex Fuel	F.LPGX	31.12	31.97	32.29	32.55	32.73	32.80	32.80	32.80	32.80	32.80
Full Size	Methanol Flex Fuel	F.MTHX	27.05	27.98	28.24	28.44	28.58	28.62	28.62	28.62	28.62	28.62
Full Size	PHEV	F.PHEV				38.00	36.19	36.27	36.27	36.27	36.27	36.27
SUV-Large	Adv GSL	LS.AGSL	35.19	36.40	36.70	36.99	37.21	37.29	37.29	37.29	37.29	37.29
SUV-Large	DSL HEV	LS.DHEV				43.40	43.54	43.65	43.65	43.65	43.65	43.65
SUV-Large	DSL	LS.DSL	35.30	36.38	36.61	36.85	37.07	37.18	37.18	37.18	37.18	37.18
SUV-Large	Ethanol Flex Fuel	LS.ETHX	34.23	35.45	35.73	36.01	36.20	36.28	36.28	36.28	36.28	36.28
SUV-Large	Fuel Cell - Hydrogen	LS.FCH					73.90	68.09	68.09	68.09	68.09	68.09
SUV-Large	Conventional	LS.GSL	33.89	35.11	35.41	35.70	35.92	36.00	36.00	36.00	36.00	36.00
SUV-Large	HEV	LS.HEV	38.58	38.43	38.06	38.23	38.42	38.53	38.53	38.53	38.53	38.53
SUV-Large	PHEV	LS.PHEV					42.99	43.07	43.07	43.07	43.07	43.07
Minivan	Adv GSL	M.AGSL	24.28	25.40	25.66	25.94	26.18	26.28	26.28	26.28	26.28	26.28
Minivan	CNG	M.CNG	27.86	28.96	29.23	29.52	29.79	29.93	29.93	29.93	29.93	29.93
Minivan	CNG Flex Fuel	M.CNGX	27.07	28.17	28.44	28.73	29.02	29.17	29.17	29.17	29.17	29.17
Minivan	DSL HEV	M.DHEV			34.22	34.36	34.51	34.61	34.61	34.61	34.61	34.61
Minivan	DSL	M.DSL	23.36	26.07	26.14	26.26	26.40	26.47	26.47	26.47	26.47	26.47
Minivan	Ethanol Flex Fuel	M.ETHX	24.50	25.27	25.51	25.75	25.95	26.01	26.01	26.01	26.01	26.01
Minivan	Fuel Cell - Gasoline	M.FCG			90.47	78.15	77.93	77.75	77.75	77.75	77.75	77.75
Minivan	Fuel Cell - Hydrogen	M.FCH			72.83	65.41	59.18	54.45	54.45	54.45	54.45	54.45
Minivan	Conventional	M.GSL	22.99	24.11	24.37	24.64	24.88	24.99	24.99	24.99	24.99	24.99
Minivan	HEV	M.HEV		32.50	28.45	27.96	27.92	27.84	27.84	27.84	27.84	27.84
Minivan	LPG	M.LPG	27.22	28.35	28.60	28.86	29.08	29.18	29.18	29.18	29.18	29.18
Minivan	LPG Flex Fuel	M.LPGX	26.17	27.30	27.57	27.87	28.13	28.25	28.25	28.25	28.25	28.25
Minivan	PHEV	M.PHEV					31.95	32.05	32.05	32.05	32.05	32.05
Mini Compact	Adv GSL	MC.AGSL	48.06	49.00	49.22	49.38	49.52	49.56	49.56	49.56	49.56	49.56
Mini Compact	Electric	MC.ELC	64.92	65.08	63.63	63.65	63.61	63.60	63.60	63.60	63.60	63.60
Mini Compact	Conventional	MC.GSL	47.23	48.17	48.39	48.55	48.69	48.73	48.73	48.73	48.73	48.73
Mini Compact	HEV	MC.HEV	47.07	47.38	47.23	47.36	47.48	47.53	47.53	47.53	47.53	47.53

Pickup	Adv GSL	P.AGSL	24.26	25.49	25.79	26.07	26.26	26.31	26.31	26.31	26.31	26.31
Pickup	CNG	P.CNG	30.16	31.35	31.67	31.98	32.22	32.33	32.33	32.33	32.33	32.33
Pickup	CNG Flex Fuel	P.CNGX	29.38	30.61	30.92	31.24	31.50	31.60	31.60	31.60	31.60	31.60
Pickup	DSL	P.DSL	25.34	25.65	25.89	26.08	26.22	26.28	26.28	26.28	26.28	26.28
Pickup	Ethanol Flex Fuel	P.ETHX	24.09	25.30	25.54	25.76	25.87	25.86	25.86	25.86	25.86	25.86
Pickup	Conventional	P.GSL	22.96	24.20	24.50	24.77	24.97	25.02	25.02	25.02	25.02	25.02
Pickup	HEV	P.HEV		29.62	29.02	28.42	28.32	28.11	28.11	28.11	28.11	28.11
Pickup	LPG	P.LPG	29.50	30.73	31.02	31.29	31.47	31.51	31.51	31.51	31.51	31.51
Pickup	LPG Flex Fuel	P.LPGX	28.46	29.71	30.03	30.34	30.57	30.65	30.65	30.65	30.65	30.65
Pickup	PHEV	P.PHEV					32.04	32.09	32.09	32.09	32.09	32.09
SUV-Small	Adv GSL	SS.AGSL	27.32	28.54	28.81	29.06	29.26	29.33	29.33	29.33	29.33	29.33
SUV-Small	DSL HEV	SS.DHEV				35.27	35.36	35.43	35.43	35.43	35.43	35.43
SUV-Small	DSL	SS.DSL	27.99	28.96	29.19	29.40	29.58	29.67	29.67	29.67	29.67	29.67
SUV-Small	Electric	SS.ELC	51.53	51.55	49.82	49.89	49.85	49.82	49.82	49.82	49.82	49.82
SUV-Small	Ethanol Flex Fuel	SS.ETHX		27.49	27.78	28.04	28.25	28.32	28.32	28.32	28.32	28.32
SUV-Small	Fuel Cell - Gasoline	SS.FCG			87.27	75.78	75.59	75.44	75.44	75.44	75.44	75.44
SUV-Small	Fuel Cell - Hydrogen	SS.FCH	89.72	78.71	69.88	62.96	57.17	52.76	52.76	52.76	52.76	52.76
SUV-Small	Conventional	SS.GSL	26.03	27.25	27.52	27.77	27.97	28.04	28.04	28.04	28.04	28.04
SUV-Small	HEV	SS.HEV		29.79	29.56	29.72	29.86	29.92	29.92	29.92	29.92	29.92
SUV-Small	PHEV	SS.PHEV					35.04	35.11	35.11	35.11	35.11	35.11

Adv GSL: advanced gasoline vehicles; HEV: hybrid electric vehicles; PHEV: plug-in hybrid electric vehicles. DSL: diesel vehicles; CNG: dedicated natural gas vehicles; LPG: liquefied petroleum gas vehicles

Table S2 lists the assumptions for light-duty passenger-vehicle efficiency (in miles per gallon). These unadjusted values will need to be adjusted for degradation factors, which convert the unadjusted fuel economy to actual “on the road” fuel economy that takes into account three factors: increases in city/highway driving, increasing congestion levels, and rising highway speeds. Sources for Table S2 include the AEO 2006 *(10)*, the AEO 2007 *(4)*, and the DOE’s Multi-Path Transportation Futures Study *(11, 12)*, with authors’ modification based on literature reviews. Efficiency improvement after 2040 is 2% every 5 yrs. A cell with a value in Table S2 but no corresponding value in Table S1 signifies that the type of vehicle is not available for the given year. Table S3 shows the degradation factors after modification based on the NEMS Transportation Demand Module, Table 28 *(13)*. Compared with the NEMS assumptions, the degradation factors are higher (indicating less degradation) in order to account for the more stringent requirement of the new CAFE standard on vehicle efficiency that may not be sufficiently reflected in Table S2.

Table S2. Efficiency of light-duty passenger vehicles (in miles per gasoline gallon equivalent, mpgge).

Size	Type	Abbrev.	Unadjusted							
			2005	2010	2015	2020	2025	2030	2035	2040
Compact	Adv GSL	C.AGSL	36.01	39.59	40.45	41.03	42.05	42.62	43.47	44.34
Compact	CNG	C.CNG	34.35	37.16	39.15	39.40	40.01	40.35	41.15	41.98
Compact	CNG Flex Fuel	C.CNGX	31.86	34.70	36.27	36.47	37.03	37.32	38.06	38.82
Compact	DSL HEV	C.DHEV		39.23	43.13	44.07	44.70	45.82	46.74	47.67
Compact	DSL	C.DSL	42.53	43.72	46.03	46.13	46.62	46.97	47.91	48.87
Compact	Ethanol Flex Fuel	C.ETHX	32.23	34.08	35.05	35.92	37.02	37.60	38.35	39.11
Compact	Fuel Cell - Hydrogen	C.FCH	58.34	57.48	61.21	67.88	71.05	77.09	78.63	80.20
Compact	Conventional	C.GSL	31.31	34.42	35.17	35.68	36.57	37.06	37.80	38.56
Compact	HEV	C.HEV	45.72	46.44	51.43	54.92	57.40	62.11	63.35	64.61
Compact	LPG Flex Fuel	C.LPGX	31.70	34.00	35.83	36.25	37.03	37.45	38.20	38.96
Compact	PHEV	C.PHEV			73.53	77.21	81.07	85.12	86.82	88.56
Full Size	Adv GSL	F.AGSL	31.56	34.05	34.98	35.61	36.59	37.12	37.87	38.62
Full Size	CNG	F.CNG	28.47	29.78	31.70	32.16	32.91	33.37	34.04	34.72
Full Size	CNG Flex Fuel	F.CNGX	26.32	27.21	28.90	29.49	30.37	30.82	31.43	32.06
Full Size	DSL HEV	F.DHEV			47.58	47.62	48.17	48.64	49.61	50.60
Full Size	DSL	F.DSL	37.26	37.44	39.22	39.45	40.03	40.43	41.24	42.06
Full Size	Ethanol	F.ETH	28.86	31.26	33.07	33.64	34.52	35.02	35.72	36.44
Full Size	Ethanol Flex Fuel	F.ETHX	37.50	29.73	31.47	32.04	32.91	33.42	34.09	34.77
Full Size	Fuel Cell - Gasoline	F.FCG		40.42	43.19	46.22	48.37	52.52	53.57	54.64
Full Size	Fuel Cell - Hydrogen	F.FCH			54.79	57.45	60.12	65.24	66.54	67.87
Full Size	Conventional	F.GSL	27.44	29.61	30.42	30.96	31.81	32.28	32.93	33.58
Full Size	HEV	F.HEV	40.09	39.63	43.66	46.73	48.99	53.12	54.18	55.26
Full Size	LPG Flex Fuel	F.LPGX	27.32	28.83	30.49	31.08	31.93	32.36	33.01	33.67
Full Size	Methanol Flex Fuel	F.MTHX	28.33	30.70	32.45	33.00	33.86	34.36	35.04	35.75
Full Size	PHEV	F.PHEV			79.10	79.10	83.05	87.20	88.95	90.73
SUV-Large	Adv GSL	LS.AGSL	22.65	24.49	25.71	26.50	27.53	28.22	28.79	29.36
SUV-Large	DSL HEV	LS.DHEV				35.15	35.66	36.30	37.03	37.77
SUV-Large	DSL	LS.DSL	25.72	27.05	27.85	28.22	29.01	29.53	30.13	30.73
SUV-Large	Ethanol Flex Fuel	LS.ETHX	19.28	20.99	22.15	22.84	23.72	24.33	24.81	25.31
SUV-Large	Fuel Cell - Hydrogen	LS.FCH					39.31	42.69	43.55	44.42
SUV-Large	Conventional	LS.GSL	19.36	20.93	21.98	22.65	23.53	24.12	24.61	25.10
SUV-Large	HEV	LS.HEV	27.81	28.06	30.29	32.63	34.62	37.84	38.59	39.36
SUV-Large	PHEV	LS.PHEV			43.97	43.97	43.97	48.05	49.01	49.99
Minivan	Adv GSL	M.AGSL	30.04	32.18	33.56	34.27	35.47	36.26	36.99	37.73

Minivan	CNG	M.CNG	27.93	29.57	30.76	31.21	32.11	32.70	33.35	34.02
Minivan	CNG Flex Fuel	M.CNGX	25.33	27.01	28.27	28.74	29.61	30.19	30.79	31.40
Minivan	DSL HEV	M.DHEV			44.22	43.95	44.50	45.13	46.03	46.96
Minivan	DSL	M.DSL	34.87	36.07	36.75	36.95	37.70	38.24	39.01	39.79
Minivan	Ethanol Flex Fuel	M.ETHX	25.69	27.36	28.68	29.32	30.35	31.04	31.66	32.29
Minivan	Fuel Cell - Gasoline	M.FCG			36.95	39.39	41.20	44.74	45.63	46.54
Minivan	Fuel Cell - Hydrogen	M.FCH			43.23	46.09	48.21	52.35	53.40	54.46
Minivan	Conventional	M.GSL	25.67	27.51	28.68	29.29	30.32	30.99	31.61	32.25
Minivan	HEV	M.HEV		38.10	42.97	45.62	47.94	52.27	53.31	54.38
Minivan	LPG	M.LPG	27.11	28.93	30.14	30.71	31.72	32.44	33.09	33.75
Minivan	LPG Flex Fuel	M.LPGX	25.99	27.77	29.00	29.54	30.53	31.17	31.79	32.43
Minivan	PHEV	M.PHEV			60.89	60.89	60.89	66.38	67.70	69.06
Mini Compact	Adv GSL	MC.AGSL	29.15	32.38	33.48	34.11	35.09	35.61	36.32	37.05
Mini Compact	Electric	MC.ELC	38.10	48.14	48.45	48.79	49.50	50.09	51.09	52.12
Mini Compact	Conventional	MC.GSL	25.35	28.16	29.11	29.66	30.51	30.97	31.59	32.22
Mini Compact	HEV	MC.HEV	35.83	36.69	40.50	43.49	45.76	49.71	50.71	51.72
Pickup	Adv GSL	P.AGSL	23.53	25.31	26.60	27.34	28.29	28.88	29.46	30.05
Pickup	CNG	P.CNG	20.70	21.93	22.78	23.28	24.01	24.39	24.88	25.38
Pickup	CNG Flex Fuel	P.CNGX	18.75	20.02	20.93	21.42	22.02	22.34	22.79	23.25
Pickup	DSL	P.DSL	25.75	27.86	28.58	28.90	29.54	29.95	30.55	31.16
Pickup	Ethanol Flex Fuel	P.ETHX	20.12	21.81	22.96	23.61	24.46	24.95	25.45	25.96
Pickup	Conventional	P.GSL	20.11	21.63	22.74	23.37	24.18	24.69	25.18	25.69
Pickup	HEV	P.HEV		0.00	32.42	36.56	38.47	41.91	42.75	43.60
Pickup	LPG	P.LPG	20.03	21.37	22.41	23.01	23.83	24.32	24.80	25.30
Pickup	LPG Flex Fuel	P.LPGX	19.29	20.66	21.64	22.19	22.91	23.33	23.80	24.28
Pickup	PHEV	P.PHEV			48.85	48.85	48.85	53.23	54.29	55.38
SUV-Small	Adv GSL	SS.AGSL	27.09	30.01	31.42	32.29	33.62	34.29	34.98	35.68
SUV-Small	DSL HEV	SS.DHEV				43.76	43.99	44.61	45.51	46.42
SUV-Small	DSL	SS.DSL	30.97	32.52	33.66	34.02	34.85	35.39	36.10	36.82
SUV-Small	Electric	SS.ELC	29.89	38.43	38.55	38.66	39.20	39.71	40.50	41.31
SUV-Small	Ethanol Flex Fuel	SS.ETHX		25.05	26.54	27.39	28.55	29.13	29.71	30.31
SUV-Small	Fuel Cell - Gasoline	SS.FCG			39.48	42.08	44.02	47.81	48.76	49.74
SUV-Small	Fuel Cell - Hydrogen	SS.FCH	42.96	43.25	46.20	49.24	51.51	55.94	57.06	58.20
SUV-Small	Conventional	SS.GSL	23.16	25.65	26.86	27.60	28.73	29.31	29.89	30.49
SUV-Small	HEV	SS.HEV		34.38	37.32	40.14	42.54	46.40	47.32	48.27
SUV-Small	PHEV	SS.PHEV			54.03	54.03	54.03	58.92	60.10	61.30

Table S3. Car and light-truck degradation factors.

Vehicle Type	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Car	0.877	0.880	0.923	0.926	0.929	0.932	0.932	0.932	0.932	0.932
Light Truck	0.851	0.852	0.892	0.894	0.895	0.897	0.897	0.897	0.897	0.897

The CO_2 emissions of the vehicles (in gCO_2/mile) are based on the carbon content of the fuels (lbs CO_2/MMBtu) divided by the efficiency of the vehicles (which are converted to miles per MMBtu) and times a converting factor of 453.59 g/lb. CO_2 emission factors for key transportation fuels are listed in Table S4. The emission factor of blended gasoline will depend on the amount of biofuels blended in the gasoline and the CO_2 emission factors of biofuels.

Table S4. Carbon emission factors of transportation fuels. Source: *(14)*

Fuel	Emission coefficients (lbs CO_2/MMBtu)
Reformulated or low-sulfur gasoline	168.87
Low-sulfur diesel	173.96
Liquefied petroleum gas (LPG)	149.74
Methane	158.83
Compressed natural gas (CNG)	130.71

Ethanol production costs, efficiency and emissions

Table S5 describes the production process for ethanol fuel including the characterization of the technologies (capital and operation and maintenance costs, efficiency, emissions), energy sources, feedstocks, and co-products. The technology described below represents a generic dry mill technology and a generic "cellulosic technology" that is based on the production process converting switchgrass to ethanol even though the cellulosic resources included in the database encompass a wider range of potential cellulosic resources including energy crops, agricultural residues, forestry residues, and urban wood/milling waste.

Table S5. Input assumptions for corn ethanol and cellulosic ethanol production costs, efficiencies, and emissions.

Corn (dry mill)	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Investment cost (2000$M/PJ/a)	16.8	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3
Variable O&M* (2000$M/PJ/a)	-0.199	-0.199	-0.199	-0.199	-0.199	-0.199	-0.199	-0.199	-0.199	-0.199
Emission coefficient** (Mil. Tonnes C/PJ)	-0.0059	-0.0067	-0.0069	-0.0070	-0.0071	-0.0072	-0.0073	-0.0074	-0.0075	-0.0076
Availability factor	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95

Energy carrier output (PJ): Ethanol	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Energy carrier input (PJ): Corn	1.74	1.70	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67
Energy carrier input (PJ): Natural gas	0.43	0.38	0.37	0.37	0.36	0.35	0.35	0.34	0.33	0.33
Energy carrier input (PJ): electricity	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Residual capacity (PJ/a)	348	1248	0	0	0	0	0	0	0	0
Cellulosic	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Investment cost (2000$M/PJ/a)			56.2	56.2	56.2	50.6	50.6	50.6	50.6	50.6
Variable O&M* (2000$M/PJ/a)			4.7	4.7	4.7	4.2	4.2	4.2	4.2	4.2
Emission coefficient** (Mil. Tonnes C/PJ)			-0.0146	-0.0147	-0.0148	-0.0149	-0.0150	-0.0150	-0.0151	-0.0152
Availability factor			0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Energy carrier output (PJ): Ethanol			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Energy carrier input (PJ):Herbaceous crops			1.83	1.83	1.83	1.74	1.74	1.74	1.74	1.74
Energy carrier input (PJ): electricity			-0.07	-0.07	-0.07	-0.09	-0.09	-0.09	-0.09	-0.09

* O&M includes labor, chemical inputs, and coproduct credits, and excludes debt service, depreciation, electricity, natural gas, and biomass feedstocks.

** Emission coefficient ignores coproduct credits for exported electricity, assuming these are handled by "negative electricity." The emission factors do not explicitly account for the issue of induced land use conversion and large CO_2 emissions by some biofuel feedstock.

Most of the values for corn ethanol are extracted from GREET 1.7. We made many modifications in various places in order to be consistent with MARKAL's general modeling philosophy. These changes are briefly summarized below. The emission factors shown above do not include the full upstream energy or emissions for feedstock production but they include the two largest contributors: nitrogen fertilizer production and soil N_2O emissions from N fertilizer application. They also include emissions from corn and switchgrass soil carbon sequestration. Since MARKAL does not model animal feed markets, we incorporate the economic value and greenhouse gas benefits of coproduced distillers grains into the modeled corn ethanol biorefinery. We calculated corn ethanol costs and O&M costs net of coproduct sales from Shapouri, et al *(15)*.

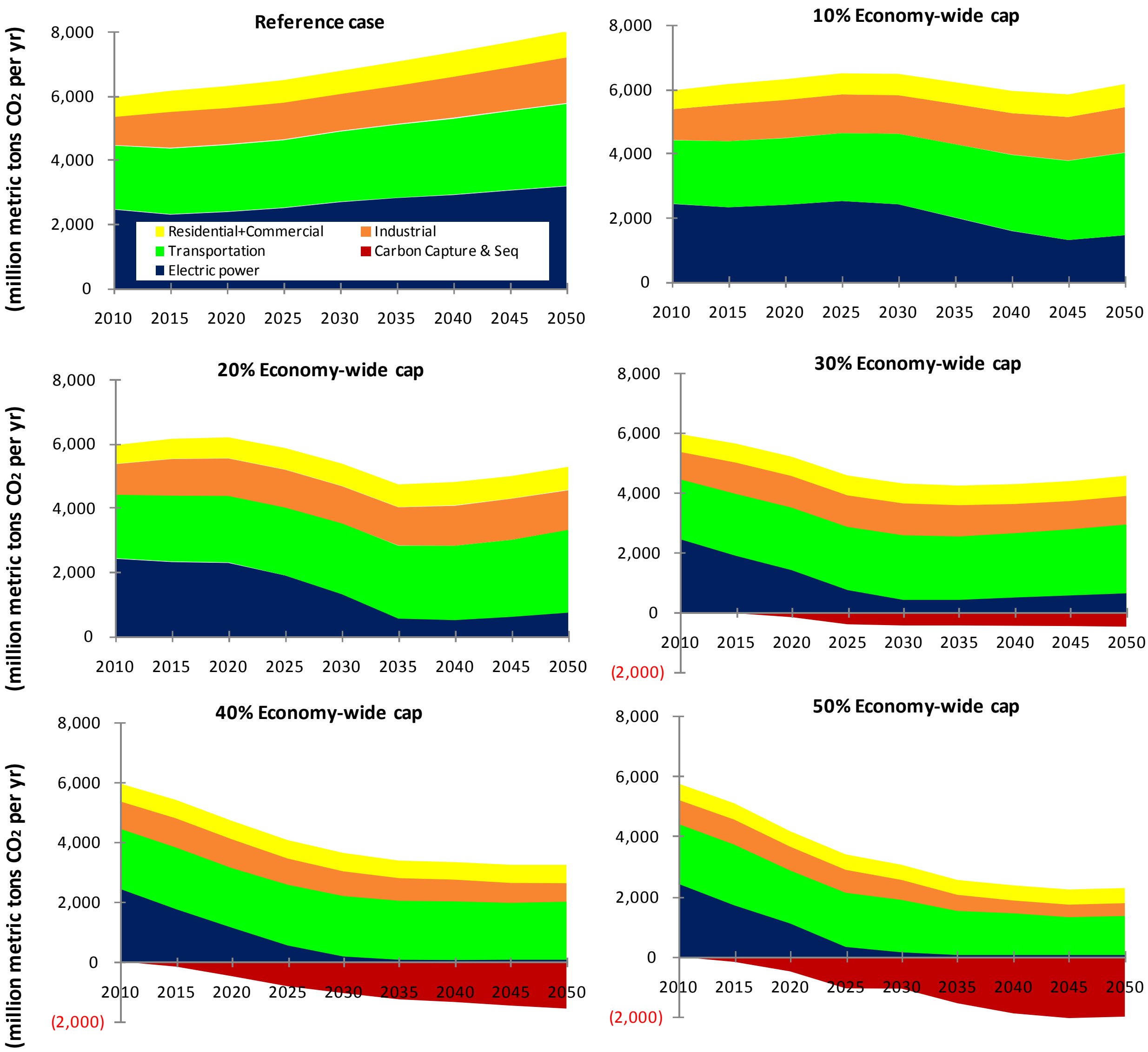
For thermal energy requirement (in natural gas, specifically) for corn production, we assumed a 2% reduction per time-step. Given the variety of ways to reduce energy demand (no-cook fermentation, cogeneration, improved insulation and heat recapture, substitution of biomass and biogas) this seems conservative as an average for the corn ethanol industry. We also assume an increasing conversion rate over time due to better enzymes, fractionation technology, and higher-starch corn varieties.

The technologies to produce cellulosic ethanol are still pre-commercial and are thus much more difficult to project. While there are numerous studies exploring the issue, they vary with regards to the whether they are predicting near-term or long-term technologies. Given our objective of constructing a stylized characterization of ethanol production in MARKAL, we adopt values liberally from several studies *(5-9, 16, 17)* to create an amalgam of shifting technologies, performance, and costs over time to 2050.

Section S2. Additional Modeling Results

Projected emissions, emission reductions, and mitigation costs

Detailed descriptions of the scenarios can be found in Table 1 of the main text. Figure S1 shows projected CO_2 emissions between 2010 and 2050 for all the economy-wide cap scenarios (E scenarios) and economy-wide + transportation cap scenarios (E&T scenarios). The projected emission reductions in the transportation sector are comparable between 40%E (40% economy-wide cap) and 10%E&T (10% economy-wide cap + transportation cap). The projected transportation emission reduction for 50%E is between 20%E&T and 30%E&T.



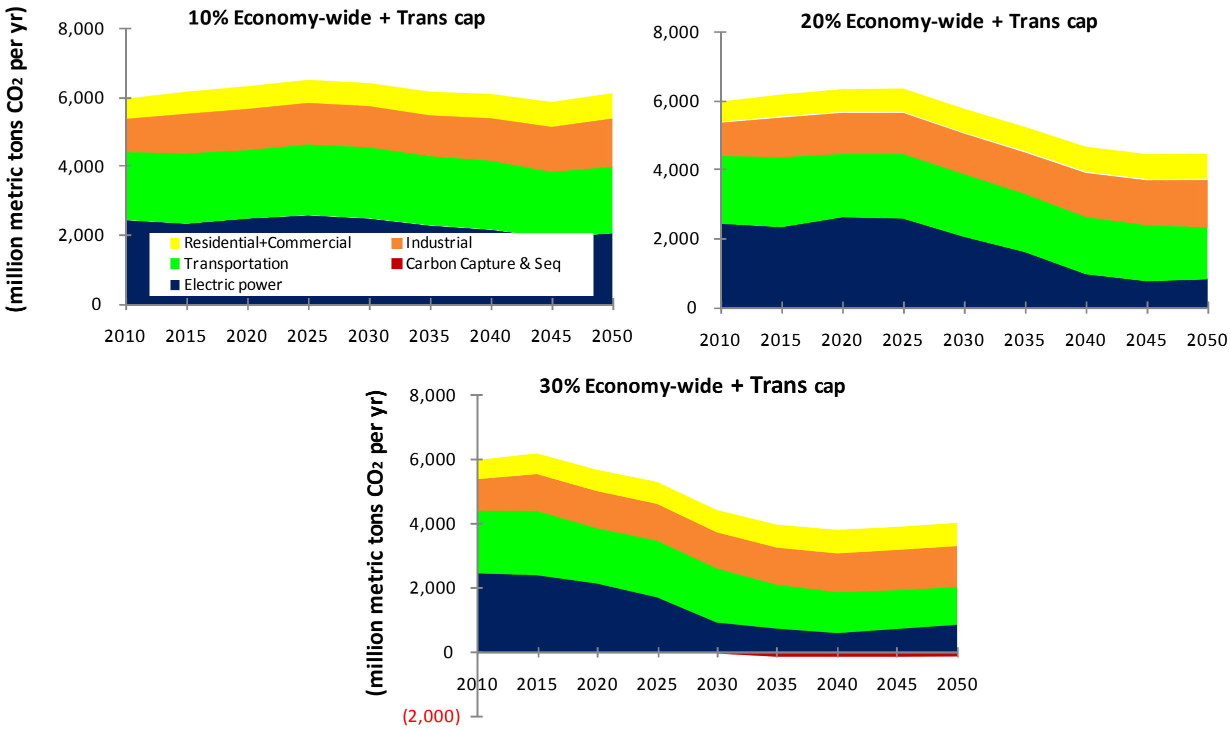
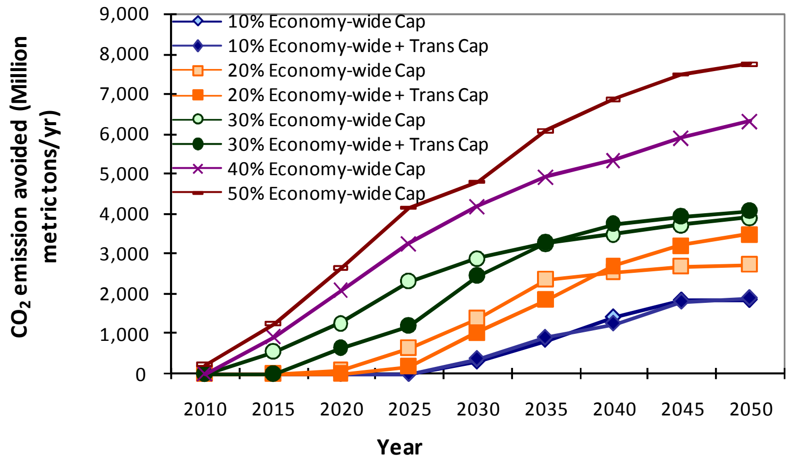


Figure S1. Projected CO_2 emissions by sector, 2010-2050.

Figure S2 shows the total CO_2 emission reductions and Figure S3 shows the marginal costs of emission reduction for the transportation sector. For comparison, the economy-wide marginal costs of CO_2 emission reduction for 30%E and 40%E are also shown. The total CO_2 emission reduction with no international offsets examined in the EIA's analysis of S. 2191 is 3030 million metric tons CO_2-equivalent in 2030 *(18)*. This roughly corresponds to our 30%E scenario (2879 million metric tons CO_2 reduction) in 2030. The model estimates that the marginal CO_2 mitigation costs for the 30% economy-wide cap scenario (30%E) are \$70, \$126, and \$213 per metric ton CO_2 (in 2000 dollars) in 2030, 2040, and 2050 respectively. The interpretation of the marginal abatement costs presented here should be interpreted with great caution. As mentioned in the main text, the goal of this paper is not to analyze the cost impacts of a particular policy, but to inform policy design regarding the potential roles of transportation mitigation strategies and the importance of uncertainties. More importantly, the discussion about CO_2 mitigation and its costs should be accompanied by its benefits in avoided damages and increased welfare. Our studies do not attempt to quantify the benefits of CO_2 mitigation, which are often argued to be greater than its costs *(19)*.



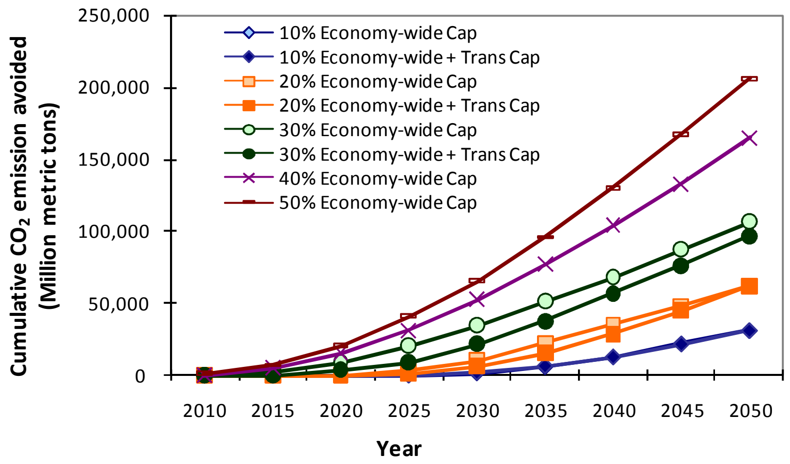


Figure S2. CO_2 emissions reduction per year (top) and total cumulative CO_2 emissions reduction (bottom).

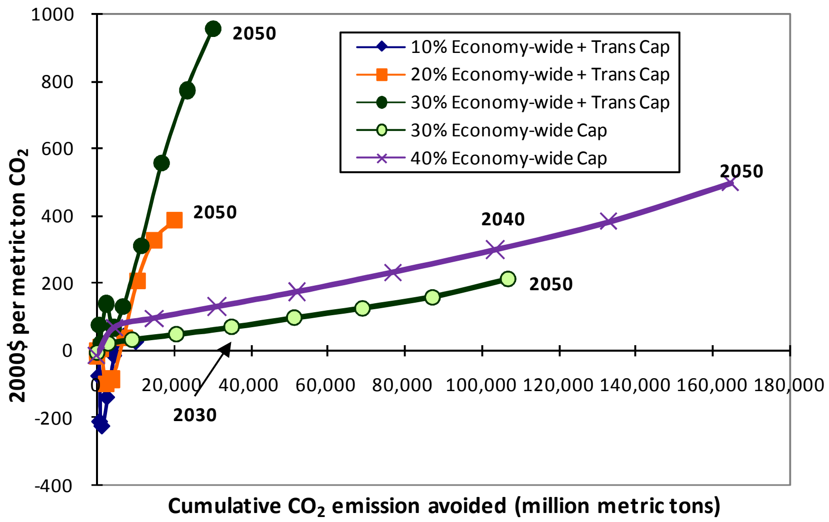


Figure S3. Marginal CO_2 mitigation costs for the transportation sector (10%-30% Economy-wide + transportation cap) and the economy-wide marginal CO_2 mitigation costs (30-40% Economy-wide cap).

Mitigation contribution from vehicle travel demand reduction, vehicle efficiency improvement, and fuel CO_2 intensity reduction

To isolate the amount of CO_2 emission reduction by a specific mitigation strategy within a dynamic model can be tricky because so many variables are changing at one time. We therefore devised a simple estimation that approximates the contribution of CO_2 emission mitigations from vehicle travel demand reduction, vehicle efficiency improvement, and fuel CO_2 intensity reduction. The calculation is shown in Table S6.

Table S6. Modelling results and methods to estimate CO_2 emission mitigations from vehicle travel demand reduction, vehicle efficiency improvement, and reduction in fuel CO_2 intensity.

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Emissions from light-duty vehicles (million metric tons CO2) Emission factors are based on fuel carbon content and not on a life cycle-based (with the exception of ethanol, per explanation in Section S1). Emissions from electricity use are accounted in the electric sector.									
Reference Case	1,078	1,072	1,062	1,105	1,198	1,229	1,237	1,296	1,392
10%E&T	1,075	1,087	908	932	953	888	855	763	758
20%E&T	1,071	1,068	834	843	810	659	617	557	400
30&E&T	1,066	1,042	775	772	714	384	279	175	118
50%E	1,071	1,066	823	828	795	505	423	255	247
Travel demand (billion VMT)									
Reference Case	2,799	3,125	3,474	3,839	4,227	4,565	4,930	5,324	5,750
10%E&T	2,799	3,125	3,422	3,839	4,227	4,565	4,930	5,324	5,750
20%E&T	2,799	3,125	3,422	3,839	4,227	4,565	4,930	5,324	5,750
30&E&T	2,799	3,125	3,370	3,839	4,227	4,565	4,930	5,324	5,750
50%E	2,799	3,125	3,370	3,839	4,227	4,565	4,930	5,324	5,750
Fuel use (trillion Btu)									
Reference Case	14,748	14,906	15,187	16,158	17,553	18,153	18,989	20,031	20,769
10%E&T	14,712	15,101	13,094	13,741	14,156	13,549	14,018	14,374	14,376
20%E&T	14,669	14,845	12,204	12,715	12,531	11,461	11,718	12,379	12,638
30&E&T	14,600	14,504	11,528	11,986	11,712	9,435	9,404	10,083	10,796
50%E	14,665	14,815	11,993	12,477	12,253	10,274	10,257	10,479	11,194
Fleet average efficiency (mpg)									
Reference Case	23.5	24.8	26.7	28.1	29.4	31.2	32.2	33	34.3
10%E&T	23.6	25.7	32.4	34.7	37	41.8	43.6	45.9	49.6
20%E&T	23.7	26.1	34.8	37.5	41.8	49.4	52.2	53.4	56.4
30&E&T	23.8	26.7	36.3	39.7	44.8	60	65	65.5	66.1
50%E	23.7	26.2	34.9	38.2	42.8	55.1	59.6	63	63.7

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Method to estimate the contributions of CO_2 emission mitigations (million metric tons CO_2) from VMT reduction, efficiency improvement and fuel CO_2 intensity reduction. Shaded areas are hypothetical emission changes *if* all other factors are held constant except the specified variable(s)									
Reference Case									
Hold emission constant	1,078	1,078	1,078	1,078	1,078	1,078	1,078	1,078	1,078
Emission changes: VMT only	1,078	1,204	1,338	1,479	1,628	1,758	1,899	2,051	2,215
Emission changes: VMT & efficiency	1,078	1,141	1,181	1,237	1,302	1,327	1,388	1,464	1,518
Actual total emission changes	1,078	1,072	1,062	1,105	1,198	1,229	1,237	1,296	1,392
10% Economy-wide + Trans Cap (10%E&T)									
Emission changes: VMT only	1,078	1,204	1,318	1,479	1,628	1,758	1,899	2,051	2,215
Emission changes: VMT & efficiency	1,078	1,106	959	1,007	1,037	993	1,027	1,053	1,053
Emission mitigation: VMT	0	0	20	0	0	0	0	0	0
Emission mitigation: efficiency	0	34	201	230	265	334	361	411	465
Emission mitigation: fuel CO_2 intensity	3	-50	-67	-57	-20	6	22	122	169
20% Economy-wide + Trans Cap (20%E&T)									
Emission changes: VMT only	1,078	1,204	1,318	1,479	1,628	1,758	1,899	2,051	2,215
Emission changes: VMT & efficiency	1,078	1,091	897	934	921	842	861	910	929
Emission mitigation: VMT	0	0	20	0	0	0	0	0	0
Emission mitigation: efficiency	0	50	264	302	382	485	527	554	589
Emission mitigation: fuel CO_2 intensity	6	-46	-56	-40	6	85	94	184	403
30% Economy-wide + Trans Cap (30%E&T)									
Emission changes: VMT only	1,078	1,204	1,298	1,479	1,628	1,758	1,899	2,051	2,215
Emission changes: VMT & efficiency	1,078	1,071	851	885	865	696	694	744	797
Emission mitigation: VMT	0	0	40	0	0	0	0	0	0
Emission mitigation: efficiency	0	70	290	352	438	630	694	720	721
Emission mitigation: fuel CO_2 intensity	12	-40	-43	-18	46	215	264	401	553
50% Economy-wide Cap (50%E)									
Emission changes: VMT only	1,078	1,204	1,298	1,479	1,628	1,758	1,899	2,051	2,215
Emission changes: VMT & efficiency	1,078	1,089	881	917	901	755	754	770	823
Emission mitigation: VMT	0	0	40	0	0	0	0	0	0
Emission mitigation: efficiency	0	52	259	319	402	572	634	694	695
Emission mitigation: fuel CO_2 intensity	7	-45	-61	-42	1	152	181	347	450
Method to estimate emission mitigation (million metric tons CO_2/yr) from fuel CO_2 intensity reduction from ethanol fuels and others									
Total ethanol fuels emissions									
Reference case	-31	-58	-91	-126	-140	-156	-188	-195	-177
10% Economy-wide + Trans Cap	-31	-58	-86	-115	-124	-142	-178	-257	-272
20% Economy-wide + Trans Cap	-31	-58	-91	-120	-126	-151	-186	-262	-408
30% Economy-wide + Trans Cap	-31	-58	-91	-126	-144	-161	-212	-330	-456
50% Economy-wide Cap (50%E)	-31	-58	-86	-112	-108	-128	-155	-266	-345
Emission mitigation from fuel CO_2 intensity reduction - ethanol fuels									
10% Economy-wide + Trans Cap	0	0	-5	-12	-15	-14	-10	62	95
20% Economy-wide + Trans Cap	0	0	0	-6	-14	-5	-2	66	231
30% Economy-wide + Trans Cap	0	0	0	0	4	5	24	134	279
50% Economy-wide Cap (50%E)	0	0	-5	-14	-32	-28	-33	71	168
Emission mitigation from fuel CO_2 intensity reduction – others									
10% Economy-wide + Trans Cap	3	-50	-61	-45	-4	20	31	60	74
20% Economy-wide + Trans Cap	6	-46	-56	-34	20	90	96	118	171
30% Economy-wide + Trans Cap	12	-40	-43	-17	42	209	241	267	274
50% Economy-wide Cap (50%E)	7	-45	-55	-27	33	180	214	276	282

The average fuel CO_2 intensity (gCO_2/MJ) for passenger vehicles can be calculated by dividing the total passenger vehicle emissions (million metric tons CO_2) by the total fuel use (billion Btu) and then multiplying by a conversion factor of 947.817 Btu/MJ (Figure S4). With the exception of ethanol, fuel CO_2 intensity is calculated based on the carbon content of the fuels, shown in Table S4, and not on a life-cycle basis. For ethanol feedstocks, the considerable N_2O emissions are included as CO_2 equivalents because they can comprise a sizeable share of the direct GHG effects of bioenergy crop production. The emission factors for corn ethanol and cellulosic ethanol are listed in Table S5. Note that our paper only considers two generic types of ethanol: corn ethanol and cellulosic ethanol. Many biofuel production pathways can contribute to significantly lower greenhouse gas emission reductions *(20, 21)*, and this would be an important research area that needs to be incorporated into our future database. The emission accounting in our database adopts the sector-specific approach. Therefore emissions from electricity use for plug-in hybrid vehicles will be accounted for in the electric sector.

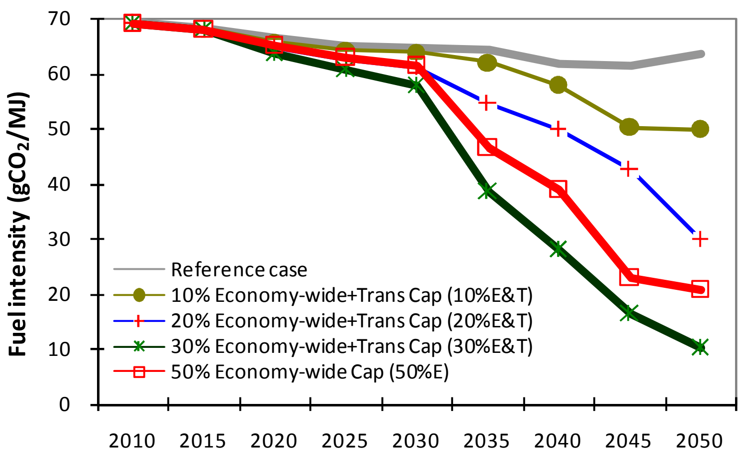


Figure S4. The average fuel CO_2 intensity for passenger vehicles by scenario. The emissions for the CO_2 intensity of the fuels are sector-specific and not life-cycle based.

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