SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

A Research Summary for Decision Makers

Edited by Joan Ogden and Lorraine Anderson

ITS UCDAVIS
INSTITUTE OF TRANSPORTATION STUDIES

Institute of Transportation Studies
University of California, Davis
One Shields Avenue, Davis, California 95616

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Chapter 8:
Scenarios for Deep Reductions in Greenhouse Gas Emissions

Christopher Yang, David McCollum, and Wayne Leighty

The Intergovernmental Panel on Climate Change has suggested that annual greenhouse gas (GHG) emissions must be cut 50 to 80 percent worldwide by 2050 in order to stabilize the climate and avoid the most destructive impacts of climate change. California governor Arnold Schwarzenegger and U.S. president Obama lined up behind this goal.[1] Yet the strategies for meeting these ambitious economy-wide targets have not been clearly defined, and the technology and policy options are not well understood. This chapter explores how such deep reduction targets (50 to 80 percent) could be met in the transportation sector by 2050, with a focus on California and the United States as a whole. It presents a framework for understanding emission reductions in the transportation sector, lays out the major mitigation options for reducing emissions, and presents scenarios to explore how deep reductions could be achieved. Additionally, this chapter also presents an analysis that looks at the transition scenarios for vehicles in the light-duty sector to investigate how they may evolve from the present fleet to achieve the deep-reduction scenarios by 2050.

GHG Emissions in the Transportation Sector

Transportation is one of the primary sources of GHG emissions in California (where it accounts for 40 percent), the United States (29 percent), and globally (23 percent).[2] These emissions are growing quickly in each of these regions and in all subsectors—from personal light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs, meaning buses and trucks) to rail, aviation, marine, agriculture, and off-road. The main drivers of transportation GHG emissions are population, transport intensity (passenger or freight miles per person), energy intensity (vehicle fuel consumption), and fuel carbon intensity. We can estimate transportation GHG emissions by plugging these four variables into a simple equation. In this equation, total transportation activity in miles is the product of the total human population (P) and transport intensity (T). The amount of carbon emitted per mile of transport is a product of energy intensity (E) and carbon intensity (C). By working out this equation and summing the results for all vehicle types and subsectors, we can arrive at a figure that describes the total CO_2-equivalent GHG emissions from the entire transportation sector on a full fuel-cycle basis in any given year (whether 1990 or 2050 or some point in between). Further, by comparing these figures we can estimate potential reductions in transportation GHG emissions between 1990 and 2050 for a given region.

THE EQUATION WE USED IN OUR ANALYSIS

A decomposition equation is a useful tool for estimating potential reductions in transportation emissions. We developed a transportation variant of the Kaya identity (Equations 1-3) in our analysis. In this decomposition equation, the main drivers for transportation GHG emissions are population (P), transport intensity (T), energy intensity (E), and fuel carbon intensity (C).

$$(1)\quad CO_{2,\ \mathrm{Transport}} \equiv (\mathrm{Population})\left(\frac{\mathrm{Transport}}{\mathrm{Person}}\right)\left(\frac{\mathrm{Energy}}{\mathrm{Transport}}\right)\left(\frac{\mathrm{Carbon}}{\mathrm{Energy}}\right)\qquad (1)$$

$$(2)\quad CO_{2,\ \mathrm{Transport}} \equiv \quad P \quad \mathrm{X} \quad T \quad \mathrm{X} \quad E \quad \mathrm{X} \quad C \qquad (2)$$

$$(3)\quad CO_{2,\ \mathrm{Transport}} \equiv \sum_{i}\sum_{j} CO_{2i,\,j} \equiv \sum_{i}\sum_{j} P \times T_{i,\,j} \times E_{i,\,j} \times C_{i,\,j} \qquad (3)$$

where *i* = subsector and *j* = vehicle type.

Emissions in a given region can be classified into two categories: emissions generated by trips occurring entirely within the borders of the region and emissions from trips that cross the borders. This affects the jurisdiction of a given policy. For instance, in our California analysis, in-state emissions are linked to trips that occur entirely within the state's borders, while overall emissions also include half of emissions from trips that cross state boundaries. Similarly, for our U.S. analysis, emissions taking place entirely within the United States are called domestic emissions, whereas overall emissions also include half of emissions from international trips that originate or terminate in the United States.

For smaller regions like California or other U.S. states, within-region (in-state) emissions are a smaller proportion of overall emissions than for a larger region like the United States. In 1990, California's in-state emissions (on a full life-cycle basis) accounted for 73 percent of overall emissions (193 vs. 264 $MMTCO_2e$), whereas for the United States, domestic emissions accounted for 91 percent of overall emissions (1,921 vs. 2,104 $MMTCO_2e$). (MMT = million metric tonnes; CO_2e includes CO_2, CH_4, and N_2O weighted by their respective global warming potentials.)

In the United States in 1990 (which is the baseline year used for GHG emission reduction targets in this analysis), light-duty cars and trucks (passenger cars, pickup trucks, SUVs, minivans, and motorcycles) were responsible for about 60 percent of domestic life-cycle GHG emissions in the transportation sector. Heavy-duty vehicles (large trucks and buses) accounted for another 17 percent. Domestic aviation (including commercial passenger, freight, and general aviation) comprised 11 percent of emissions, and the remaining 12 percent were from a combination of rail, domestic marine, agriculture, and off-road equipment. The breakdown of energy use by subsector is very similar to that for GHG emissions because of the overwhelming reliance on various forms of petroleum fuels, all of which have roughly similar carbon intensity values.

U.S. TRANSPORTATION ENERGY USE AND GHG EMISSIONS, 1990

To understand the 1990 baseline for GHG emission reduction targets, we broke down transportation energy use and GHG emissions by subsector and vehicle type. These figures are based on our calculations using data from numerous sources. Emissions estimates reported here are higher than those from other published studies because we include the GHGs produced during upstream ("well-to-tank") fuel production processes.

PJ = petajoule, a measure of energy equivalent to a thousand trillion joules or roughly 30 million kilowatt hours. MMT = million metric tonnes; CO_2e includes CO_2, CH_4, and N_2O weighted by their respective global warming potentials.

		Energy Use				**GHG Emissions**			
Subsector	**Vehicle Type**	**Domestic**		**Overall**		**Domestic**		**Overall**	
		(PJ)	**%**	**(PJ)**	**%**	**MMT CO2e**	**%**	**MMT CO2e**	**%**
Light-duty	Cars and trucks	12,603	60.1%	12,603	54.8%	1,159	60.3%	1,159	55.1%
Heavy-duty	Buses	176	0.8%	176	0.8%	16	0.8%	16	0.8%
	Heavy trucks	3,370	16.1%	3,370	14.7%	304	15.8%	304	14.5%
Aviation	Commercial (passenger)	1,779	8.5%	2,335	10.2%	160	8.3%	210	10.0%
	Freight	365	1.7%	555	2.4%	33	1.7%	50	2.4%
	General	139	0.7%	139	0.6%	13	0.7%	13	0.6%
Rail	Passenger	77	0.4%	77	0.3%	14	0.7%	14	0.6%
	Freight	458	2.2%	458	2.0%	41	2.1%	41	2.0%
Marine	Large marine – intl.	-	0.0%	1,278	5.6%	-	0.0%	115	5.5%
	Large marine – domestic	341	1.6%	341	1.5%	31	1.6%	31	1.5%
	Personal boats	197	0.9%	197	0.9%	18	0.9%	18	0.9%
Agriculture	Agriculture	444	2.1%	444	1.9%	40	2.1%	40	1.9%
Off-road	Off-road	1,017	4.9%	1,017	4.4%	92	4.8%	92	4.4%
Total – All subsectors		20,966		22,990		1,921		2,104	

Options for Reducing Transport GHG Emissions

Three of the four drivers of transportation GHG emissions—transport intensity (T), energy intensity (E), and carbon intensity (C)—can also be thought of as levers that technologies and policies can use in order to reduce transport GHG emissions. (Population growth forecasts are taken as given in our work.)

- Travel demand can be reduced—which in turn can reduce transport intensity (T) in many of the subsectors—by integrated land-use planning, high-density development, and improved public transit.

- Energy intensity (E) can be reduced by improving the efficiency of the vehicle drive train, reducing dissipative forces on the vehicle (for example, by improving aerodynamics, reducing vehicle weight, or lowering rolling resistance), changing drivers' acceptance of smaller vehicles and less powerful engines and driving behavior (reducing "lead-foot" acceleration and deceleration).

- Fuel carbon intensity (C) can be reduced by switching to, or blending in, lower-carbon alternative fuels (including biofuels, hydrogen, or electricity). Of course, in order to accurately assess GHG reductions from fuel switching, emissions must be estimated on a full life cycle (that is, well-to-wheels or cradle-to-grave) basis.

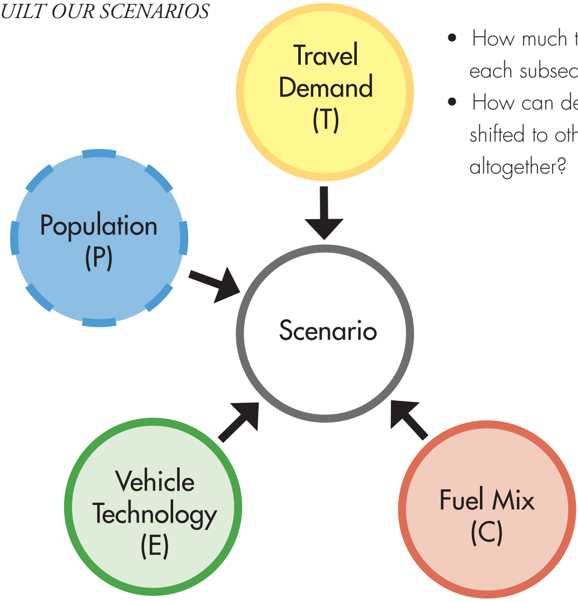
These three levers are, to some extent, interdependent, and synergies between them can be realized—for example, shorter travel distances make highly efficient electric vehicles more attractive. These vehicles could, in turn, be powered by low- or zero-carbon electricity. However, because of the multiplicative Kaya identity, using multiple levers simultaneously reduces the impact of any single mitigation option (for example, doubling vehicle efficiency will have a much smaller impact on the absolute quantity of GHG emissions if vehicles are driving half as much or using fuel with lower carbon intensity.)

We worked with these three levers in order to quantify the emission reduction potential of various GHG mitigation strategies in the transportation sector in California and the United States as a whole. The model we developed is called, fittingly, the Long-term Evaluation of Vehicle Emission Reduction Strategies (LEVERS) model.[3]

Our Three Sets of Scenarios

In our LEVERS model, we created three sets of scenarios to illustrate different potential snapshots of the transportation sector in the United States and in California in 2050 and to estimate the extent to which different GHG mitigation options (technologies and policies) can help meet a deep-reduction target of 50 to 80 percent below 1990 levels.

HOW WE BUILT OUR SCENARIOS



- How much transport is required in each subsector?
- How can demand for one mode be shifted to other modes or reduced altogether?

- What vehicle technologies are used?
- What is the mix of technology penetration in each subsector?
- How efficient are the vehicles?

- What fuels are used?
- What is the fuel mix in each subsector?
- How "green" are they? (How are they produced?)

Each of our transportation scenarios is comprised of a unified story line of the future, as well as a variety of individual input assumptions for vehicles, fuels, and travel demand that correspond to the given story line.

- The reference scenario describes a business-as-usual future in 2050.
- The silver-bullet scenarios summarize the extent to which single mitigation strategies alone may reduce emissions.
- The deep-reduction scenarios combine mitigation options to achieve 50-to-80-percent reductions in transportation GHG emissions by 2050.

These scenarios should not be taken as predictions or forecasts of the future, although we have made reasonable judgments—and have included input from external experts—to create snapshots of the future that are technically plausible. It is important to note that political plausibilty is another issue entirely.

While this collection of scenarios is by no means exhaustive, they are nevertheless useful in informing the policy debate because they are clear and transparent. Stakeholders and policy makers can use them to help guide future decision making. These scenarios are meant to highlight the challenges associated with meeting the deep emission reduction targets and promote discussion about the feasibility of the proposed levels of technology and behavioral change and the policies needed to bring these changes about.

The reference scenario

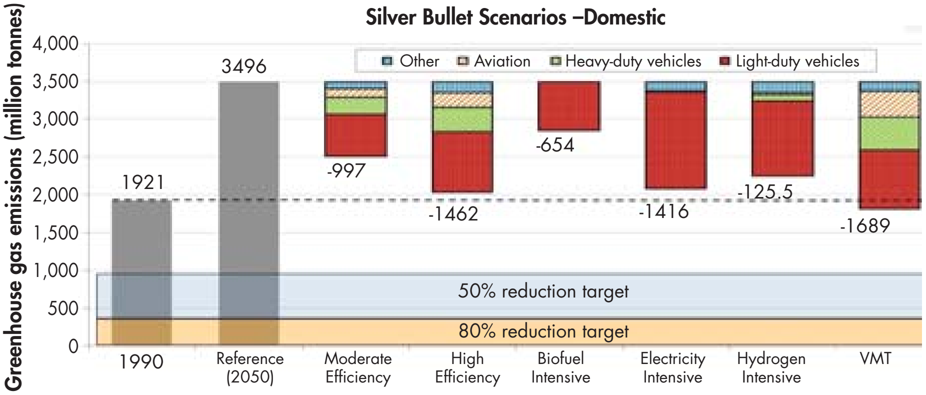
Our reference scenario describes a future in which very little has been done to address climate change, and transportation activity and technology development follow historical trends. The only expected improvement that helps to mitigate growth in GHG emissions in this scenario is a modest reduction (45 percent, roughly 1 percent per year) in energy intensity. In the light-duty sector, this level of improvement is consistent with the entire light-duty fleet achieving 35 mpg on-road new-vehicle fuel economy. However, since both population and transport intensity (travel demand per person) are expected to increase significantly between 1990 and 2050 (a 70-percent increase in the U.S. population, a 100-percent increase in the California population, and an approximate doubling in per-capita transport demand, coming primarily from aviation travel, are forecast), total travel demand increases by a factor of 3.4. The average carbon intensity of transportation fuels is essentially unchanged relative to 1990, as petroleum-based fuels are assumed to remain dominant. Improvements in carbon intensity that result from biofuels being blended into gasoline and diesel in small quantities are balanced by the increased usage of unconventional oil sources, such as oil sands or coal-to-liquids.

In this scenario, U.S. domestic GHG emissions from transportation increase by 82 percent (to 3,496 MMTCO_2e) and overall emissions double (to 4,210 MMTCO_2e) from 1990 to 2050; California in-state GHG emissions from transportation increase by 61 percent (to 311 MMTCO_2e) and overall emissions increase by 86 percent (to 492 MMTCO_2e) from 1990 to 2050. Aviation is responsible for the greatest increase in emissions because, in spite of moderately more efficient airplanes, demand for air travel is expected to grow rapidly in the coming decades. Freight transport—by aircraft, heavy trucks, rail, and large marine vessels—is another area where considerable growth is expected. While the exact numbers are slightly different, the same general trends hold true for both the United States and California.

The silver-bullet scenarios

Our silver-bullet scenarios for the United States and California describe futures in which one single mitigation option, such as an advanced vehicle technology or alternative fuel, is scaled up quickly from today and is employed to the maximum extent possible from a technology perspective in 2050. Emissions are calculated in order to understand the GHG reduction potential of particular vehicle and/or fuel technologies or travel demand reduction. The silver-bullet scenarios modify specific individual elements of the reference scenario.

U.S. DOMESTIC GHG EMISSIONS: SILVER-BULLET SCENARIOS



We compared actual GHG emissions from domestic transportation in the United States in 1990, emissions projected for 2050 in the reference scenario, and projected reductions for each subsector in each of six silver-bullet scenarios for 2050. Each silver-bullet scenario describes a future in which one mitigation option is scaled up quickly and employed as fully as technologically possible. Not one of the silver-bullet scenarios by itself achieves the 50-to-80-percent emission reductions goal, implying that a multi-pronged "portfolio" approach is necessary.

In the Biofuel Intensive scenario, the level of biofuels demand is consistent with projected total U.S. supply (~90 billion gge), although this projection may be overly optimistic.[4] *Significant uncertainties surrounding indirect land-use change impacts from biofuels production lead to the large variability in potential GHG changes from 1990 levels.*

The major take-away message from these silver-bullet scenarios is that none of the individual mitigation options, even ones as encompassing as shifting to the use of biofuels or widespread electrification, can take the transportation sector anywhere close to a 50-to-80-percent reduction. This is in part due to the large projected increase in transportation demand, which counteracts the improvements in efficiency and from fuel switching. However, another factor that prevents a single mitigation option from achieving deep reductions is the diverse nature of the transportation sector. Because of differences in vehicle types, duty cycles, and other application requirements, a given option such as electrification or use of hydrogen and fuel cells cannot be applied universally to all vehicles in each of the subsectors. Aviation and marine are among the most difficult subsectors in which to apply these advanced propulsion systems.

The deep-reduction scenarios

While not one of the silver-bullet scenarios achieves the ambitious 50-to-80-percent reduction goal, several of the options examined in those scenarios are complementary (such as improving efficiency, using low-carbon alternative fuels, and reducing travel demand) and can be combined in a portfolio approach to achieve deep GHG emission reductions.

We developed three different scenarios that represent different potential futures for the United States in which a 50-to-80-percent reduction in domestic GHG emissions might be realized. The scenarios are snapshots of the transportation sector in 2050 and illustrate different mixes of mitigation options in various subsectors. The first scenario relies on moderately high vehicle efficiencies using low-carbon biofuels and the second on higher-efficiency electric-drive vehicles using low-carbon electricity and hydrogen. The third scenario considers a combination of these two strategies. All three assume the same growth in population as in the reference scenario, and each envisions a significant slowing of growth in transport intensity (per-capita VMT) in each subsector to about half of the reference scenario growth, which translates into a 25-percent reduction from the reference scenario in per-capita VMT across all modes. This means that in most cases 2050 transport intensities are still somewhat higher than 2010 levels, but not significantly so.

- US-Efficient Biofuels 50in50 describes a future in which low-carbon biofuels are relatively abundant. In this scenario, a 50-percent reduction in transportation emissions is achieved primarily through the use of low-carbon biofuels, more-efficient internal combustion engine (ICE) vehicles, and travel demand reduction. However, even with relatively optimistic assumptions about the biofuel supply, only 64 percent of total fuel requirements can be met by biofuels, with the remainder coming from petroleum.

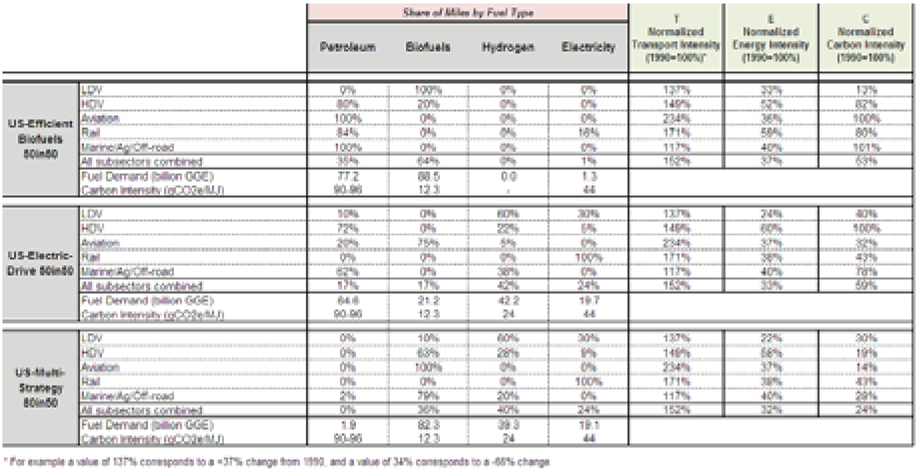
- US-Electric-Drive 50in50 describes a future in which significant advances in electric-drive technologies (fuel cells and electric vehicle batteries) reshape the transportation sector, improving vehicle efficiency and advancing low-carbon alternative fuels. Hydrogen and electricity make up 66 percent of total fuel use, with all biofuels (a smaller quantity compared to US-Efficient Biofuels 50in50 due to less optimistic supply estimates) used in the aviation sector.

- US-Multi-Strategy 80in50 is, in essence, a combination of these two 50in50 scenarios, describing a future in which the technology breakthroughs of both are realized, thus leading to an 80-percent reduction in GHG emissions. Extensive biofuels usage and significant penetration of fuel cell vehicles (FCVs) and electric vehicles—plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs)—essentially result in the elimination of petroleum consumption.

A similar approach was taken to develop three scenarios representing different potential futures for California. However, underrepresentation of the aviation and marine sectors in in-state emissions allows the state to achieve greater emission reductions than in the corresponding U.S. domestic case for the same level of effort. Consequently, all three California scenarios achieve an 80-percent reduction in in-state transportation GHG emissions from 1990 levels. These are the CA-Efficient Biofuels 80in50, CA-Electric-Drive 80in50, and CA-Multi-Strategy 80in50 scenarios.

ASSUMPTIONS: U.S. DEEP-REDUCTION SCENARIOS

Each of our three deep-reduction scenarios for U.S. domestic emissions in 2050 makes different assumptions about transport intensity (T), energy intensity (E), carbon intensity (C), and the share of transport miles powered by each type of fuel/technology.



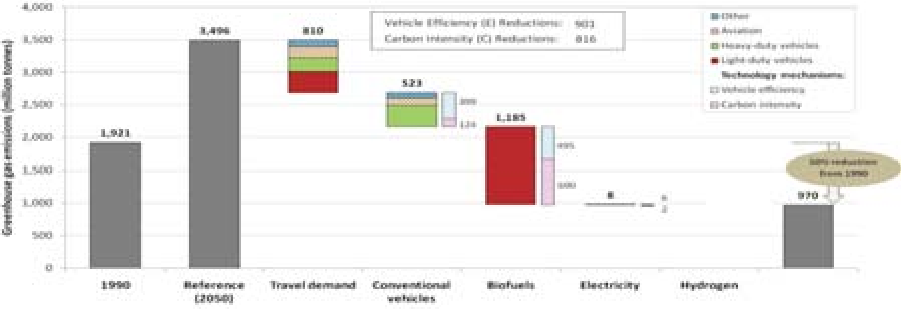
		Share of Miles by Fuel Type				T Normalized Transport Intensity (1990=100%)*	E Normalized Energy Intensity (1990=100%)	C Normalized Carbon Intensity (1990=100%)
		Petroleum	Biofuels	Hydrogen	Electricity			
US-Efficient Biofuels 50in50	LDV	0%	100%	0%	0%	137%	32%	17%
	HDV	80%	20%	0%	0%	149%	52%	82%
	Aviation	100%	0%	0%	0%	234%	36%	100%
	Rail	84%	0%	0%	16%	171%	58%	80%
	Marine/Ag/Off-road	100%	0%	0%	0%	117%	40%	101%
	All subsectors combined	35%	64%	0%	1%	152%	37%	63%
	Fuel Demand (billion GGE)	77.2	88.5	0.0	1.3			
	Carbon intensity (gCO2e/MJ)	90-96	12.3	-	44			
US-Electric-Drive 50in50	LDV	10%	0%	60%	30%	137%	24%	40%
	HDV	72%	0%	22%	6%	149%	60%	100%
	Aviation	20%	75%	5%	0%	234%	37%	32%
	Rail	0%	0%	0%	100%	171%	38%	43%
	Marine/Ag/Off-road	62%	0%	38%	0%	117%	40%	78%
	All subsectors combined	17%	17%	42%	24%	152%	33%	59%
	Fuel Demand (billion GGE)	64.6	21.2	42.2	19.7			
	Carbon intensity (gCO2e/MJ)	90-96	12.3	24	44			
US-Multi-Strategy 80in50	LDV	0%	10%	60%	30%	137%	22%	30%
	HDV	0%	63%	28%	9%	149%	58%	19%
	Aviation	0%	100%	0%	0%	234%	37%	14%
	Rail	0%	0%	0%	100%	171%	38%	43%
	Marine/Ag/Off-road	2%	79%	20%	0%	117%	40%	29%
	All subsectors combined	0%	36%	40%	24%	152%	32%	24%
	Fuel Demand (billion GGE)	1.9	82.3	39.3	19.1			
	Carbon intensity (gCO2e/MJ)	90-96	12.3	24	44			

* For example a value of 137% corresponds to a +37% change from 1990, and a value of 34% corresponds to a -66% change

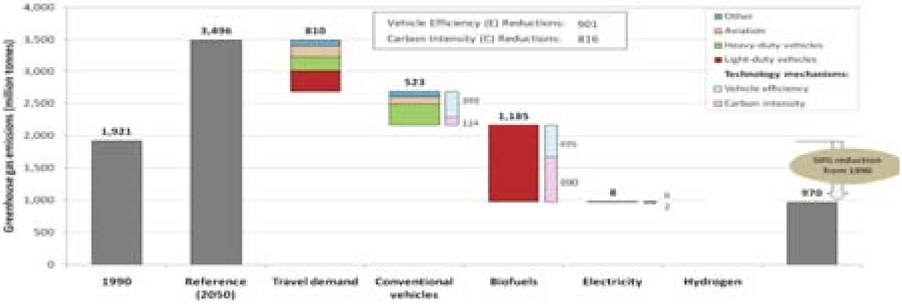
When we tease out the effects of different mitigation options in the U.S. case, we see that slowing the rapid growth in travel demand makes a major contribution to emission reductions in all three scenarios. US-Multi-Strategy 80in50 is more successful at making deeper emission reductions because it combines the strategies of the two 50in50 scenarios, which are somewhat complementary, and helps to address their key limitations.

U.S. DOMESTIC GHG EMISSIONS: DEEP-REDUCTION SCENARIOS

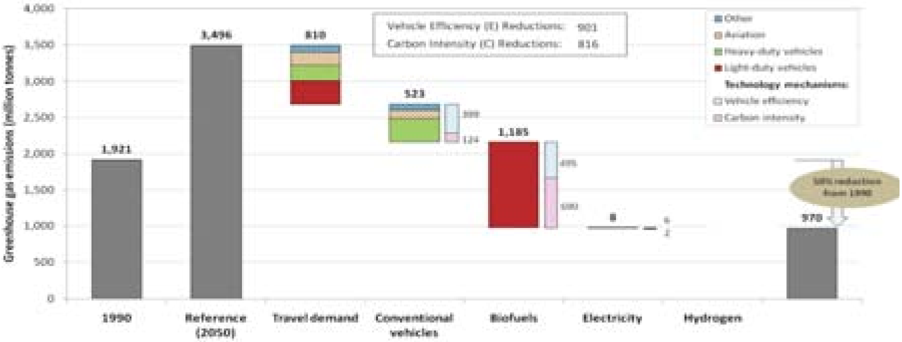
US-Efficient Biofuels 50in50



US-Electric-Drive 50in50



US-Multi-Strategy 80in50



For each of our three US deep-reduction scenarios, we compared actual GHG emissions from domestic transportation in the United States in 1990, emissions projected for 2050 in the reference scenario, and projected reductions for each subsector by 2050 when the various reduction levers—travel demand, vehicle efficiency, and fuel carbon intensity—are used. Slowing the growth of travel demand makes a major contribution to emission reductions in all three scenarios. US-Multi-Strategy 80in50 is more successful at making deeper emission reductions because it combines the strategies of the two 50in50 scenarios (biofuels and electric-drive technologies), which are somewhat complementary, and helps to address their key limitations.

Biofuels are a convenient replacement for liquid fuels that, in theory, can be relatively easily substituted for conventional petroleum fuels in any subsector. However, in US-Efficient Biofuels 50in50, even with relatively optimistic assumptions about the quantity of low-carbon biofuels available, there are limits on biomass resources, which in turn limit how much biofuel substitution can take place. The quantity of low-carbon biofuels is a source of significant uncertainty and one of the most critical parameters in determining the level of GHG reductions possible in the transportation sector. Significant constraints on biofuel availability will require greater contributions from other mitigation options.

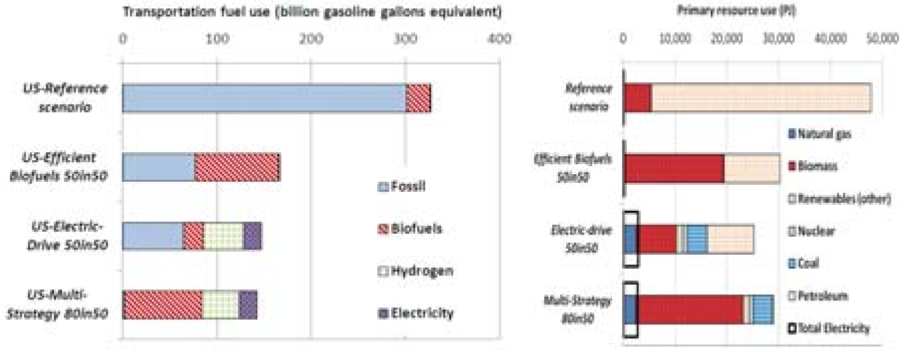
Electric-drive vehicles such as FCVs, PHEVs, and BEVs offer the potential for greatly improved vehicle efficiency and the use of low-carbon energy carriers from a variety of primary resources. In US-Electric-Drive 50in50, GHG reductions are not limited by constraints on primary energy resources but rather by the challenges associated with applying electric-drive vehicles to certain subsectors (such as aviation, shipping, and heavy-duty trucks) because of specific technical considerations, most notably energy storage density, as well as temporal limits associated with the market penetration and social acceptance of these vehicles and building their requisite refueling infrastructure.

It should be noted that because the three scenarios rely heavily on very low-carbon-intensive fuels to achieve the GHG target, they are quite sensitive to assumptions about fuels production. The use of higher-carbon-intensive fuels (for example, hydrogen and electricity produced with coal or natural gas without carbon capture and storage, or biofuels associated with significant land-use change impacts) would eliminate many of the emission reductions gained in these scenarios.

The three deep-reduction scenarios can be compared with respect to fuel consumption and primary resource requirements. Increased vehicle efficiencies in Electric-Drive reduce fuel use more than in Efficient Biofuels. Less-efficient biomass-to-biofuels conversion processes and lower internal combustion engine drive train efficiencies lead to increased primary resource requirements in Efficient Biofuels compared to the more-efficient hydrogen and electricity production processes and higher fuel cell vehicle and battery-electric vehicle drive train efficiencies used in Electric-Drive.

The use of hydrogen and electricity in the Electric-Drive scenario leads to a greater diversity of primary energy resources, including contributions from biomass, natural gas, coal, and petroleum, among other resources. The Energy Information Administration's business-as-usual projections suggest that domestic U.S. energy production in 2030 will be sufficient to meet the primary resource demands of the deep-reduction scenarios.[7] For renewable electricity generation, the scenario resource demands are well below the untapped supply potential using domestic resources[8]. Additional analysis should be performed to determine whether there are sufficient energy resources for all energy-consuming sectors (not just transportation) in a given future demand scenario.

U.S. DOMESTIC TRANSPORT FUEL AND PRIMARY RESOURCE USE IN 2050



We compared U.S. domestic transportation fuel use and primary resource consumption in 2050 for each of the three US deep-reduction scenarios. The Total Electricity bar in the Primary Resource Use chart (on the right) refers to the total amount of electricity used for transportation purposes in the given scenario. Because electricity is not a primary resource, the bar is superimposed on top of the primary resource bar.

The deep-reduction scenarios were designed to meet a goal of 50-to-80-percent reduction in U.S. *domestic* and California *in-state* CO_2 emissions by 2050. Reducing U.S. and California *overall* emissions by this amount requires even greater levels of implementation of advanced vehicle technologies, fuels substitution, and/or travel demand reduction. However, since we assume that the aviation and marine sectors will still be powered by liquid fuels in 2050, limitations in biofuel availability appear to preclude these targets from being reached in the overall case.

Limiting the US-Multi-Strategy 80in50 scenario to the same quantity of biofuels and biomass as in the domestic case (82 billion gge, 1.4 billion BDT) would yield overall emission reductions of 68 percent relative to 1990. Achieving an 80-percent reduction in overall emissions in this scenario by increasing the use of biofuels would require an additional 28 billion gge (+34 percent), for a total of 110 billion gge of low-carbon (that is, 12.3 gCO_2e/MJ) biofuels (or 1.8 billion BDT of biomass, including H_2 production). This highlights the fact that achieving these targets for overall emissions will be even more of a challenge than in the domestic case.

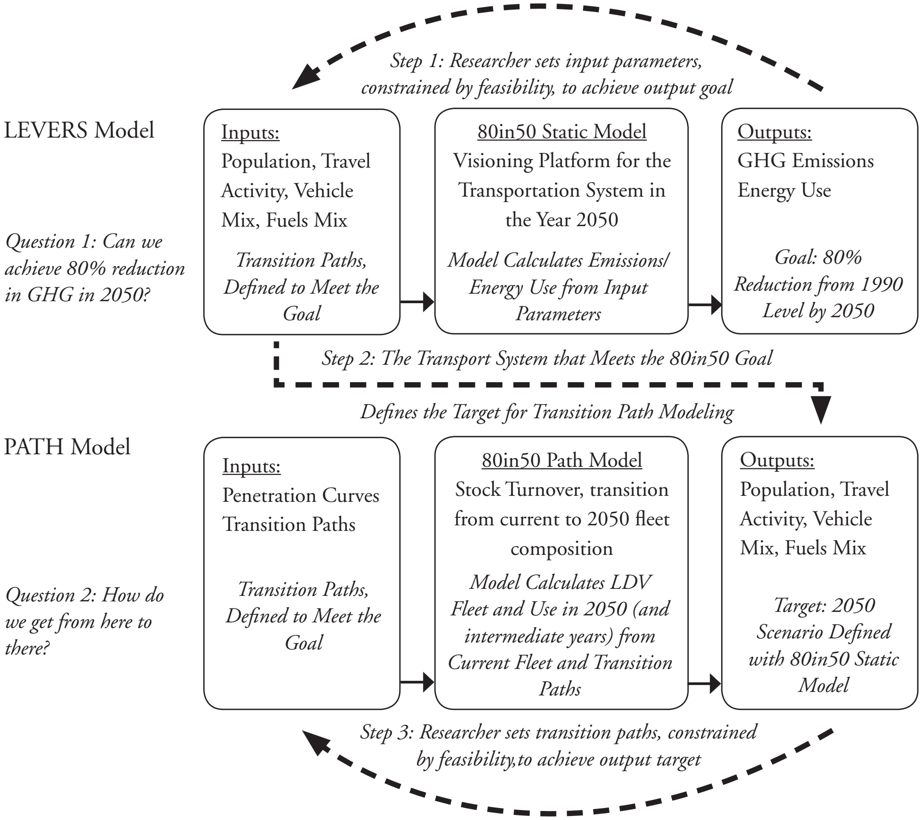
How Do We Get There?

The static snapshot scenarios of 2050 just described provide a stark picture of the transformations required in the transportation sector to reduce GHG emissions 50 to 80 percent below 1990 levels. But what does the path to making these changes by 2050 look like, and does it matter which scenario and transition path is followed for the goal of mitigating climate change? We provide some answers to these questions by using the California light-duty vehicle (LDV) subsector as a case study.

We developed the 80in50 PATH model in order to analyze the transition to advanced technologies in the California LDV subsector. The model is a version of the VISION stock-turnover model[9] adapted to California. We applied the model to study of the three deep-reduction scenarios developed for California using the LEVERS model. As mentioned earlier, in each of these scenarios GHG emissions are reduced by 80 percent.

The heart of the VISION model is a stock-turnover module that tracks annually new vehicles entering the fleet, the use and performance of the vehicles in the fleet, and old vehicles exiting the fleet. Inputs to this model include rates of change in new vehicle technology market penetration, vehicle fuel economy, fuel carbon intensity, car and truck market shares, increasing all-electric range for PHEVs, and biofuel blend in gasoline and diesel. These inputs are defined by the current conditions and characteristics defined for 2050 by each scenario from the LEVERS model, are informed by policy requirements and goals between now and 2050 ("waypoints"), and are informed by transition scenarios presented in the literature.

FROM LEVERS TO PATH



The 80in50 LEVERS model answers the question, Can we achieve an 80-percent reduction in GHG emissions by 2050? The 80in50 PATH model answers the question, How do we get there from here? The inputs required in the LEVERS model to meet emission reduction targets become the desired outputs of the PATH model. Solid arrows indicate the direction of model calculation, and dashed arrows indicate the direction of research inquiry.

We used the 80in50 PATH model to generate transition paths over time for market and fleet share for each vehicle technology, total annual vehicle miles traveled (VMT), vehicle emissions per mile, GHG emissions, fuel carbon intensity, and total energy use. The transition paths spotlighting market shares and annual VMT describe a range of potential answers to the question of how to get from the current transportation system to one in 2050 that meets the 80in50 goal. The transition paths spotlighting GHG emissions reveal that the path taken does matter for cumulative emissions and the potential for continued emission reduction past 2050.

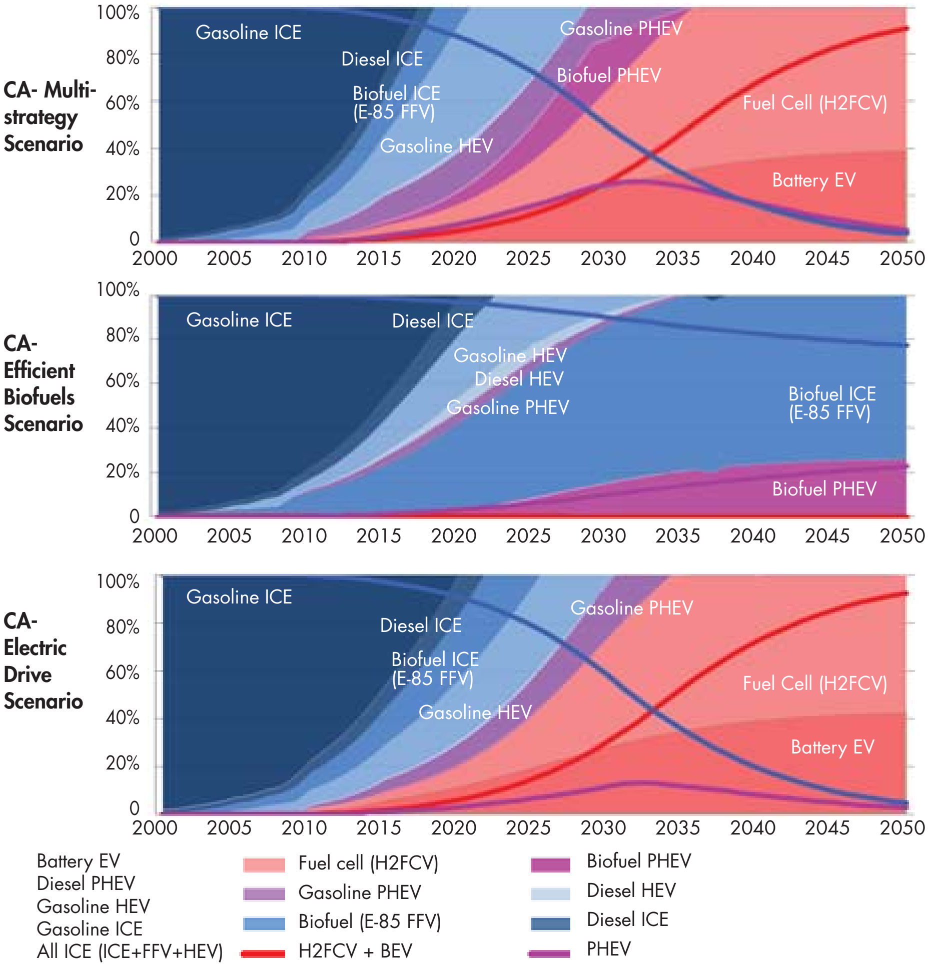
Transition paths: Market and fleet share

To meet our 2050 emission reduction goal and aggressive intermediate waypoints in California, higher-emission vehicles like conventional gasoline ICE vehicles and hybrid electric vehicles (HEVs) must be replaced in the marketplace quickly by lower-emission alternatives like FCVs and BEVs. Of the scenarios we considered, only the CA-Multi-Strategy 80in50 scenario succeeds in reducing light-duty GHG emissions to 1990 levels by 2020 (a policy waypoint). Thus, if binding, intermediate waypoints may begin to constrain the range of acceptable scenarios.[10]

The transitional role of some technologies (such as HEVs and PHEVs) is evident as their market share increases to achieve intermediate waypoints and then decreases. While these vehicles share many components with more advanced electric-drive vehicles (BEVs and FCVs), they do not provide sufficient emission reduction to play a major role in the 2050 transportation system. It is important in any scenario to understand whether the technologies (and resulting infrastructures) used to achieve intermediate emission reduction goals lie along the path to achieving the long-term goals. Further study is needed to determine whether these rapid transitions to multiple technologies, and the investments needed are reasonable.

Although the transitions needed to achieve the 80in50 goal in California are believed to be feasible, they must begin very soon and with rapid rates of market adoption. This takes into account the lag between changes in market share and fleet share due to inertia in the existing fleet of vehicles.

CALIFORNIA LIGHT-DUTY VEHICLES: MARKET AND FLEET SHARE 2000–2050



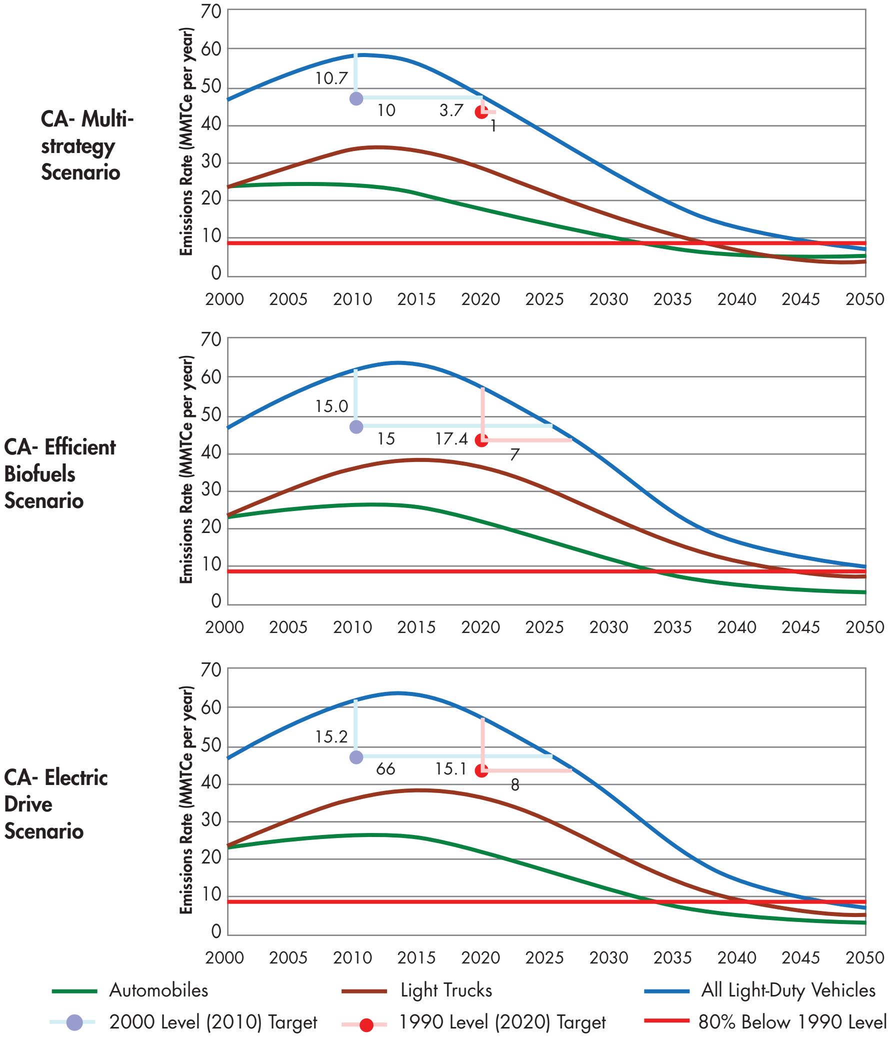
We used the 80in50 PATH model to generate the transition paths for light-duty vehicles (LDVs) in California to reach the market shares (shaded area) and fleet shares (lines) required in each of our three CA deep-reduction scenarios. In all scenarios, higher-emission vehicles like gasoline ICEs and HEVs must be replaced quickly by lower-emission alternatives like FCVs and BEVs.

Transition paths: GHG emissions

Using the 80in50 PATH model, we compared total GHG emissions from LDVs in California along the path to 2050 for each of our three CA deep-reduction scenarios. The annual GHG emission rate from LDVs exceeds the intermediate waypoint for 2010 (that is, emissions at 2000 levels) in all scenarios, and only the CA-Multi-Strategy 80in50 scenario meets the 2020 waypoint.

By 2050, LDVs must reduce their GHG emissions more than 80 percent below 1990 levels in order to compensate for other transportation subsectors (such as aviation) that do not meet the goal.

CALIFORNIA LIGHT-DUTY VEHICLES: GHG EMISSIONS 2000–2050


CA- Multi-strategy Scenario

CA- Efficient Biofuels Scenario

CA- Electric Drive Scenario

We used the 80in50 PATH model to project GHG emissions for LDVs in California along the path to 2050 in each of our three CA deep-reduction scenarios. The shortfall in GHG emissions reduction for the 2010 and 2020 intermediate waypoints is shown in MMTCe in the target year (vertical line) and in the additional number of years required to meet the target (horizontal line). All scenarios fall short of meeting the 2010 target, and only the CA-Multi-Strategy scenario meets the target for 2020.

Transition paths: Total energy used

The total quantity of energy used by LDVs in California during the transition from 2000 to 2050 decreases most dramatically in the CA-Multi-Strategy 80in50 and CA-Electric-Drive 80in50 scenarios. Electricity and hydrogen become the primary forms of energy used by LDVs in these scenarios, while biofuels dominate in the CA-Efficient Biofuels 80in50 scenario. Biofuels play a transitional role for LDVs in the CA-Multi-Strategy 80in50 and CA-Electric-Drive 80in50 scenarios; over time, the limited supply of low-carbon biofuels shifts to other transportation subsectors (especially aviation and marine) in order to meet the 80in50 goal for the whole transportation sector. Overall use of biofuels in the transportation sector increases steadily over time, consistent with rational expansion of production capacity, while the chemical nature of these biofuels may change over time (from predominantly lighter gasoline-like fuels for LDVs to heavier fuels such as diesel-like and jet-like fuels).

The effect on cumulative GHG emissions of acting early vs. late

Does it matter which path we take to get to the 80in50 goal? Our analysis of cumulative GHG emissions from California LDVs between 2010 and 2050 suggests that it does. The largest difference among scenarios is 439 MMTCe, a 30-percent variation. Furthermore, initiating the transition paths early versus delaying action results in a 22-to-27-percent difference in cumulative GHG emissions from LDVs, depending on the scenario. In other words, delaying action to initiate transitions can increase cumulative emissions by 22 to 27 percent compared to acting early. Thus, even though all scenarios still meet the 80-percent GHG reduction target for the transportation sector in the year 2050, both the scenario path and the transition timing within each scenario matter for effective climate change mitigation.

From a different perspective, acting early to initiate transitions may increase the probability of success in mitigating climate change. If success were defined by a target for cumulative emissions for the period 2010 to 2050 rather than an emission rate in the year 2050, acting early could yield success even if emissions in the year 2050 are higher than the 80in50 goal.

COMPARISON OF CUMULATIVE GHG EMISSIONS

Comparing the cumulative GHG emissions from California LDVs in three different transition path scenarios for the period 2010 to 2050 makes clear that the scenarios differ in climate change mitigation, and acting early can decrease cumulative emissions compared to acting late.

	CA-Multi-Strategy		**CA-Efficient Biofuels**		**CA-Electric-Drive**	
Cumulative GHG emissions, 2010–2050 (MMTCe)	**1,250**		**1,518**		**1,503**	
	Act-Early	Act-Late	Act-Early	Act-Late	Act-Early	Act-Late
Cumulative GHG emissions, 2010–2050 (MMTCe)	1,166	1,443	1,375	1,756	1,365	1,777
Change from PATH scenario	-7%	15%	-9%	16%	-9%	18%

Summary and Conclusions

- The major drivers of transportation GHG emissions are population, transport intensity (T), energy intensity (E), and carbon intensity (C); the latter three are the levers that technology and policy can use to reduce these emissions in the future. Low carbon intensity alternative fuels (biofuels, hydrogen, and electricity) appear to be a feasible means of lowering transportation carbon intensity (C), but carbon intensity can vary widely for these fuels based upon the details of their life cycle. There is significant potential for greatly improved vehicle efficiency (reduced E) for use in all of the transportation subsectors.

- Not all vehicle technology and fuel options can be applied to each of the transportation subsectors because of specific requirements for characteristics such as power, weight, or vehicle range. Biofuels appear to be most applicable across all transportation subsectors as a "drop-in" fuel replacement for petroleum-based fuels. However, because they can only be made from biomass, they are likely to be limited by biomass resource availability and may also be limited by land-use change impacts, which may reduce or negate their GHG benefits. Hydrogen and electricity can be made from a wide range of domestic resources, and resource constraints are unlikely to be major impediments to their adoption; however, they may be limited in their applicability to some transportation subsectors (especially aviation, marine, and off-road).

- The scenarios developed in this chapter highlight the level of effort and extent of transformation required to meet an ambitious greenhouse gas emission reduction goal of 50 to 80 percent below 1990 levels by 2050, whether in the United States or California. The scenarios are not meant to show exactly how these reductions should or will be achieved but instead are presented to provide stakeholders with a sense of the enormous challenges ahead. The hope is that these scenarios will provide a useful starting point for stakeholders and policy makers in discussing whether these changes are possible and what steps must be taken in the near term to ensure that we are on a path to meet the long-term goals.

- The silver-bullet scenarios show that while many mitigation options can yield small-to-moderate GHG reductions, no single mitigation option or strategy can meet a 50-to-80-percent reduction goal individually. By contrast, the three deep-reduction scenarios are each able to meet the goal, and each in a different way, requiring very extensive penetration of advanced technologies and large quantities of low-carbon fuels in addition to significant reductions in the growth of per-capita travel demand. Meeting the reduction goals for *overall* emissions is more difficult than meeting the goals for *domestic* and *in-state* emissions because aviation and marine are two of the more challenging subsectors to address from a technology perspective, and demand for these travel modes is growing rapidly, especially in the aviation subsector.

- The transitions in vehicle fleets and energy supply systems necessary to reach the deep-reduction scenarios for 2050 are feasible but must begin soon and progress rapidly, with rates of market penetration and change near feasible limits, because of the lag between market transition and fleet transition. Technologies that play a transitional role (that is, have a relatively short period of high market share) are necessary for meeting intermediate waypoints for GHG emission reduction but may be challenging from an industry perspective, and even then we may not achieve some waypoints.

- Both the scenario and the path taken to 2050 matter for effective climate change mitigation. Based on the 80in50 transition path analysis for California, it appears that although the deep-reduction scenarios are equal in meeting the 80 percent target for the transportation sector in 2050, they differ by as much as 30 percent in cumulative GHG emissions over the period 2010 to 2050. Similarly, initiating transitions early versus delaying action can cause up to a 27-percent difference in cumulative emissions for each scenario.

- From a policy perspective, current vehicle and fuels regulations address only some of the transportation subsectors (mainly light-duty vehicles), and almost none address options for reducing travel demand to a significant extent. These policy gaps may impede the development of options to address transportation GHGs. Furthermore, while this analysis developed and analyzed scenarios that achieve 50-to-80-percent reductions in GHG emissions for the transportation sector as a whole, it is not yet clear what exact role the sector will ultimately play in bringing down total economy-wide emissions from all sources. That said, given the size of the sector and the likely need for even deeper GHG reductions after 2050, transportation is certain to play a major role in the coming decades.

Notes

1. In 2005, California governor Arnold Schwarzenegger signed Executive Order S-3-05, calling for an 80-percent reduction in greenhouse gas (GHG) emissions relative to 1990 levels by 2050 (the “80in50” goal). Later, U.S. president Obama proposed an 80-percent reduction goal for the country as a whole (an 80-percent reduction in annual U.S. GHG emissions below 1990 levels is equivalent to an 83-percent reduction below 2005, since annual GHG emissions in 1990 were 14 percent lower than in 2005), and in fact several climate change bills have been proposed in the U.S. Congress that would set up a domestic cap-and-trade program to help reduce GHG emissions 50 to 80 percent by 2050. See World Resources Institute, “Net Estimates of Emission Reductions Under Pollution Reduction Proposals in the 111th Congress, 2005–2050,” http://www.wri.org/publication/usclimatetargets and http://www.wri.org/chart/net-estimates-emission-reductions-under-pollution-reduction-proposals-111th-congress-2005-2050.
2. California Air Resources Board, “California Greenhouse Gas Emission Inventory,” 2008; U.S. Environmental Protection Agency, Office of Transportation and Air Quality, “Greenhouse Gas Emissions from the U.S. Transportation Sector, 1990–2003,” 2006; International Transport Forum, Organization for Economic Co-operation and Development (OECD), “Greenhouse Gas Reduction Strategies in the Transport Sector: Preliminary Report,” 2008.
3. For an expanded description of the LEVERS model and all input assumptions, see the appendix to D. McCollum and C. Yang, “Achieving Deep Reductions in U.S. Transport Greenhouse Gas Emissions: Scenario Analysis and Policy Implications,” *Energy Policy* 37 (2009): 5580–96.
4. See N. Parker, P. Tittmann, Q. Hart, R. Nelson, K. Skog, A. Schmidt, E. Gray, and B. Jenkins, “Development of a Biorefinery Optimized Biofuel Supply Curve for the Western United States,” *Biomass and Bioenergy* 34 (2010): 1597–607.
5. For an extended discussion of our silver-bullet scenarios and results, including descriptions of the scenarios themselves, see the appendix to McCollum and Yang, “Achieving Deep Reductions in U.S. Transport Greenhouse Gas Emissions.”
6. D. McCollum, G. Gould, and D. Greene, “Greenhouse Gas Emissions from Aviation and Marine Transportation: Mitigation Potential and Policies,” Pew Center on Global Climate Change, December 2009.

7. EIA, *Annual Energy Outlook 2008 with Projections for 2030* (Washington, DC: Energy Information Administration, U.S. Department of Energy), 2008. EIA's projections for domestic energy production in 2030 include: crude oil (12,699 PJ), natural gas (21,099 PJ), coal (30,202 PJ), biomass (8,570 PJ), total electric generation (17,599 PJ), nuclear power (10,093 PJ), and renewable power (1,991 PJ).
8. National Renewable Energy Laboratory (NREL), "PV FAQs—How Much Land Will PV Need to Supply Our Electricity?" (Washington, DC: Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy), 2004, http://www1.eere.energy.gov/solar/pdfs/35097.pdf.
9. Argonne National Laboratory, "VISION 2008 AEO Base Case Expanded," VISION Model, 2009, http://www.transportation.anl.gov/modeling_simulation/VISION/index.html.
10. It is important to remember, however, that the 2020 and 2050 targets for reducing GHG emissions in California are economy-wide goals that are not specific to the transportation sector; many analysts believe the transportation sector will not play an equal role with other sectors, especially in meeting the 2020 goal.