SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

A Research Summary for Decision Makers

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Chapter 10: Optimizing the Transportation Climate Mitigation Wedge[1]

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The previous two chapters have looked at scenarios for making deep reductions in GHG emissions in the transportation sector by 2050. We now turn to considering what role the transportation sector might play under economy-wide CO_2 constraints in the United States. If we see emission reductions achieved in different sectors of the economy—including commercial and residential buildings, industry, agriculture, and electric power, as well as transportation—as wedges that add up to an emission reduction target mandated by policy, how might the transportation wedge reduce its emissions to meet the policy goals under optimized least-cost solutions? Will economy-wide carbon taxes and cap-and-trade programs result in emission reductions from the transportation sector commensurate with its contribution to economy-wide emissions? Or are other approaches needed to incentivize the transportation climate mitigation wedge? To address these questions, we used an integrated energy-economics model called the MARKet ALlocation (MARKAL) model to examine least-cost emission reductions scenarios within economy-wide emission cap scenarios.

Background: Other Models and Their Findings

Policymakers rely on integrated climate-energy-economics models to help them identify the most economical way to meet climate mitigation objectives. Few of these models examined in greater detail the role transportation GHG emission reductions will play under economy-wide emission cap policies. These models found that carbon taxes and cap-and-trade programs will have a large effect in the electric power sector but little effect in the transportation sector. In other words, these analyses find that electric power sector responds well to market-based policies such as cap-and-trade, while all the other end-use sectors including residential, commercial, industrial and transportation sectors respond poorly to market-based policies. For example, analyses of proposed U.S. cap-and-trade programs by the U.S. Environmental Protection Agency (EPA) and Energy Information Administration (EIA) suggest that less than 5 percent of total emission reductions would come from the transportation sector by 2030, even though transportation accounts for almost a third of total emissions.[2] If these proposed cap-and-trade policies were implemented, the transport sector would become the single largest emission source by 2050, accounting for more than half of total GHG emissions in the United States.[3]

On the other hand, studies that have used engineering economic analyses to examine the potential of transportation GHG emission reductions suggest that the cost of improving energy efficiencies of light-duty vehicles will be minor. For example, a McKinsey & Company report concluded that a cluster of transportation technologies—including improvement of vehicle efficiency, use of cellulosic biofuels, and hybridization of vehicles—could avoid 340 megatons of GHG emissions at a cost of less than $50 per ton (in 2005 dollars) by 2030.[4]

Why the difference in results between the economy-wide models where transportation emission reductions are estimated to be expensive and unlikely, and studies specifically examining the transport sector that conclude that moderate emission reductions from the transport sector can be achieved with reasonable costs? The contradictions lie in the "energy paradox" that has been widely researched in the literature outside of the energy modelling community, i.e., energy markets are particularly inefficient and ineffective in addressing end-use technology efficiency and demand reduction. Thus, while market-based policies are more effective in reducing GHG emissions on the supply-side, separate policies are needed to reduce GHG emissions from end-uses, including transportation. Policies such as vehicle, building, and appliance efficiency standards, R&D programs targeting advanced technologies, and subsidies for infrastructure development are a few examples of policies needed to overcome market barriers and imperfect decision making in the real world.

In this chapter, however, we use a model that assumes perfect decision making and a perfect market to estimate GHG reductions needed to achieve deeper climate reduction goals. The purpose of the modelling exercise is not to predict the future, but to understand *the least-cost technology mix (given our assumptions) that will be required to meet the policy targets*. The results provide a useful roadmap for policymakers to decide policy solutions and incentive structures needed to overcome market barriers in order to achieve emission reduction goals.

Our Modeling Framework and Scenarios

We used the MARKet ALlocation (MARKAL) model developed by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency to help us identify the most cost-effective technological pathway to meet GHG emission reduction targets economy-wide while also satisfying future end-use demands and other policy constraints. 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. The model also accounts for fuel supply, resource potentials, and other user constraints. It assumes rational decision making, with perfect information and perfect foresight, and computes a supply-demand equilibrium where energy demand is responsive to changes in price. The model finds the least expensive combination of technologies to meet future energy demands, subject to resource availability and user constraints such as economy-wide GHG emission reduction targets or technology-specific appliance efficiency/emission standards that become increasingly stringent over time.

We used the model to examine cumulative emission-reduction targets from 10 to 50 percent economy-wide (E scenarios) and from 10 to 30 percent economy-wide and equal percent reduction from the transportation sector (E&T scenarios) for the period 2010 to 2050. These reductions (also referred to as CO_2 avoided) are in comparison to a reference case where no significant GHG policies have been adopted. We assume that under GHG reduction scenarios, complementary policies (such as policies to improve access to transit, incentivize fuel infrastructure development to lower consumers' risk aversion (represented as high hurdle/discount rate) to new technologies, etc.) will be adopted to address market barriers, and consumers will be more likely to respond to price changes by reducing vehicle travel demands (by driving less, taking more transit trips, or using other modes of transportation) and more willing to purchase new technologies that have higher up-front costs and a longer payback time. For example, we assume that when gasoline prices increase by 10 percent, consumers in the reference case (no climate policy) will reduce their travel demand by 1 percent (a demand elasticity of –0.1), while consumers in the climate policy scenarios will reduce their travel demand by 3 percent (a demand elasticity of –0.3). Similarly, we assume that in the policy case consumers will be willing to wait longer (indicated by a lower discount rate) to recover their investment in more advanced and efficient vehicles than they normally would have. Later, we will demonstrate that the first assumption (increased elasticity) has very little effect on the results, while the second (longer payback period) is necessary to broadly adopt advanced, low-carbon vehicles within the policy timeframe.

SCENARIOS EXAMINED

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 percent 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 percent economy-wide + 10–30 percent transportation cap	

The scenarios examined in this chapter are not intended to project the future with and without climate policies. Instead, our aim is to identify least cost mitigation technology mix based on our assumptions about technology costs and resource availability within an integrated energy system, if society were to act in the least-cost manner with perfect foresight.

There are three things to note about our use of the MARKAL model. First, the MARKAL type of bottom-up model is not suited to analyze nontechnology policies—such as policies encouraging behavior changes or those regarding land use, smart growth, mass transit, carpooling, or telecommuting—even though 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) assume a flat rate for transportation and distribution cost and ignore infrastructure hurdles such as refueling stations and transport distance, the classic chicken-and-egg problem. Mitigation strategies involving alternative fuels must take into consideration not only cost but also other social factors and policies that encourage technology adoption. Third, we do not take into account the social and environmental benefits and co-benefits of reducing CO_2 emissions, such as reducing air pollution, improving energy security risk, and reducing the costs of climate change.

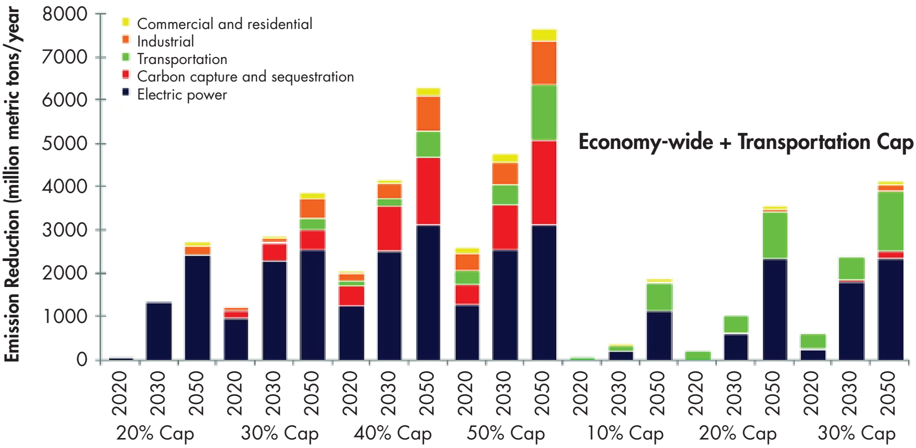
Our Modeling Results: Where Emission Reductions Will Come From

Our modeling results suggest that more stringent economy-wide emission caps than currently proposed, or transportation-sector emission caps, will be needed in order to effectively reduce long-term transportation sector CO_2 emissions. We also found that the market penetrations of low-carbon fuels and advanced vehicle technology depend on policy drivers. As the GHG reduction target becomes more stringent, faster penetration of low-carbon fuels and advanced vehicles becomes necessary to achieve the policy target. And finally, our model projects that emission reductions beyond current policy requirements will be contributed almost entirely by the interactions of three mitigation wedges: vehicle efficiency improvement, advanced vehicle technologies, and low-carbon fuels including electricity and biofuels. The role of price-induced VMT reduction in reducing GHG emissions is small in this economic modeling, primarily due to the low elasticity (albeit higher in the policy case), the rebound effect, and the resulting longer payback period with reduced VMT.

Emission caps and emission reductions by sector

Consistent with previous research findings, our analysis shows that when economy-wide emission caps are low to moderate (our 10%E to 30%E scenarios), the transportation sector contributes just a small portion of the overall reductions and the electric power sector contributes the majority. Our 30%E scenario (2,879 million metric tons CO_2 reduction in 2030) is roughly consistent with the EIA analysis of S. 2191 (America's Climate Security Act of 2007), which projects the total CO_2 emission reduction by 2030 with no international offsets at 3,030 million metric tons CO_2-equivalent.[5] The transportation sector starts to make more substantial reduction contributions at the 40-percent reduction target and above (7 percent in the 40%E scenario and 13 percent in the 50%E scenario between 2010 and 2050). If the same percentage emission caps (10 to 30 percent) apply equally to the full economy and to transportation (the E&T scenarios), the transportation sector contributes roughly 30 percent of the overall reductions between 2010 and 2050, while the electric power sector contributes 51 to 66 percent.

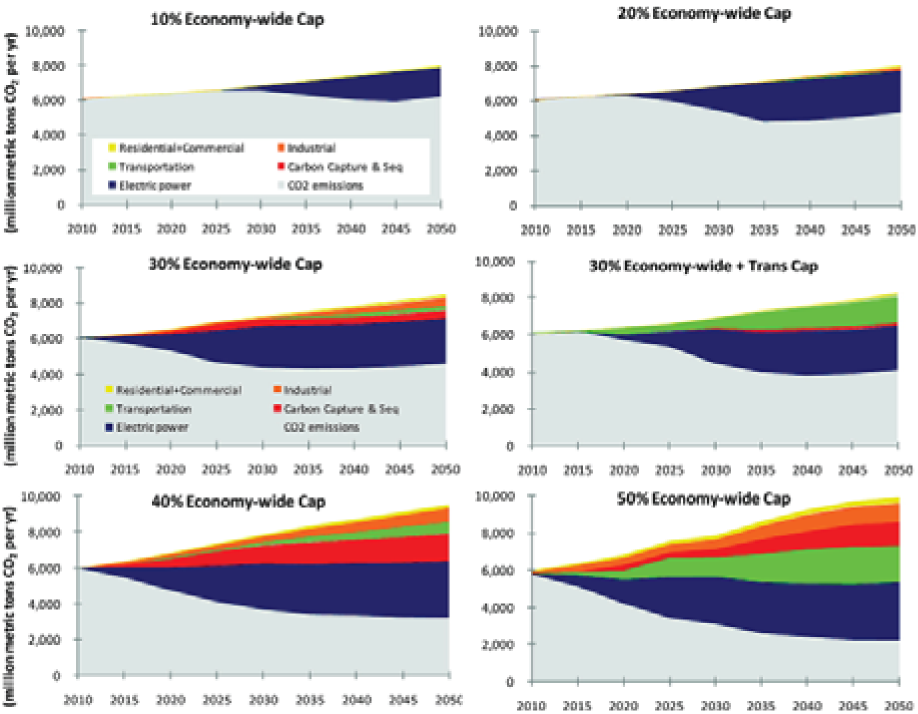
CO_2 EMISSION REDUCTIONS BY SECTOR FOR SEVEN SCENARIOS IN 2020, 2030, AND 2050



We compared energy-related CO_2 emission reductions in 2020, 2030, and 2050 by sector for seven of our scenarios (the 20%E to 50%E scenarios and the 10%E&T to 30%E&T scenarios). Electric power and carbon capture and sequestration (CCS) account for most of the reduction in the economy-wide scenarios. The transportation sector starts to make more substantial reduction contributions at the 40-percent reduction target and above.

Holding emissions constant to 2050 (constituting an emission stabilization trajectory) roughly corresponds to our 10%E scenario, and the shape of our 50%E scenario roughly corresponds to the 450 ppm early-action mitigation wedge proposed by Stephen Pacala and Robert H. Socolow in their 2004 article in *Science*.[6] Our model, which chooses the least-cost solution with perfect foresight, suggests that most of the emission reduction will come from the electric power 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 percent and above economy-wide cap scenarios.

MITIGATION WEDGES BY SECTOR FOR SIX SCENARIOS, 2010–2050



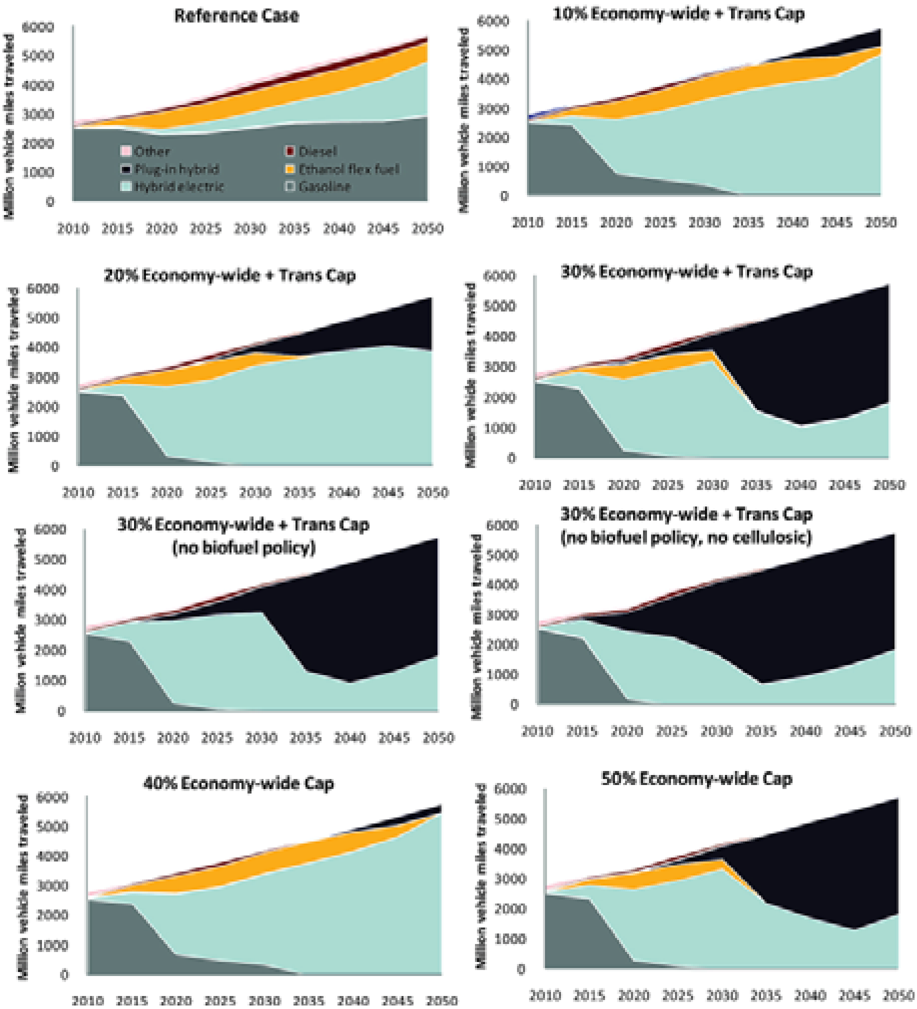
Another way of looking at emission reductions is by picturing each sector as a wedge representing emissions avoided from the reference case. The gray areas here show overall CO_2 emissions. Again we can see that the majority of emission reductions in all scenarios come from the electric power sector. The transportation sector is a significant contributor only in the 30%E&T and the 50%E scenarios.

Fuel and vehicle mix and emission reduction

In all the policy cases that require significant reductions from the transportation sector, gasoline hybrid electric vehicles (HEVs) quickly start replacing conventional gasoline vehicles. In 30%E&T, the scenario that requires the most GHG emission reduction from the transportation sector, plug-in hybrid electric vehicles (PHEVs) are quickly adopted and comprise roughly 68 percent of the total passenger vehicle fleet in 2050. 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 percent in efficiency in 2050 over the reference case), and fuel usage also decreases significantly (up to 48 percent in 2050 in 30%E&T).

In our scenarios, ethanol usage increases from 3.5 billion gasoline-equivalent gallons per year in 2005 to 36 billion gallons per year in 2050 under the reference case, and to the highest level of 88.4 billion gallons per year under 30%E&T. These assumptions about ethanol do not take into account the possibility that there will be policies either to limit the use of biofuel produced from arable land or to phase out food-based ethanol, since biofuels that induce land-use conversion may result in overall greater GHG emissions than gasoline on a life-cycle basis while causing other adverse sustainability impacts. Neither does the scenario take into account the possibility that cellulosic ethanol, which would avoid these pitfalls, will not be commercially successful on a large scale by 2050. In both cases, the mix of fuels and vehicles to meet emission reduction targets will be different from what we have projected above. In a 30%E&T scenario where there is no biofuel mandate, there will also be no ethanol flex-fuel vehicles and a slightly higher PHEV penetration, and a smaller amount of the biofuels will be used in blended gasoline. In a 30%E&T scenario where there is no biofuel mandate and no cellulosic ethanol industry, we see the highest and fastest penetration of PHEVs.

PROJECTED VEHICLE MIX FOR SIX SCENARIOS, 2010–2050

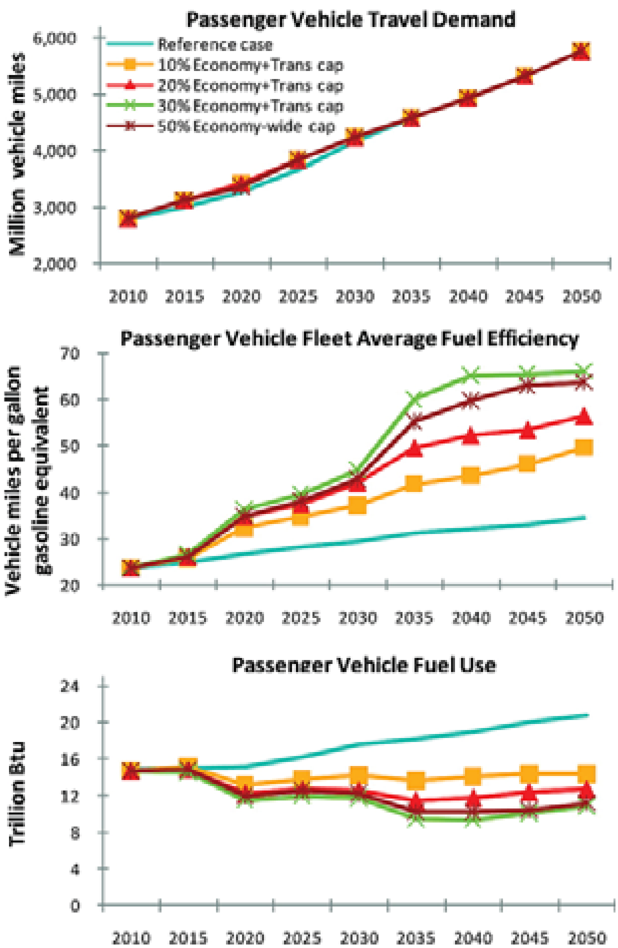


The market penetration of various vehicle types depends on policy drivers. As the GHG reduction target becomes more stringent, faster penetration of advanced vehicles becomes necessary to achieve the policy target. The penetration of ethanol flex-fuel vehicles is entirely driven by biofuel policy that requires 36 billion gallons of biofuels by 2022. To meet deeper reduction goals without biofuels, earlier penetration of PHEVs at higher volumes will be necessary. In almost all of the climate-policy cases, conventional gasoline vehicles need to be replaced by advanced vehicle technology by 2020-2030, depending on the stringency of the targets.

Mitigation strategies and emission reduction

Mitigation strategies for the transportation sector include reducing vehicle miles traveled (VMT), increasing vehicle efficiency, and adopting low-GHG fuels and advanced vehicle technologies. Overall, our model projects that CO_2 emission reductions in all our scenarios are contributed almost entirely by vehicle efficiency improvement, with a growing proportion contributed by switching to electricity and biofuels after about 2030. The travel demand levels are similar in all cases we examined (and contribute nearly nothing to reducing CO_2 emissions in any of the scenarios), reflecting two facts: (1) although we have made consumers *more* willing to change their demand level compared with a no-policy scenario (by increasing the elasticity from -0.1 to -0.3), elasticity of travel demand remains low; (2) improvements in vehicle efficiency and the transition to electricity fuels reduce the cost of driving (in dollars per mile driven), which further decreases consumers' response to the underlying trend of fuel price increases. Though we did not explicitly calculate the rebound effect (as vehicles become more fuel-efficient, it costs less to drive and so VMT increases), it likely explains the lack of response in price-induced VMT reduction as an effective way of contributing to GHG mitigation. It should also be noted that our model cannot simulate the effects of policies that encourage behavior change—such as policies regarding land use, smart growth, mass transit, carpooling, or telecommuting—although such policies are likely to be adopted when climate policies become reality.

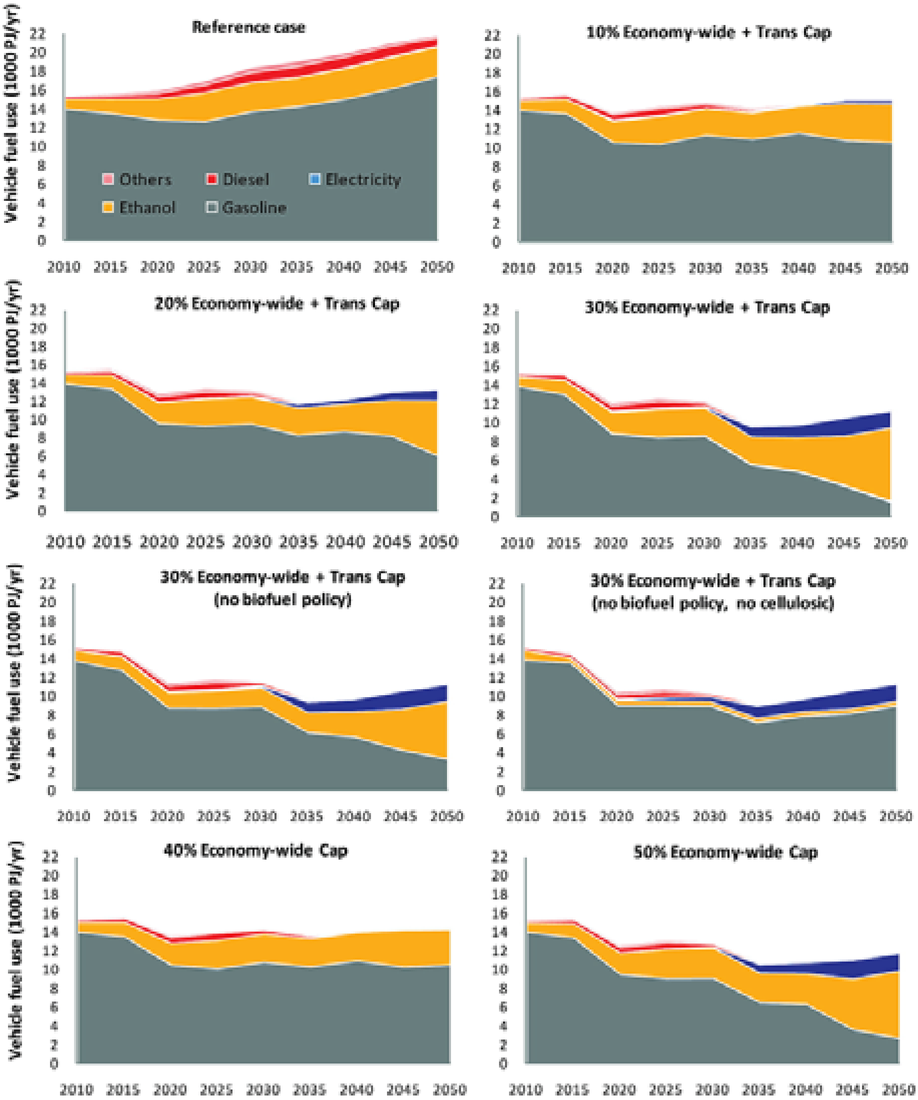
TRAVEL DEMAND, FUEL EFFICIENCY, AND TOTAL FUEL USE BY SCENARIO, 2010–2050



When we compare passenger-vehicle travel demand, fuel efficiency, and total fuel use for our three E&T scenarios and the 50%E scenario, it is clear that fuel efficiency and total fuel use need to improve significantly over the reference case in order to meet the reduction targets. The lack of response in price-induced VMT reduction as an effective way of contributing to GHG mitigation may be explained by low elasticity to travel demand and the decreasing cost of driving per mile due to improvement in vehicle efficiency and the transition to lower cost of alternative fuel, electricity.

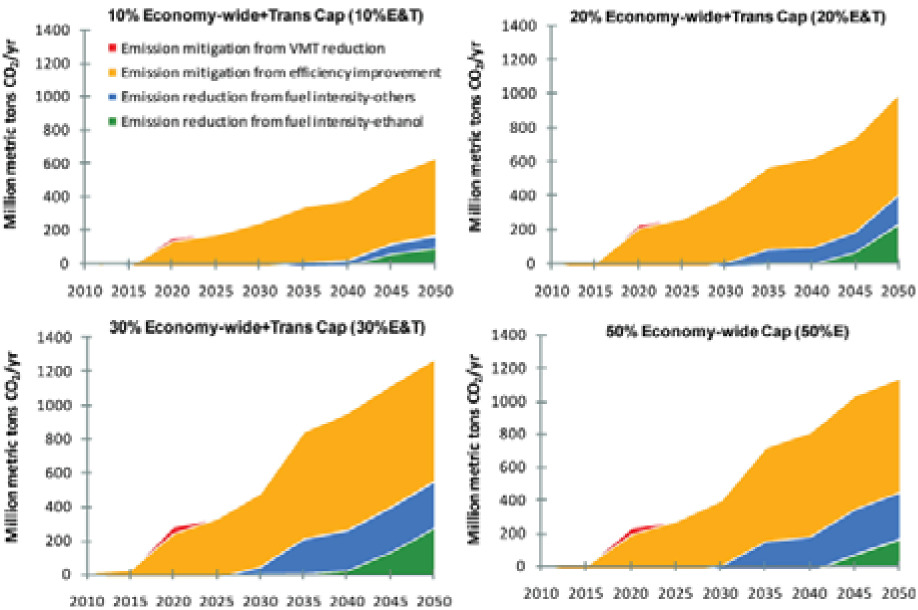
We found that even without a specific mandate for biofuel production, cellulosic ethanol can still be a favorable mitigation strategy to achieve significant transportation emission reductions albeit at lower initial volume and slowly ramping up to a higher level by 2050 compared with the reference case. However, if there is neither a biofuel mandate nor commercially successful cellulosic technology on a large scale, more gasoline and electricity, and overall less fuel will be necessary to achieve the required reduction in transportation CO_2 emissions.

FUEL USE BY TYPE OF FUEL FOR FOUR SCENARIOS, 2010–2050



We compared total passenger-vehicle fuel use by type of fuel for the reference scenario, the 30% E&T scenario, and scenarios where (1) there is no biofuel mandate, and (2) there is no successful cellulosic technology to make low-carbon biofuels at the estimated costs. We found that the success of biofuels may not be entirely dependent on a biofuel mandate and can occur without a mandate, although the availability of truly low-carbon biofuels can be a major uncertainty.

RELATIVE CONTRIBUTIONS OF MITIGATION STRATEGIES TO CO_2 EMISSION REDUCTIONS



For passenger vehicles, CO_2 emissions can be reduced by reducing fuel CO_2 intensity, improving vehicle efficiency, and reducing vehicle miles traveled (VMT). With the exception of biofuels, fuel CO_2 intensity is based on combustion emissions and is not life-cycle based. Our model projects that vehicle efficiency improvement is the low-hanging fruit in all of the scenarios. Fuel CO_2 intensity reduction can be achieved by increasing the use of electricity (blue wedges) and of biofuel (green wedges) above and beyond the existing mandate. The use of electricity further increases efficiency improvement in the transport sector due to the superior efficiency of electric-drive vehicles compared with conventional internal combustion engines. Because our model cannot simulate behavior changes not related to economic factors, it does not predict significant reductions in travel demand.

Summary and Conclusions

- Mitigation strategies in a number of different sectors might be combined to achieve policy goals in reducing CO_2 emissions. The results illustrated here are by no means predictive of the future outcome of any particular policies. But what we can say with certainty is that much more stringent system-wide CO_2 reduction targets than those that have been discussed in Congress will be required to achieve significant CO_2 reductions in the transportation sector.

- Our study confirms the conclusions of analyses by government agencies, that economy-wide cap-and-trade programs acceptable to politicians are unlikely to reduce transportation emissions, despite the fact that this sector makes a significant contribution to total emissions and is the second largest emission source after the electric power sector. Achieving significant transportation emission reductions over the long term will require much more aggressive economy-wide policies than are currently proposed—or a cap on transportation-specific emissions.

- Realistically, a transportation cap is neither likely nor the most economical approach to reduce economy-wide GHG emissions. The well-known "energy paradox" implies that energy markets are particularly inefficient and ineffective in addressing end-use technology efficiency and demand reduction. Thus, while market-based policies are more effective in reducing GHG emissions on the supply-side, separate policies are needed to reduce GHG emissions from end-uses, including transportation. Policies such as vehicle efficiency standards, R&D programs targeting advanced technologies, and subsidies for infrastructure development are a few examples of policies needed to overcome market barriers and imperfect decision making in the real world.

- Comparable policies could be adopted to achieve the same goal. Examples of these policies include policies to improve vehicle efficiencies (such as the CAFE fuel economy standard or the vehicle GHG emission standard), policies that encourage the reduction of fuel carbon intensities (such as the Low Carbon Fuel Standard discussed in Chapter 11), and polices that encourage the production and adoption of advanced vehicle technologies that both reduce fuel GHG intensity and increase vehicle efficiency (such as the zero-emission vehicle or ZEV program).

- Our model does not predict significant price-induced travel demand reduction. The lack of response in reducing VMT as an effective way of contributing to GHG mitigation may be explained by low elasticity to travel demand and the decreasing cost of driving per mile due to improvement in vehicle efficiency and the transition to lower cost of alternative fuel, particularly electricity. But such reductions should be pursued in parallel in order to reduce congestion, improve air quality, and reduce oil dependence as well as to reduce emissions.

- Though our modelling results do not project the penetration of hydrogen fuel cell vehicles given our scenarios, a portfolio approach is needed to invest in advanced fuel and vehicle technologies including plug-in hybrid electric vehicles, battery electric vehicles and hydrogen fuel cell vehicles to deal with uncertainties in technology costs, market barriers and consumers' preferences.

- More research is needed to help identify robust policies that will achieve the best outcome in the face of uncertainties that we have not addressed here.

FUTURE WORK

In California, the Global Warming Solutions Act of 2006 (AB 32), which enacts former Governor Schwarzenegger's Executive Order #S-3-05, requires the state to reduce its greenhouse gas (GHG) emissions to the 1990 level by 2020 and 80 percent below the 1990 level by 2050. The scoping plan adopted both technology-forcing measures that mandate specific emission reduction strategies/technologies that are estimated to reduce 174 million tonnes GHG emissions by 2020, and a market-based approach (cap-and-trade program) that limits emissions from all major point sources, allowing market mechanisms to determine the most cost-effective strategies to reduce GHG emissions. Though the total emissions reduction needed by 2020 has been adjusted downward due to the economic downturn, the State still faces significant challenges and currently lacks a roadmap to meet its 2050 reduction target. We've developed a California-specific energy-economic-environment model that will help us understand the cost-effective mitigation options needed to achieve the long-term GHG reduction target, and potential impacts of various climate and energy policies adopted or being considered in California. The CA-TIMES (the Integrated MARKAL EFOM System) is a bottom-up, technology-rich model that encompasses all sectors of the economy, including electric, transportation, industrial, commercial, residential, agricultural, and non-energy sectors. Our goal is to understand the impacts of policies on economic costs, energy consumption, and technology portfolios; and to identify market barriers and policies needed to encourage the adoption of advanced technologies. The basic modeling structure is described in McCollum, David L. (2011) *Achieving Long-term Energy, Transport and Climate Objectives: Multi-dimensional Scenario Analysis and Modeling within a Systems Level Framework,* Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-11-02. More work is ongoing to improve the modeling as well as scenario analysis in order to learn insights for guiding policy design.

Notes

1. This chapter is a condensed version of S. Yeh, A. Farrell, et al., "Optimizing U.S. Mitigation Strategies for the Light-Duty Transportation Sector: What We Learn from a Bottom-Up Model," *Environmental Science and Technology* 42 (2008): 8202–10.
2. U.S. Energy Information Administration, "Energy Market and Economic Impacts of S. 2191, the Lieberman-Warner Climate Security Act of 2007" (Washington, DC: Energy Information Administration, Office of Integrated Analysis and Forecasting, U.S. Department of Energy, 2008); U.S. Environmental Protection Agency, "United States Environmental Protection Agency's Analysis of Senate Bill S.280 in the 110th Congress, The Climate Stewardship and Innovation Act of 2007" (U.S. Environmental Protection Agency, 2007).
3. Ibid.
4. J. Creyts, A. Derkach, S. Nyquist, K. Ostrowski, and J. Stephenson, *Reducing U.S. Greenhouse Gas Emissions: How Much at What Cost?* (McKinsey & Company, 2007). http://www.mckinsey.com/clientservice/sustainability/pdf/US_ghg_final_report.pdf
5. U.S. EIA, "Energy Market and Economic Impacts of S. 2191, the Lieberman-Warner Climate Security Act of 2007" (U.S. Energy Information Administration, 2008), http://www.eia.doe.gov/oiaf/servicerpt/s2191/.
6. S. Pacala and R. Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science* 305 (2004): 968–72. See also OECD/IEA, *Energy Technology Perspectives* (Paris, France: International Energy Agency, 2008).