Title

Identifying Options for Deep Reductions in Greenhouse Gas Emissions from California Transportation: Meeting an 80% Reduction Goal in 2050

Authors

Yang, Christopher
McCollum, David L
McCarthy, Ryan
et al.

Publication Date

2008-09-01

September 2008 *UCD-ITS-RR-08-23*

Identifying Options for Deep Reductions in Greenhouse Gas Emissions from California Transportation:

Meeting an 80% Reduction Goal in 2050

Full Report including Policymaker Summary and Appendix

Christopher Yang

David McCollum

Ryan McCarthy

Wayne Leighty

Institute of Transportation Studies • University of California, Davis
One Shields Avenue • Davis, California 95616
Phone: (530)752-6548 • Fax: (530)752-6572
Web: http://its.ucdavis.edu/

UCDAVIS
SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS
An Institute of Transportation Studies Program

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

The authors would like to thank the sponsors of the Sustainable Transportation Energy Pathways (STEPS) Program for financial support of this work. They also thank Anthony Eggert, Nicolas Lutsey, Joan Ogden, Daniel Sperling, and Joshua Cunningham for their valuable input, comments, and reviews of this report, and they acknowledge the participants of the 2007 Asilomar Conference on climate change and transportation, whose shared wisdom and dialogue spawned this research effort. The views and opinions expressed in this report are those of the authors alone and do not necessarily represent those of any sponsoring organization or outside reviewer.

PS. SUMMARY FOR POLICYMAKERS

PS-1. Introduction

Climate change in California could have a large impact on the state's economy, natural and managed ecosystems, and human health and mortality. In an effort to mitigate such consequences, Governor Schwarzenegger signed Executive Order S-3-05 in 2005, and the state passed landmark legislation, the Global Warming Solutions Act (AB32), in 2006. The Executive Order calls for an 80% reduction in greenhouse gas (GHG) emissions relative to 1990 levels by 2050. The 80% reduction goal is not based on known mitigation options, but rather on emissions rates that are thought to be needed to stabilize atmospheric concentrations of GHGs before catastrophic climate changes occur. As a result, strategies for meeting this ambitious target have not been clearly defined, and the technology and policy options are not well understood. This report explores how the 80% reduction goal (*80in50*) may be met in the transportation sector, the largest contributor to GHG emissions in California.

PS-1.1 Goals and scope of project

This report has two primary objectives. The first goal is to explore the options for reducing emissions across all transportation subsectors, including options for reducing travel demand, improving efficiency, and using advanced vehicle technologies with alternative fuels. This information is compiled to summarize the potential for GHG reductions in each of the transportation subsectors—personal light-duty vehicles (LDV), heavy-duty vehicles (HDV) (buses and trucks), rail, aviation, marine, agriculture, and off-road—as well as potential reductions across subsectors from particular alternative fuels or advanced technologies. The second goal is to combine mitigation options to develop scenarios in which transportation GHG emissions in California are reduced by 80% below their 1990 level in 2050. These represent "snapshots" of such a future and do not describe the timing of technology adoption or policy implementation that may be needed to enable them. They illustrate how an *80in50* future looks using transparent assumptions, providing a baseline from which decision-makers and stakeholders may extrapolate necessary trajectories for implementing technologies and policy.

In an attempt to keep the scenario analysis simple and transparent, this report does not consider the important and complex issues of economics (e.g. costs and benefits) and dynamics (e.g. interactions, timing and transition issues) associated with specific mitigation options. These issues may be explored in future research. In addition, the co-benefits of greenhouse gas reduction measures—in terms of air pollution, road congestion, reduction in petroleum usage and others—are not analyzed.

PS-1.2 Scenario GHG reduction analysis framework

This report uses a transportation-variant of the Kaya identity to analyze changes in GHG emissions from 1990 levels. This analytical framework is embedded into a spreadsheet model called the Long-term Evaluation of Vehicle Emission Reduction Strategies (LEVERS) model, which organizes the Kaya parameters for technologies and fuels into scenarios; transportation emissions are then calculated. The main drivers for transportation GHG emissions are population, travel demand, vehicle fuel consumption, and fuel carbon intensity.

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

$$CO_{2,Transport} \equiv \quad P \quad \times \quad T \quad \times \quad E \quad \times \quad C \tag{2}$$

Total transportation activity is represented as the product of population (P) and transport intensity (T), which is defined here as passenger- or freight-miles per capita (e.g., miles/person). The product of the latter two parameters, energy intensity (E) and carbon intensity (C), defines the amount of carbon emitted per-mile of transport. Altogether, the four parameters describe total GHG emissions from a transportation sector.

PS-1.3 GHG mitigation options from the transportation sector

California is unique in that the transportation sector is the state's largest contributor of GHG emissions, comprising over 40% of total state emissions. In 1990, *Instate* transportation emissions totaled 195 MMTCO_2e, and *Overall* (including trips that cross state boundaries) emissions were 246 MMTCO_2e. (MMT = million metric tonnes; CO_2e includes CO_2, CH_4, and N_2O weighted by their respective global warming potentials) Each transportation subsector serves different market segments (including personal mobility, work vehicles, and goods and freight movement) on different transportation networks (highways, railways, waterways/sea, and air). As a result, each subsector has a unique set of service, operation, energy, and financial requirements to meet in order to fulfill the needs of its users.

The Kaya equation illustrates that GHG emissions can be decomposed into several parts. In this report, energy intensity, fuel carbon intensity, and transport activity are considered the primary "levers" for reducing emissions (population is taken as given). Improving vehicle efficiency, or reducing energy intensity (E), may be accomplished by improving the efficiency of the drivetrain or reducing dissipative forces on the vehicle (by improving aerodynamics, reducing vehicle size or weight, or lowering rolling resistance). Fuel carbon intensity (C) may be reduced by switching to, or blending in, lower carbon alternative fuels (including biofuels, hydrogen or electricity). In order to accurately assess GHG reductions of these fuels, emissions must be estimated on a lifecycle basis. Finally, travel demand reductions can reduce transport intensity (T) in many of the subsectors, and may be brought about by integrated land-use planning, high- density development, and improved public transit.

PS-2. Scenario descriptions and results

This study uses scenarios to illustrate different potential snapshots of the transportation sector in 2050 and to estimate the extent to which different GHG mitigation options can help California meet its 80% reduction target. These clear and transparent scenarios may inform the policy debate regarding policies, technologies, and other options that will be needed to realize deep cuts in GHG emissions. Policy-makers may assess the feasibility, costs, and benefits associated with various scenarios and mitigation strategies to guide future decision-making.

Three sets of scenarios are presented and discussed below: (1) *Reference* scenario describes a business-as-usual future in 2050, (2) *Silver Bullet* scenarios summarize the extent to which single mitigation strategies may reduce emissions in isolation, and (3) *80in50* scenarios combine mitigation options to achieve 80% reductions in California transportation GHG emissions by 2050. These scenarios should not be taken as predictions or forecasts of the future, but reasonable judgments have been made—including input from external experts—in order to create plausible snapshots for the future.

PS-2.1 Reference scenario

The *Reference* scenario describes a future where very little is done to address climate change, and transportation activity and technology development follow historical trends. The only expected improvement in this scenario is a modest reduction (35%) in energy intensity, which corresponds to a 50% improvement in average vehicle fuel economy. However, since population is expected to double, and transport intensity is expected to increase moderately (23%) by 2050, total travel demand in the *Instate* case is nearly 2.5 times the 1990 value and nearly four times the 1990 value in the *Overall* case. The average carbon intensity of transportation fuels is 1% higher than in 1990, as petroleum-based fuels are assumed to remain dominant but unconventional oil sources are utilized to a greater extent.

The *Reference* scenario leads to a 62% increase in GHG emissions from 1990 to 2050. *Instate* emissions reach 317 $MMTCO_2e$ in 2050 while in the *Overall* emissions case they reach 421.5 $MMTCO_2e$. Aviation is responsible for the greatest increase in emissions from 1990 because, in spite of slightly more efficient airplanes, demand for air travel is expected to grow rapidly in the coming decades. Freight transport—carried in aircraft, heavy trucks, rail, and large marine vessels—is another area that is expected to continue growing rapidly, contributing to the growth in California's transportation emissions.

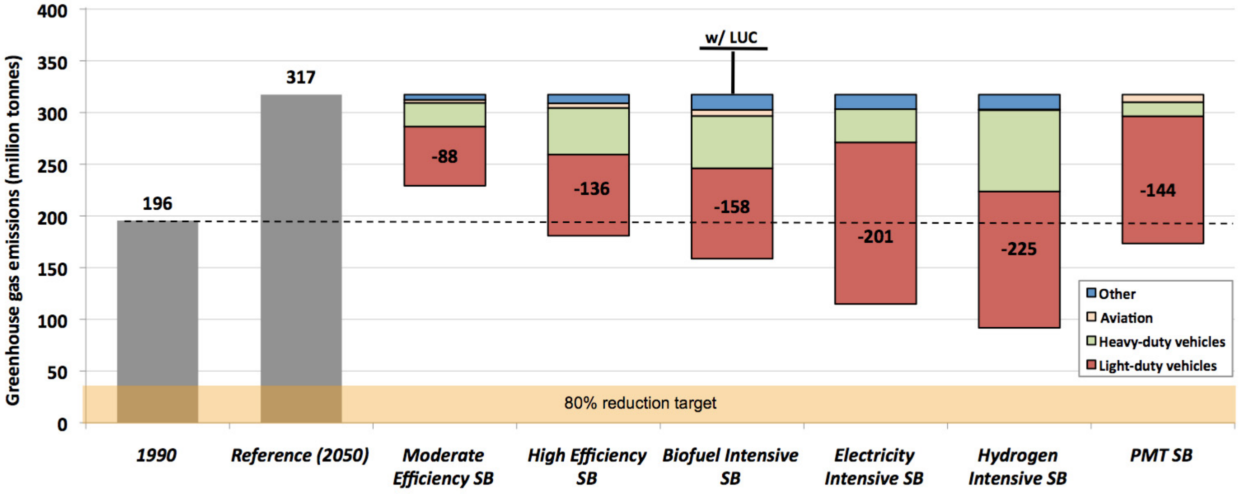
PS-2.2 "Silver Bullet" scenarios

Silver Bullet (SB) scenarios describe futures in which one mitigation option, such as an advanced vehicle technology or alternative fuel, is employed to the maximum extent possible from a technology perspective in 2050. Emissions are calculated to understand the GHG reduction potential of a particular mitigation option. The *Silver Bullet* scenarios modify individual elements of the *Reference* scenario, and are described in the table below.

Figure PS-1 shows each of the *Silver Bullet* scenarios and the reduction in GHG emissions relative to the 1990 level and the 2050 *Reference* scenario. None of the *Silver Bullet* scenarios achieve the *80in50* reduction goal, implying that no single technology can successfully meet California's 80% emission reductions goal; a portfolio approach is necessary.

Table PS-1 Description of *Silver Bullet* scenarios

Scenario Name	***Scenario Summary***
Reference scenario	Doubling of population, modest increase (23%) in transport intensity, slight efficiency improvement (35%) and similar carbon intensity relative to 1990
Moderate efficiency SB	Uses moderate advances in conventional technologies to achieve doubling of vehicle efficiency from 1990
High efficiency SB	Breakthroughs in conventional technologies to achieve nearly triple (270%) vehicle efficiency from 1990
Hydrogen-intensive SB	Applies FCV and low-carbon hydrogen fuels aggressively across most subsectors, except aviation
Electricity-intensive SB	Electric vehicles (BEVs and PHEVs) and very low-carbon electricity are applied across many subsectors except marine and aviation
Biofuel-intensive SB	Low-carbon biofuels are the primary fuels in conventional vehicles (low efficiency) in all transport subsectors
PMT SB	Reductions in travel demand for LDVs and aviation, low vehicle efficiency, no alternative fuels



* In *Biofuel Intensive SB* scenario, ~60% of transportation fuel supply comes from biofuels. This level is consistent with California consuming 15-20% of total US supply.

* Significant uncertainties surrounding indirect land use change impacts from biofuels production lead to the large variability in potential GHG changes from 1990 levels.

Figure PS-1 Greenhouse gas emission reductions for Silver Bullet scenarios relative to Reference scenario for Instate emissions.

In the efficiency scenarios, gains from the *E* parameter are largely negated by significant increases in travel demand that are expected over the next several decades. The *Biofuel-intensive SB* scenario achieves a small reduction in emissions, even though low-carbon biofuels are applied quite substantially across all transportation subsectors at a 60% fuel share. This scenario requires a large quantity of biofuels (16.4 billion gge), which would consume about 15-20% of total potential U.S. biofuel production under optimistic estimates. Moreover, significant uncertainty exists regarding lifecycle GHG emissions from biofuels. If the additional emissions associated with land-use change (LUC) are included, the benefits of biofuels could disappear, and emissions could increase. The *Hydrogen-intensive SB* and *Electricity-intensive SB* do not achieve the 80% reduction goal mainly because it is challenging to apply electricity and hydrogen technologies across all subsectors, especially in aviation and marine transport. Finally, reducing per-capita travel demand may reduce future emissions significantly, but the *PMT SB* scenario only achieves an 8% reduction from 1990 emissions. This is due to the projected doubling of state population by 2050, which more than negates reductions in per-capita travel demand. In this scenario, energy intensity improvements from the *Reference* scenario lead to the reduction in emissions relative to 1990 levels.

PS-2.3 80in50 *scenarios*

It is clear that none of the individual mitigation strategies examined in the *Silver Bullet* scenarios can achieve the ambitious *80in50* goal by themselves. However, several of the options examined in these scenarios are complementary (such as improving efficiency, utilizing alternative fuels and reducing travel demand) and can be combined in a portfolio approach to achieve California's GHG emission reductions target.

Three scenarios are presented that represent different potential futures for California in which the *80in50* reduction goal in *Instate* GHG emissions is realized. The scenarios are snapshots of the transportation sector in 2050 and illustrate different mixes of mitigation options in various subsectors that can achieve the necessary reductions. The first two scenarios focus primarily on technology—one relying on moderately high vehicle efficiencies using low-carbon biofuels and the other on electric-drive vehicles using electricity and hydrogen. The third scenario considers actor-based decisions to reduce travel demand and energy intensity. Population is the same in each scenario, equal to twice its value in 1990.

Table PS-2 Description of *80in50* scenarios

Scenario Name	***Scenario Summary***
Efficient Biofuels 80in50	**Advanced technologies are developed for biofuel production.** *Reference* travel demand. Low-carbon biofuels are the primary fuel in efficient vehicles (2x vehicle efficiency) across all subsectors. Petroleum accounts for only 3% of fuel used.
Electric-drive 80in50	**Advanced technologies for electric drive vehicles and very low-carbon electricity and hydrogen are developed.** *Reference* travel demand. Higher efficiency (3x) electric drive vehicles (EVs, PHEVs and FCVs) used in most subsectors, except marine aviation and off-road where biofuels are used. Petroleum accounts for only 10% of fuel used.
Actor-based 80in50	**High prices and actor-based decisions reduce travel demand and lead to smaller, high efficiency vehicles.** Reduced travel demand, very high efficiency vehicles, increased carpooling and use of transit. Fuels are not as decarbonized as in other scenarios. Biofuels used in aviation and marine. Petroleum still accounts for 35% of fuel used.

Figure PS-2 compares the distribution of emissions and emission reductions for the three scenarios. The *Actor-based 80in50* scenario provides the most diverse solution, drawing on a number of strategies to reduce emissions, including both travel demand reductions and technology improvements across a suite of vehicle types and fuels.

The technology-driven scenarios present futures with similar underpinnings, but emphases on different fuels and technologies lead to distinct scenarios for vehicle energy intensities and fuel carbon intensities. *Electric-drive 80in50* yields a more energy-efficient system on whole, as a higher fraction of fuel cell vehicles (FCV) and battery electric vehicles (BEV) in the fleet mix reduces aggregate energy intensity, while *Efficient Biofuels 80in50* relies more on reduced carbon-intensity of fuels to meet the *80in50* goals. Travel demand reductions do not contribute to emission reductions in either of the technology-driven scenarios. If demand were to be reduced, then the required reductions in energy consumption and fuel carbon-intensity to meet the 80% target would decrease accordingly.

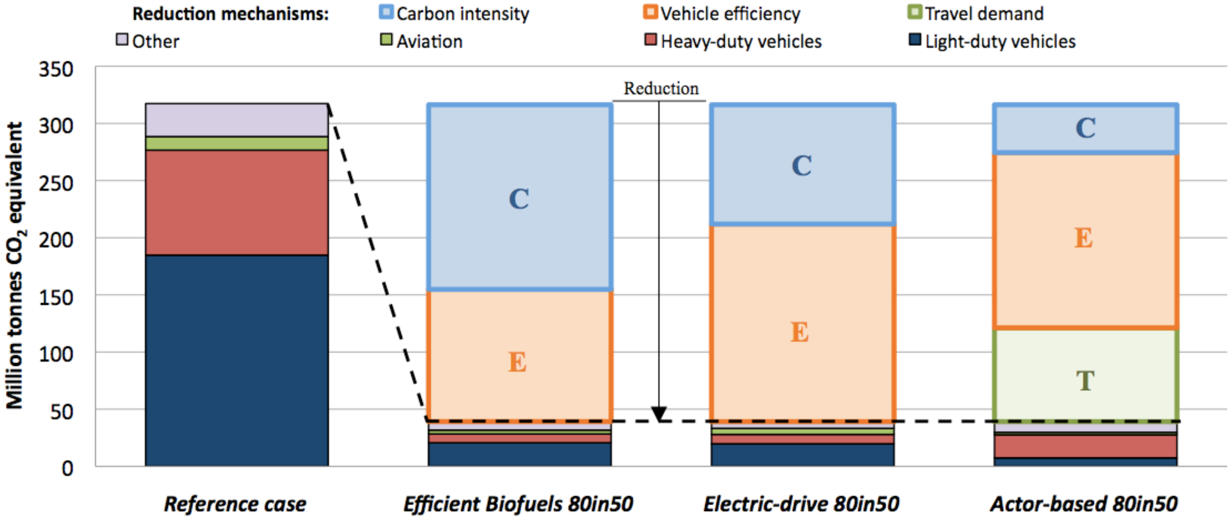


Figure PS-2 Comparison of 80in50 scenarios: Final emissions by vehicle type and emission reductions by strategy.

Figure PS-3 allocates emissions reductions in the *80in50* scenarios by mitigation option. In the *Efficient Biofuels 80in50* scenario, switching from petroleum to biofuels accounts for 231 $MMTCO_2e$ of GHG emission reductions, and switching to electricity reduces emissions an additional 40 $MMTCO_2e$. As seen in the figure, most of the reductions from biofuels (144 $MMTCO_2e$) can be attributed to their lower carbon intensity (relative to conventional fuels in the *Reference* scenario). For electricity, vehicle efficiency improvements (mostly through plug-in hybrid electric vehicle, PHEV, penetration in the light-duty subsector) account for nearly two thirds of the emission reductions (27 $MMTCO_2e$), while the lower carbon-content of electricity as a fuel (14 $MMTCO_2e$) comprises the balance. The broad applicability of biofuels in conventional combustion engines allows dramatic reductions in the GHG-intensity of all modes of transportation in this scenario. This scenario demands a large quantity of low-carbon biofuels, however. (In the *Instate* case, 16.2 billion gge are needed, while the *Overall* emissions case requires 21.1 billion gge.) As in the *Biofuel-intensive SB* scenario, this would consume about 15-20% of total potential U.S. biofuel production under optimistic estimates. Biofuels consumption is roughly the same level as in the *Biofuel-intensive SB* scenario, but because of the lower efficiency of vehicles in the *Silver Bullet* scenario, 16 billion gge can only supply 60% of fuel used in that scenario. Given a constrained supply of biofuels, efficiency is an important strategy for helping to stretch the biomass resource base.

In the *Electric-drive 80in50* scenario, the largest portion of emission reduction comes from the use of FCVs and hydrogen fuel (159 $MMTCO_2e$), although electric vehicles also contribute to emission reductions (105 $MMTCO_2e$) mainly from PHEVs and BEVs in the LDV subsector. Approximately two-thirds of the emission reductions in the scenario can be attributed to improvements in fuel economy associated with electric-drive vehicles (FCVs, EVs, and PHEVs), while most of the remainder can be attributed to the use of low-carbon intensive hydrogen and electricity. Biofuels are responsible for emission reductions in other subsectors where hydrogen and electric vehicles are ill-suited. Consumption of low-carbon biofuels is only about 1.0 billion gge in 2050. (The *Overall* emissions case requires 4.4 billion gge of biofuels.)

The two largest contributors in the *Actor-based 80in50* scenario are reductions in overall travel demand (unlike the two technology-driven scenarios) and the use of electricity in vehicles (mainly via gasoline and diesel PHEVs). Smaller, efficient electric-drive vehicles, primarily in the LDV and HDV subsectors, and the fact that consumers accept reduced vehicle performance in response to very high energy prices both lead to a large improvement in vehicle efficiency. Biofuels consumption in this scenario is just 1.3 billion gge in 2050. (The *Overall* emissions case requires 4.2 billion gge of biofuels.)

It should be noted that because the three scenarios, especially *Electric-drive 80in50* and *Efficient Biofuels 80in50*, 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 (e.g., hydrogen and electricity produced from 'dirtier' methods or biofuels associated with significant land use change impacts) would eliminate many of the emission reductions gained in these scenarios. This is less the case for *Actor-based 80in50*, however, since reductions in travel demand and increases in vehicle efficiencies bear more of the responsibility for lowering emissions.

Clear distinctions between the two technology scenarios appear when comparing fuel consumption and primary resource requirements (Figure PS-4). Increased vehicle efficiency in *Electric-drive 80in50* reduces fuel use more than for *Efficient Biofuels 80in50*. Less-efficient biomass-to-biofuels conversion processes and lower ICE drivetrain efficiencies lead to increased primary resource requirements in *Efficient Biofuels 80in50* compared to the more-efficient hydrogen and electricity production processes and higher FCV and BEV drivetrain efficiencies utilized in *Electric-drive 80in50*. *Efficient Biofuels 80in50* requires 12% more primary energy (mainly biomass) than even in the *Reference* scenario. The use of hydrogen and electricity in the *Electric-drive 80in50* scenario leads to a greater diversity of primary energy resources that includes relatively equal shares of biomass and natural gas, as well as a significant fraction of coal, among other resources. In the *Actor-based 80in50* scenario, fuel use and primary resource use are reduced dramatically below the *Reference* scenario, as well as the other two *80in50* scenarios. By reducing travel demand and significantly increasing vehicle efficiency across all subsectors, a substantial amount of both fuel and primary energy resources are saved. The *Actor-based 80in50* scenario reduces fuel requirements by almost 21 billion gge, or about 73%, compared to the *Reference* scenario, and by 40% and 57%, respectively, compared to *Electric-drive 80in50* and *Efficient Biofuels 80in50*. Similar percent reductions hold for primary resource consumption as well.

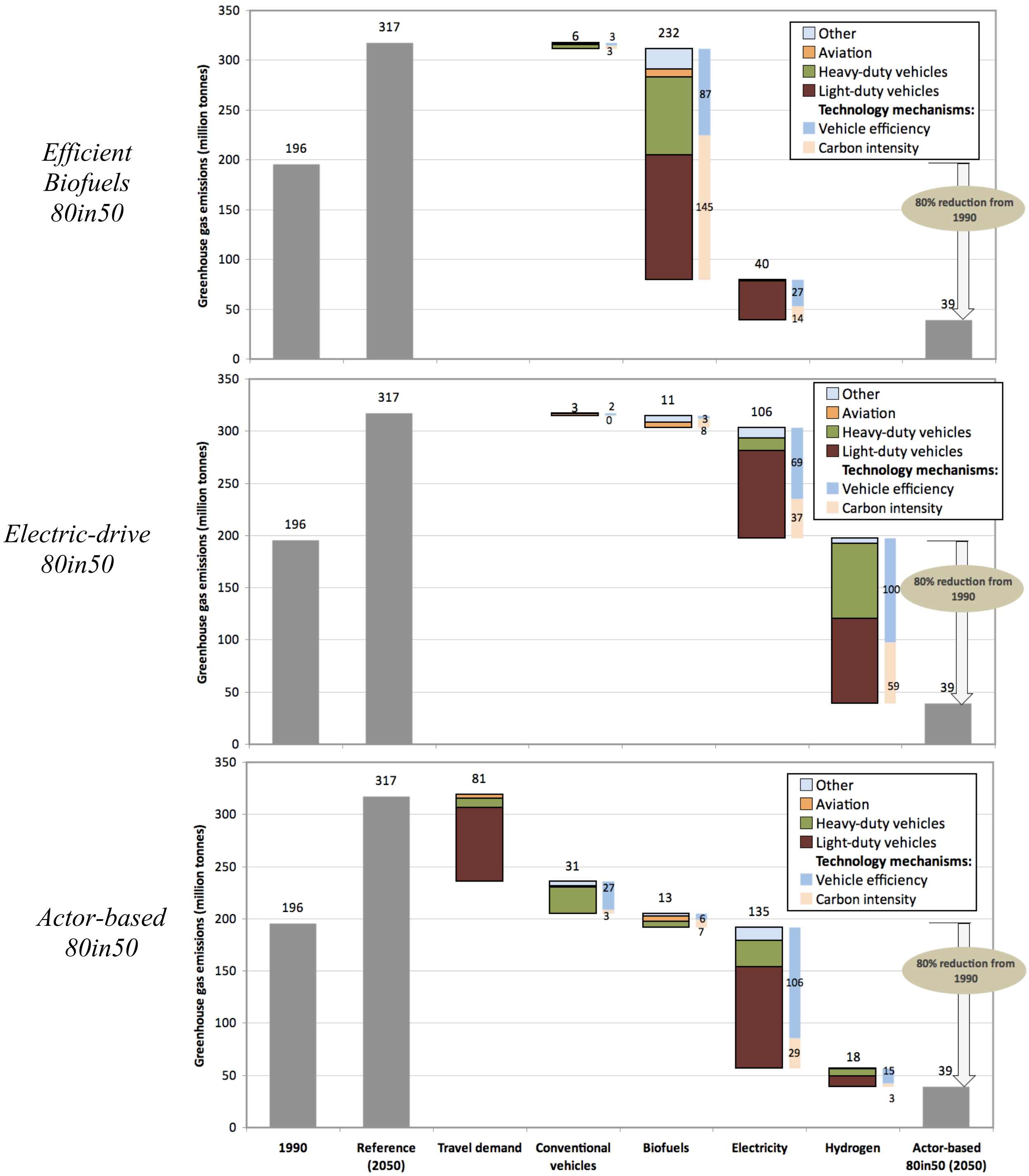


Figure PS-3 Instate GHG reductions by control strategy for three 80in50 scenarios.

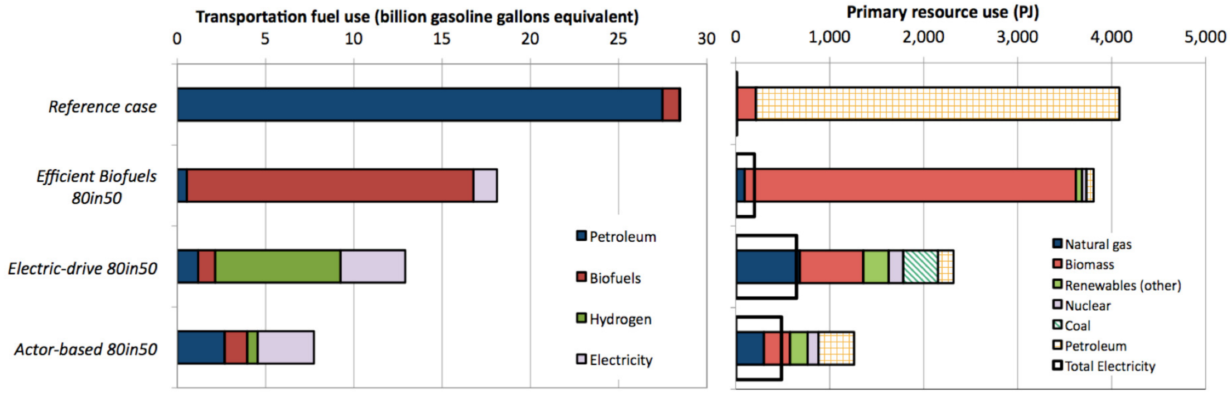


Figure PS-4 Transportation fuel use and primary resource consumption in 2050 by scenario (*Instate* emissions).

PS-2.4 Overall emissions

The *80in50* scenarios described above are designed to reduce *Instate* emissions 80% below 1990 levels by 2050. When *Overall* emissions are analyzed, the *80in50* target is not met. *Overall* emissions include additional aviation and marine travel that crosses the state's boundaries. When these trips are included, emissions are only reduced by 71% in *Efficient Biofuels 80in50*, 66% in *Electric-drive 80in50*, and 73% in *Actor-based 80in50* (compared to 1990 *Overall* emissions). The discrepancy stems from the fact that low-carbon hydrogen and/or electricity see limited application in the aviation and marine subsectors.

If *Overall* emissions are to be reduced by 80% or more, dramatic changes are needed in the aviation and large marine subsectors. The *Actor-based 80in50* scenario addresses the discrepancy better than the other scenarios—by reducing travel demand, increasing efficiency, and utilizing a larger share of available biofuels in the aviation subsector. The two technology scenarios highlight the consequences of increased travel demand in the aviation and large marine subsectors. Advances in other vehicle subsectors are largely erased by activity growth in air travel and domestic and international shipping by sea and air, unless low-carbon biofuels or hydrogen can be utilized in those subsectors on a large scale.

PS-3. Policy considerations

Developing durable and robust policies to reduce GHG emissions from the transportation sector is a pressing challenge. A number of policy gaps have been identified that, if not addressed, may impede the ability of the state to meet its GHG emission reductions target. Policy gaps exist on a sectoral basis, particularly in the aviation, marine and heavy-duty subsectors, and on a "lever" basis, especially in addressing transport intensity (T) as a potential mitigation option. Gaps exist in regulating overall emissions as well, which will likely require a national or international framework to address adequately. Significant challenges inhibit any transportation sector-specific policy, including the long time-scales associated with converting vehicle fleets and fueling infrastructure, and the uncertainties surrounding lifecycle GHG impacts of biofuels.

PS-4. Study conclusions and future research needs

1. *The modified Kaya equation is a useful decomposition that highlights the major drivers of transportation GHG emissions and the targets for mitigation options: population, transport intensity, energy intensity and carbon intensity.*
2. *Very low carbon intensity alternative fuels (biofuels, hydrogen and electricity) appear to be 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.*
3. *There is significant potential for greatly improved vehicle efficiency (reduced E) for use in all of the transportation subsectors.*
4. *The business-as-usual Reference scenario exhibits large growth in GHG emissions (63%) due to growth in population (P) and transport intensity (T).*
5. *The Silver Bullet (SB) scenarios show that while many mitigation options can yield moderate GHG reductions, no single mitigation option or strategy can meet the 80% reduction goal individually.*
6. *Three distinct 80in50 scenarios are presented that meet the 80% reduction goal in different ways, and they show that meeting the goal is a challenging prospect and requires very extensive penetration of advanced technologies and low carbon fuels.*
7. *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.*
8. *Biofuels are probably most applicable across all transportation subsectors. However they can only be made from biomass and are likely to be limited by biomass resource availability and may also be limited by land use change (LUC) impacts, which may reduce or negate their GHG benefits.*
9. *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 by their applicability to all of the transportation subsectors (especially aviation, marine and off-road).*
10. *Slowing the growth in travel demand (i.e., reducing transport intensity, (T) can help reduce the extent to which technological advances will be required to reduce the amount of carbon emitted per mile of travel (ExC).*
11. *It is more challenging to meet the 80% reduction goal with Overall 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.*
12. *Current policies only address some of the transportation subsectors and do not currently address options for reducing travel demand. These gaps may impede the development of options to address transportation GHGs.*

This report investigates how California may reduce transportation GHG emissions 80% below 1990 levels by 2050. It uses a variation of the Kaya framework that decomposes GHG emissions into four major drivers—population, transport intensity, energy intensity and carbon intensity. This framework is applied across each of the transportation subsectors, including LDVs, HDVs, aviation, rail, marine, agriculture, and off-road, to understand the potential for GHG emissions reductions in the transportation sector as a whole.

An *80in50* reduction in GHG emissions from the California transportation sector is challenging but potentially feasible. While the *Silver Bullet* scenarios show that no one mitigation option can singlehandedly meet the target, the *80in50* scenarios illustrate that the goal can be met in multiple ways, utilizing a combination of technological and behavioral options. The *Efficient Biofuels 80in50* and *Electric-drive 80in50* scenarios offer two distinct technology-dependent visions of the future. Both show that if vehicle and fuels technologies are able to "save the day", Californians can essentially preserve their current lifestyles and will be required to make very few changes in terms of their transportation choices. The *Actor-based 80in50* scenario shows how shifts in social and travel behavior (e.g., more carpooling, use of public transit, high-density land-use developments, etc.) can contribute to reduction targets, and how travel demand reductions reduce technology and resource requirements accordingly. A diverse, portfolio approach for mitigating GHG emissions requires continued research and policy support for both technology- and activity-based mitigation options. Activity-based strategies are not well understood and deserve significant attention and study. Behavioral and structural changes, and policies promoting them, are critically important to alleviate dependence on future technology developments and breakthroughs.

Whether or not 80% emissions reductions will ultimately be required in the transportation sector is uncertain. Deep, long-term reductions are not yet law, and it remains to be seen how near-term emission limits (i.e., AB32) are implemented; reductions may not be mandated equally across sectors. But while it may prove to be less expensive to reduce emissions from other sectors (e.g., power generation, industrial, agriculture and forestry, etc.), as the largest current contributor of GHG emissions in the state, transportation must still play a major role if significant emission reductions are to be achieved. Moreover, it is likely that between 1990 and 2050 relative emissions among transportation subsectors will shift, as demand growth and technology adoption will not be uniform across subsectors. Although LDVs were responsible for the largest share of emissions in 1990, if the *T*, *E*, and *C* "levers" can be more easily pulled in that subsector than others, this could change. With significant growth projected in air travel demand and uncertainty surrounding the development of low-carbon fuels, aviation could very well become the largest contributor to GHG emissions in the state.

FULL REPORT

1. Introduction

Climate change is one of the most important environmental issues of the 21st century, and has been linked to human activities that release emissions and increase the concentration of greenhouse gases (GHG) in the atmosphere.

An altered climate could potentially have wide-ranging and highly variable effects [1]. California and its diverse ecosystems are especially vulnerable. Several climate studies show significant impacts for the state, including 1.5-4ºC increases in average temperature; reductions in snowfall, snowpack accumulation and water supplies; and higher extreme temperatures with more heat waves [2, 3]. These major climate changes could have a large impact on the economy, natural and managed ecosystems, and human health and mortality in the state [4]. As a result, in 2005, Governor Schwarzenegger announced an aggressive GHG reductions target (Executive Order S-3-05) that calls for a reduction in GHG emissions to 1990 levels by 2020 and an 80% reduction in emissions relative to 1990 levels by 2050. (In this report the 80% reduction goal is referred to as "*80in50*" since it is to be achieved by the year 2050.) In 2006, the state passed landmark legislation (i.e., AB32) to limit GHG emissions, which adopted the near term (2020) goal. The near-term goals were formulated based upon estimates of policy and technology options to help the state reduce emissions. In contrast, the 80% reduction goal was not based upon known mitigation options but rather on emissions rates that are thought to be needed to stabilize the atmospheric concentrations of GHGs before catastrophic climate change occurs [4]. As a result, the strategies for meeting this ambitious target have not been clearly defined and the technology and policy options are not well understood.

This report explores how the target may be met in the transportation sector, which accounts for over 40% of total GHG emissions in the state.

1.1 Goals and scope of project

This report has two primary objectives. The first is to review the existing literature regarding options for reducing emissions across all transportation subsectors, including options for reducing travel demand, improving efficiency, and using advanced vehicle technologies with alternative fuels. This information is compiled to summarize the potential for GHG reductions in each of the transportation subsectors—personal light-duty vehicles, heavy-duty vehicles (buses and trucks), rail, aviation, marine, agriculture, and off-road vehicles—as well as potential reductions across subsectors from particular alternative fuels or advanced technologies. The second goal is to combine mitigation options to develop scenarios in which transportation GHG emissions in California are reduced by 80% below their 1990 level in 2050. These represent "snapshots" of such a future and do not describe the timing of technology adoption or policy implementation that may be needed to enable them. They illustrate how an *80in50* future looks using transparent assumptions, providing a baseline from which decision-makers and stakeholders may extrapolate necessary trajectories for implementing technologies and policy.

In an attempt to keep the scenario analysis simple and transparent, this report does not consider the important issues of economics (e.g. costs and benefits) and dynamics (e.g. interactions, timing and transition issues) associated with specific mitigation options. These issues may be explored in future research. In addition, the co-benefits of greenhouse gas reduction measures—in terms of air pollution, road congestion, and others—are not analyzed.

Several major research questions are addressed in this study.

- What does California's "*80in50*" emission reductions goal require of the transportation sector? What options could the state employ to meet this ambitious goal of an 80% reduction in transportation GHG emissions below 1990 levels by 2050?
- What are the effects of transportation activity growth and technology improvements on business-as-usual GHG emissions?
- What is the potential for GHG emission reductions and what technology and activity-based options are available in each of the transportation subsectors?
- What is the potential for reductions from specific alternative fuels or advanced technologies?
- What combination of mitigation strategies will allow California to meet its long-term goal and how aggressively must these strategies be utilized?
- How much of each type of fuel (conventional petroleum, biofuels, hydrogen, electricity) and primary energy resources will be required in each subsector?
- Which subsectors and strategies merit greater policy and research focus, considering GHG emission reductions potential and the trade-offs involved?

1.2 Organization of report

This report is organized into distinct sections. Section 2 provides an overview of the transportation sector in California and describes the subsectors, and their contribution to GHG emissions. It gives readers, especially those unfamiliar with transportation in California, some important background context. Section 3 describes the analytical framework used in this study, including the Kaya decomposition and the LEVERS model which was designed to quantify the emission reduction potential of the various GHG mitigation strategies in the transportation sector. These mitigation options and their applicability to each transportation subsector are discussed in Section 4. Section 5 outlines the scenario approach used in this study, while Section 6 describes the scenarios and compares results. Section 7 discusses policy implications, and Section 8 provides conclusions and future research needs.

2. Transportation context

In order to understand opportunities and challenges associated with reducing GHG emissions from transportation, it is helpful to provide some context. The main drivers for GHG emissions from the sector are population, travel demand, vehicle fuel consumption and fuel carbon intensity. These parameters have been steady or increasing over the past few decades, and attempts to slow or reverse their growth have met with little success.

There are a number of major challenges associated with reducing GHG emissions from transportation. Mobile energy systems for vehicles are relatively small (1 kW to 100 MW) and numerous, and have stringent requirements in use. These factors make it difficult to use energy as efficiently as it is used in other parts of the economy, such as in buildings or the electric power and industrial sectors.

2.1 Importance of transportation in California economy

Transportation is a vital part of the U.S. and California economies. Private and public transportation in the form of cars, buses, trains and aircraft provides personal mobility for people to access jobs, shopping and recreational activities. Estimates are that approximately 27% of total light-duty vehicle-miles traveled (VMT) is commuter traffic and nearly 15% is for shopping [5]. In addition, tourism, which relies heavily on transportation, is an important contributor to the state economy. Agriculture is another major component of the economy and relies on both agricultural vehicles to cultivate and harvest crops and large trucks and other transportation modes to move these products to market. Finally, because of the state's location on the western edge of the continental U.S., goods movement (in the form of large marine vessels and then trucks and trains to move goods over land) to and from countries in Asia and Oceania accounts for a growing proportion of the state's transportation needs.

2.2 Transportation contributions to GHGs

California is unique in that the transportation sector is the largest contributor of GHG emissions, accounting for over 40% of the state's total emissions in 2006 (see Figure 1). In most other states and the U.S. as a whole, the electric power sector accounts for the largest share of emissions. California has a long history of regulating vehicle emissions, dating back to 1959 when the state legislature mandated the development of air quality standards and air pollutant controls from motor vehicles. The most recent state regulatory activities, AB 1493 and the low carbon fuel standard (LCFS), focus on reducing transportation GHG emissions, specifically from passenger cars and trucks. AB1493, also known as the "Pavley bill", sets specific targets for overall GHG intensity of driving (i.e., gCO_2e/mile), while the LCFS targets the carbon intensity of vehicle fuels (i.e., gCO_2e/MJ of fuel). Note that both regulations limit GHG intensity—the amount of GHG emitted from a unit of activity—rather than the total amount of emissions.

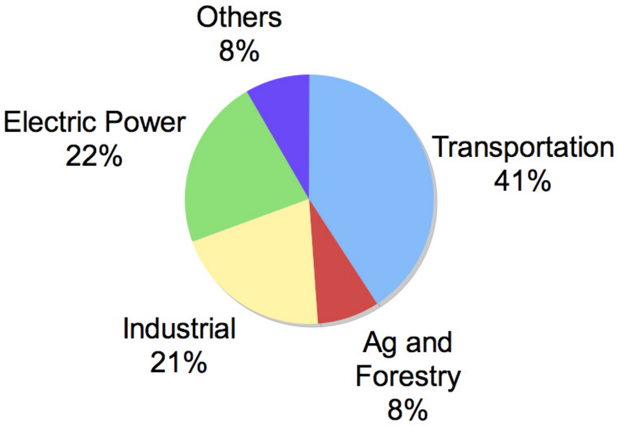


Figure 1 Breakdown of 2006 greenhouse gas emissions in California (CEC 2006)

Also important is that the AB 1493 only addresses emissions from light-duty vehicles (LDV) (i.e., passenger cars and trucks), while the LCFS also includes heavy-duty vehicles (HDVs) such as trucks and buses. LDVs account for approximately two-thirds of California's *Instate* transportation emissions and approximately half of the state's *Overall* transportation emissions (see Figure 2), which also include trips with origins or destinations outside of California. The fraction of emissions from the light-duty subsector is smaller in the *Overall* emissions case because the *Overall* emissions category includes additional emissions from aircraft and marine transportation that cross state boundaries.

Transportation emissions almost exclusively come from the combustion of petroleum products (gasoline, diesel, jet fuel and heavy fuel oil), although a small fraction comes from natural gas and electricity, as well. The overwhelming reliance on petroleum for primary energy and the difficulty in finding an acceptable substitute pose challenges for reducing GHG emissions. While efficiency can play a large role in reducing emissions, the substitution of sustainable, low-carbon and renewable fuels must play a significant role, as well. Finding an acceptable substitute that meets vehicle requirements and can operate in a wide variety of conditions (temperature, altitude) and extreme environments (marine environments and off-road and construction sites) is challenging. Figure 2 shows the breakdown of emissions for the various transportation subsectors for both *Instate* and *Overall* travel.

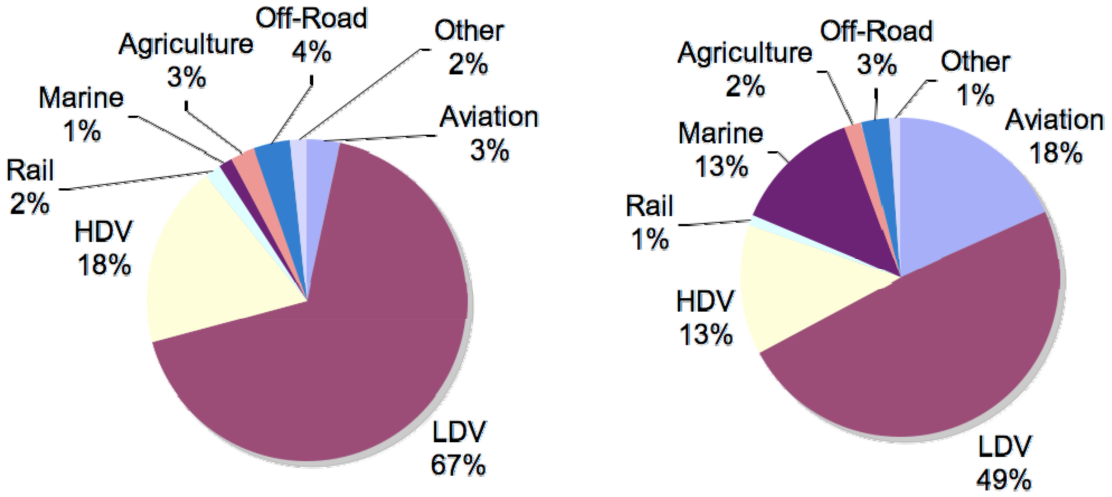


Figure 2 1990 Instate emissions and Overall emissions from transportation sources in California. Overall emissions include additional marine and aviation emissions for trips that travel out of California.

2.3 Regulating emissions (in-state vs. out-of-state)

The sources and location of transportation emissions is an important consideration for California regulators. Some trips do not take place entirely within California, and there is some question as to how to account for the emissions associated with those trips.

The California GHG emissions inventory defines certain emissions in the aviation and marine subsectors as "excluded". These are emissions generated from trips with either an origin or destination outside of California. In this study, two categories of emissions are defined, "*Instate* emissions*"* and "*Overall* emissions". The first category matches the state of California's definition: only non-excluded instate emissions are counted. The second includes all emissions, including those currently "excluded" by the state of California. The difference in these two categories can be significant. For example, in 1990, *Instate* transportation emissions were 195 MMTCO$_2$e and *Overall* emissions were 246 MMTCO$_2$e. The difference is associated with trips whose origins and destinations do not both lie entirely within the state, which primarily happens in the aviation and marine subsectors. Aviation and marine make up 3% and 1%, respectively, of all transportation emissions in the *Instate* emissions case and 18% and 13%, respectively, of all transportation emissions in the *Overall* emissions case.

2.4 Transportation subsectors

The transportation sector is comprised of many subsectors such as light duty vehicles, heavy duty vehicles, marine, rail, aviation, agricultural, and off-road. Each of these subsectors serves different combinations of market segments (including personal mobility, work vehicles and goods and freight movement) on different transportation networks (marine, aircraft, rail and highway). As a result, each transportation subsector has a unique set of service, operation, energy and financial requirements to meet in order to fulfill the needs of its users.

2.4.1 Personal light-duty vehicles

Light-duty vehicles are the passenger cars and light trucks that make up the vast majority of vehicles found on highways. There are over 20 million light-duty cars and trucks in California. Nearly all of them, in California as elsewhere in the U.S., are powered by gasoline internal combustion (reciprocating) engines. Light-duty vehicles make up roughly 67% of total transportation emissions that occur within the state (about 50% of *Overall* emissions). There are a number of alternative technologies for LDVs, but none of these alternatives has achieved a significant penetration into the market. Unlike many other subsectors, where large institutions or agencies own the majority of vehicles and decide how they are operated, LDVs are owned mainly by individuals and households. As a result, the introduction of new fuels and vehicle technologies is constrained by the adoption rates of large numbers of consumers.

2.4.2 Heavy-duty on-road vehicles

Heavy-duty vehicles (HDV) are a class of large vehicles, typically with large diesel engines, that include buses and trucks. Buses are passenger vehicles, typically organized as a public transportation system either as city transit, intercity service or school buses. Trucks (with trailers) are designed to carry goods and freight and can come in a variety of sizes (up to 75 feet long and 100 tons). These vehicles and their engines receive a great deal of wear because they are driven several hundred thousand miles in their lifetime, carrying large and heavy loads. Consequently, durability, efficiency, and fuel costs are important considerations. Heavy trucks and buses have primarily used diesel engines in the past, though air quality concerns have induced some municipalities to switch over a portion of their bus fleets to cleaner alternatives, such as natural gas. Heavy trucks make up over 80% of total HDV mileage and energy usage.

2.4.3 Rail

Rail transport consists of trains that are typically powered by diesel or electric locomotives and carry passengers and freight. The majority of rail energy usage results from the movement of freight, but passenger travel also accounts for a significant portion of rail energy use. Passenger rail is broken into several categories including intercity, commuter, light, and heavy rail. Current passenger rail usage is relatively small, but because passenger rail is one form of public transportation, a significant shift in personal mobility from automobiles to rail could lead to a rapid increase in the usage and energy requirements of rail transport. Freight transport is expected to increase in the future even without mode shifting.

2.4.4 Aviation

The aviation subsector encompasses commercial passenger and freight aircraft and general aviation, which includes air taxis, corporate jets, personal planes, and other aircraft. The energy requirements to overcome drag forces and attain speeds required to generate lift are typically generated by jet turbines or propellers powered by internal combustion engines. Most aircraft use petroleum-based jet fuel (kerosene) or aviation gasoline. The large majority of aircraft-miles and energy use are associated with transporting passengers on commercial flights, while freight and general aviation contribute a small portion of total aircraft energy and emissions. This trend is expected to continue into the future (although freight and general aviation are expected to gain share), but there are projections for significant increases in all types of air travel over the next decades.

2.4.5 Marine

The marine subsector encompasses several categories of vessels including large ships for the movement of freight, commercial fishing, and passengers, as well as smaller harbor craft such as work or tug/tow boats, ferries and personal recreational boats. Large marine vessels are an integral part of the global supply chain for goods and freight movement. Nearly all large ships are powered by diesel engines running on marine diesel oil or heavy residual fuel oil. Large ships account for most of the marine miles and energy usage, compared to harbor craft and personal boats. Smaller boats, particularly personal boats, can run on gasoline as well.

2.4.6 Agriculture and Off-road

This transportation subsector is defined mainly by off-road work vehicles and includes agricultural equipment (e.g., tractors, combines, and balers), off-road equipment (e.g., all-terrain vehicles and snow mobiles) and construction equipment (e.g., cranes, forklifts, and earthmovers). This category encompasses a wide diversity of potential vehicle types, sizes and operating uses and patterns for both heavy and light work. These vehicles primarily use gasoline and diesel fuels; natural gas is used in niche applications.

3. Framework for analyzing GHG reductions

As stated previously, one of the main goals of this project is to quantify the emission reductions potential of the various GHG mitigation strategies in the transportation sector. Decomposing transportation GHG emissions into their fundamental drivers and expressing emissions as a product of these drivers is a convenient way of doing so. A transportation-variant of the Kaya identity is used to analyze changes in GHG emissions from 1990 levels. This framework is embedded into a spreadsheet model called the Long-term Evaluation of Vehicle Emission Reduction Strategies (LEVERS) model, which organizes important parameters into scenarios and calculates GHG emissions.

3.1 Kaya identity

The Kaya identity [6] is a variant of the IPAT equation from Ehrlich and Holdren [7], who were the first to describe environmental impacts in terms of a decomposition of underlying parameters. They defined environmental impact (I) as the product of three factors: population (P), affluence (A) and technology (T). The original Kaya identity specifically looks at CO_2 or GHG emissions as the product of population, GDP per capita, energy intensity, and carbon intensity (see equation 1).

$$CO_2 \equiv (Population)\left(\frac{GDP}{Person}\right)\left(\frac{Energy}{GDP}\right)\left(\frac{Carbon}{Energy}\right) \qquad [1]$$

This equation is an identity because the terms on the right side of the equation are merely a multiplicative decomposition of CO_2 emissions into underlying components. This approach has been used and adapted in a number of scenario studies of emissions (e.g., [8-10]).

The modified identity used in the *80in50* study (see equations 2 and 3) is a transportation variation of the Kaya identity, which, instead of focusing on economic elements such as GDP, focuses on transport activity. Transport is defined here in terms of distance, specifically in units of miles. Beyond the population term, each of the Kaya parameters described here is an intensity (or intensive) parameter (i.e., transport intensity, energy intensity and carbon intensity). They are also designated P, T, E and C and will be referred to by these abbreviations in tables and figures. It is important to note that the terms carbon, CO_2 and greenhouse gases are used interchangeably as calculations are based upon equivalent carbon dioxide emissions (CO_2e) using the global warming potential of non-CO_2 GHGs.

$$CO_{2,Transport} \equiv (Population)\left(\frac{Transport}{Person}\right)\left(\frac{Energy}{Transport}\right)\left(\frac{Carbon}{Energy}\right) \qquad [2]$$

$$CO_{2,Transport} \equiv \quad \mathrm{P} \quad \times \quad \mathrm{T} \quad \times \quad \mathrm{E} \quad \times \quad \mathrm{C} \qquad [3]$$

3.1.1 Societal or activity parameters

The role of the transportation sector is to meet transportation needs by various types of transportation modes. Total transportation activity can be decomposed into population and transport activity per person. Together these two parameters form the societal, or activity, parameters. California's population (P) is expected to increase significantly from the 1990 value of approximately 30 million people to about 60 million people in 2050 [11]. Transport intensity (T) is the amount of transport activity per person. A transport intensity value can be determined by aggregating activity across all transportation modes for the entire transportation sector, and it can also be determined for individual transportation subsectors, such as aviation or passenger cars. Transport intensity can take multiple forms, but for the purposes of this project, it is defined as individual miles per capita. Mitigation options to reduce emissions by addressing the societal parameters focus on reducing the amount of travel demand, as discussed in section 4.3.

3.1.2 Technology parameters

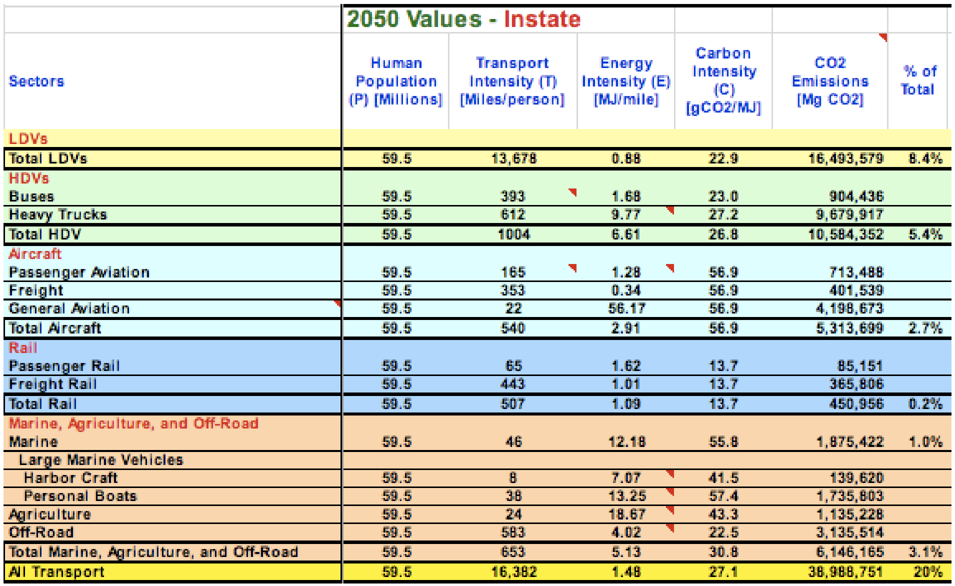
The last two parameters in the Kaya identity are energy intensity (E) and carbon intensity (C), and their product (ExC) defines the amount of carbon emitted per mile of transport. The components of this metric are energy intensity, which describes the energy use per mile of transport, and the carbon intensity, which describes the carbon emissions per unit of energy. This decomposition is useful because it coincides with specific vehicle and fuel characteristics with which people are generally familiar. Energy intensity (energy/distance) is the inverse of vehicle fuel economy (typically described in the U.S. as miles per gallon, mpg) and corresponds to fuel consumption (described in Europe as liters per 100 km). Carbon intensity correlates with the type of fuel and is determined by the feedstock and any processes involved in the production of fuel. Thus, the discussion of mitigation options that involve vehicle efficiency or alternative fuels addresses these two parameters, E and C, specifically. GHG mitigation options that target energy intensity relate to improving vehicle efficiency and also improving occupancy rates, or loads, on vehicles. Methods for improving carbon intensity involve switching to alternative primary energy feedstocks and energy carriers, improving the efficiency of fuel production and delivery, and/or sequestering carbon that would otherwise be released to the atmosphere during the fuel cycle.

3.2 LEVERS model

The Long-term Evaluation of Vehicle Emission Reduction Strategies (LEVERS) model is a spreadsheet model that organizes future transportation scenarios (including assumptions about technologies, fuels, and transport activity) and calculates transportation GHG emissions. The model also compiles the findings of an extensive literature survey that investigated the potential for GHG emission reductions from a number of mitigation options (advanced vehicle technologies, alternative fuels, and transport demand reduction) in each of the transportation subsectors. This information can be used to develop scenarios, which consist of different combinations of these mitigation options, including assumptions about mix of technologies and fuels used, levels of technology development and optimism. For each subsector, the model calculates the four Kaya parameters (P, T, E, and C) from the 1990 baseline and the 2050 scenarios and uses them to estimate and compare emissions, fuel usage, and primary resource usage.

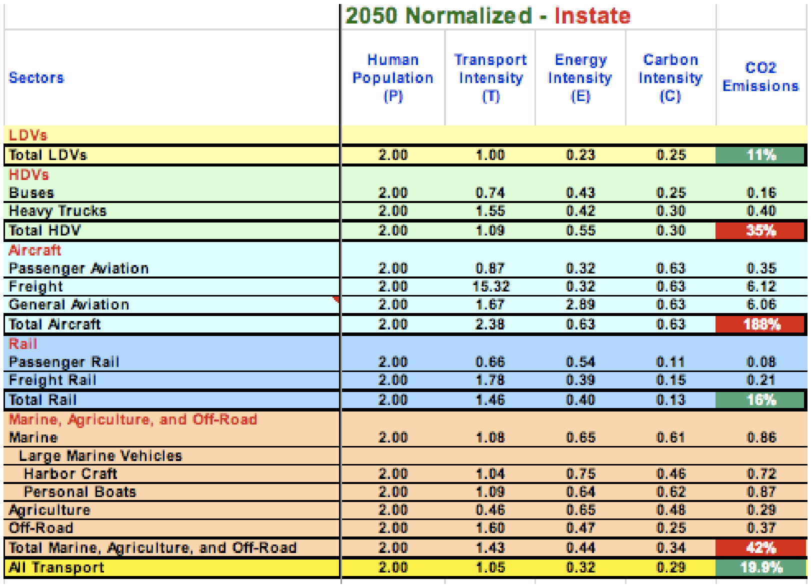
In the LEVERS model, different levels of travel demand can be specified by modifying the underlying population (P) and transport intensity (T) default assumptions from the literature. In addition, the mix of technologies that is used to meet the transport intensity demands for a given subsector is specified. For instance, total passenger-mile demand for buses in 2050 can be broken down by the percent market shares of the different types of bus technologies (e.g., diesel hybrid, biofuel PHEV, fuel cell, electric, etc.) that are available. The model also contains default assumptions from the literature on future efficiencies of different vehicle types by subsector. These assumptions, which are ultimately used to compute values for energy intensity (E), can be modified on a scenario-by-scenario basis. Finally, assumptions regarding the carbon intensity (C) of various fuels can be easily changed by specifying fuel production processes, including characteristics of the mix of production technologies for hydrogen, electricity, biofuels, and conventional petroleum production. Once a set of model assumptions (of which there are hundreds) has been defined for a given future scenario, the LEVERS model then determines the relevant Kaya parameters for each of the various levels of aggregation—from single vehicle types to subsectors to the transportation sector as a whole.

The LEVERS model organizes the relevant input assumptions for a given scenario, as well as 1990 base year data, into a *Kaya Matrix*, which is a table within the model that computes the Kaya parameters at different levels of aggregation—by vehicle type, subsector, and total transportation sector. The *Kaya Matrix* provides two ways of viewing 2050 GHG emissions compared to 1990 levels. The first (Figure 3) puts Kaya parameters and calculated GHGs into a set of consistent units so that one can compare the absolute magnitude and relative distribution of emissions across subsectors. The second (Figure 4) normalizes the parameters by computing a ratio between 2050 and 1990 values (i.e., the 1990 value is equal to 1), which allows one to compare the change in P, T, E, C, and GHG emissions between 1990 and 2050



	2050 Values - Instate					
Sectors	Human Population (P) [Millions]	Transport Intensity (T) [Miles/person]	Energy Intensity (E) [MJ/mile]	Carbon Intensity (C) [gCO2/MJ]	CO2 Emissions [Mg CO2]	% of Total
LDVs						
Total LDVs	59.5	13,678	0.88	22.9	16,493,579	8.4%
HDVs						
Buses	59.5	393	1.68	23.0	904,436	
Heavy Trucks	59.5	612	9.77	27.2	9,679,917	
Total HDV	59.5	1004	6.61	26.8	10,584,352	5.4%
Aircraft						
Passenger Aviation	59.5	165	1.28	56.9	713,488	
Freight	59.5	353	0.34	56.9	401,539	
General Aviation	59.5	22	56.17	56.9	4,198,673	
Total Aircraft	59.5	540	2.91	56.9	5,313,699	2.7%
Rail						
Passenger Rail	59.5	65	1.62	13.7	85,151	
Freight Rail	59.5	443	1.01	13.7	365,806	
Total Rail	59.5	507	1.09	13.7	450,956	0.2%
Marine, Agriculture, and Off-Road						
Marine	59.5	46	12.18	55.8	1,875,422	1.0%
Large Marine Vehicles						
Harbor Craft	59.5	8	7.07	41.5	139,620	
Personal Boats	59.5	38	13.25	57.4	1,735,803	
Agriculture	59.5	24	18.67	43.3	1,135,228	
Off-Road	59.5	583	4.02	22.5	3,135,514	
Total Marine, Agriculture, and Off-Road	59.5	653	5.13	30.8	6,146,165	3.1%
All Transport	59.5	16,382	1.48	27.1	38,988,751	20%

Figure 3 One view of the Kaya Matrix that lists all of the Kaya parameters for each transportation subsector in consistent units.



	2050 Normalized - Instate				
Sectors	Human Population (P)	Transport Intensity (T)	Energy Intensity (E)	Carbon Intensity (C)	CO2 Emissions
LDVs					
Total LDVs	2.00	1.00	0.23	0.25	11%
HDVs					
Buses	2.00	0.74	0.43	0.25	0.16
Heavy Trucks	2.00	1.55	0.42	0.30	0.40
Total HDV	2.00	1.09	0.55	0.30	35%
Aircraft					
Passenger Aviation	2.00	0.87	0.32	0.63	0.35
Freight	2.00	15.32	0.32	0.63	6.12
General Aviation	2.00	1.67	2.89	0.63	6.06
Total Aircraft	2.00	2.38	0.63	0.63	188%
Rail					
Passenger Rail	2.00	0.66	0.54	0.11	0.08
Freight Rail	2.00	1.78	0.39	0.15	0.21
Total Rail	2.00	1.46	0.40	0.13	16%
Marine, Agriculture, and Off-Road					
Marine	2.00	1.08	0.65	0.61	0.86
Large Marine Vehicles					
Harbor Craft	2.00	1.04	0.75	0.46	0.72
Personal Boats	2.00	1.09	0.64	0.62	0.87
Agriculture	2.00	0.46	0.65	0.48	0.29
Off-Road	2.00	1.60	0.47	0.25	0.37
Total Marine, Agriculture, and Off-Road	2.00	1.43	0.44	0.34	42%
All Transport	2.00	1.05	0.32	0.29	19.9%

Figure 4 Another view of the Kaya Matrix that lists all of the Kaya parameters for each transportation subsector relative to 1990 values that are normalized to 1.0.

4. Main options for transportation GHG mitigation

One of the main goals of this study is to provide researchers, policymakers and readers with a better understanding of the options for reducing GHG emissions from the transportation sector and the potential challenges and opportunities for meeting the 80% reduction goal. Several review articles are available that provide an overview of the options and potential for mitigating emissions from the transportation sector [12, 13].

The transport-specific forms of the Kaya equation (2 and 3) shown above illustrate that GHG emissions from transportation can be decomposed into the product of several parts—energy intensity, fuel carbon intensity, and transport activity. These different parts also emphasize the three areas that can be addressed to reduce emissions. The next three sections highlight the mitigation options that were compiled after significant review of the literature to determine the potential for the use of advanced vehicle and fuel technologies in each of the transportation subsectors as well as the potential for structural changes such as land-use patterns and smart growth to impact the growth of travel demand. Note that in this analysis, population is not considered to be an emissions-reducing lever and is projected to double between 1990 and 2050 [11].

4.1 Vehicle efficiency "E"

Increasing vehicle fuel economy is equivalent to decreasing energy intensity ("E" in the Kaya equation), which has the effect of reducing overall GHG emissions, if all else is equal. The two measures (fuel economy and energy intensity) are inversely related to each other as fuel economy is typically calculated in the U.S. as miles per gallon of fuel, and energy intensity is defined in this analysis as energy per mile.

Any land-based vehicle must be supplied energy at the drive wheels in order to overcome dissipative energy losses associated with moving the vehicle. This is shown by the road load equation:

$$E_{road} = d[C_R M_v g + \tfrac{1}{2}\rho_a C_D A_v V^2] \qquad [4]$$

where d is the distance, C_R is the coefficient of rolling resistance; M_v is the mass of the vehicle; g is the acceleration due to gravity; ρ is the air density; C_D is the drag coefficient; A_v is the frontal area of the vehicle; and V is the vehicle speed. As seen in the equation, the rolling resistance component of energy loss (the first term) depends on the road surface and the vehicle's tires and mass. The air resistance component of energy loss (the second term) depends upon the aerodynamic shape and frontal area of the vehicle, air density and the vehicle speed.

However, of the energy that is supplied to the vehicle in the form of fuel, not all of it can be used at the wheels due to inefficiencies of the drivetrain (including the engine, batteries, electric motors, transmission and other mechanical components). As a result, one can rewrite the road load equation into the following fuel/energy requirements equation:

$$E_{fuel} = \frac{E_{road}}{\eta_{drivetrain}} = \frac{d[C_R M_v g + \frac{1}{2}\rho_a C_D A_v V^2]}{\eta_{drivetrain}} \qquad [5]$$

where $\eta_{\text{drivetrain}}$ is the overall efficiency of the drivetrain. As this equation makes clear, the energy required to propel a vehicle can be reduced by either reducing dissipative losses (rolling resistance and drag) and/or increasing the drivetrain efficiency.

When considering the energy required to propel non-land-based vehicles, such as marine and aircraft, the main sources of energy dissipation are hydrodynamic drag (in the case of marine vessels) and aerodynamic drag (for aircraft). However, the importance of reducing dissipative forces and improving engine/drivetrain efficiency remains the same.

A number of different options exist for reducing the energy intensities of different vehicle types. These options are discussed below for each of the transportation subsectors.

4.1.1 Personal light-duty vehicles

The LDV fleet is disaggregated by three major dimensions—fuel type (gasoline, diesel, electricity, hydrogen, and biofuels); energy conversion technology (internal combustion engines, batteries, hybrids and fuel cells); and vehicle type (car, truck).

Technologies for improving efficiency for light-duty gasoline and diesel vehicles center around improvement of the engine and drivetrain efficiency and reducing idling and braking losses. Individual options (with potential improvement in fuel economy relative to conventional gasoline vehicles) include direct injection (5-8%), variable valve timing (5-18%), cylinder deactivation (5-25%), lightweight materials (4-8%), continuously variable and electro-mechanical automatic transmissions (4-8%), idle stop/start systems (4-8%), and hybridization (54-82%) [14]. Diesel (compression-ignition) engines are inherently more efficient than gasoline (spark-ignition) engines mainly because of their higher compression ratio. However, thermodynamic limits for internal combustion engines (without hybridization) are on the order of 30-40% thermal efficiency. Hybridization (utilization of a battery and an electric motor in combination with the combustion engine) can increase overall drivetrain efficiencies above these levels.

The use of alternative drivetrains is one means of getting around these limits and can dramatically improve energy conversion and overall vehicle efficiency. Electric vehicles are often called battery electric vehicles (BEVs) because they store electricity in batteries on-board the vehicle. One reason for the improvement in vehicle fuel economy for BEVs is the significantly higher efficiency of the drivetrain relative to an internal combustion engine vehicle. The efficiency of converting chemical energy in the battery to mechanical energy at the wheels can be as much as 80% (compared with 20% for a conventional internal combustion engine vehicle) [15, 16]. Depending on the means of electric power generation, however, the thermodynamic limits that constrain the conversion of chemical energy in fossil fuels are shifted from the vehicle's engine to the electric power plant. The improved energy conversion efficiency enabled by combined cycle systems at stationary power plants is offset to some degree by line losses and battery charging losses. Another reason for the improved efficiency with BEVs is the optimization for very low road load energy requirements in previous vehicle designs that were necessary to achieve adequate driving range given the poor energy storage of batteries (relative to gasoline).

Fuel cell vehicles (FCV) are another alternative vehicle technology that can improve fuel economy for LDVs. Like BEVs, FCVs are electric drive-vehicles that use electricity to power electric motors which move the vehicle. Unlike BEVs, however, FCVs convert hydrogen stored onboard the vehicle to electricity in a fuel cell. The fuel cell drivetrain is also significantly more efficient than a conventional gasoline vehicle drivetrain; many studies estimate the relative efficiency (and fuel economy) to be about a factor of two or greater [15, 16]. As with BEVs, one must consider the hydrogen pathways (i.e. the energy resource and production, delivery and refueling methods) in assessing overall energy efficiency and GHG emissions for FCVs.

Plug-in hybrid electric vehicles (PHEV) offer many of the benefits of BEVs because they can take advantage of the higher electric drivetrain efficiency, without some of the consumer limitations associated with the shorter driving range of BEVs. PHEVs combine a gasoline or diesel engine with an electric motor and battery system, which can be recharged from an external source of electricity. The actual fuel economy of the vehicle depends very much on how it is driven, the key determinant being the ratio between the amount of electricity to petroleum fuel used. In the current analysis, the fuel economy of a PHEV is estimated as a weighted average of the fuel economies of a hybrid-electric vehicle and a battery-electric vehicle. The weights are the share of miles driven in the HEV and BEV modes; these shares may change in the different scenarios.

While the premise for most analyses is that vehicle performance in 2050 will be equal to performance today, it is also possible to improve vehicle efficiencies further, significantly so, by reducing vehicle performance (size, speed, comfort). Whether or not consumers will accept further reductions in vehicle weight, size and engine power is another matter entirely, however.

The literature does not provide estimates for vehicle performance in 2050; most estimates only go out to 2020 or 2030. Improvements in the efficiency of internal combustion engines, batteries, fuel cell and various drivetrain components are expected to continue into the future based upon the normal progress of commercial technologies. While the historical rate of engine efficiency improvement has been 1-2% per year, historical trends in vehicle fuel economy do not track this relatively steady rate of engine efficiency improvement due to changes in other aspects of vehicle design [17, 18]. If future trends break from the past and if these improvements are instead applied to fuel economy, then increased vehicle efficiency can be an important means of mitigating GHG emissions from the LDV subsector.

4.1.2 Heavy-duty on-road vehicles

Heavy-duty truck fuel efficiency can be improved by the use of advanced drivetrain systems as well as methods for reducing the road load energy requirements of the truck. Advanced drivetrain systems include hybridization of the diesel engines (40% efficient) or the use of fuel cells and electrified drivetrains (60% efficient), which will improve drivetrain efficiency

($\eta_{\text{drivetrain}}$), with greater improvements seen for local truck deliveries rather than long-haul highway driving. Other techniques are used to reduce road load energy requirements (E_{road}) of long-haul trucks, including improving aerodynamic efficiency (4%), reducing tire rolling resistance (1-3%), reducing vehicle weight (2%), reducing idling time (9%), and reducing driver speeds (6-14%) [19, 20].

The strategies and technologies available for improving the energy efficiency of buses are similar to those for LDVs and heavy-duty trucks. The main option for increasing bus efficiencies is advanced propulsion and drivetrain systems, such as diesel hybrids and diesel plug-in electric hybrids (PHEV), all-electric drivetrains, and hydrogen fuel cells.

4.1.3 Rail

As mentioned in the most recent IPCC report, several strategies and technologies exist for improving the efficiency (or reducing the energy intensity) of freight and passenger railroads. Frey and Kuo [21] and the International Union of Railways (IUR) also suggest similar options [22]. In this analysis, only the following are considered: reduced train weight, reduced aerodynamic drag, lubrication of wheels and tracks, better driving advice and traffic managements systems, switching off of traction groups under low loads, and regenerative braking. Application of these technologies and strategies has the effect of lowering the energy intensity of trains by reducing dissipative losses (rolling resistance and drag) and/or increasing drivetrain efficiencies.

IUR estimates the potential energy efficiency gain of reducing train weight for a single vehicle is 2-5%, while applying the technology throughout the fleet could increase efficiency by 1-2% (fleet efficiency gains are less than for individual vehicles because long vehicle lifetimes require decades for the fleet to fully turn over). Reduced aerodynamic drag can improve energy efficiency 5-10% for a single passenger car, as much as 10% for a single freight car and 1-2% for the entire fleet. Because mechanical friction can account for up to 10% of the total energy demand of trains, efficiency can be improved 4-6% for a single rail car by lubricating wheels and tracks; this is especially effective on tracks with a lot of curves. Shutting off some of a train's traction groups during partial loads can increase efficiency 2-5% for a single rail car (1-2% for the entire fleet). Regenerative braking can improve energy efficiency more than 10% for a passenger train but less than 5% for a freight train (1-2% or less for the entire fleet). Optimization of train operations with driving advice and control systems can improve efficiency as much as 5-10% for a single vehicle (2-5% for the entire fleet).

If all the energy-saving technologies and strategies mentioned above were applied throughout the rail fleet, the total energy intensity reduction potential would be on the order of 15%. For trains using more efficient propulsion systems (e.g., all-electric motors, hydrogen fuel cells) compared to diesel-electric motors, the potential efficiency gains could be even greater. In this study, electrically-powered locomotives are assumed to be 80% efficient, after recharging and transmission losses are taken into account. Similarly, hydrogen fuel cell locomotives are assumed to be 60% efficient. Note that state-of-the-art diesel engines can obtain efficiencies approaching 50% at peak [12].

4.1.4 Aircraft

Numerous opportunities exist to reduce the energy intensity of air travel. Aside from technical improvements onboard the aircraft, energy intensity may be reduced by increasing the load factor of aircraft (utilizing available capacity), improving air traffic control or flying at higher altitudes.[1] The domestic commercial aircraft energy intensity (Btu/passenger-mile) improved 37% from 1990 to 2006 [24] in large part due to a 30% increase in aircraft load factors [25]. But system-wide passenger load factors for commercial aviation are practically limited to approximately 80%, which the industry has approached in recent years [25].

Technological and design improvements can increase efficiency further. Improved propulsion systems may increase efficiency by 20%. Aerodynamics offer additional improvements, through new wing designs (up to 10%) or flow control (up to 20% in the long term), and utilizing lightweight materials may add another 20% efficiency gain [26]. Reducing ancillary electricity loads or otherwise light-weighting an aircraft (designs that reduce wiring length and weight, or the amount of water a plane must carry onboard, for example) can improve efficiency as well. All told, a 50% reduction in aircraft energy intensity by 2050 may be reasonable [12]. Entirely new platforms, such as shifting to blended-wing-body designs or liquid hydrogen are far off, but could offer further energy intensity reductions [27].

4.1.5 Marine

Like all other vehicles described previously, one of the main methods for reducing energy intensity of marine vessels is improving propulsion system energy conversion efficiency. Advanced propulsion systems for marine vessels are similar to those for LDVs and HDVs, with improved engine efficiency and increasing electrification of the drivetrain (mainly in the form of hybridization), but also using combined cycle and fuel cell-based power production. These systems can improve primary energy conversion by 25% or more. In addition to energy conversion efficiency, further reductions in fuel consumption can be made by reducing the sources of energy dissipation on marine vessels. Unlike land-based vehicles, the main source of energy dissipation in marine vehicles is hydrodynamic drag, which refers to the combination of wave, eddy and frictional forces and is significantly greater than aerodynamic drag. The major methods for reducing drag forces, especially on large marine vessels, are to improve hull shape and design (up to 20%), reduce propeller drag (up to 10%), and speed reduction and other operational methods (up to 40%) [28].

4.1.6 Agriculture and Off-road

Given the varied terrain in which many of the vehicles in the agriculture and off-road subsectors work and the fact that many are low speed or even stationary, the primary improvements in

---

[1] There are complicated tradeoffs associated with efficiency, emissions, and altitude. While designing planes to fly at lower altitudes decreases efficiency—thus increasing fuel use and CO_2 emissions—reductions in NO_x emissions and contrail formation may more than offset increased CO_2 emissions to provide a net gain from a climate perspective 23. Greener by Design, *Mitigating the Environmental Impact of Aviation: Opportunities and Priorities*. 2005, Royal Aeronautical Society..

vehicle efficiency are expected to be gained from improved engine and drivetrain efficiency and reducing engine idling. Improved gasoline and diesel engine efficiency can be coupled with hybridized systems to reduce fuel consumption, or alternative energy sources can also be used, including fuel cells and batteries. Fuel cells and batteries also provide a means of providing auxiliary loads with electricity, without having to run the large propulsion engine continuously.

4.1.7 Vehicle energy intensities

Table 1 shows representative energy intensity values for the various types of vehicles in each of the transportation subsectors. Higher values indicate vehicle/fuel technologies that are more energy intensive in providing a mile of vehicle, freight or passenger travel. The reader should note the differences in units among some subsectors, which makes them difficult to compare directly. ("---" indicate vehicle types not considered in this study) The values in the table are not input assumptions for the all the scenarios described in this report; rather, they represent feasible future energy intensities that can be met under moderate technological improvement by 2050.

Table 1 Energy intensity of different vehicle categories

	1990	**2050**						
	Reference Tech.	Conv. Gasoline ICE	Conv. Diesel ICE	Diesel HEV	Gasoline PHEV	Diesel PHEV	Hydrogen FCV	Battery EV
Light-Duty Vehicles	3.88	2.04	1.92	---	1.80	1.73	1.40	0.82
Heavy-Duty Vehicles								
Heavy-Duty Trucks	23.05	---	24.58	18.44	---	18.44	12.29	16.39
Buses	3.93	---	2.93	---	---	2.63	2.34	2.09
Rail								
Passenger Rail	2.99	---	---	2.24	---	---	1.79	2.09
Freight Rail	2.61	---	---	2.37	---	---	1.90	1.35

	1990	**2050**
Aircraft	Reference Tech.	Gas Turbine Engine
Passenger Aviation	4.02	1.71
Freight Aviation	1.06	0.45
General Aviation	19.45	74.89

	1990	**2050**
Marine	Ref Tech.	ICE or H2FC
Large Marine Vehicles	---	---
Harbor Craft	9.43	9.42
Personal Boats	20.66	17.66

Agriculture	**1990**	**2050**
	Reference Tech.	ICE or H2FC
	28.68	24.89

Off-Road	**1990**	**2050**
	Ref Tech.	ICE, H2FC, or EV
	8.60	4.47

Units:

MJ/passenger-mile: LDV, HDV Buses, Passenger Rail, Passenger Aviation, General Aviation, Agriculture, Off-road

MJ/vehicle-mile: HDV Trucks, Marine

MJ/person-mile: Freight Aviation, Freight Rail

4.2 Fuel decarbonization “C”

“Fuel decarbonization” refers to lowering the lifecycle or well to wheels carbon content of vehicle fuels by replacing high carbon content fuels with lower carbon fuels. This is equivalent to reducing the carbon intensity of fuels (“C” in the Kaya equation), which has the effect of reducing overall GHG emissions. Since petroleum-based fuels (gasoline, diesel, jet fuel/kerosene, and marine bunker fuels) were principally used in 1990, fuel decarbonization generally refers to fuel switching—i.e., replacing petroleum fuels with biofuels, hydrogen, and/or electricity. It is now important to estimate the carbon content of fuels on a lifecycle GHG basis, which includes feedstock production and transportation, conversion of feedstock to fuel, distribution of fuel, and fuel combustion, because the carbon emissions from some fuels occur in the fuel use stage (onboard the vehicle) while for other fuels they occur during fuel production and distribution. Moreover, there are a number of different feedstocks and production methods for each of the different fuel types, meaning the carbon content of a particular fuel can vary dramatically depending on how it is produced. The GREET-CA model, a modified version of Argonne National Laboratory’s GREET model developed by the consulting firm TIAX with California-specific parameters in mind, is used as the basis for estimating lifecycle GHGs in this study [29]. The following sections describe the life-cycle carbon intensities and GHG reduction potential of different types of alternative fuels.

4.2.1 Petroleum-based fuels

In 1990, petroleum-based fuels (gasoline, diesel, jet fuel/kerosene, and marine bunker fuels) dominated the vehicle fuels market, much as they still do today. (In addition, some buses and off-road vehicles used liquefied natural gas, liquefied petroleum gases, and compressed natural gas, but their total use was quite small.) These fuels were produced by refining of crude oil and their carbon intensity was 90-92 gCO_2e/MJ. In the future, as crude oil supply decreases and unconventional sources are increasingly utilized, the carbon intensity of fossil fuels is expected to rise [30]. This will be due to more carbon-intensive feedstocks and more energy-intensive production methods, including oil/tar sands, gas-to-liquids, coal-to-liquids, and oil shale. This shift could potentially raise the carbon intensity of gasoline, diesel, jet fuel, and marine bunker fuel to over 100 gCO_2e/MJ by 2050, though the actual value will depend on the extent to which these unconventional sources are used.

4.2.2 Biomass derived fuels (Biofuels)

Petroleum-derived liquid transportation fuels (e.g., gasoline, diesel, jet fuel, and marine bunker fuel) can *potentially* be decarbonized by blending in, or entirely replacing them with, biomass-derived fuels such as ethanol, biodiesel, biobutanol, etc. One advantage of biofuels is they are liquids that can be directly used in internal combustion and jet engines with only minor modifications. A number of different feedstocks (corn, sugar cane, soybean, palm oil, switchgrass, algae, agricultural and forest residues, and so on) and production processes (fermentation, trans-esterification, cellulosic hydrolysis/fermentation, gasification, catalytic synthesis) can be used to make biofuels. Depending on the feedstock and process, lifecycle GHG emissions can vary dramatically—anywhere from well below those of petroleum-derived fuels to well above them. By most estimates, ethanol production via corn fermentation results in a slight decrease in GHG emissions compared to gasoline—on the order of 75 gCO_2e/MJ for an average plant in the Midwest (~18% reduction from gasoline and diesel). Ethanol from cellulosic sources could be much lower, however: less than 20 gCO_2e/MJ, a reduction in carbon intensity of 80% or more. Biodiesel from trans-esterification of soybeans or other crops has a carbon intensity of about 25-39 gCO_2e/MJ, and from biomass-to-liquids (BTL) gasification of cellulosic biomass it is around 5 gCO_2e/MJ [29].

Obtaining accurate estimates of lifecycle GHG emissions for biofuels is difficult and even controversial because of the challenge of estimating emissions related to land-use change (LUC). In the past, much of the debate about estimating biofuel lifecycle emissions has focused on assumptions for the different process fuels (coal, natural gas) used, nitrogen and lime application rates, co-product allocation, and several other uncertainties. But more recently, the debate has shifted to the emissions associated with indirect land-use changes (LUC) as a result of increased biofuels production. Although several studies are currently in progress, only a few preliminary estimates of indirect land-use GHGs currently exist. One of these studies, Searchinger et al. [31], estimates the GHG impact of ethanol production from corn and switchgrass that are grown on U.S. corn lands; this conversion of agricultural land to fuel production displaces food production to native ecosystems (typically forests) which must then be converted to agricultural production. If such LUC were to occur, the loss of organic biomass and soil carbon would lead to a large release of greenhouse gases, which would mitigate much of the GHG benefits associated with using biomass for fuels production. Their analysis estimates that the lifecycle GHG emissions for both corn ethanol and cellulosic ethanol would be substantially greater than others have estimated—177 gCO_2e/MJ and 138 gCO_2e/MJ, respectively, a 93% (corn ethanol) and 50% (cellulosic ethanol) increase above the GREET model estimates for biofuel emissions. While these estimates are much higher than previously thought, the authors mention that their values may be underestimates. Others, (e.g., [32]), contend that Searchinger's results are highly preliminary and probably overestimated. This analysis uses the estimates (or some variation of them) of indirect land-use change calculated by Searchinger et al., but it is important to acknowledge that these numerical estimates are preliminary and controversial. That said, since the current debate will probably not be resolved for some time, these values can be reasonably considered as an upper bound of what indirect LUC emissions impacts could possibly be. Future research will help to refine these numbers further.

Another important issue surrounding the use of biofuels is the supply of biomass resources. Biomass resources are constrained because of limited lands designated for agricultural production and limited yield per unit area. Traditionally, since agricultural production is mainly dedicated to food, paper and fiber, the use of agricultural lands for energy purposes may raise the price of these commodities. Several studies [35-37] have estimated the total amount of biomass and biofuels production available in the U.S. and this number varies considerably from tens of billions of gallons (gge) to over one hundred billion gge. Waste biomass, such as agricultural wastes and forestry trimmings, is a low-cost resource for producing biofuels that are not expected to result in LUC, but it is a limited resource. Estimates from Jenkins (2006) show that with the quantity of waste biomass resources available in California about 2.3 billion gallons gasoline equivalent (gge) of biofuels could be produced [33]. (See section 6.2.1 for further discussion of potential biofuels supply.)

4.2.3 Decarbonized energy carriers (H_2 and electricity)

Hydrogen can be used in an internal combustion engine or to produce electricity in a fuel cell to power an electric motor. The hydrogen fuel cell and electric motor are generally more efficient than combustion engines, and hydrogen and electricity energy carriers are themselves completely decarbonized and can potentially have much lower life-cycle carbon intensities than petroleum-based fuels, depending on feedstock and production/delivery methods. In this analysis, feedstocks for hydrogen production considered include natural gas, coal, biomass, and water electrolysis (with varying degrees of carbon intensity for electricity). Similarly, electricity production from natural gas combined cycle, coal IGCC, biomass, nuclear, and renewables (wind, solar, etc.) are all considered. The lowest carbon intensities are associated with electricity and/or hydrogen production from nuclear and renewables. Production via these pathways can potentially reduce lifecycle GHG emissions to essentially zero. Biomass-based electricity and hydrogen production is also quite low in carbon intensity (15-20 gCO_2e/MJ), if land-use change impacts are not considered. Hydrogen and electricity produced from natural gas without carbon capture and storage (CCS) have a carbon intensity greater than petroleum-based fuels (>100 gCO_2e/MJ), though it is important to note that on a per-mile basis (i.e., when combined with the energy intensity term, ExC), carbon emissions for hydrogen and electricity are actually lower due to the higher efficiencies of fuel cells, batteries and electric motors. However, if CCS is utilized for natural gas based production, the carbon intensity of hydrogen and electricity can be quite a bit less than for petroleum fuels. Similarly, utilization of CCS at coal facilities could reduce emissions from 185.1 to 45.7 gCO_2e/MJ for coal-to-hydrogen plants and from 345.3 to 63.4 gCO_2e/MJ for coal power plants. The future of CCS is uncertain, and while no hydrogen or electricity production plants currently utilize CCS, the situation could change by the year 2050 [29].

4.2.4 Fuel decarbonization summary

Table 2 shows the life-cycle carbon intensity of a number of fuels from a range of sources. Though there are several fuels that show very low carbon intensity values, not all fuels can be used in all transportation subsectors. There may be several reasons why fuels may not be used in specific subsectors including the availability of the fuel and the applicability of engines that can use the fuel for the specific requirements of the vehicles in that subsector.

Because of the size and importance of the LDV subsector, it is the subsector that is often targeted to introduce the fuels and appropriate vehicle technologies mentioned above. Building a widespread, convenient consumer fuel supply infrastructure (refueling stations, pipelines, storage terminals, and so on) presents another set of challenges entirely. Municipal and corporate fleets (for LDVs as well as HDVs such as buses and trucks) are also widely targeted for the introduction of alternative fuels and developing the centralized fuel infrastructure for fleets may pose less of a challenge than for consumer LDVs, which are widely dispersed and require an expansive refueling network. There are significant challenges with using certain fuels in some transportation subsectors, however. For instance, heavy-duty trucks and marine vehicles may not be well suited to electricity stored in batteries given the long-distances they are generally required to travel before refueling. It may also be challenging, if not impossible, to use electricity to power airplanes in flight; and the prospects for fueling planes with hydrogen (either by fuel cells or jet engines) is debatable. Yet, while hydrogen and electricity might not see large application in some subsectors, there may be significant niche applications.

Table 2 Carbon intensity comparison of representative future fuels.

Fuel / Pathway	Carbon Intensity				% Change from 1990 Gasoline
	gCO$_2$e/MJ		gCO$_2$e/gge		
	1990	2050	1990	2050	
Gasoline and Diesel					
Conventional Crude Oil	90 to 92	90 to 92	10,877	10,877	0.0%
Unconventional Sources	---	101 to 210	---	12,073 to 25,101	11 to 131%
Biofuels					
Biodiesel (FT/BTL from biomass)	---	4.9	---	582	-94.6%
Biodiesel (Trans-esterification from soy, etc.)	---	25 to 38	---	2,988 to 4,542	-72 to -58%
Ethanol (Brazil Sugar Cane)	---	13.0	---	1,548	-85.8%
Ethanol (Corn)	---	49 to 111	---	5,857 to 13,268	-46 to 22%
Ethanol (Cellulosic biomass)	---	6 to 18	---	717 to 2,152	-93 to -80%
Potential Land-Use Change Impacts of Biofuels (additional increases on top of values shown above)					
	Low	High	Low	High	
Corn-based fuels	0.0	104.0	0	12,431	
Cellulosic Biomass-based fuels	0.0	111.0	0	13,268	
Biodiesel, Methanol, DME, Sugar Cane Ethanol	0.0	100.0	0	11,953	
Hydrogen					
Natural Gas	---	90 to 112	---	10,757 to 13,387	-1 to 23%
Natural Gas w/ CCS	---	15 to 17	---	1,793 to 2,032	-84 to -81%
Coal	---	185.1	---	22,125	103.4%
Coal w/ CCS	---	45.7	---	5,463	-49.8%
Biomass	---	17.3	---	2,068	-81.0%
Electrolysis	---	0 to 138	---	0 to 16,495	-100 to -52%
Electricity					
Natural Gas Combined Cycle	---	134.6	---	16,083	47.9%
Natural Gas Combined Cycle w/ CCS	---	20.2	---	2,412	-77.8%
Coal, IGCC	---	345.3	---	41,274	279.5%
Coal, IGCC w/ CCS	---	63.4	---	7,572	-30.4%
Wind, Solar, Biomass, Nuclear, Other Renewables	---	0 to 15	---	0 to 1,793	-100 to -84%
California average electric grid mix	111.6	---	13,336	---	---
Other Fuels					
Liquefied Natural Gas (LNG)	72.6	75.8	8,679	9,064	-16.7%
Compressed Natural Gas (CNG)	65.7	67.2	7,852	8,037	-26.1%
Liquefied Petroleum Gases (LPG)	77.4	77.1	9,246	9,212	-15.3%
Jet Fuel (Kerosene)	90.0	95.3	10,758	11,394	4.7%
Residual Fuel Oil (Marine Bunker Fuel)	90.0	95.3	10,758	11,394	4.7%

4.3 Travel and service demand reductions "T"

Decreasing transport intensity, the amount of transport activity per person ("T" in the Kaya equation), is the third way to reduce GHG emissions. This can potentially be achieved by several means. Improving the ability of people to access their desired destinations can reduce their need for motorized travel. This might be accomplished, for example, through better land-use planning, higher-density developments, and more collocation of jobs and housing. Another method is mode-switching. Since public transit systems (buses, trains, etc.) have the capacity to carry a large number of people at a given time, the number of vehicle-miles traveled (VMT) may be reduced even if individual people continue to travel the same amount on a passenger-miles traveled basis. These larger vehicles will have lower GHG emissions per passenger mile of travel compared with single-occupancy automobiles if occupancy is adequate. Reducing freight miles is another important means of reducing transportation GHG emissions. Each of these options requires behavioral and structural changes in society and the economy, unlike fuel decarbonization or vehicle efficiency improvements, which rely on technological fixes. The following sections describe options for reducing transport intensity.

4.3.1 Smart growth and compact development

An obvious way to the reduce passenger transport intensity is to reduce demand for passenger travel. Restrictions on vehicle use or high operating costs (due to congestion charging or high fuel prices) could potentially motivate a reduction in transport demand. Absent any change in the built environment, however, this loss in transport could equate to lost accessibility as well. In other words, people's inability to drive their cars could result in reduced access to jobs, housing, education, retail, and recreational opportunities in a world that is still geared towards private car ownership, as has been the case over the past several decades. Land-use planning policies could help to mitigate the negative effects by requiring or encouraging mixed land-use developments that strike a balance between jobs, housing, and other services. This could lessen people's reliance on cars (and perhaps motorized transport in general) while at the same time maintaining, or even improving, access to their desired destinations. Improved pedestrian and bicycling infrastructure (paths, traffic signals, etc.), as well as higher population densities, would probably aid in the success of such communities. With an expected doubling of California's population over the next several decades, it is not unreasonable to think that higher density areas will become more common in and around the state's major urban centers, as long as planning policies make some attempt at containing suburban sprawl. The specific land-use policies that can potentially be used are numerous, and listing them all here is outside the scope of this paper. (For further reading on this topic, see [13, 34] and the list of references therein.)

One study by Ewing et al estimates that smart growth and compact development can reduce per capita automobile VMT by 20-50% relative to business as usual [34]. This level of VMT reduction would require significant structural change in how communities are laid out across the state and significant policy incentives to guide the development process.

4.3.2 Increased vehicle occupancy and mode shifting

Mode-shifting and vehicle pooling is another key strategy for reducing GHG emissions. The demand for travel among individuals could remain the same, but by switching to higher-occupancy vehicles and modes, the amount of motorized vehicle traffic would be reduced. Increasing occupancy factors in vehicles, by ridesharing and carpooling, reduces the number of vehicle-miles required to support a given number of passenger-miles. This outcome could also be achieved by shifting passenger-miles from private cars, which have low vehicle occupancy rates (about 1-2 passengers/vehicle, on average), to high-occupancy public transit modes such as buses or trains, which can potentially accommodate much higher occupancy rates (several dozen passengers/vehicle or more, depending on the vehicle type) and as a result, lower energy use and carbon emissions per passenger mile.[2] Land-use planning is critical to the success of mode-shifting as higher population densities increase the quality (timeliness and convenience) of service. Most of the major urban centers in California already provide some form of bus or rail transit service. The success of these systems varies by city, with lower rates of ridership in lower density areas, and vice-versa. As densities rise in the future, mode-shifting could become more feasible and attractive. Another potential mode-shift could occur in California if people switch from using airplanes to rail, buses, or even cars for long-distance intercity transport. This is particularly relevant to travel between the major population centers in northern California (Sacramento and the Bay Area) and southern California (Los Angeles and San Diego). High-speed rail is cited most often as an alternative to air travel along this corridor, though it is unclear whether or not the rail system will ever be built. Intercity buses and even cars could potentially be more energy efficient and/or less carbon-intensive modes of transport than airplanes, too, depending on the efficiency and fuel types used in these vehicles. Ultimately, a person’s decision to shift modes is based on cost, time, and a number of other factors. It is, therefore, quite difficult to predict the potential for mode-shifting in California in a precise way. Due to these inherent uncertainties, mode shifting is explored in this study in several scenarios.

5. ***80in50*** **scenarios**

5.1 Scenario goals

Scenarios are used to investigate the GHG reduction impacts associated with a set of assumptions about the types of technologies, fuels, and changes in transport activity. The goal is to create scenarios, each with a clear and transparent set of assumptions about the options and technologies needed to reach the 80% emission reductions target. As stated above, each of the Kaya parameters in the model can be modified, and each is independent from each other. The scenarios are collections of assumptions that tell a coherent story about transportation technology and activity choices.

---

[2] On a per *vehicle*-mile basis, cars are less energy intensive than buses or trains because they are smaller and take more direct (less circuitous) routes. On a per passenger-mile basis, there will be some break-even occupancy rate at which public transit becomes less energy intensive than car travel. It is important to note that this break-even point is not an equal number of passengers (i.e., buses and trains must carry a greater number of passengers than cars in order to be less energy intensive on a per passenger-mile basis).

There are important benefits to using scenarios rather than predictive or optimization models to investigate GHG reduction options in the future:

- Simplicity
- Transparency
- Diversity

Scenarios using the Kaya equation are simple because each parameter (P, T, E, and C) is specified independently. The LEVERS model does not optimize or forecast the future, but rather leaves the specification to the user. The scenario approach allows for the development of diverse scenarios to investigate a range of possible futures and explore sensitivities to scenario and individual parameter assumptions. In this study scenarios have been developed that investigate the mitigation potentials associated with a number of GHG reduction strategies, including travel demand reduction, utilization of specific technologies in various transportation subsectors, assumptions about their level of technology advancement and market penetration, and the use of alternative fuels and different fuel production methods. Scenarios differ in terms of these specified assumptions (the options employed, their penetration, and their efficacy), as shown in Figure 5.

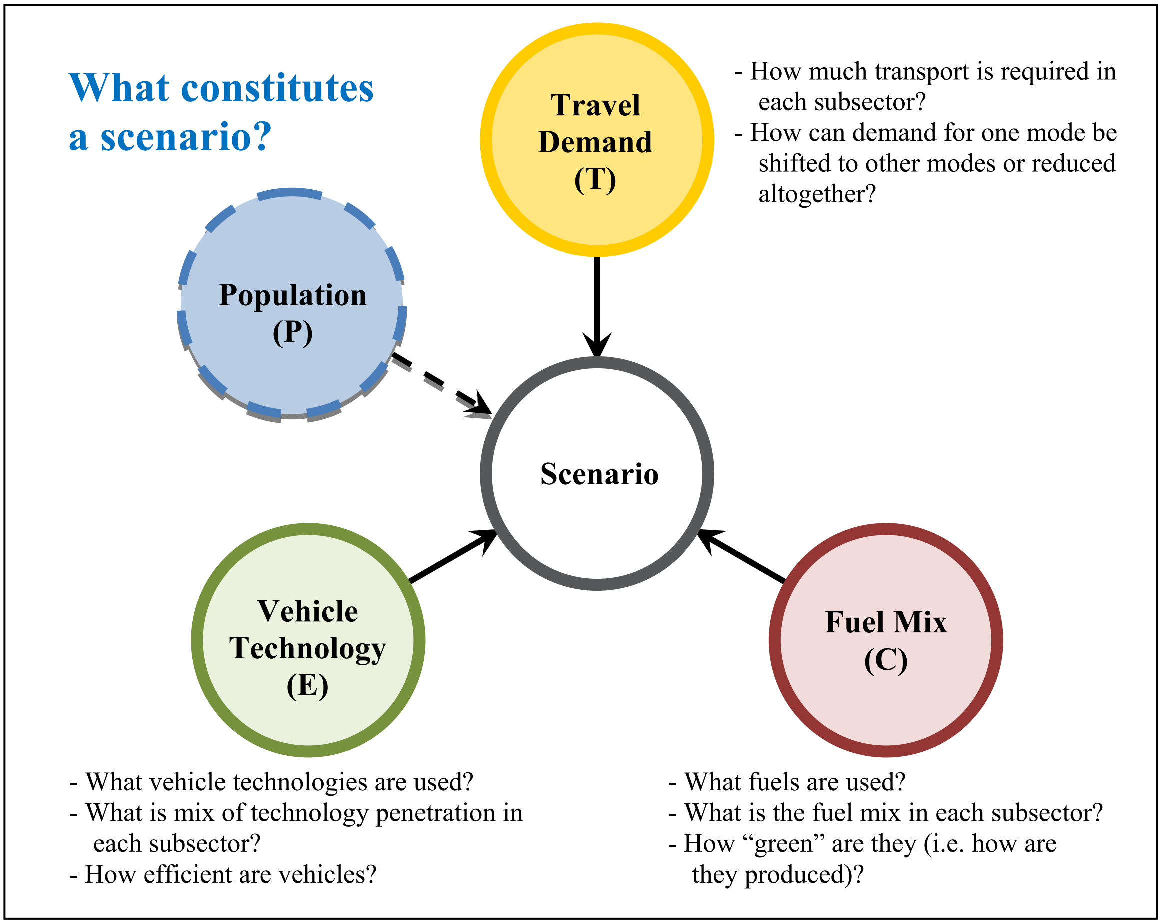


Figure 5 Schematic showing building blocks of a scenario

5.2 Scenario methodology

5.2.1 Literature review

As mentioned previously, the LEVERS model is used to specify and organize scenario-specific assumptions and display scenario outputs, including quantification of emission reductions and graphs and tables. The model contains the results of a broad literature survey on transportation vehicle efficiency potential in 2050. These literature values were found for each of the four Kaya parameters. The first parameter, population (P), was gathered from the California Department of Finance official statewide population projections for 2050. Transport intensities (T) and energy intensities (E) for each of the vehicle types and transportation subsectors come from various literature sources, which are documented in the LEVERS model. Estimates of fuel carbon intensities (C) are, with few exceptions, from the GREET-CA model.

5.2.2 Developing scenarios

Given the assumptions based upon literature values that are built into the LEVERS model, creating a scenario is relatively simple. The default assumptions can be directly used, or they can be modified depending on the questions that are to be explored by scenario analysis. Three sets of scenarios have been developed for this project and are presented and discussed below. First, a *Reference* scenario describes a continuation of business-as-usual practices into the future where very little is done to address climate change. This establishes a baseline for comparison for the other scenarios. A second class of scenarios, called *Silver Bullet* scenarios, describe futures in which one mitigation option, such as a single advanced vehicle type or alternative fuel, is employed to the maximum feasible extent in 2050. Emission reductions are calculated for each *Silver Bullet* scenario and compared to understand emission reduction potentials for individual mitigation strategies and vehicle and fuel technologies. Third are the *80in50* scenarios, which look at distinct futures in which the 80% emission reductions target is achieved in each scenario by utilizing a different mix of technologies and strategies. These scenarios illustrate the multiple approaches and the extent of technological and behavioral changes required to achieve these deep reductions.

6. Scenario descriptions and results

6.1 Reference scenario

The *Reference* scenario describes a future where very little is done from a technical or policy standpoint to address climate change. In this future, transportation activity and technology development follow historical trends. As a result, the only expected improvement in vehicle fuel efficiency is a modest increase that is consistent with the latest CAFE[3] rules from 2008 and a similar level of vehicle efficiency improvement across other transportation modes. However,

---

[3] According to the Energy Independence and Security Act (EISA) of 2007, the average efficiency of new light-duty vehicles (both cars and trucks) must achieve 35 mpg by the year 2020. In this study, the average efficiency of the entire light-duty vehicle fleet (not only new cars) is assumed to be 35 mpg in 2050.

despite this improvement in vehicle efficiency (i.e., reduction in energy intensity, E, of 35%), population (P) is expected to double[4], the transport activity (T) per capita is expected to increase moderately (23%), and the average carbon intensity (C) of all transportation fuels increases very slightly from the 1990 level (since petroleum-based fuels remain dominant, and unconventional oil sources are utilized more)[5]. Figure 6 shows the number of miles traveled per capita in 1990 for each of the various transportation subsectors and highlights the extent to which demand is projected to grow (under business-as-usual conditions) between 1990 and 2050. Both the *Instate* and *Overall* emissions cases are shown. In the *Overall* case in particular, aircraft travel is expected to grow significantly and is a large driver for emissions growth. Coupled with the doubling of population, total travel demand (PxT) in the *Instate* case is nearly 2.5 times the 1990 value; it is nearly four times the 1990 value in the *Overall* case.

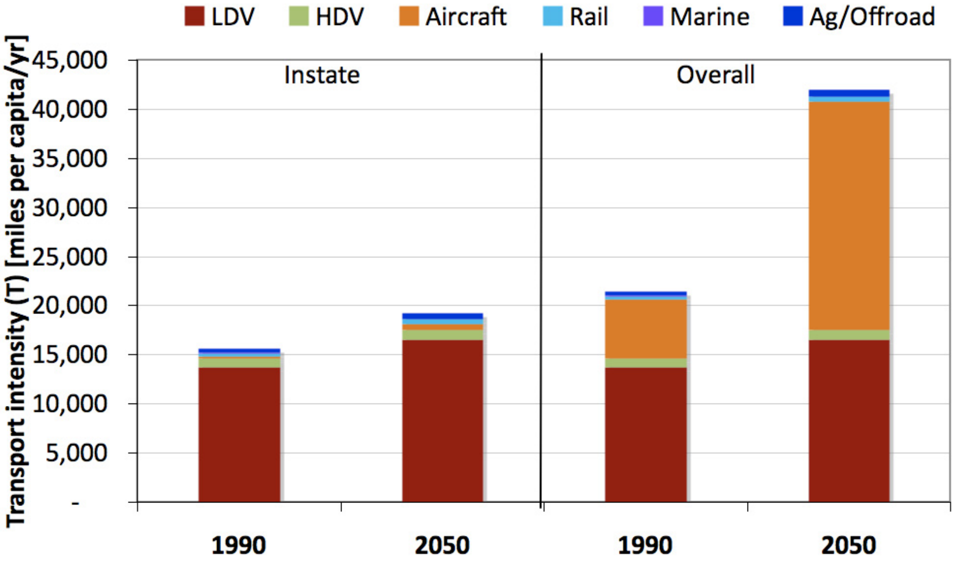


Figure 6 Transport intensity (T) comparison for Instate and Overall emissions for 1990 and the 2050 Reference scenario.

The relative change in parameters between 1990 and the 2050 *Reference* scenario can be seen in Figure 7. Aggregated over all of the transportation subsectors, the energy intensity declines by 35%, and carbon intensity is about 2% higher than in 1990. Overall, this leads to a 62% increase in emissions from 1990 to 2050 rather than a decline. *Instate* emissions reach 317 MMTCO$_2$e in 2050 while in the *Overall* emissions case they reach 422 MMTCO$_2$e.

---

[4] The official state projections estimate a doubling of population from 29.8 million in 1990 to 59.5 million in 2050 [11].

[5] This scenario does not include implementation of the LCFS, which applies to on-road transportation fuels and requires a 10% reduction in average fuel carbon intensity by 2020 and may be tightened in later years.

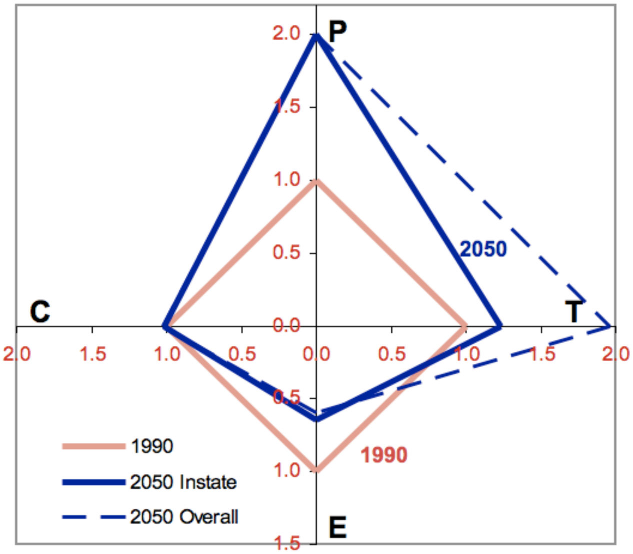
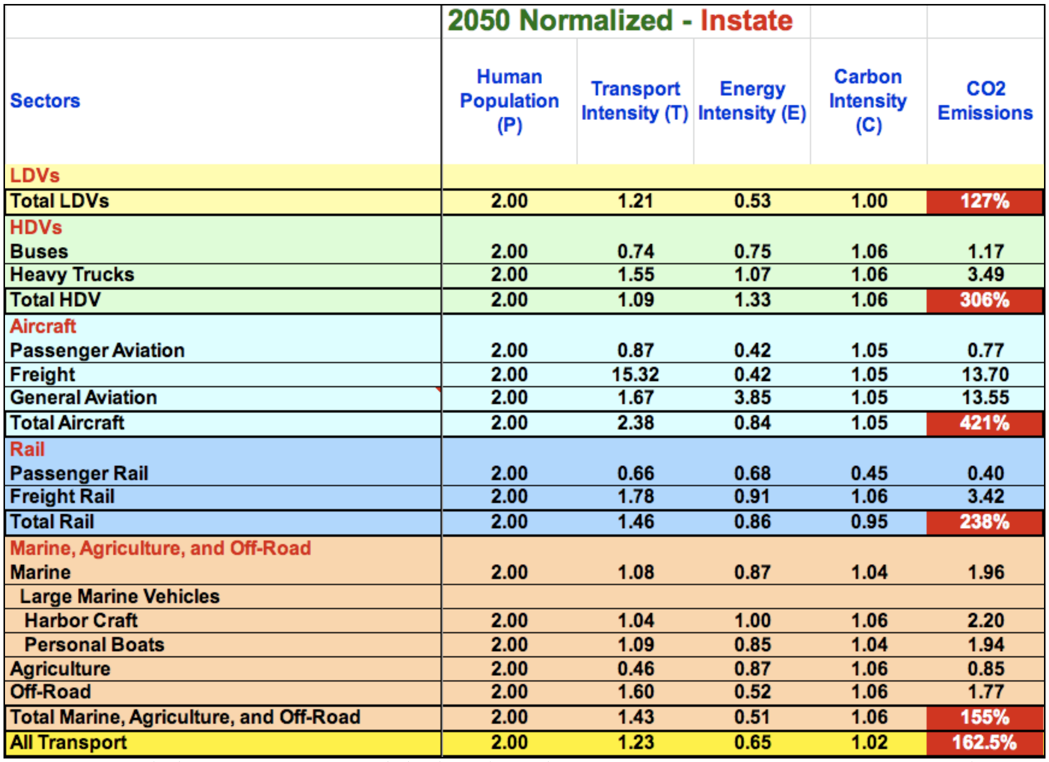


Figure 7 Kaya parameter diagram for the Instate aggregate transportation sector in the 2050 Reference scenario and 1990.

Figure 8 shows the normalized values (i.e., 2050 values relative to 1990 values) of the Kaya parameters for each of the transportation sectors and subsectors. Aviation shows the greatest increase in emissions from 1990 because, in spite of slightly more efficient airplanes, demand for air travel (PxT) is expected to grow rapidly in the coming decades. Freight transport—carried in aircraft, heavy trucks, rail, and large marine vessels—is another area that is expected to continue growing rapidly, contributing to the growth in California's transportation emissions.



	2050 Normalized - Instate				
Sectors	Human Population (P)	Transport Intensity (T)	Energy Intensity (E)	Carbon Intensity (C)	CO2 Emissions
LDVs					
Total LDVs	2.00	1.21	0.53	1.00	127%
HDVs					
Buses	2.00	0.74	0.75	1.06	1.17
Heavy Trucks	2.00	1.55	1.07	1.06	3.49
Total HDV	2.00	1.09	1.33	1.06	306%
Aircraft					
Passenger Aviation	2.00	0.87	0.42	1.05	0.77
Freight	2.00	15.32	0.42	1.05	13.70
General Aviation	2.00	1.67	3.85	1.05	13.55
Total Aircraft	2.00	2.38	0.84	1.05	421%
Rail					
Passenger Rail	2.00	0.66	0.68	0.45	0.40
Freight Rail	2.00	1.78	0.91	1.06	3.42
Total Rail	2.00	1.46	0.86	0.95	238%
Marine, Agriculture, and Off-Road					
Marine	2.00	1.08	0.87	1.04	1.96
Large Marine Vehicles					
Harbor Craft	2.00	1.04	1.00	1.06	2.20
Personal Boats	2.00	1.09	0.85	1.04	1.94
Agriculture	2.00	0.46	0.87	1.06	0.85
Off-Road	2.00	1.60	0.52	1.06	1.77
Total Marine, Agriculture, and Off-Road	2.00	1.43	0.51	1.06	155%
All Transport	2.00	1.23	0.65	1.02	162.5%

Figure 8. Output of the LEVERS model showing the *Instate* 2050 Kaya parameters for each of the transportation sectors and subsectors in the Reference scenario.

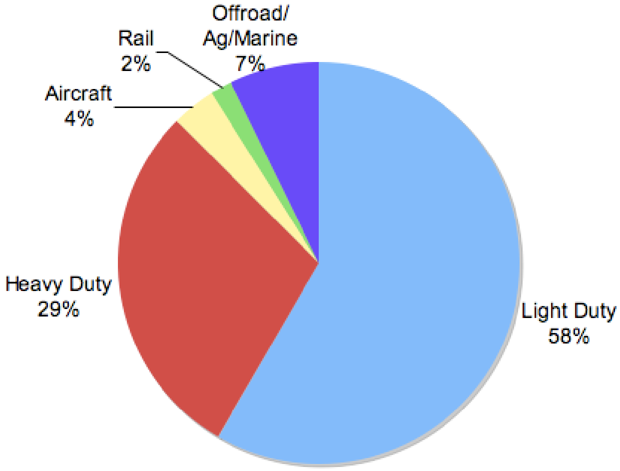


Figure 9 Breakdown of Instate emissions for the 2050 Reference scenario by transportation subsector.

Figure 9 shows the distribution of emissions in 2050 for the *Instate* emissions case. It is quite similar to the distribution in 1990 (see Figure 2), except that HDVs make up a larger share of emissions and the share from LDVs is slightly lower. Still, LDVs and HDVs continue to make up the vast majority of *Instate* transportation emissions (85% in 1990 vs. 87% in 2050).

6.2 "Silver bullet" scenarios

Silver Bullet (SB) scenarios describe futures in which a single mitigation option, such as an advanced vehicle technology or alternative fuel, is employed to the maximum feasible extent from a technology perspective in 2050. The level of emission reduction is calculated for each of the *Silver Bullet* scenarios and also compared across scenarios to better understand the emission reduction potential for different mitigation strategies and technologies.

Several *Silver Bullet* scenarios are developed. They modify individual elements of the *Reference* scenario, which assumes a doubling in population, a continuation of current trends in transport activity, and very little fuel switching or penetration of new vehicle technologies (i.e., in 2050 the same fuels and vehicles are used in each of the transportation subsectors as were used in 1990). There are two scenarios that focus exclusively on increasing the efficiency of conventional vehicles (*Moderate efficiency SB* and *High efficiency SB*). There are also three *Silver Bullet* scenarios that focus on alternative fuels and advanced vehicle drivetrains (*Hydrogen-intensive SB*, *Electricity-intensive SB*, and *Biofuel-intensive SB*) and one scenario that focuses on reductions in automobile and airline passenger-miles traveled (*PMT SB*). In all *Silver Bullet* scenarios, population (P) in 2050 is 59.5 million, and other than in the *PMT SB* scenario, transport activity (T) in 2050 for the various subsectors is the same as in the *Reference* scenario. Hence, total travel demand (PxT) is the same across all of the *SB* scenarios except for *PMT SB*; the differences in GHG emissions result from differences in the scenario energy intensity (E) and carbon intensity (C). Each of the scenarios meet the transportation demand in each subsector with a different mix of vehicle technologies and fuels, which leads to a difference in the amount of CO_2 emitted per mile of travel (ExC) across the scenarios.

The *Moderate efficiency SB* scenario does not require any major technological advances but implies a focus on improving efficiency that results in a steady increase in drivetrain efficiency, which is applied to reducing fuel consumption rather than increasing vehicle performance, speed, or comfort. The efficiency improvement in this scenario exceeds the *Reference* scenario efficiency improvement. In the marine and heavy-duty truck subsectors, aside from drivetrain efficiency improvements, the efficiency assumptions also include relatively easy-to-implement strategies such as improved logistics and speed reduction as a means to improve efficiency. Overall, this scenario achieves approximately a doubling of average vehicle efficiency. Conventional petroleum fuels power the bulk (94%) of total transportation miles-traveled, just as they do in the *Reference* scenario (see Table 3). The breakdown of miles-traveled by fuel type varies by subsector, with HDVs, aircraft, and marine, agricultural, and off-road vehicles using petroleum fuels for 100% of their needs. Rail relies less on petroleum since some rail is already electrified, and will likely continue to be so in the future.

The *High efficiency SB* scenario is another variation of the *Reference* scenario that only modifies efficiency. In this scenario, vehicle efficiencies are improved beyond the normal historical rate of incremental improvement in engine and drivetrain efficiencies, which implies either significant breakthroughs in the development of next-generation engines and/or a reduction in vehicle size, weight, and performance, as well as increased occupancy to reduce the energy used for moving people relative to the *Moderate efficiency SB* scenario. This scenario achieves nearly triple the average vehicle fuel economy (270%) of 1990 vehicles. The breakdown of miles-traveled by fuel type within each subsector is the same as in the *Reference* and *Moderate efficiency SB* scenarios, as described above.

The *Hydrogen-intensive SB* scenario applies FCV technologies and hydrogen fuel aggressively across many transportation subsectors. Significant technology development and cost reductions for hydrogen technologies are assumed so that hydrogen FCVs can be used for 75% of vehicles in the light-duty subsector, 80% of buses, 90% of heavy-duty trucks, and for 100% of intercity, commuter, and freight rail. Additionally, 5% of aviation fuel, up to 50% of marine fuel, 20% of agricultural vehicle fuel, and 50% of off-road fuel is hydrogen. Hydrogen is also assumed to be produced in a relatively decarbonized fashion, with 40% from zero carbon electricity (renewable and nuclear), 20% from biomass gasification, and 40% from natural gas reforming, which employs carbon capture and storage (CCS) to reduce emissions. Hydrogen is responsible for powering 73% of all miles-traveled in this scenario. All other miles are powered by conventional petroleum fuels, except for biofuels blended into LDV gasoline and some electricity used for rail.

The *Electricity-intensive SB* scenario applies electric vehicle technologies to a number of transportation subsectors. Because most electric vehicles would have to use some sort of electricity storage (though some, like rail and even buses, can use electric lines without intermediate battery storage), there are several subsectors in which electric vehicles see limited application, including marine and aviation. Other transportation subsectors, such as light-duty and rail can be almost exclusively electric vehicles. (Note that electrification of road vehicles includes both all-electric BEVs and PHEVs.) Electricity generation is assumed to be very clean, mainly generated from low carbon resources such as natural gas with CCS (30%) or zero carbon resources such as nuclear (30%) and renewables (40%). Electricity is responsible for powering 78% of all miles-traveled in this scenario, but again there is some variation in electrically-powered shares: LDVs (84%), HDVs (35%), Aviation (0%), Rail (100%), Marine/Agricultural, and Off-road (45%). All other miles are powered by conventional petroleum fuels, except for biofuels blended into LDV gasoline.

The *Biofuel-intensive SB* scenario does not require the development and deployment of advanced technologies such as electric drivetrains or fuel cells, but rather the development of abundant, low carbon biofuels production. These advanced low-carbon fuels can be applied in conventional and advanced internal combustion engine technologies across the range of transportation subsectors. As a result, biofuels have broad applicability to each of the transportation subsectors because they are substitutes for the conventional petroleum fuels currently used. Biofuels account for roughly 60% of all transportation fuels use in this scenario. The balance of fuel consumption in every subsector is conventional petroleum fuels (gasoline, diesel, jet fuel or marine bunker fuels). This level of biofuels market penetration was designed so that the quantity of biofuel demand in California is of a reasonable magnitude when compared to total potential U.S. supply (see section 6.2.1 for further discussion of potential biofuels supply). Biofuels are responsible for powering 60% of all miles-traveled in this scenario. This is generally true of the individual subsectors as well.

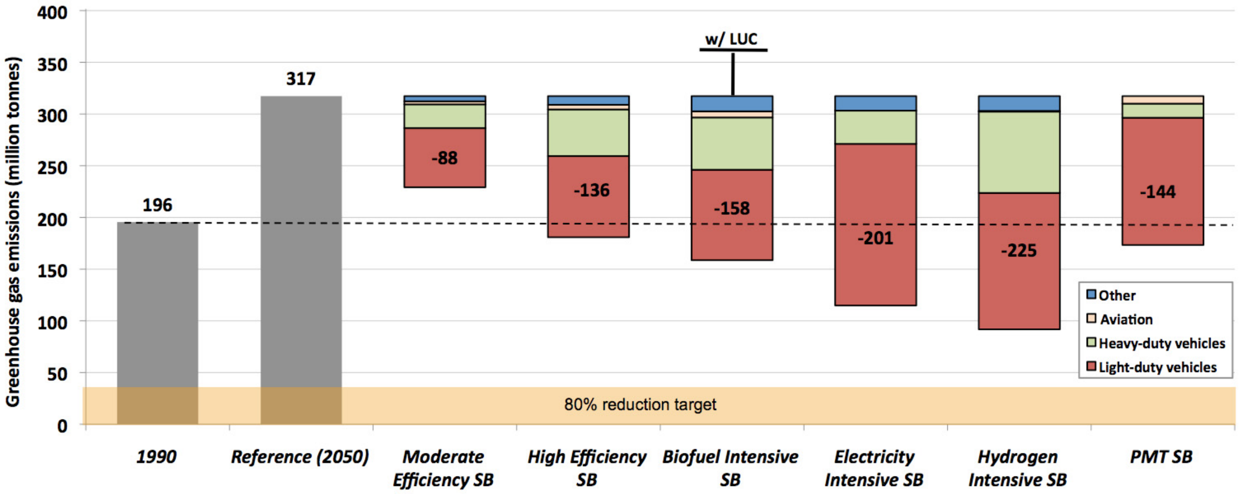
The final *Silver Bullet* scenario, the *PMT SB* scenario, maintains all of the same vehicle efficiency and fuel carbon assumptions as in the *Reference* scenario. However, in this scenario the travel demand assumptions for LDVs and aircraft are reduced to represent a future California in which smart growth, better land-use planning, telecommuting and teleconferencing, mode-shifting, and perhaps high travel costs lead to reductions in the demand for travel. Reductions in passenger-miles traveled coupled with increased vehicle occupancy rates due to carpooling and higher transit usage lead to a very large reduction (60%) in light-duty VMT per capita relative to 1990 (3300 vs. 8400 miles per person). Instate passenger aircraft miles are similarly reduced relative to 1990 values due to the use of high-speed rail. Because of these reductions in PMT, the shares of miles-traveled by fuel type are slightly different. In this scenario conventional petroleum is responsible for powering 90% of miles, down a bit from the *Reference* scenario since there is a mode shift from LDVs to electrified light- and heavy-rail for passenger transportation in the *PMT SB* scenario.

Table 3 Breakdown of *Instate* miles-traveled by fuel type and subsector for each *Silver Bullet* scenario

		Petroleum	Biofuels	Hydrogen	Electricity	Energy Intensity (1990=100%)	Carbon Intensity (1990=100%)
Reference Scenario	LDV	94%	6%	0%	0%	53%	100%
	HDV	100%	0%	0%	0%	133%	106%
	Aviation	100%	0%	0%	0%	84%	105%
	Rail	91%	0%	0%	9%	86%	95%
	Marine/Ag/Off-road	100%	0%	0%	0%	51%	106%
	All sectors combined	95%	5%	0%	0%	65%	102%
	Total # of miles (billions)	*1,146.3*	*billion*				
Moderate Efficiency SB	LDV	94%	6%	0%	0%	36%	100%
	HDV	100%	0%	0%	0%	100%	106%
	Aviation	100%	0%	0%	0%	63%	105%
	Rail	91%	0%	0%	9%	64%	95%
	Marine/Ag/Off-road	100%	0%	0%	0%	44%	106%
	All sectors combined	95%	5%	0%	0%	47%	102%
	Total # of miles (billions)	*1,146.3*	*billion*				
High Efficiency SB	LDV	94%	6%	0%	0%	30%	100%
	HDV	100%	0%	0%	0%	68%	106%
	Aviation	100%	0%	0%	0%	52%	105%
	Rail	91%	0%	0%	9%	54%	95%
	Marine/Ag/Off-road	100%	0%	0%	0%	38%	106%
	All sectors combined	95%	5%	0%	0%	37%	102%
	Total # of miles (billions)	*1,146.3*	*billion*				
Biofuel-intensive SB	LDV	40%	60%	0%	0%	53%	53%
	HDV	51%	49%	0%	0%	115%	55%
	Aviation	40%	60%	0%	0%	84%	53%
	Rail	30%	63%	0%	7%	86%	43%
	Marine/Ag/Off-road	40%	60%	0%	0%	51%	53%
	All sectors combined	40%	60%	0%	0%	62%	53%
	Total # of miles (billions)	*1,146.3*	*billion*				
Electricity-intensive SB	LDV	15%	1%	0%	84%	30%	27%
	HDV	65%	0%	0%	35%	99%	92%
	Aviation	100%	0%	0%	0%	84%	105%
	Rail	0%	0%	0%	100%	52%	7%
	Marine/Ag/Off-road	55%	0%	0%	45%	49%	71%
	All sectors combined	21%	1%	0%	78%	43%	55%
	Total # of miles (billions)	*1,146.3*	*billion*				
Hydrogen-intensive SB	LDV	24%	1%	75%	0%	31%	48%
	HDV	14%	0%	86%	0%	61%	33%
	Aviation	95%	0%	5%	0%	84%	101%
	Rail	0%	0%	93%	7%	54%	10%
	Marine/Ag/Off-road	53%	0%	47%	0%	51%	67%
	All sectors combined	25%	1%	73%	0%	39%	49%
	Total # of miles (billions)	*1,146.3*	*billion*				
PMT SB	LDV	94%	6%	0%	0%	35%	100%
	HDV	100%	0%	0%	0%	47%	106%
	Aviation	100%	0%	0%	0%	58%	105%
	Rail	56%	0%	0%	44%	65%	71%
	Marine/Ag/Off-road	100%	0%	0%	0%	54%	106%
	All sectors combined	90%	3%	0%	7%	53%	99%
	Total # of miles (billions)	*820.5*	*billion*				

Detailed tables that describe all of the assumptions in each of the *Silver Bullet* scenarios are found in Appendix A.

6.2.1 Summary of Silver Bullet scenarios



* In *Biofuel Intensive SB* scenario, ~60% of transportation fuel supply comes from biofuels. This level is consistent with California consuming 15-20% of total US supply.

* Significant uncertainties surrounding indirect land use change impacts from biofuels production lead to the large variability in potential GHG changes from 1990 levels.

Figure 10 Greenhouse gas emission reductions for Silver Bullet scenarios relative to Reference scenario for Instate emissions.

Figure 10 shows each of the *Silver Bullet* scenarios and the reduction in GHG emissions relative to the 1990 value and the 2050 *Reference* scenario projection. Table 4 and Table 5 provide additional details with regard to the emission reductions (total and by subsector), fuel usage by type, and Kaya parameters associated with each of the *Silver Bullet* scenarios for both the *Instate* and *Overall* emissions cases. As seen in the figure, none of the *Silver Bullet* scenarios achieve the 80% emission reduction goal, and the emissions of one scenario (*Moderate efficiency SB*) are still higher than 1990 emissions. Both of the efficiency scenarios show that while improving vehicle technologies can help to reduce emissions relative to business-as-usual, the gains are largely negated by the significant increases in travel demand inherent in the *Reference* scenario. In terms of the Kaya equation (GHGs = P x T x E x C), reductions in E are not enough to offset the large increases in PxT, so emission reductions are small or nonexistent in the efficiency-only *Silver Bullet* scenarios.

The *Biofuel-intensive SB* scenario achieves a small reduction in emissions (18.8% in the *Instate* case; 14.0% *Overall*), even though low-carbon biofuels are applied across all transportation subsectors at a 60% market penetration rate. Because vehicle efficiencies do not significantly increase in this scenario, the lower average fuel carbon intensity (C) (53% of 1990 values) is not enough to reduce GHG emissions more dramatically. This argues for greater vehicle efficiencies to accompany any significant use of biofuels. The GHG benefits of biofuels are quite uncertain, however. In Table 4 another set values for the emissions change have been calculated, which include the additional emissions associated with land-use change (LUC) from biofuels production, as discussed in section 4.2.2. The incorporation of LUC impacts into the calculation potentially makes the *Biofuel-intensive SB* scenario the worst *Silver Bullet* scenario from a GHG perspective; in fact, emissions in 2050 are higher than in the business-as-usual *Reference* case. It is very important to note that there exists considerable uncertainty over the LUC impacts associated with biofuels and their lifecycle GHGs. Likely the value for the GHG change associated with use of this quantity of biofuels is somewhere between the two extremes shown here, though it is difficult to be certain about the exact value—and whether biofuels would provide a net benefit or net detriment—without additional research and analysis.

The *Biofuel-intensive SB* scenario consumes 16.4 billion gge of biofuels (21.9 billion gge in the *Overall* case). It is unlikely that California will be able to produce this quantity of biofuels on its own without shifting agricultural lands to biomass production, severely impacting food prices, and/or causing other harmful impacts. For reference, the recently adopted US mandate (EISA 2007) calls for 36 billion gallons of renewable fuel (24 billion gge, assuming ethanol) in the US by 2022. Studies have shown that with the amount of biomass waste residues available in California (i.e., feedstocks that need not be grown on agricultural lands), the state is capable of producing just 2.3 billion gge [33]. The 16.4 billion gge of biofuels used in this scenario is potentially feasible if optimistic assumptions are made about U.S. biofuel supplies. There are a number of studies yielding a wide range of estimates of the amount of biofuels that could be produced in the U.S. in 2050. These include the “Billion Ton Vision” study (USDA and DOE), which found that 85-92 billion gge could be “sustainably” supplied (without impacting food, feed, and export demands, or displacing corn croplands) from 1.3 billion dry tons of annual biomass [35][6]; an NRDC estimate of up to 120 billion gge [36]; and a National Research Council estimate of 39-51 billion gge [37]. These analyses differ in their assumptions about the cellulosic resource base, competing energy use demands for biomass (e.g., power generation), cost and water limitations, and conversion technology. Based on a moderately optimistic estimate (“Billion Ton”), it appears that the quantity used in this scenario, 16.4 billion gge (60% of California’s transportation fuel consumption needs across all subsectors), could be provided if California were able to obtain 15-20% of total U.S. biofuel production capacity.[7] If imported biofuels are considered, then California’s biofuels supply could potentially be larger, since world biofuel production capacity is higher. IEA’s review found a very wide range; the “practical” and “economic” figures cited in the report show a global liquid biofuels potential in 2050 of 443-536 billion gge [43]. If California were able to obtain more than 16.4 billion gge of low-carbon biofuels in 2050 and could power a greater share of vehicle-miles with these fuels, then even larger reductions in GHG emissions could potentially be achieved. But California’s ability to secure these larger quantities, even from overseas imports (due to global competition for biomass

---

[6] While the “Billion Ton Vision” study is not explicit about the exact quantity of transportation fuels that could be produced from the 1.3 billion dry tons of biomass that it estimates is available in the U.S., personal communication with one of the lead authors of the study, Bob Perlack at Oak Ridge National Laboratory indicated that 85 billion gge (127.46 billion gallons ethanol) could be potentially available by 2050, if competing demands for biomass are ignored. Other calculations indicate that 1.3 billion tons of biomass can be converted to 90-95 billion gge (assuming 79 gge/metric tonne dry biomass).

[7] California currently accounts for anywhere between 11% and 18% of U.S. population, GDP, VMT, motor vehicles registrations, transportation fuels consumption, and ethanol consumption, depending on the metric. And given that California’s population is expected to grow more quickly than most other areas of the country between now and 2050 (12% of U.S. population in 1990, 14.2% in 2050), it may be reasonable to assume that California could secure 15-20% of the country’s biofuels in 2050. (Estimates based on various sources [11, 38-42] and authors’ calculations.)

resources and competing demands for other energy uses), may not be feasible, as this might constitute an unreasonable share of global biofuels supply.

Other fuel-intensive scenarios (*Hydrogen-intensive SB* and *Electricity-intensive SB*) do not achieve the 80% reduction goal either. They can achieve significant emission reductions in the light-duty, heavy-duty bus and rail subsectors, but because there are more restrictions in applying electricity and hydrogen technologies across all subsectors, they yield only moderate reductions from 1990 (53% and 41%, respectively). Hydrogen makes up 57% of total fuel used on an energy basis and 73% of the miles in the *Hydrogen-intensive SB* scenario while electricity makes up 50% of total fuel use and 78% of the miles in the *Electricity-intensive SB* scenario. These figures show that although these fuels can have very low carbon intensity, unless technology breakthroughs allow them to be used widely in every transportation subsector, they will not be able to achieve deep GHG reductions.

Reducing per capita travel demand can also lead to GHG reductions relative to the *Reference* scenario, but the *PMT SB* scenario still only achieves an 8% reduction from 1990 emissions due largely to the projected doubling of population by 2050, which causes an increase in total travel demand (76% increase in PxT) relative to 1990.

It is clear that none of the individual mitigation strategies examined in the *Silver Bullet* scenarios can achieve the ambitious 80% reduction goal by themselves. The scenarios fails to meet the target for a number of reasons: some options will be limited by the supply resources (e.g., biofuels), some cannot be applied across all transportation subsectors (e.g., hydrogen and electricity), and some cannot reduce the target Kaya parameters enough to overcome the growth in population and travel demand (e.g., efficiency and PMT scenarios). However, many of the options examined in these scenarios are complementary (such as improving efficiency, utilizing alternative fuels and reducing travel demand) and can be combined in a portfolio approach to help reduce California's transportation emissions. This is a critical point, and scenarios examining how these approaches can be combined are analyzed in the next section.

Table 4 Emission reductions and fuel usages associated with Silver Bullet scenarios

Scenario Name		**% GHG Change**	**Fuels Usage (Billion GGE)**				
			Petroleum	**Biofuels**	**H2**	**Elec**	**Total**
Reference Scenario	Instate Total	**+62%**	27.5	1.0	0.0	0.0	28.5
	Overall Total	**+72%**	36.7	1.0	0.0	0.0	37.7
Moderate efficiency SB	Instate Total	**+17%**	19.9	0.7	0.0	0.0	20.5
	Overall Total	**+25%**	26.8	0.7	0.0	0.0	27.4
High efficiency SB	Instate Total	**-7%**	15.7	0.6	0.0	0.0	16.2
	Overall Total	**+1%**	21.6	0.6	0.0	0.0	22.2
Hydrogen-intensive SB	Instate Total	**-53%**	7.0	0.2	9.8	0.0	17.1
	Overall Total	**-25%**	14.9	0.2	11.1	0.0	26.3
Electricity-intensive SB	Instate Total	**-41%**	9.4	0.1	0.0	9.5	19.0
	Overall Total	**-11%**	18.6	0.1	0.0	9.5	28.2
*Biofuel-intensive SB**	Instate Total	**-19% (+81%)**	11.0	16.4	0.0	0.0	27.4
	Overall Total	**-14% (+94%)**	14.6	21.9	0.0	0.0	36.6
PMT SB	Instate Total	**-8%**	15.5	0.3	0.0	0.7	16.5
	Overall Total	**+6%**	22.6	0.3	0.0	0.7	23.7

Note: Positive % changes in GHG emissions represent increases from 1990; negative % changes represent decreases.
* For the *Biofuel-intensive SB* scenario, the values in parentheses show how the results change when severe land-use change (LUC) impacts are considered; otherwise, values shown are for the no-LUC case.

Table 5 Emission reductions for individual transportation subsectors and normalized Kaya parameters associated with the Silver Bullet scenarios

Scenario Name		**GHG emissions change from 1990**					**Kaya Parameters**			
		LDV	**HDV**	**Aircraft**	**Rail**	**Marine Ag/OR**	**P**	**T**	**E**	**C**
Reference Scenario	Instate Total	+27%	+206%	+321%	+138%	+55%	2.00	1.23	0.65	1.02
	Overall Total	+27%	+206%	+167%	+138%	+35%	2.00	1.96	0.59	1.02
Moderate efficiency SB	Instate Total	-12%	+129%	+216%	+78%	+32%	2.00	1.23	0.47	1.02
	Overall Total	-12%	+129%	+100%	+78%	+8%	2.00	1.96	0.43	1.02
High efficiency SB	Instate Total	-27%	+56%	+163%	+49%	+14%	2.00	1.23	0.37	1.02
	Overall Total	-27%	+56%	+67%	+49%	0%	2.00	1.96	0.34	1.02
Hydrogen-intensive SB	Instate Total	-64%	-57%	+302%	-86%	-2%	2.00	1.23	0.39	0.49
	Overall Total	-64%	-57%	+155%	-86%	-20%	2.00	1.96	0.37	0.64
Electricity-intensive SB	Instate Total	-80%	+99%	+321%	-90%	0%	2.00	1.23	0.43	0.55
	Overall Total	-80%	+99%	+167%	-90%	+9%	2.00	1.96	0.41	0.71
Biofuel-intensive SB	Instate Total	-33%	+38%	+111%	+7%	-22%	2.00	1.23	0.62	0.53
	Overall Total	-33%	+38%	+34%	+7%	-32%	2.00	1.96	0.57	0.53
PMT SB	Instate Total	-58%	+161%	+64%	+439%	+35%	2.00	0.88	0.53	0.99
	Overall Total	-58%	+161%	+83%	+439%	+25%	2.00	1.40	0.38	1.00

Note: Positive % changes in GHG emissions represent increases from 1990; negative % changes represent decreases.

6.3 80% reduction (*80in50*) scenarios

Three scenarios are presented that represent different potential futures in California in which 80% reductions in GHG emissions are realized by 2050 (so-called "*80in50*" scenarios). They illustrate three snapshots of the transportation sector in 2050 and highlight the different mixes of mitigation options in the various subsectors, such as activity reduction and technology deployment that can achieve the necessary reductions. The three *80in50* scenarios are unique from the *Silver Bullet* scenarios described above and should be not considered as combinations of them.

The results focus on *Instate* emissions, but *Overall* emissions are discussed as well, in section 6.3.5. *Instate* emissions account for trips that occur entirely within California, while *Overall* emissions include half of all trips that either originate in, or are destined for, California. In the latter case, aviation and marine contribute significantly to emissions. The scenarios here are constructed so that *Instate* emissions are reduced 80% below 1990 levels in 2050; *Overall* emissions do not reach the 80% target in any of the scenarios.

With hundreds of confluent parameters that define a model scenario, any number of 80% reduction scenarios may be developed. Three relatively distinct scenarios are described and compared here. The first two scenarios focus on technology—one relying on low-carbon biofuels and another on electric-drive vehicles using electricity and hydrogen. The third scenario considers actor-based decisions to reduce travel demand and energy intensity. Population is constant in each scenario, equal to twice its value in 1990. The goal of this section is two-fold: first, to provide several snapshots of a future in which an 80% reduction in GHG is achieved in the transportation sector, and second, to explore the sensitivity of emissions to activity, efficiency, and carbon intensity.

Two technology-driven scenarios are presented that rely on low-carbon fuels to reduce emissions. They assume society "invents" its way out of trouble—that technology development can reduce the carbon emissions from transportation and eliminates the need for behavioral changes (i.e., reducing transportation activity). Different vehicle and fuel choices are made in each scenario, but assumptions regarding activity (population and transport intensity) are identical. The scenarios differ in the distribution of vehicle types and technologies that are employed, however, leading to different aggregate fleet efficiencies. In other words, PxT in these scenarios is the same as in the *Reference* scenario, but ExC is much different.

Activity in these scenarios follows a "business as usual" trend, as described in the *Reference* scenario. People continue to travel as expected, goods movement and commercial vehicle activity continues to increase with economic growth, and vehicle efficiency incrementally improves, with the efficiency gains being applied to increased fuel economy instead of greater size, weight, or power of vehicles. Passengers travel in private cars to and from low-density developments without carpooling. Demand for air travel continues to increase rapidly, as airplanes are preferred over buses, railroads, and LDVs for long-distance travel. Per-capita travel in 2050 increases by 23% compared to 1990, consistent with the *Reference* scenario. Coupled with the projected doubling of state population, total travel activity (in terms of passenger-miles traveled) in the technology-driven scenarios is almost 2.5 times greater in 2050 than it was in 1990.

Vehicle efficiencies increase beyond the assumptions in the *Reference* scenario (e.g., in the light-duty subsector, the average internal combustion engine vehicle achieves over 50 mpg). These efficiency improvements are significant but not unreasonable. The scenario assumes that aggressive energy efficiency measures are made that generally apply to increasing vehicle efficiency, rather than performance. But the gains are within reason for current vehicle technologies (as described in section 4.1, above) and presumably maintain mobility and performance as they are currently known.

The electricity generation and hydrogen production mixes in the two technology-driven scenarios are the same, relying on centralized production of both energy carriers. Renewable electricity generation (including hydro) gains significant share (40% of generation), but additional capacity is assumed to be economically and logistically impractical. A change in public sentiment allows for additional nuclear power plants to be constructed in the state, leading nuclear-fired generation to contribute 30% of electricity in California in 2050. Ultimately, the limits of non-fossil fuel resources push the commercial development of carbon capture and storage (CCS) technologies to enable expanded fossil fuels usage, which are employed widely in California to reduce CO_2 emissions from hydrogen and electricity generation. Fossil-fired technologies with CCS account for the remaining 30% of electricity generation and for 60% of hydrogen production. Biomass gasification (35%) and renewable electrolysis (5%) comprise the balance of hydrogen production.

6.3.1 Efficient Biofuels 80in50 scenario

The first technology-driven scenario relies heavily on biofuels with low GHG intensity to meet the emission reductions target. Pushed by federal and state policy mandates and strong societal support for local farmers and energy independence, the biofuels industry develops vigorously. Agricultural yields continue to increase and advanced biofuel production technologies develop robustly. By 2050, very low-carbon biofuels (with negligible indirect land-use change impacts) are abundant and relatively inexpensive in California.

With a strong culture of support for biofuels, a wide infrastructure is developed to support their use, and each transportation subsector comes to depend heavily on them. Biofuels become the primary fuel offered at gas stations and the only fuel at centralized infrastructure dedicated to fleets and many commercial vehicles, allowing a complete transition to biofuels in some subsectors. The LDV subsector uses biofuels and a small amount of electricity, with biofuel hybrid-electric vehicles (HEV)[8] accounting for 75% of the vehicle fleet and biofuel plug-in hybrid electric vehicles (PHEV) making up the remaining 25%. Together, they yield a fleet-average fuel economy of 56 mpgge (miles per gasoline gallon equivalent). Heavy-duty vehicles (including both buses and heavy-duty trucks), rail systems (except for already-electrified light and heavy/metro rail networks), and boats—each with a largely centralized refueling infrastructure—rely entirely on biofuels. Commercial vehicles whose fleets are slower to turn over or who often fuel outside of California are slower to adopt biofuels, but use them to a great extent: aviation and large marine vehicles use biofuels for 75% and 50%, respectively, of their energy needs and agricultural and off-road vehicles use 75% biofuels. The balance of energy in every transportation subsector is conventional, petroleum-based fuels. Overall, biofuels make up 90% of fuel used in transportation. By 2050, continual improvements in efficiency have reduced

---

[8] It is assumed that in 2050 a “conventional” light-duty internal combustion engine (ICE) vehicle will be a HEV.

the transportation sector-wide average energy intensity by 59% compared to 1990 levels, an average annual reduction of 1.5%.

Figure 11 and Figure 12 show how GHG emissions are reduced in the *Efficient Biofuels 80in50* scenario, compared to the *Reference* scenario. The emission reductions primarily come from using low-carbon biofuels, which reduces GHG emissions by 231 MMTCO$_2$e, and electricity, which reduces emissions by 40 MMTCO$_2$e. As seen in the figure, over half of the reductions from biofuels (144 MMTCO$_2$e) can be attributed to their lower carbon intensity, C (relative to conventional fuels in the *Reference* scenario). The higher fuel economies (lower E) assumed in this scenario (compared to the *Reference* scenario) account for the remainder of reductions from biofuel vehicles. For electricity, vehicle efficiency improvements (mostly through PHEV penetration in the light-duty subsector) account for nearly two thirds of the emission reductions (27 MMTCO$_2$e) while the lower carbon content of electricity as a fuel (14 MMTCO$_2$e) makes up the remainder. An advantage of biofuels over other fuel types is that they can be widely applied across all transportation subsectors since they can be used in conventional combustion engines. As a result of this broad applicability, reductions in GHG emissions from the use of biofuels are seen across multiple subsectors.

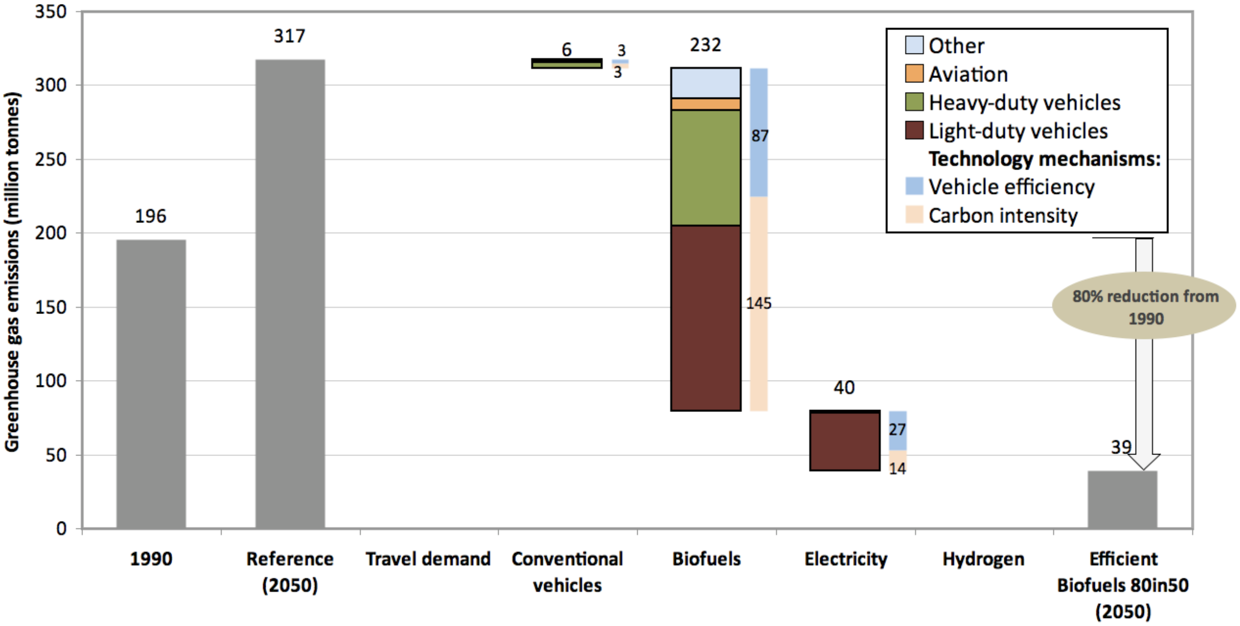


Figure 11 *Efficient Biofuels 80in50* scenario greenhouse gas emission reductions by control strategy.

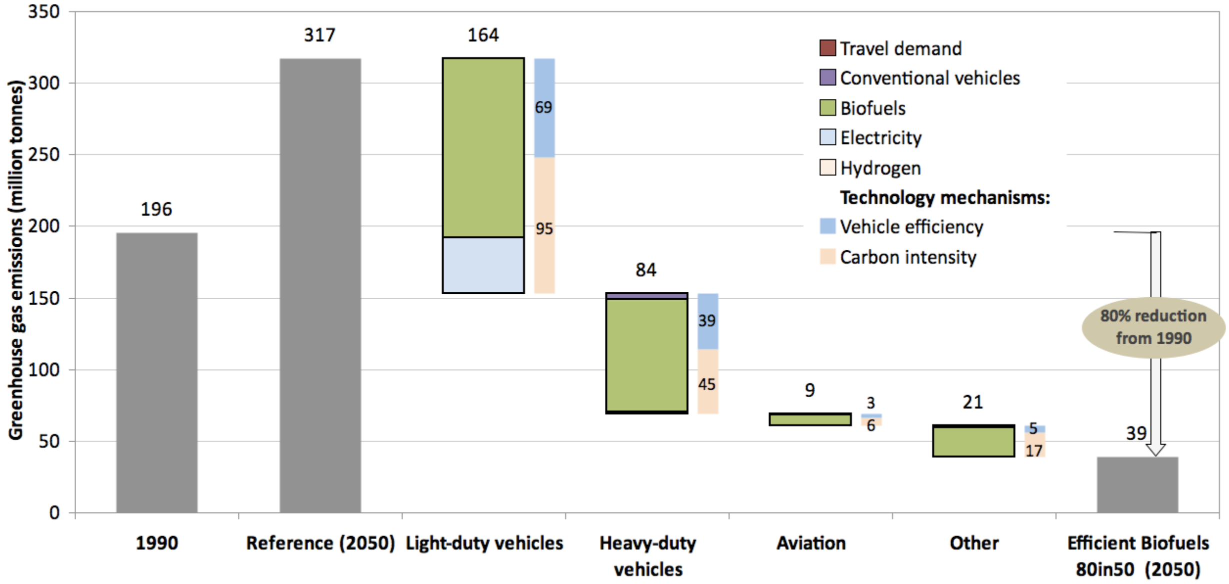


Figure 12 *Efficient Biofuels 80in50* scenario greenhouse gas emission reductions by vehicle subsector.

The sensitivity of *Instate* emission reductions in *Efficient Biofuels 80in50* to the penetration of different biofuel transportation technologies in each vehicle subsector is illustrated in Figure 13. If all vehicles in the light-duty subsector were biofuel PHEVs, total transportation sector GHG emissions would be reduced by 85% below 1990 levels. If, instead, all LDVs were simply biofuel HEVs, emissions would still be reduced by almost 80%. However, if no biofuels or PHEVs were introduced in the light-duty subsector (i.e., if all vehicles were gasoline HEVs), total emissions would only be 25% below 1990 levels. *Instate* emission reductions in *Efficient Biofuels 80in50* are also very sensitive to the heavy-duty truck subsector, where biofuels provide all of the subsector's energy. If diesel were to remain dominant in the subsector, and no penetration of biofuels materialized, total scenario emissions would only be reduced by 51% below 1990 levels if the trucks were conventional ICEs, and by 59% if they were HEVs. Total *Instate* emission reductions are much less sensitive to biofuels penetration in the aviation and other subsectors because these are relatively small contributors to total emissions, but note that these subsectors play a more important role in the *Overall* emissions case (due to the large number of trips across the state's borders).

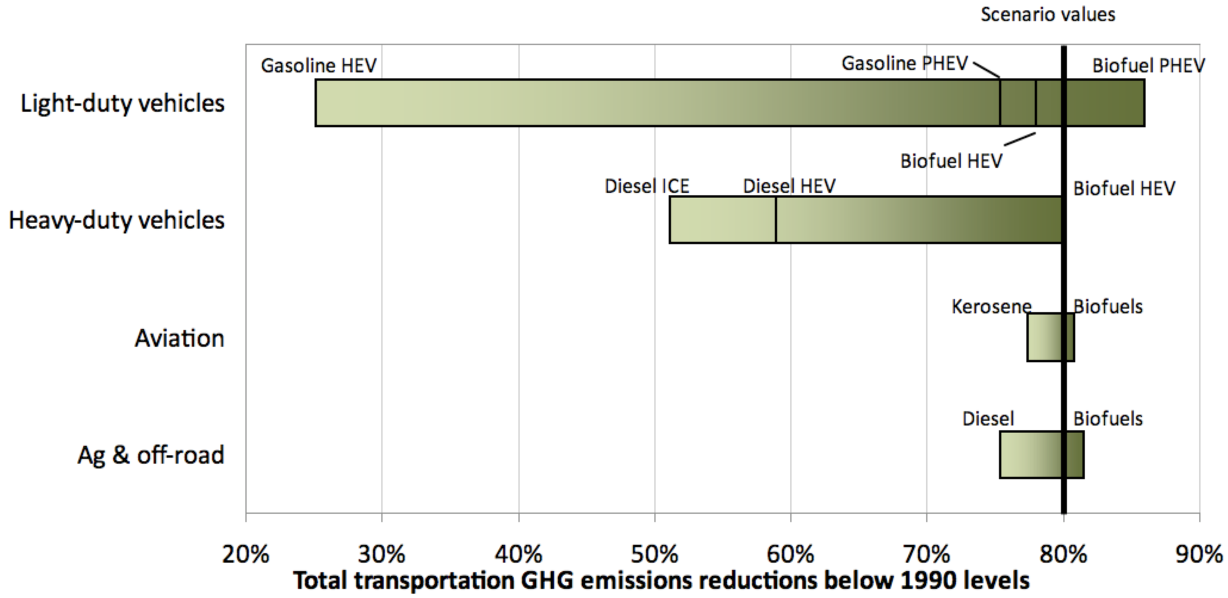


Figure 13 Sensitivity of Instate emission reductions in 2050 to vehicle type by subsector for the *Efficient Biofuels 80in50* scenario.

Underlying the dramatic transition to biofuels (and electricity, for LDVs) in pursuit of GHG emission reductions are very low-carbon fuel and electricity generation mixes. Biofuels production comes entirely from cellulosic sources with negligible land-use change impacts, and 70% of electricity generation comes from carbon-neutral biomass, nuclear, and renewable technologies, the balance coming from natural gas combined-cycle plants utilizing CCS. In total, the carbon intensity of transportation fuels in 2050 is 80% lower than it was in 1990.

The total value of emission reductions in this scenario, then, is highly sensitive to the carbon intensity of biofuels and electricity, as explored in Figure 14. The biofuel production and electricity generation mixes in this scenario are very low-carbon. Indeed, if all biofuels were assumed to derive from best-in-class California cellulosic sources (as defined by the GREET model [16]), or if the entire electricity sector were zero-carbon, transportation sector emissions would be reduced below 1990 levels by only a few additional percentage points. But if either mix were higher-carbon, the total transportation-wide emission reductions envisioned in this scenario would be much less. For instance, if the GHG intensity of the biofuels mix were equal to the current average intensity from corn ethanol in the Midwest (assuming negligible land-use change impacts), *Instate* emissions would be just 29% below 1990 levels, rather than 80%. If large land-use impacts were included, the emission reductions would not only be eliminated, emissions would actually increase substantially. Similar sensitivities can be seen for electricity. If the generation mix were equal to the mix in 1990, emissions would be reduced by 62% compared to 1990 levels, and if all generation came from natural gas combined-cycle power plants, the emission reductions would be just 58%. The sensitivity analysis highlights the extreme reliance on low-carbon biofuels in the *Efficient Biofuels 80in50* scenario.

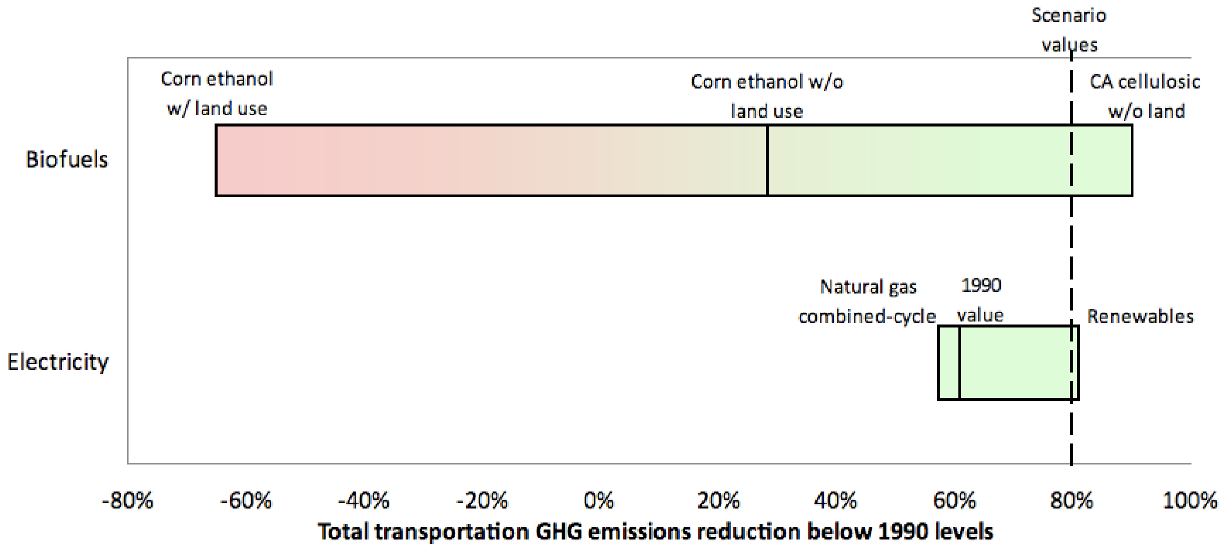


Figure 14 Sensitivity of *Instate* greenhouse gas emission reductions to fuel carbon intensity in *Efficient Biofuels 80in50* scenario.

Another important issue concerns the large, though potentially feasible, quantity of low-carbon biofuels required in this scenario—16.2 billion gge (or 21.1 billion gge in the *Overall* case). This accounts for 90% of total fuel used in the scenario and represents about 15-20% of total potential U.S. supply (85-92 billion gge) under optimistic estimates (as discussed in section 6.2.1). Biofuels consumption is roughly the same level as in the *Biofuel-intensive SB* scenario, but because of the lower efficiency of vehicles in the *Silver Bullet* scenario, 16 billion gge can only supply 60% of fuel used in that scenario. In other words, higher efficiency vehicles allow a greater share of vehicle-miles to be powered by biofuels given a constrained level of biofuels supply. Efficiency is one strategy that can help stretch the biomass resource base.

In summary, the *Efficient Biofuels 80in50* scenario presents a future where very large quantities of biofuels are combined with more efficient vehicles to achieve 80% reductions in GHGs in the transportation sector. However, the scenario also illustrates the enormity of the task of supplying this quantity of biofuels in California, which may require agricultural and scientific breakthroughs to realize.

6.3.2 Electric-drive 80in50 scenario

The second technology-driven scenario relies heavily on electric-drive technologies, including battery-powered vehicles (both PHEVs and BEVs) and hydrogen-powered FCVs. Similar political and social sentiments pervade California as described in *Efficient Biofuels 80in50*, but limited availability of low-carbon biofuels constrains their use. In this scenario, concerted research efforts and technological breakthroughs enable the development of commercially-viable, high efficiency, electric-drive technologies, so that plug-in hybrid, all-electric, and hydrogen-powered vehicles have all penetrated the California market significantly by 2050.

As per-capita vehicle travel continues to grow, consumers rely heavily on hydrogen—and to a lesser extent, biofuels in a few subsectors—to provide long-range and low-carbon mobility. All-electric vehicles play an important role, too, but are limited mainly to a few subsectors. In the light-duty subsector, 50% of vehicles are hydrogen FCVs, while 25% are gasoline PHEVs, and 25% are all-electric BEVs, which yields a fleet fuel economy of 84 mpg. Penetration of electric-drive vehicles is split in the bus market between FCVs (50%) and BEVs (50%).[9] Due to challenges with refueling and limited range, the heavy-duty truck subsector is much more reliant on hydrogen (90%), with the remaining 10% of vehicles being BEVs. Rail becomes entirely electrified, and hydrogen and electricity contribute to marine (<25%), agricultural (30%), and off-road (70%) energy consumption, as well. The balance of energy for each subsector, including all of aviation energy, is a mix of biofuels and conventional, petroleum-based fuels. In fact due to supply constraints, all low-carbon biofuels are directed toward the aviation, marine, agricultural, and off-road subsectors, where it is potentially more challenging to use either hydrogen or electricity for power.

As one of the technology-driven scenarios, the *Electric-drive 80in50* scenario depends on high efficiency vehicles and low-carbon fuels to meet the *80in50* goals. The political and social impetus that grows commercially-viable electric-drive technologies (i.e., batteries and fuel cells) also promotes technological development in low-carbon fuels supply. As mentioned above, the electricity generation and hydrogen production mixes in the *Efficient Biofuels 80in50* and *Electric-drive 80in50* scenarios are the same, relying on centralized production of both energy carriers. The biofuels that replace a significant fraction of the petroleum-based fuels in the agricultural, aviation, marine, and off-road subsectors also have very low GHG intensity. They derive entirely from cellulosic sources using advanced production technologies, and the indirect land use change impacts are negligible. Altogether, technological developments for supplying biofuels, electricity, and hydrogen reduce the carbon intensity of transportation fuels by 72% compared to 1990 levels. Biofuels consumption in this scenario is about 1.0 billion gge in 2050, dramatically less than the level in the *Efficient Biofuels 80in50* scenario and well within California's capability to produce these fuels from biomass waste residues, which avoid conflict with agricultural croplands [33]. (In the *Overall* emissions case, higher levels of out-of-state aviation and marine travel raise this demand to a larger, but still feasible, quantity of 4.4 billion gge.) By 2050, continual improvements in efficiency have reduced the transportation sector-wide average energy intensity by 71% compared to 1990 levels, an average annual reduction of 2%.

Figure 15 and Figure 16 show the GHG emission reductions in the *Electric-drive 80in50* scenario, relative to the *Reference* scenario and attributed to activity, fuel, and technology options. The largest portion of emission reduction occurs from the use of FCVs and hydrogen fuel (159 of 277 $MMTCO_2e$ reduced or 57%) and is split relatively evenly between the LDV and HDV subsectors. Electric vehicles also contribute to emission reductions (105 of 277 $MMTCO_2e$ reduced or 38%) and result mainly from PHEVs and BEVs in the LDV subsector. Approximately two-thirds of the emission reductions in the scenario can be attributed to improvements in fuel economy (lower E) associated with electric-drive vehicles (FCVs, EVs, and PHEVs), while most of the remainder can be attributed to the use of low carbon intensity hydrogen and electricity (lower C). Biofuels are responsible for emission reductions in other subsectors where hydrogen and electric vehicles are ill-suited, namely aviation and marine. As

---

[9] Buses can get their electricity from overhead wires.

with each of the scenarios, the large majority of emission reductions come from LDVs, with HDVs also contributing significantly to the overall reduction.

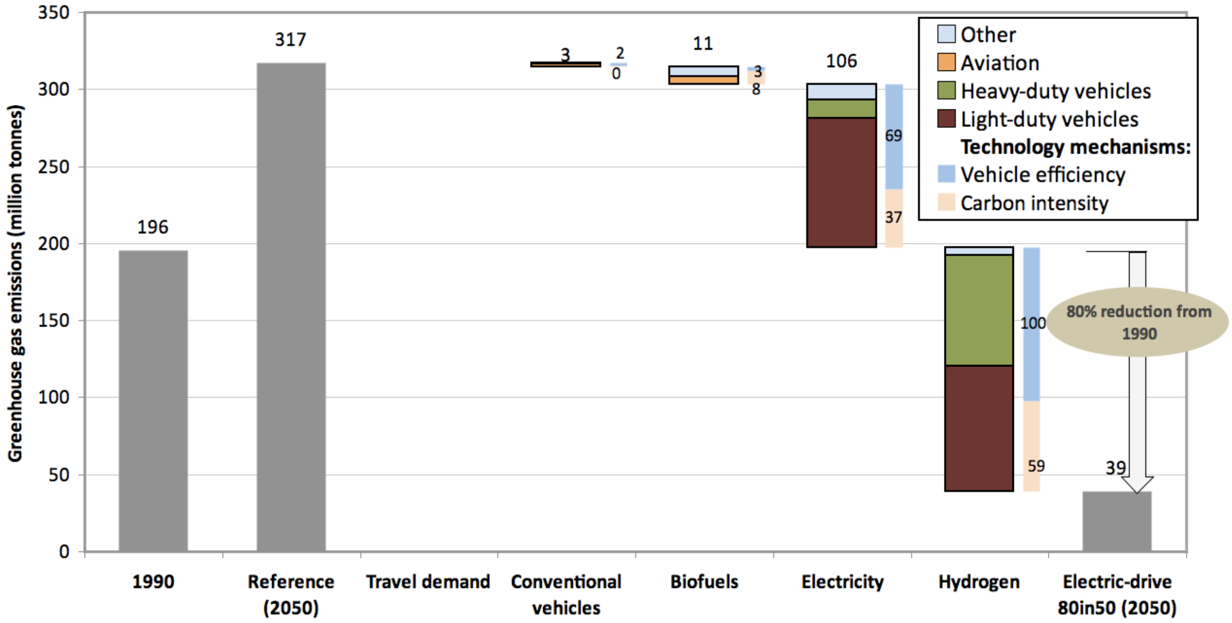


Figure 15 *Electric-drive 80in50* scenario *Instate* greenhouse gas emission reductions by control strategy.

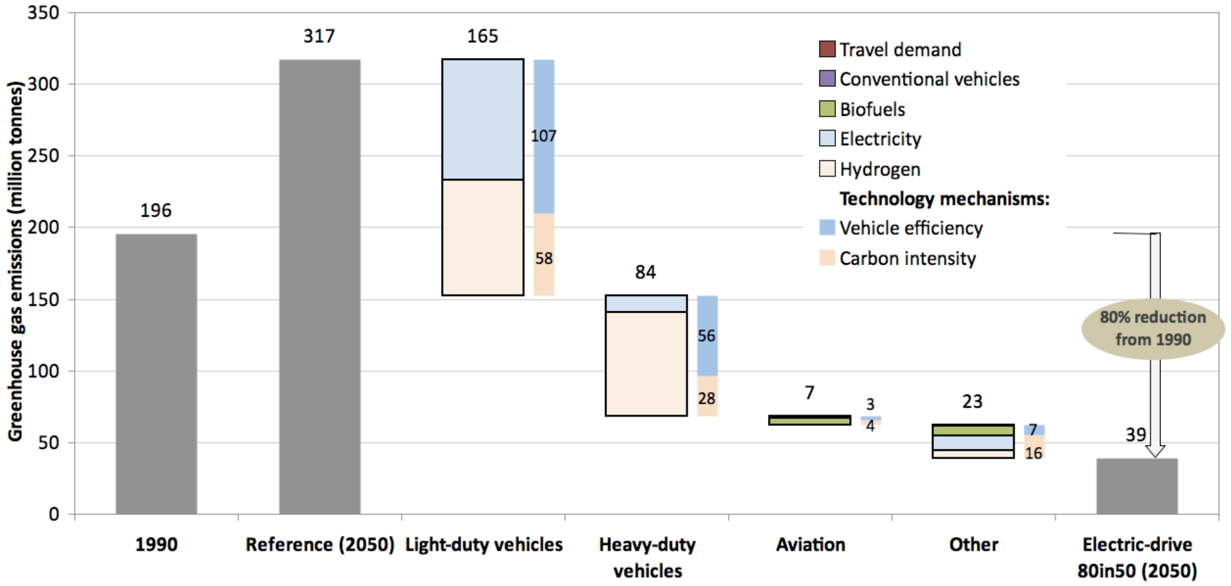


Figure 16 *Electric-drive 80in50* scenario *Instate* greenhouse gas emission reductions by vehicle subsector.

The sensitivity of *Instate* emission reductions in *Electric-drive 80in50* to the penetration of different transportation technologies in each vehicle subsector is illustrated in Figure 17. If all vehicles in the light-duty subsector were BEVs, total transportation sector emissions would reduce to 88% below 1990 levels. If hydrogen FCVs were the sole technology employed, then total emission reductions would be just shy of 80%. In contrast, if all LDVs were simply gasoline

HEVs, emissions would only be reduced by 25% below 1990 levels. *Instate* emission reductions in *Electric-drive 80in50* scenario are also somewhat sensitive to the heavy-duty truck subsector, where hydrogen and electricity provide all of the subsector's energy. If diesel were to remain dominant in the subsector, and no penetration of hydrogen or electricity materialized, scenario emissions would only be reduced by 53% below 1990 levels if the trucks were conventional ICEs, and by 60% if they were HEVs. Total *Instate* emission reductions are much less sensitive to hydrogen and electricity penetration in the aviation and other subsectors, but note that these subsectors play a more important role in the *Overall* emissions case (due to the large number of trips that cross the state's borders).

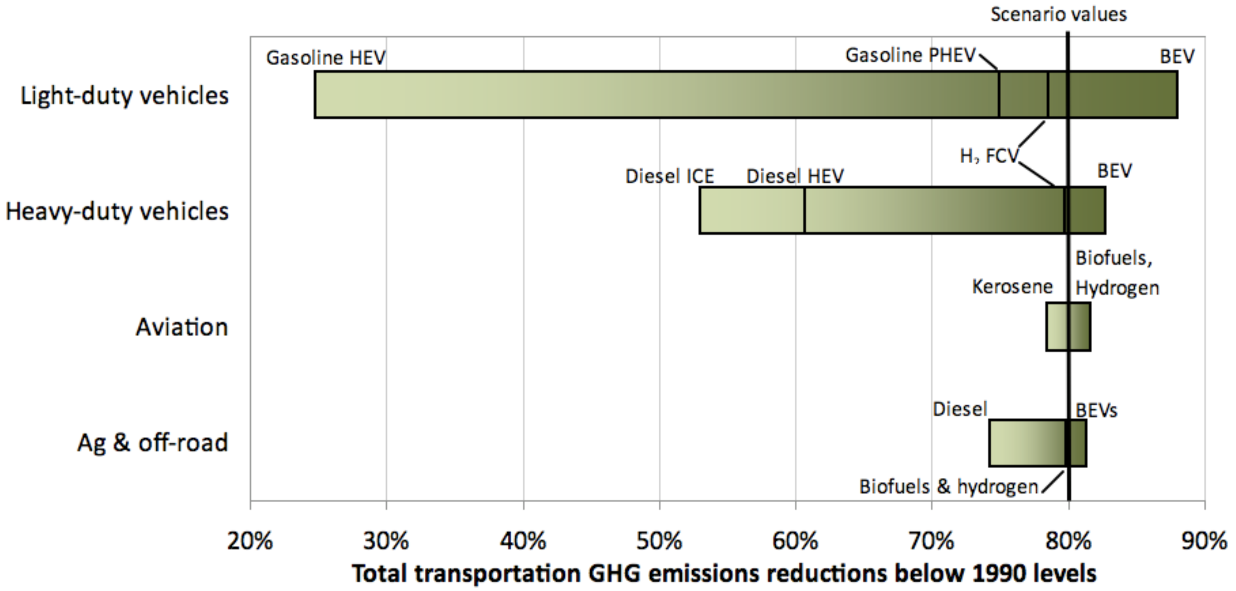


Figure 17 Sensitivity of *Instate* emission reductions in 2050 to vehicle type by subsector for the *Electric-drive 80in50* scenario.

As with the *Efficient Biofuels 80in50* scenario, relying heavily on fuels and energy carriers with very low GHG intensities leaves the scenario sensitive to assumptions about fuels production (Figure 18). Similar to *Efficient Biofuels 80in50,* using fuels with higher GHG intensities would eliminate many of the emission reductions gained in *Electric-drive 80in50*. Here, the magnitude of sensitivity to an individual fuel is smaller than in *Efficient Biofuels 80in50* because of greater fuel diversity. Moreover, it is apparent that if hydrogen were decarbonized further, additional emission reductions could be realized.

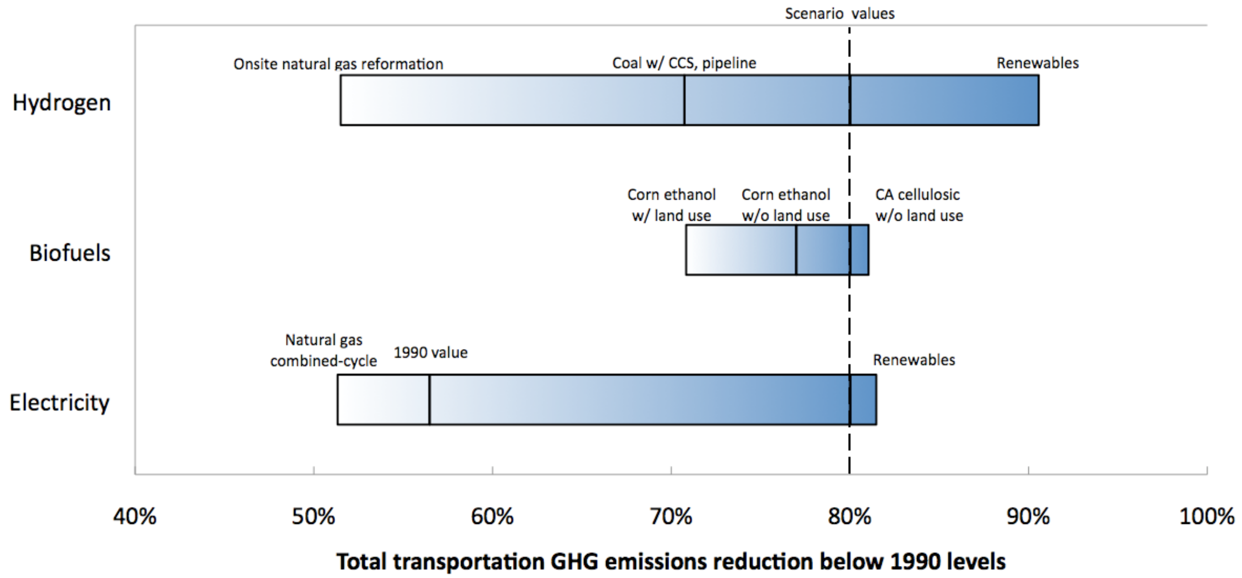


Figure 18 Sensitivity of greenhouse gas emission reductions to fuel carbon intensity in *Electric-drive 80in50* scenario.

6.3.3 Actor-based 80in50 scenario

While the previous scenarios rely on technological progress to develop alternative vehicle types and fuels with low GHG intensities and allow business-as-usual transportation demand growth to continue, the *Actor-based 80in50* scenario presents a different world. In this scenario energy prices are very high and companies, governments, and individuals are motivated to reduce energy consumption and GHG emissions. Each participant, or *actor*, in California's transportation economy takes an active role to reduce its contribution to GHG emissions. Passengers travel less and go a long way in trading size, weight, and power for efficiency in their vehicles. Commercial operators emphasize efficiency and logistics to reduce energy consumption. Businesses and consumers encourage local production of food and goods. And governments lead the way with effective urban planning that provides for efficient mobility and a reduced demand for travel at the level of the individual. In 2050, the transportation sector in California is in a different place: People and goods are traveling fewer miles and more efficiently than ever before. In terms of Kaya parameters, both E and the PxT product are lower than in the two technology-only scenarios while C is higher.

Compared to the projected values in the *Reference* scenario, effective actor-based decisions reduce per-capita activity 20%-50% depending on the subsector, and increase load factors by 25% in all subsectors. High gasoline prices and effective integration of transportation and land-use planning reduce travel demand for LDVs; and passengers increasingly carpool and telecommute. Improved logistics and consumer focus on local production reduce goods movement. Advances in agricultural and construction practices increase productivity while reducing vehicle activity. Altogether, per-capita PMT demand across all subsectors is about the same as it was in 1990. However, because of mode switching and higher density developments, per capita light-duty PMT is significantly lower (25% lower than the 1990 level). Per-capita

VMT is lower still (40% lower than the 1990 level) as a result of increased vehicle occupancies. Total VMT, when accounting for population growth, is only 20% higher than in 1990. Californians are driving much less but are still able to access the destinations they desire. The economy is growing, and standards of living are increasing despite reduced vehicle travel and higher fuel prices.

Actor-based decisions also contribute to an increase in fuel efficiency of an additional 20% in each subsector beyond those in the technology-driven scenarios (i.e., similar to the *High efficiency SB* scenario described in section 6.2). The LDV fleet shifts from trucks and SUVs to cars (10% and 90%, respectively). While conventional internal combustion engines remain the dominant propulsion system, highway vehicles are increasingly electrified using gasoline and diesel PHEV technology, and FCVs and BEVs to a smaller extent where possible. These electric-drive technologies, along with improved engines and vehicle weight reductions, significantly increase the average efficiency of the transportation fleet. Moreover, vehicle operators change their behavior to maximize efficiency: They travel at slower freeway speeds, accelerate gradually, operate PHEVs to maximize all-electric miles, and reduce idling whenever possible. By 2050, continual improvements in efficiency have reduced average energy intensity in the transportation sector by 77% compared to 1990 levels, an average annual reduction of 2.4%.

Powering these smaller vehicles, advanced vehicle technologies and fuels are employed in the *Actor-based 80in50* scenario. Hydrogen gains 10% share in each subsector besides aviation, rail, and personal boats. All-electric vehicles comprise a significant fraction of transit vehicles (all passenger rail and half of buses), subsectors that are already partially electrified today. However, electricity contributes only marginally in other subsectors. Smaller plug-in hybrids dominate the LDV subsector, accounting for 80% of vehicles (50% gasoline and 30% diesel) and make up 30% of buses (25% from gasoline and diesel and 5% from biofuels). Biofuels are limited, too, as a government mandate only allows biofuels from waste cellulosic resources. Those that are available are used in the heavy-duty truck (10%), agricultural (30%), off-road (20%), marine (10-20%), and aviation (70%) subsectors, or for blending with petroleum-based fuels (20% by volume). The balance of fuels used is petroleum-based.

Reductions in fuel carbon-intensity are significant, but conventional petroleum-based fuels persist and contribute almost half of transportation energy. As in the *Efficient Biofuels 80in50* and *Electric-drive 80in50* scenarios, the electricity sector is essentially de-carbonized, with the generation mix being the same. The carbon intensity of this electricity (23 gCO_2e/kWh) is just 6% of the 1990 level. Hydrogen production is less clean than in *Electric-drive 80in50,* as the focus here is on decentralized production without capturing and sequestering emissions. Eighty percent of hydrogen is produced locally using on-site natural gas reformers (50%) or renewable electrolysis (30%). Centralized natural gas with CCS makes up the remainder. Total carbon intensity of fuels across the entire transportation sector is reduced by 54% compared to 1990 levels, a much smaller reduction than in the *Efficient Biofuels 80in50* and *Electric-drive 80in50* scenarios. Biofuels consumption in this scenario is 1.3 billion gge in 2050, dramatically less than the level in the *Efficient Biofuels 80in50* scenario and probably well within California's ability to produce fuels from waste residues [33]. (In the *Overall* emissions case, higher levels of out-of-state aviation and marine travel raise this demand to a larger, but still feasible, quantity of 4.2 billion gge.)

Figure 19 and Figure 20 show the various contributions to emission reductions in the *Actor-based 80in50* scenario relative to the *Reference* scenario. Actor-based decisions have both technological and behavioral impacts. The two largest contributors are reductions in overall travel demand and the use of electricity in vehicles. The use of electricity is primarily in the LDV subsector, and the majority (nearly 80%) of the benefit is a result of the large improvement in vehicle efficiency rather than reductions in carbon intensity. Efficiency improvements in conventional vehicles as well as the use of low-carbon biofuels and hydrogen also contribute to emission reductions. The LDV and HDV subsectors are responsible for the bulk of the reductions.

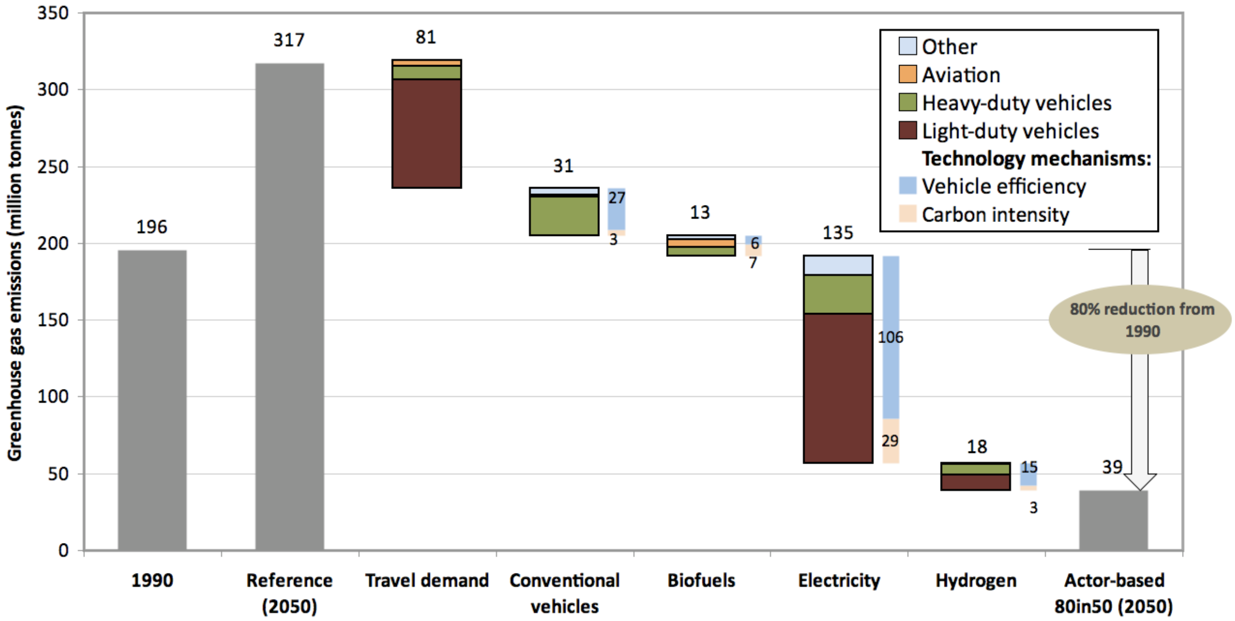


Figure 19 *Actor-based 80in50* scenario *Instate* greenhouse gas emission reductions by control strategy.

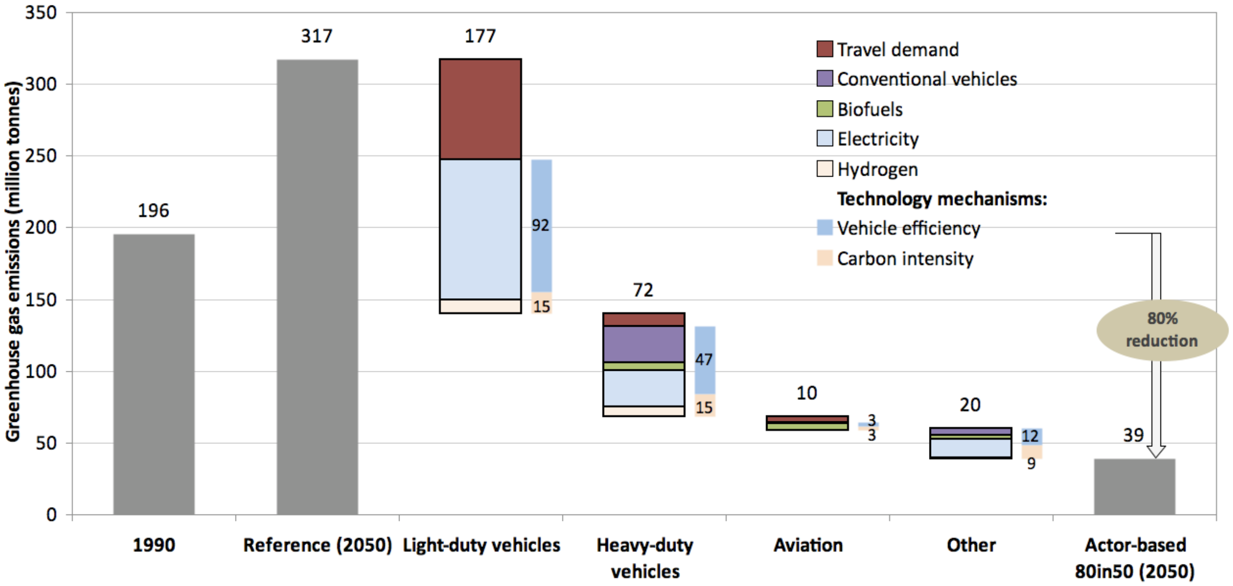


Figure 20 *Actor-based 80in50* scenario *Instate* greenhouse gas emission reductions by vehicle subsector.

The sensitivity of *Instate* emission reductions in *Actor-based 80in50* to the penetration of different transportation technologies in each vehicle subsector is illustrated in Figure 21. If all vehicles in the LDV subsector were BEVs, total transportation-wide emissions would reduce to 83% below 1990 levels. Even a full fleet of gasoline HEVs, due to their assumed high efficiency, would keep total emission reductions to 65% below 1990 levels. Similarly, if either hydrogen FCVs or gasoline PHEVs were the sole technology employed in the LDV subsector, total emission reductions would be 76% and 80%, respectively. However, total *Instate* emission reductions are less sensitive to the type of vehicle technology employed in the heavy-duty, aviation, and other subsectors because they make up a smaller fraction of total emissions. This scenario assumes a significant reduction in transport intensity and higher efficiencies for all vehicle types, so the emission reductions in this scenario are less sensitive to the choice of vehicle technology than the other scenarios (which is evidenced by the smaller size of the sensitivity bars in Figure 21).

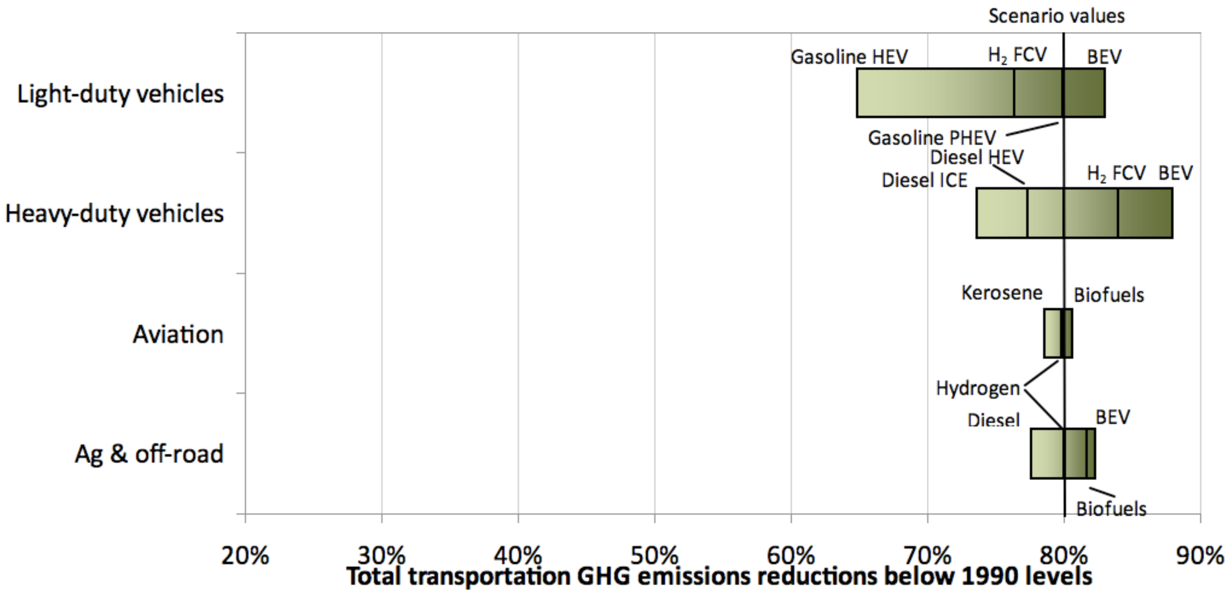


Figure 21 Sensitivity of *Instate* emission reductions in 2050 to vehicle type by subsector for the *Actor-based 80in50* scenario.

Relying heavily on PHEVs in the LDV subsector leaves the scenario sensitive to assumptions about electricity generation (Figure 22), although to a lesser extent than in the *Efficient Biofuels 80in50* and *Electric-drive 80in50* scenarios. While a completely carbon-free, renewable electricity supply would extend total emission reductions slightly beyond the 80% target, even a grid mix comprised entirely of natural gas combined-cycle electricity would reduce emissions 54% below 1990 levels.

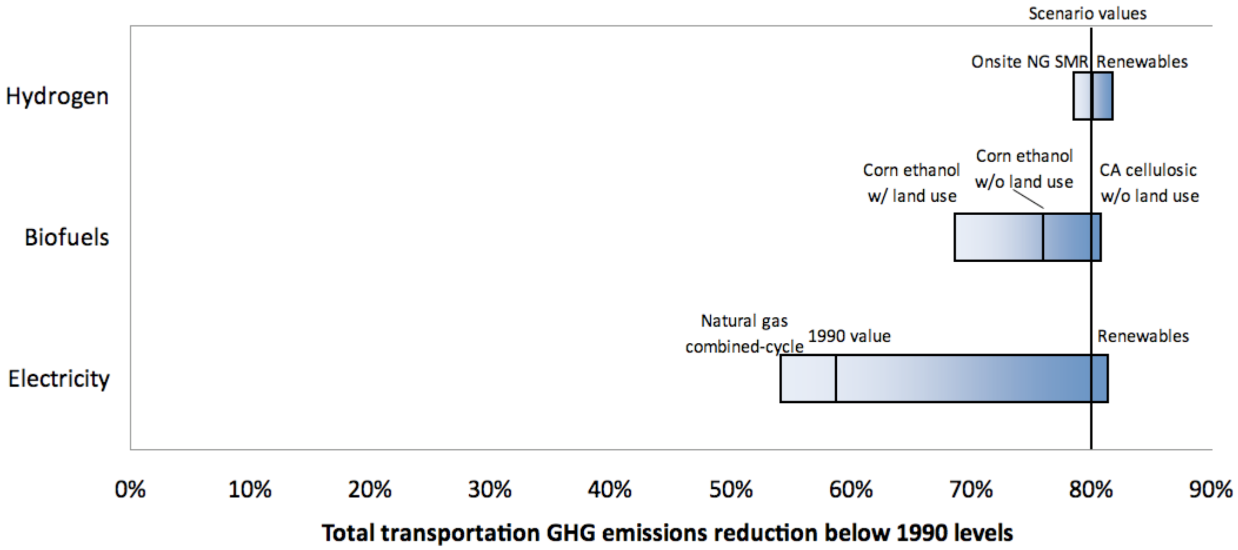


Figure 22 Sensitivity of *Instate* greenhouse gas emission reductions to fuel carbon intensity in *Actor-based 80in50* scenario.

6.3.4 Comparing scenarios

The scenarios described here offer three unique visions for reaching California's *80in50* emission reductions target in the transportation sector. Table 6 breaks down the miles-traveled by subsector in each scenario by the fuels that are used to power those vehicles and highlights the differences between the scenarios. Comparing the shares of miles-traveled to the shares of fuel consumption (on an energy basis) described in the sections above reveals the value of higher vehicle efficiency. In the *Electric-drive 80in50* scenario, hydrogen and electricity account for 83% of total transportation fuels consumption, but because of the highly efficient electric drivetrains (FCVs and BEVs) used in the scenario, the two fuels are responsible for powering 92% of all miles-traveled. Similarly in the *Actor-based 80in50* scenario, which has even higher vehicle drivetrain efficiencies than the other two *80in50* scenarios, hydrogen and electricity account for 49% of total transportation fuels consumption in this scenario but power 71% of all miles-traveled.

Table 6 Breakdown of miles-traveled by fuel type and subsector for each *80in50* scenario

		Petroleum	Biofuels	Hydrogen	Electricity	Energy Intensity (1990=100%)	Carbon Intensity (1990=100%)
Efficient Biofuels 80in50	LDV	0%	83%	0%	17%	33%	18%
	HDV	0%	95%	0%	5%	77%	15%
	Aviation	25%	75%	0%	0%	63%	40%
	Rail	0%	93%	0%	7%	69%	18%
	Marine/Ag/Off-road	23%	77%	0%	0%	44%	36%
	All sectors combined	1%	83%	0%	15%	41%	20%
	Total # of miles (billions)	*1,147.2*	*billion*				
Electric-drive 80in50	LDV	8%	0%	50%	42%	22%	25%
	HDV	0%	0%	74%	26%	52%	24%
	Aviation	50%	50%	0%	0%	63%	63%
	Rail	0%	0%	0%	100%	42%	7%
	Marine/Ag/Off-road	4%	32%	37%	27%	44%	31%
	All sectors combined	8%	2%	48%	41%	29%	28%
	Total # of miles (billions)	*1,146.3*	*billion*				
Actor-based 80in50	LDV	20%	5%	10%	64%	10%	33%
	HDV	25%	10%	10%	55%	25%	60%
	Aviation	30%	70%	0%	0%	44%	45%
	Rail	12%	3%	0%	85%	45%	18%
	Marine/Ag/Off-road	44%	20%	9%	27%	35%	62%
	All sectors combined	21%	8%	9%	62%	23%	46%
	Total # of miles (billions)	*894.9*	*billion*				

Figure 23 shows a comparison of the distribution of emissions and emission reductions for the three scenarios. *Actor-based 80in50* provides the most diverse solution, drawing on a number of strategies to reduce emissions, including both travel demand reductions and technology improvements across a suite of vehicle types and fuels. In this scenario 30% of emission reductions (relative to the *Reference* scenario) come from decreases in per-capita travel demand (T), while 55% and 15% of the reductions come from vehicle efficiency improvements (E) and lower-carbon fuels (C), respectively. Note that per-capita travel demand is just below 1990 levels (refer to Table 7), and additional demand reductions would reduce transportation emissions further.

The technology-driven scenarios present futures with similar underpinnings to one another but different implementation. They have identical travel demand growth within each subsector, but emphases on different fuels and technologies lead to distinct scenarios for vehicle energy intensities and fuel carbon intensities. *Electric-drive 80in50* yields a more energy-efficient system on whole, as a higher fraction of FCVs and BEVs in the fleet mix reduces aggregate energy intensity, while *Efficient Biofuels 80in50* relies more on reduced carbon-intensity of fuels to meet the *80in50* goals. In *Efficient Biofuels 80in50*, reductions in fuel carbon intensity outweigh improvements in vehicle efficiency in terms of their contribution to emission reductions (58% versus 42%), whereas in *Electric-drive 80in50*, vehicle efficiency accounts for 62% of the reductions. Travel demand reductions do not contribute to emission reductions in either of the technology-driven scenarios. If demand were to be reduced, then the required reductions in energy consumption and fuel carbon-intensity to meet the 80% target would decrease accordingly.

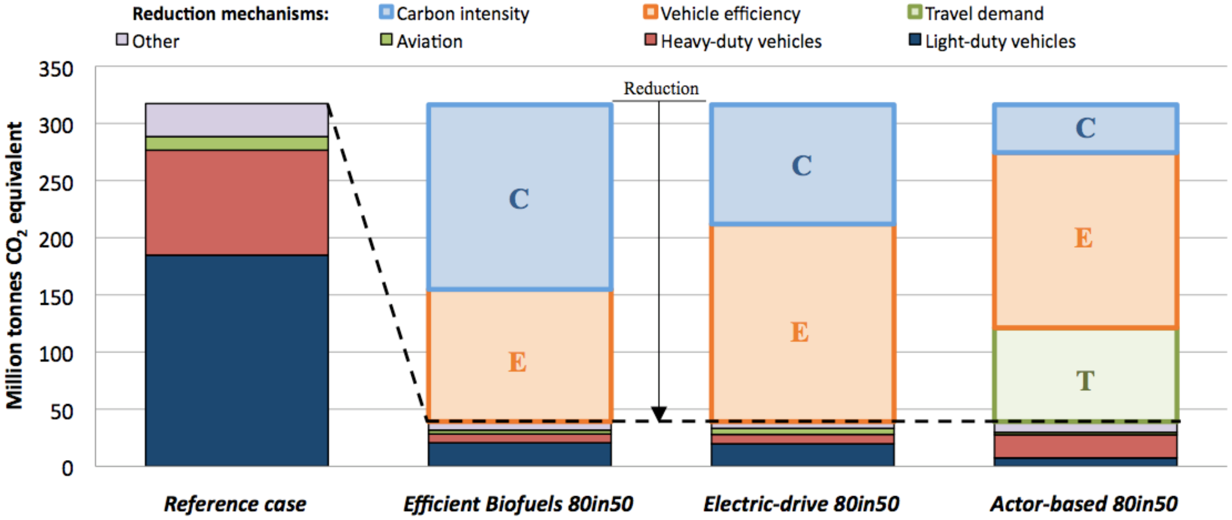


Figure 23 Comparison of *80in50* scenarios: Final emissions by vehicle type and emission reductions by strategy.

Clear distinctions between the two technology scenarios appear when comparing fuel consumption (Figure 24) and primary resource requirements (Figure 25). Increased fleet-average vehicle efficiency in *Electric-drive 80in50* reduces fuel use by 5.2 billion gge, or 29%, compared to *Efficient Biofuels 80in50* (and by over 15 billion gge, or 55%, compared to the *Reference* scenario). A similar result is found for primary resource requirements.[10] Less-efficient biomass-to-biofuels conversion processes and lower ICE drivetrain efficiencies lead to increased primary resource requirements in *Efficient Biofuels 80in50* compared to the more-efficient hydrogen and electricity production processes and higher FCV and BEV drivetrain efficiencies utilized in

---

[10] The following efficiencies are assumed for energy conversion technologies in 2050: Petroleum refining (85%); biofuels conversion from feedstock biomass (55%); hydrogen production from: centralized natural gas reformation with pipeline distribution (64%), centralized natural gas reformation with liquid truck distribution (53%), onsite natural gas reformation (71%), centralized biomass gasification with pipeline distribution (60%), centralized coal gasification with pipeline distribution (65%), and onsite electrolysis (67%); and electricity generation from: biomass (40%), coal (45%) and natural gas (50%).

Electric-drive 80in50. *Efficient Biofuels 80in50* requires 64% more primary energy (mainly in the form of biomass) than *Electric-drive 80in50*. The different types of primary energy used in the two scenarios are also noteworthy. Biofuels dominate fuel use and, thus, primary resource use in *Efficient Biofuels 80in50*, while hydrogen and electricity dominate fuel use in *Electric-drive 80in50*. The use of hydrogen and electricity in the latter case leads to a greater diversity of primary energy resources that includes relatively equal shares of biomass and natural gas, as well as a significant fraction of coal, among other resources. In *Efficient Biofuels 80in50*, biomass is, by far, the most important feedstock.

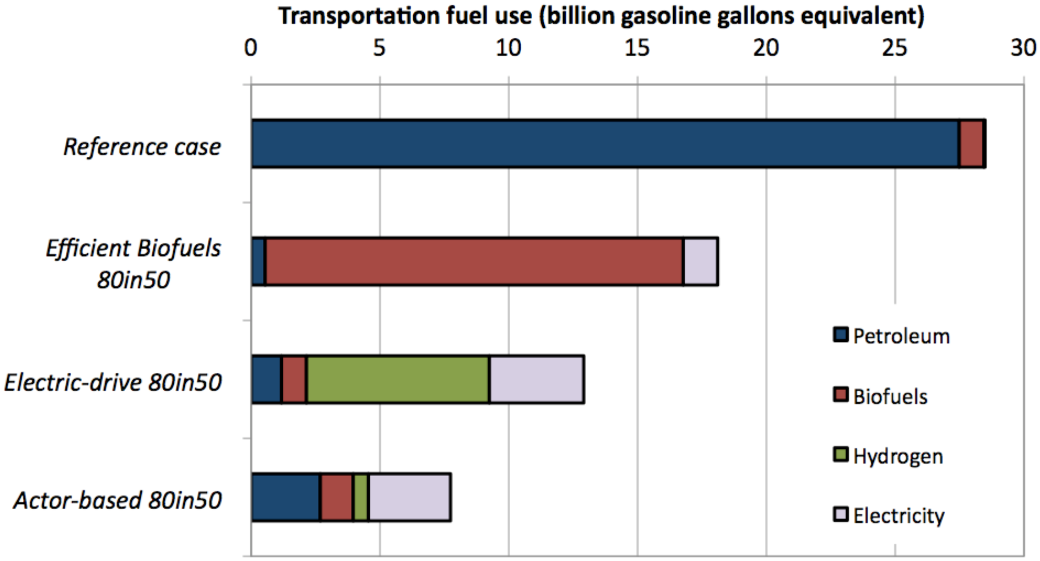


Figure 24 Transportation fuel use in 2050 by scenario (*Instate* emissions).

In the *Actor-based 80in50* scenario fuel use and primary resource use are dramatically reduced below the *Reference* scenario, and significantly beyond the reductions in *Efficient Biofuels 80in50* and *Electric-drive 80in50.* By reducing travel demand and increasing vehicle efficiency across all subsectors, a significant amount of both fuel and primary energy resources are saved. The *Actor-based 80in50* scenario reduces fuel requirements by almost 21 billion gge, or about 73%, compared to the *Reference* scenario, and by 40% and 57%, respectively, compared to *Electric-drive 80in50* and *Efficient Biofuels 80in50*. Similar percent reductions hold for primary resource consumption as well.

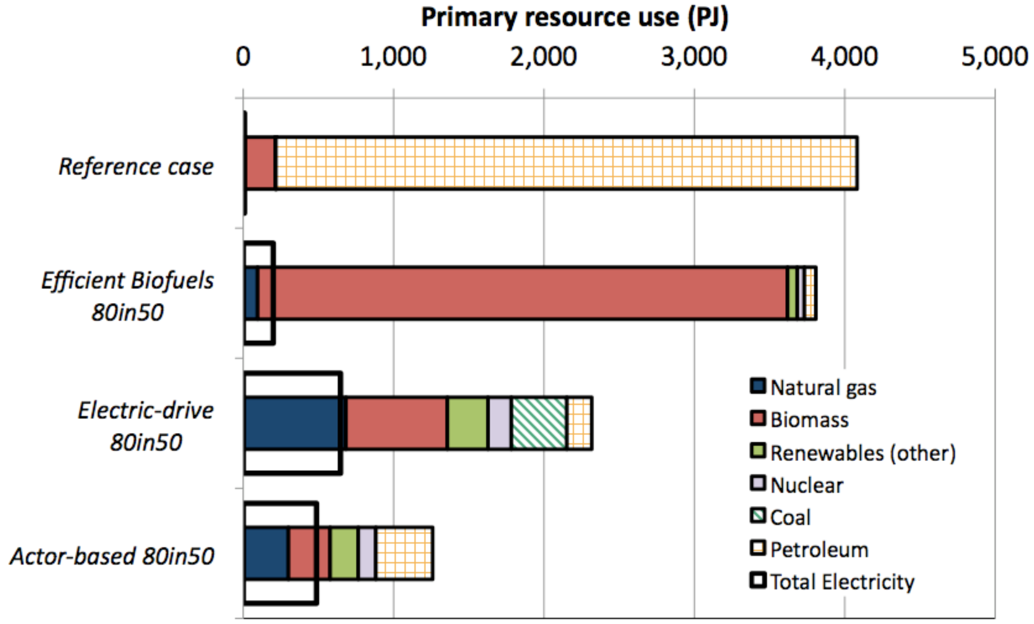


Figure 25 Primary resource consumption for the transportation subsector in 2050 by scenario (*Instate* emissions).

Table 7 compares the normalized Kaya parameters (population, transport intensity, energy intensity, and carbon intensity) by subsector for the *80in50* scenarios and the *Reference* scenario (1990 values = 1). Note that, even in the *Reference* scenario, aggregate energy intensity across all transportation subsectors is significantly less than in 1990—65% of the 1990 level. Through a combination of assumptions on increased vehicle efficiencies, greater use of more efficient electric-drive vehicles, and switching to less energy intensive transportation modes (e.g., bus, rail), each of the *80in50* scenarios extends far beyond that baseline improvement to reach the targeted reductions. Energy intensity is most noticeably reduced in the *Actor-based 80in50* scenario, where only 23% as much energy is required per unit of travel as compared to 1990. Much of this stems from a 90% reduction in energy intensity in the LDV subsector, which, combined with travel demand reductions, makes up for the higher relative carbon content of fuels and smaller emission reductions in the HDV subsector, compared to *Efficient Biofuels 80in50* and *Electric-drive 80in50*. Furthermore, the difference in relative fleet-average energy intensity between the two technology-driven scenarios is countered by a similar one in carbon intensity: Whereas energy intensity in *Electric-drive 80in50* is 29% *lower* than it is in *Efficient Biofuels 80in50* (E=0.29 vs. 0.41), the *Electric-drive 80in50* scenario has an average carbon intensity that is 40% *higher* than it is in *Efficient Biofuels 80in50* (C=0.28 vs. 0.20).

Table 7 Comparison of normalized Kaya parameters by subsector for *80in50* scenarios (1990 value = 1.00).

		P Population (Million people)	T Transport Intensity (passenger-miles/person)[1]	E Energy Intensity (MJ/passenger-mile)[1]	C Carbon Intensity (g CO2/MJ)	GHG emissions (Million tonnes CO2)
Light-duty	1990 value	29.8	13,685	3.9	92.0	145.29
	2050 (Reference)	2.00	1.21	0.53	1.00	1.27
	Efficient Biofuels 80in50	2.00	1.21	0.33	0.18	0.14
	Electric-drive 80in50	2.00	1.21	0.22	0.25	0.14
	Actor-based 80in50	2.00	0.75	0.10	0.33	0.05
	1990 value	29.8	925	12.1	90.3	30.00
	2050 (Reference)	2.00	1.09	1.33	1.06	3.06
	Efficient Biofuels 80in50	2.00	1.09	0.77	0.15	0.26
	Electric-drive 80in50	2.00	1.09	0.52	0.24	0.27
	Actor-based 80in50	2.00	2.22	0.25	0.60	0.67
	1990 value	29.8	226	4.6	90.6	2.82
	2050 (Reference)	2.00	2.38	0.84	1.05	4.21
	Efficient Biofuels 80in50	2.00	2.38	0.63	0.40	1.19
	Electric-drive 80in50	2.00	2.38	0.63	0.63	1.89
	Actor-based 80in50	2.00	1.89	0.44	0.45	0.76
Rail	1990 value	29.8	347	2.7	94.6	2.66
	2050 (Reference)	2.00	1.46	0.86	0.95	2.38
	Efficient Biofuels 80in50	2.00	1.46	0.69	0.16	0.33
	Electric-drive 80in50	2.00	1.46	0.42	0.06	0.08
	Actor-based 80in50	2.00	5.10	0.45	0.17	0.77
	1990 value	29.8	43	18.6	91.8	2.19
	2050 (Reference)	2.00	1.08	0.87	1.04	1.96
	Efficient Biofuels 80in50	2.00	1.08	0.65	0.19	0.27
	Electric-drive 80in50	2.00	1.08	0.65	0.61	0.86
	Actor-based 80in50	2.00	0.86	0.54	0.95	0.89
	1990 value	29.8	51	28.7	90.1	3.93
	2050 (Reference)	2.00	0.46	0.87	1.06	0.85
	Efficient Biofuels 80in50	2.00	0.46	0.65	0.40	0.24
	Electric-drive 80in50	2.00	0.46	0.65	0.47	0.28
	Actor-based 80in50	2.00	0.23	0.54	0.65	0.16
	1990 value	29.8	364	8.6	90.3	8.41
	2050 (Reference)	2.00	1.60	0.52	1.06	1.77
	Efficient Biofuels 80in50	2.00	1.60	0.47	0.40	0.59
	Electric-drive 80in50	2.00	1.60	0.47	0.21	0.31
	Actor-based 80in50	2.00	1.28	0.39	0.54	0.54
	1990 value	29.8	15,641	4.6	91.6	195.28
	2050 (Reference)	2.00	1.23	0.65	1.02	1.62
	Efficient Biofuels 80in50	2.00	1.23	0.41	0.20	0.20
	Electric-drive 80in50	2.00	1.23	0.29	0.28	0.20
	Actor-based 80in50	2.00	0.96	0.23	0.46	0.20

[1] Transport and energy intensities for heavy-duty trucks and freight rail vehicles are calculated on a vehicle-mile basis

6.3.5 Overall emissions

The discussion thus far has only considered *Instate* emissions (recall, *Instate* emissions refer to those resulting from trips that take place entirely within California's borders). The scenarios described above were designed to reduce *Instate* emissions 80% below 1990 levels by 2050. Yet, when *Overall* emissions are accounted (recall that these include *Instate* emissions and those resulting from half of all trips that either originate in, or are destined for, California), the *80in50* target is not met. *Overall* emissions include additional aviation and marine travel. When these trips are included, emissions are only reduced by 71% in *Efficient Biofuels 80in50*, 66% in

Electric-drive 80in50, and 73% in *Actor-based 80in50* (compared to 1990 *Overall* emissions). The discrepancy stems from two primary factors: (1) globalization is expected to drive significant travel demand growth in the aviation and large marine subsectors as people and goods are increasingly transported around the world and throughout the U.S., and (2) low-carbon fuels have limited application in the aviation and marine subsectors. While it is true that hydrogen and electricity may propel future airplanes or ships, the scenarios presented here generally assume that such technologies play limited roles in those subsectors in 2050 (perhaps for port/ground operations). In the scenarios presented here, the aviation and marine subsectors rely on petroleum or biofuels. The greater reduction in *Overall* emissions in the *Actor-based 80in50* scenario reflects the impact of demand reductions on *Overall* emissions.

The scope of California's GHG emissions regulations and national or international regulatory efforts are particularly important in estimating how far *Overall* emissions might be reduced. In the scenario modeling, it is assumed that emission reductions for *Instate* aviation and marine travel, and the strategies leading to those reductions (i.e., fuel switching, greater vehicle efficiencies, etc.), are applied equally to *Overall* (*Instate* and out-of-state) aviation and marine travel. However, this may not be the case if the two categories are not regulated similarly. For instance, one could imagine a situation in which California's regulations ensure that airplane flights within the state are fueled with low-carbon biofuels but, if other states/countries do not have similar regulations, the out-of-state flights might be fueled with higher carbon petroleum-based fuels.

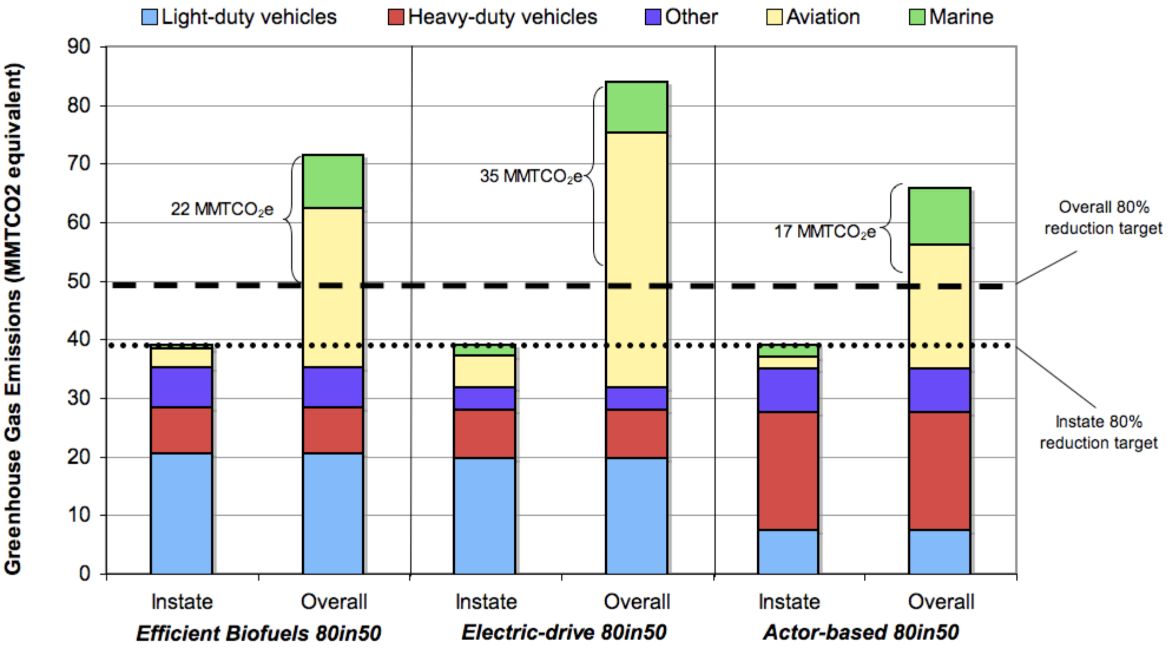


Figure 26 Comparison of Instate and Overall emissions by subsector for the 80in50 scenarios.

The difference in scenario emissions when accounting for *Overall* travel is illustrated in Figure 26. As the figure shows, *Overall* emissions are 83% greater than *Instate* emissions in the *Efficient Biofuels 80in50* scenario, 115% greater in *Electric-drive 80in50*, and 69% in *Actor-based 80in50*. These additional emissions are not accounted for in the *Instate 80in50* target and may require a national or international policy framework if they are to be mitigated. Also noteworthy is the dramatic increase in both share and absolute emissions from the aviation and marine subsectors in the *Overall* emissions case. Whereas aviation and marine account for no more than 18% of *Instate* emissions in the scenarios, they comprise between 47% and 62% of *Overall* emissions. In the *Electric-drive 80in50* scenario specifically, *Overall* aviation emissions alone exceed total *Instate* emissions, emphasizing the importance of reducing emissions from this subsector in the future.

The implications are daunting. If *Overall* emissions are to be reduced, dramatic changes are needed in the aviation and large marine subsectors, probably a combination of reductions in the growth in passenger and freight travel demand and in carbon and energy intensity. The *Actor-based 80in50* scenario addresses the discrepancy better than the other scenarios—by reducing travel demand, increasing efficiency, and utilizing a larger share of available biofuels in the aviation subsector—but still remains 17 $MMTCO_2e$ above the *Overall* 80% reductions target. The two technology scenarios highlight the consequences of increased travel demand in the aviation and large marine subsectors: Advances in other vehicle subsectors are largely erased by activity growth in air travel and domestic and international shipping by sea and air, unless low-carbon biofuels or hydrogen can be incorporated into those subsectors on a large scale.

6.4 Scenario discussion and conclusions

The scenario approach utilized in this study is helpful in thinking through how potential transportation futures in California could unfold and the impacts that various technology and policy strategies might have on reducing GHG emissions in the state. These scenarios should not be taken as predictions or forecasts of the future, however. While several scenarios are developed for this study, in reality an infinite number of year 2050 snapshots could be devised. The approach taken in this project was (1) to present a set of illustrative scenarios to make clear the level of emission reductions that might be feasible given a set of key technology and activity assumptions; and (2) to highlight tradeoffs among various technological and behavioral strategies.

The reader should recognize that any snapshot of the future is uncertain; in fact, the only certainty is that California's transportation sector in 2050 will not exactly resemble any of the scenarios that have been put forth here. The reader is free to decide which of these scenarios he/she believes is more plausible, keeping in mind that plausibility is a subjective quality that depends on one's views and biases about the future of technology development, society, the environment, and the economy. Any of the futures described in the three *80in50* scenarios could potentially unfold, but that none will materialize unless the right mix of strong policies, technological advances, and economics allow them to. This is where the largest uncertainties lie.

It should also be noted that the scenarios that are presented are not necessarily economically nor socially optimal. In this analysis, costs (of technologies, fuels, resources, emission reduction options, etc.) and availability of resources were not considered. Also. the full impacts that certain policies and strategies (e.g., higher density developments leading to reduced per-capita VMT, or the food vs. fuel dilemma) could have in California were not taken into account.

Also missing from this analysis is a consideration of dynamics. Only snapshots of California in 2050 have been looked at here; this analysis does not consider the timing of technology penetration, political action, or resulting emissions trajectories. Hence, it is inherently assumed that the various emission reduction strategies are introduced at the "right" time so that the transportation sector in 2050 eventually resembles the snapshots that are presented. For instance, while one scenario may assume that FCVs capture 50% of the LDV market in 2050, it does not specify when FCVs are introduced or how quickly they gain market share. There are constraints to how quickly energy infrastructure can change. While this analysis has not fully considered such constraints, reasonable judgments have been made and input from external experts has been sought in order to create plausible snapshots of the future. Future iterations of this study may consider dynamics.

The scenarios are unique in their sets of input assumptions—e.g., travel demand intensity and the vehicle technology and fuel mixes that are used to meet these demands in the various transportation subsectors. The modeling approach used in this study highlights the fact that the state's population (P), transport intensity (T) of each subsector, energy intensity (E) of vehicles, and carbon intensity (C) of fuels all have a role to play in reducing GHG emissions in California. However, it is important to note that each of the scenarios assumes population in 2050 (60 million) is twice the 1990 value (30 million). Though this assumption was held constant throughout the scenarios, emisisons are directly proportional to it. If population were to grow more or less rapidly, meeting the emission target would require more or fewer reductions, respectively, from the other parameters. In theory each of the Kaya parameters (P, T, E, C) has the potential to make an equal reduction in emissions, since the parameters carry equal weight in the decomposition equation (GHGs = P x T x E x C). In practice this is not likely to be the case. For example, it is hard to imagine a plausible scenario in which California's population does not increase between 1990 and 2050. The population growth rate is an uncertain variable that depends on social values, economic development, and immigration policies, among a number of other things. The extent to which it is affected by conventional transportation and land-use policies and technology development is not an issue that has been tackled in this analysis, so policies that attempt to "pull" the population "lever" are not considered here. In the face of a constantly increasing population in California, the responsibility for reducing GHG emissions necessarily falls on the other levers, whether they be behavioral (T) or technological (E, C) in nature. The maximum contribution of each is still an open question.

The scenarios highlight the potential for both technological and societal changes to reduce transportation GHG emissions in California. The *Efficient Biofuels 80in50* and *Electric-drive 80in50* scenarios offer two different technological visions of the future. Both show that absent any significant changes in social behavior, major breakthroughs in technology will be needed if the 80% reductions target is to be met; or conversely, if technology is able to "save the day", Californians can essentially preserve their current lifestyles and will be required to make very few changes in terms of their transportation choices (e.g., they can still drive their cars and take vacations via airplanes as much as, or even more than, they did in 1990). On the other hand, the *Actor-based 80in50* scenario shows that quite significant shifts in social and travel behavior (e.g., more carpooling, use of public transit, high-density land-use developments, etc.) are valuable components to a portfolio of mitigation options, especially if technology is not as successful in reducing carbon in transportation fuels.

Furthermore, the results of this analysis show that there are no "silver bullet" strategies for mitigating climate change. The *Silver Bullet* scenarios illustrate that a singular solution, such as an entirely hydrogen, electricity, or biofuels future, is unable to meet the 80% emission reductions target alone. The *80in50* scenarios make clear that a mixed strategy is necessary to mitigate GHG emissions in California's transportation sector.

With advances in battery storage technology, electric vehicles may eventually prove to be excellent options for the light-duty subsector; however, it is hard to imagine that long-distance airplanes or large marine vessels will ever be powered by electricity. Hydrogen arguably also suffers from limited applicability, but probably to a lesser extent. Biofuels, because they are liquids, are the most similar to current petroleum-based fuels, and assuming they can overcome certain hurdles (e.g., producing them at low cost and with low lifecycle GHG emissions and minimal food, water, and land-use impacts), are possibly the most broadly applicable of the various alternative fuel types. However, it remains to be seen whether biofuels can be used in all transportation applications (e.g., bio-based jet fuels currently face technical challenges), and land-use constrains conventional and advanced biofuels resources.

This study is the first to explore trade-offs and complements among various technological and behavioral strategies to achieve deep GHG emission reductions in California's transportation sector. The snapshot *80in50* scenarios provide a unique look at potential futures, highlighting potential emission reductions by strategy, subsector, and vehicle and fuel type. It is hoped that this analysis will be useful to policymakers (both inside and outside of California) trying to grapple with how their state can meet its ambitious goals. Of course, it is ultimately up to these elected officials to develop strong, durable policies that pull on the levers discussed here.

7. Policy considerations

The previous sections have provided snapshots of transportation futures in California that allow the state to meet its goal of an 80% reduction in greenhouse gas emissions by 2050. This ambitious target will require concerted efforts on the part of all stakeholders—government, multiple industries, and the public—and will demand strong, durable policy that aligns the interests and incentives of each. To this end, a number of current state and national policies already exist and are being implemented. Future policies, not yet devised, will also be needed. This section discusses both current and future policies that may be useful in helping California to meet its long-term emission reduction goal. It also identifies a number of policy gaps that, if not addressed, may impede the ability of the state to meet its GHG emission reductions target

7.1 Current California and U.S. policies

7.1.1 GHG emissions

California has been a leader in the development of policy and regulations that relate to reductions in GHG emissions from the transportation sector. A number of different policies exist that provide some incentive to various actors in the vehicle and fuels market for GHG reduction. The most overarching current policy is AB32, the Global Warming Solutions Act passed by

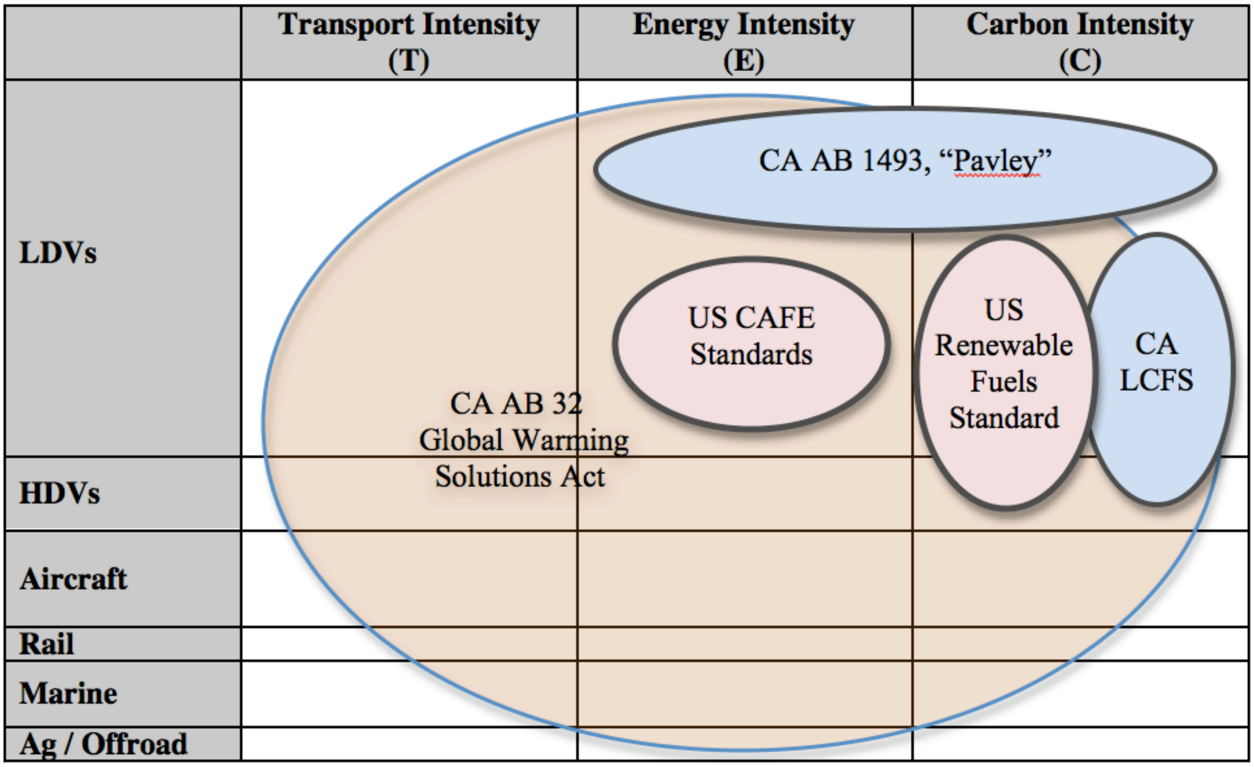
California in 2006. This law requires that total state GHG emissions be reduced to 1990 levels by 2020 and provides regulatory authority to the California Air Resources Board (CARB) to implement this bill. California executive order S-03-05 was actually signed before AB32 and called for the same target but also issued the long-term goal of 80% reduction of GHG emissions below 1990 levels by 2050, which this study is based upon. Though these are not transportation-specific policies, transportation emissions would be subject to the resulting regulations, and it appears likely that these policies may ultimately take the form of a cap and trade system. Other specific policies to address transportation emissions include AB1493 (or the Pavley Bill), which requires automakers to meet GHG intensity (gCO_2e/mile) standards for new cars and trucks. AB1493 is more specific at targeting GHGs than the conventional fuel economy standards that apply to all U.S. cars and trucks via the Corporate Average Fuel Economy (CAFE) program; these standards were recently raised as outlined in the Energy Security and Independence Act (EISA) of 2007. However, any improvements in fuel economy (i.e., reductions in energy intensity) will help reduce GHG emissions as well. Finally, the Low Carbon Fuel Standard (LCFS) Program was started as a result of the Governor's Executive Order S-01-07 in 2007 and calls for a reduction in carbon intensity of transportation fuels by 2020. It appears that this standard will initially apply to fuels for on-road vehicles (i.e. not marine, off-road or aviation fuels).

7.1.2 Alternative fuels

The U.S. Renewable Fuels Standard (RFS), which promotes the use of biofuels, was originally adopted in 2005 and called for 7.5 billion gallons of renewable fuel to be used in the U.S. by 2012. It was then amended in EISA 2007 to add a new target of 36 billion gallons of renewable fuels by 2022. In California, the Bioenergy Action Plan (executive order S-6-06) sets minimum targets for the use of bioenergy and biofuels, requiring a growing fraction of consumption to be derived from instate production (20% by 2010, 40% by 2020 and 75% by 2050).

As a result of another bill, AB1007, California devised an alternative fuels plan and also developed a lifecycle fuel model to assess the GHG emissions, energy and other environmental impacts associated with the production and use of alternative fuels. Similarly, AB118 authorizes the use of a substantial amount of state money to fund new vehicle and fuel technologies that reduce GHG emissions and meet sustainability criteria. One of the older, and more well-known, programs relating to the use of alternative fuels and vehicle technologies is the zero emissions vehicles (ZEV) program originally enacted in 1990, which mandated the production and sale of cars that would not produce any tailpipe or evaporative emissions. While it did not specifically require alternative fuels, the only vehicle technologies and fuels that could have conceivably met such a requirement were vehicles that ran on alternative fuels (i.e., electricity or hydrogen). This program has since been modified to include PHEVs (which are not true ZEVs but still offer near-zero emissions) in order to incentivize the adoption of vehicles that use an alternative fuel (electricity).

7.2 Policy gaps and challenges



Notes: -Size of box indicates relative emissions contribution in 1990 (*Overall* case).
-AB32 applies to the entire matrix, but there are currently no specific mechanisms targeting all subsectors

Figure 27 Policy matrix of transportation subsectors and Kaya parameters for current GHG emissions reduction policies in California.

7.2.1 Subsector gaps

At the present time, both of the vehicle-efficiency related emissions regulations (AB1493 and CAFE) in California that can help to reduce GHG emissions apply to light-duty vehicles only; as has been stated, this amounts to about two-thirds of the state's *Instate* emissions and half of its *Overall* emissions. While tackling emissions in the LDV subsector is critical, there is a sectoral gap for regulations that can improve vehicle efficiencies in the other transportation subsectors (i.e., heavy-duty vehicles, aircraft, marine, rail and the agricultural and off-road subsectors).

Figure 27 shows the current policies as they are applied to specific transportation subsectors. With respect to fuel carbon intensity, the current regulations on alternative fuels, such as the RFS, Bioenergy Action Plan, AB1007 and LCFS, are applicable to on-road transportation fuels and as a result, bridge the gap to other subsectors, but policies targeting vehicle efficiency in these other subsectors are still lacking. There are many reasons for the lack of such standards, including the diversity of vehicle types and their applications, which would make regulating all of these vehicles very complicated. However, this is a challenge that should be addressed in policy. As this study has demonstrated, reducing energy intensity and carbon intensity in all of the subsectors is needed in order to reach the state's long-term goals. Finding ways to address the subsectors is needed in order to reach the state's long-term goals. Finding ways to address emissions from each of the subsectors (particularly, the fast-growing aircraft and heavy-duty vehicle markets) is also critical. And in the event that advanced technologies with low-carbon fuels, such as hydrogen and electricity, face challenges in being applied in these other subsectors, low-carbon biofuels and higher vehicle efficiencies will be all the more critical.

7.2.2 Mitigation option gaps

Figure 27 also shows the current policies as they are applied to specific Kaya-related mitigation options (reducing T, E, or C). While there are specific policies and measures that can contribute to the implementation of AB32 GHG reductions in the transportation sector, including the LCFS that helps tackle fuel carbon intensity (C) and AB1493 which will likely address vehicle energy intensity (E), there are no current regulations or proposals that address the issue of reducing transportation activity (T) or population (P). Transportation activity is a lever that policy can attempt to pull, though it is a particularly challenging area compared to the E and C parameters. Regulations with technical intensity targets, such as the LCFS or AB1493, will lead to improved vehicle technologies and fuels that can meet the targets presumably without any significant loss of utility or value to the consumer; in fact, considering the potential for better air quality and quieter vehicles, and the possibilities for mobile electricity, consumer utility could be higher. However, addressing transport intensity as a key driver for GHG emission reductions is inherently complicated by manifold factors, such as land use planning, layout of the built environment and natural landscape, availability of alternative modes of transport for people and freight, the contribution of transportation to economic well-being, the location of goods production relative to consumption, and personal choices and preferences, all of which influence transport activity, the value of mobility to consumers and the economic value for transportation and goods movement. While urban planning and transportation demand management have been the subject of academic study and professional practice for many years, they still remain critical areas that deserve additional research and policy support if effective strategies are to be developed that reduce transport intensity without impacting mobility, thereby reducing transport-related GHG emissions while preserving or even improving the quality of life of California's citizens. This study has shown that unless technology can "save the day", with very low-carbon fuels and high-efficiency vehicle technologies deeply penetrating each of the transportation subsectors by 2050, travel demand must be constrained fairly significantly if the state is to have any hope of meeting its long-term emission reduction goals.

7.2.3 Instate vs. Overall emissions regulations

AB32, the Global Warming Solutions Act, regulates GHG emissions from all sectors of the state's economy. But in transport, this poses a dilemma since California does not exist in isolation, and millions of vehicle trips are made across the state's borders (by car, truck, bus, plane, train, rail, and so on) every year. In this study, the focus has been primarily on *Instate* emissions (trips taking place entirely within California's borders), though a discussion of *Overall* emissions (*Instate* emissions + half of all trips originating or terminating in California) is presented in section 6.3.5. At the present time ARB is focusing their regulations just on *Instate* emissions. It is not clear whether AB32 applies to (and ARB has jurisdiction over) these trips that cross state boundaries, but by not including emissions generated from these trips, a significant quantity of GHGs that the state is still responsible for generating is not being regulated. Moreover, as this study shows, the demand for out-of-state travel is growing faster than the demand for in-state travel, particularly due to increased demand for personal air travel and freight movement and reducing GHGs from these market segments will be a particular challenge. However, ignoring these emissions on paper does not make them disappear from the atmosphere and policies will need to be developed (perhaps at the national and international level) to address them.

7.2.4 Time scales

With policy, the issues of timing are critically important, as the time-scales required for decarbonizing the state's energy system will be long. Vehicles have long lifetimes and may not be retired for 15 years or more. Fuels supply infrastructure also will take decades. These time-scales may be short, however, in comparison to those required for land-use planning and restructuring of the built environment, the kind of development and societal changes needed to reduce the demand for travel. Policymakers should consider these long time-scales when prioritizing the GHG mitigation options they have in front of them. As this study demonstrates, all strategies will be needed to some degree, and action will likely be required across all fronts. But given the challenges and time-scales associated simply with getting policies enacted, the strategies that take the longest to implement should garner the most near-term focus. This implies increased funding and policy support for transportation research (both for vehicle technologies and fuels, but also urban planning and transportation demand management). It also argues for a continuation of California's policies that attempt to bring alternative fuel vehicles to market, as well as incentives geared toward the purchase and use of those vehicles and fuels, while recognizing that it will take a long time for the fleet to turn over and the positive impacts to be seen. Given the inherent uncertainties of technological development over these long time-scales, policymakers should avoid "picking winners", but must also be mindful of overhyping or becoming disillusioned by promising technologies. Policymakers should specifically consider strategies that have positive co-benefits. For example, modifying the state's current land-use policies can encourage mixed-use, higher density developments that require less reliance on cars; the co-benefits of such developments could include reduced local air and noise pollution, decreased congestion, and perhaps even greater health and happiness among individuals. And again, because of the time it will take to implement such land-use changes in California, policymakers need to be considering such policies in the very near-term.

7.2.5 Biofuels policy

This analysis highlights the fact that if biofuels are a primary means of reducing California's transportation GHG emissions, the quantity of biofuels demand will likely be quite substantial and will greatly exceed the waste biomass resource supply of the state, and potentially the supply of imported biofuels (given that other states and countries will also be competing for biofuels at the same time). In the scenarios that employ multiple mitigation strategies, where biofuels are just one component of a broader approach to GHG emission reductions, instate biofuels supply from waste resources might be able to handle the lower levels of demand, but only when considering instate travel. Including the rapidly growing demand for out-of-state travel, primarily from aviation and marine, in these low biofuel scenarios causes biofuels demand to exceed feasible supply from waste biomass resources. This may require the production of biofuels from dedicated energy crops and the importation of biofuels from other states or nations.

Several policy considerations come out of these results. First, policy will have to deal with the issue of land use change (LUC) with respect to the production of biofuels. Using only waste biomass to produce biofuels may eliminate these issues, but the quantities of biofuels demanded may exceed the amount that can be produced from these resources. Policy will need to be implemented that can incentivize the production of biofuels with little or no associated direct and indirect land use changes and this policy will need to address the significant uncertainty surrounding this topic. Also, the production of biofuels beyond the amount that can be supplied from waste biomass resources in the state can lead to a conflict between food and fuel production. Policies may be needed to address this conflict and also to promote more advanced biofuels production methods, such as biofuels from algae or other methods that do not occupy agricultural land. Research into these advanced technologies is at an earlier stage than for cellulosic biofuels production, though the U.S. Department of Energy is currently funding some projects.

7.3 Policy summary

The development of durable and robust policies to address the challenges associated with reducing GHG emissions from a diverse and ubiquitous transportation sector is not easy. A number of policy gaps have been identified that, if not addressed, may impede the ability of the state to meet its GHG emission reductions target. These include gaps in policy that insufficiently address emissions reductions in specific transportation subsectors beyond LDVs and fail to address specific drivers (namely transport intensity) for GHG emissions growth. The current policy landscape is a mix of high-level regulations (such as AB32, an economy-wide target) and specific technology performance standards (e.g., AB1493 and LCFS). One of the major challenges associated with broadly applied, high-level policy approaches to achieve GHG reductions in the transportation sector is that economy-wide GHG regulations such as carbon taxes and cap-and-trade do not appear to adequately incentivize the development and adoption of many of the advanced technologies described in this report. This is because the marginal cost of reducing emissions from the transportation sector (vehicle technologies and fuels) is often much higher than the cost of reductions from other sectors (e.g., electric generation). Targeted policies such as performance standards that target vehicle or carbon intensity need to be developed to address each individual transportation subsector; these can bring about specific desired changes since they are able to limit scope and target specific vehicles or fuels. This kind of targeted approach will likely be needed to address the gaps described above. Policy must also consider time-scales. If the world of 2050 is to resemble the snapshot scenarios described in this analysis, with the deep penetration of advanced technologies and fuels or the dramatic reductions in travel demand, then policy must act in the very near-term to bring these futures to reality. Biofuels policies must take into account the uncertainties and informational challenges associated with a diversity of methods for producing biofuels (including growing methods, natural and industrial inputs, local conditions) and direct and indirect land use change. These policy challenges and gaps are daunting but California is addressing many of these issues to develop the appropriate incentives that reward sustainable fuels production that truly reduce lifecycle fuel and vehicle GHG emissions.

8. Study conclusions and future research needs

A number of important conclusions were reached in the course of researching California's transportation greenhouse gas emissions and potential mitigation options, developing the model, and analyzing scenarios for achieving an 80% reduction goal in 2050. The following list describes the study's main conclusions:

1. *The modified Kaya equation is a useful decomposition that highlights the major drivers of transportation GHG emissions and the targets for mitigation options: population, transport intensity, energy intensity and carbon intensity.*
2. *Very low carbon intensity alternative fuels (biofuels, hydrogen and electricity) appear to be 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.*
3. *There is significant potential for greatly improved vehicle efficiency (reduced E) for use in all of the transportation subsectors.*
4. *The business-as-usual Reference scenario exhibits large growth in GHG emissions (63%) due to growth in population (P) and transport intensity (T).*
5. *The Silver Bullet (SB) scenarios show that while many mitigation options can yield moderate GHG reductions, no single mitigation option or strategy can meet the 80% reduction goal individually.*
6. *Three distinct 80in50 scenarios are presented that meet the 80% reduction goal in different ways, and they show that meeting the goal is a challenging prospect and requires very extensive penetration of advanced technologies and low carbon fuels.*
7. *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.*
8. *Biofuels are probably most applicable across all transportation subsectors. However they can only be made from biomass and are likely to be limited by biomass resource availability and may also be limited by land use change (LUC) impacts, which may reduce or negate their GHG benefits.*
9. *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 by their applicability to all of the transportation subsectors (especially aviation, marine and off-road).*

10. *Slowing the growth in travel demand (i.e., reducing transport intensity, (T) can help reduce the extent to which technological advances will be required to reduce the amount of carbon emitted per mile of travel (ExC).*

11. *It is more challenging to meet the 80% reduction goal with Overall 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.*

12. *Current policies only address some of the transportation subsectors and do not currently address options for reducing travel demand. These gaps may impede the development of options to address transportation GHGs.*

8.1 80in50 project summary

This report investigates how California may reduce transportation GHG emissions 80% below 1990 levels by 2050. The project used a variation of the Kaya framework that decomposes GHG emissions into four major drivers—population, transport intensity, energy intensity and carbon intensity. The project also analyzed each of the transportation subsectors, including LDVs, HDVs, aviation, rail, marine, agriculture, and off-road and an extensive literature review was performed to understand the potential for efficiency improvements, fuel switching, mode switching, and other mitigation options in each of these subsectors. This review provided input parameters that were organized and implemented within the Long-term Evaluation of Vehicle Emission Reduction Strategies (LEVERS) spreadsheet model. Scenarios were defined by a series of input assumptions that detailed the efficiencies of a wide range of vehicle technologies and the carbon intensity of a wide range of fuels, as well as the extent to which they were used in each subsector.

Three types of scenarios were developed. The *Reference* scenario investigated a business-as-usual case where historical trends in population and transport activity continued and reducing emissions was not a priority, and provided a baseline for measuring emission reductions in the other scenarios. This scenario featured a modest reduction in energy intensity—associated with improving vehicle efficiency—and static carbon intensity relative to 1990 levels. The *Reference* scenario showed a significant increase in *Instate* GHG emissions (+63%) relative to 1990. The *Silver Bullet* scenarios describe the extent to which specific technologies or approaches can reduce emissions when applied individually. Though many of the *Silver Bullet* scenarios show moderate reductions in emissions, none of them were able to meet the 80% GHG reductions target. This demonstrates the need for a combination or portfolio of mitigation approaches (including efficiency, advanced vehicle technologies, low-carbon fuels and travel demand reductions) in order to meet the ambitious emission reductions target, which is also seen in the *80in50* scenarios. Three *80in50* scenarios are discussed in detail, which describe futures in which the 80% reductions target is met. Two of the scenarios are defined as technology-driven (*Efficient Biofuels 80in50* and *Electric-drive 80in50*), in which the primary mechanisms for GHG reductions are improvements in vehicle efficiency and reductions in fuel carbon intensity. Transportation demand, on the other hand, continues to increase at business-as-usual rates in these two scenarios. The other *80in50* scenario is defined as an actor-driven scenario (*Actor-*

based 80in50), in which significant reductions in transportation demand take place. Yet, even in this scenario major advancements in efficient vehicle technologies are necessary; vehicle efficiencies improve dramatically but alternative fuels do not play a major role. The *Actor-based 80in50* scenario illustrates that even after reducing the demand for transportation, it is imperative that vehicles continue to decrease the amount of carbon they emit per mile of travel if the GHG reduction targets are to be met.

8.2 80in50 project conclusions

An 80% reduction in GHG emissions from the California transportation sector is quite challenging but most importantly, potentially feasible. While the *Silver Bullet* scenarios show that no one mitigation option that can singlehandedly meet the target goal, the *80in50* scenarios show that the goal can be met in multiple ways, utilizing a combination of technological and behavioral options. One of the main barriers to meeting the target, however, is the relentless growth of total transport activity, which is a combination of growing population and per-capita transport intensity (PxT). Vehicle and fuel technologies (E, C) will be relied upon heavily to reduce emissions in the future. Even if per-capita transport intensity is halved by 2050, the projected doubling of population would keep total activity levels (PxT) constant at 1990 levels, and the carbon intensity of travel (ExC, grams CO_2e/mile) would have to be reduced by 80% for the GHG target to be met. Since it is unlikely that carbon will be entirely eliminated from transport and since some subsectors may fall well short of the 80% reductions target on their own, some subsectors (e.g., LDV) will have to play a more significant role. Ultimately, action is needed on all fronts since some strategies have limited applications in certain subsectors. Low-carbon fuels (biofuels, hydrogen, and electricity) and more efficient vehicle technologies (including improvements to conventional vehicle technologies, BEVs, FCVs, and PHEVs) should be introduced wherever feasible. And demand should be reduced to the extent possible. Reducing the demand for motorized travel has side benefits in the form of reduced air pollution, congestion, noise, and perhaps even in the mental and physical health of travelers. But finding ways to make these reductions, particularly in the areas of personal air travel and freight travel (truck, sea, air), may prove difficult in an increasingly globalized world.

The “across the board” approach for mitigating GHG emissions necessitates continued research and policy support for both technological and behavioral fixes. While research is ongoing, the latter strategy is not well enough understood and deserves significant attention and study. Behavioral changes, and policies promoting them, are critically important to alleviate dependence on future technology developments and breakthroughs. Whether or not transportation will ultimately be required to reduce its emissions by 80% is not certain. Deep, long-term reductions are not yet law, and it remains to be seen how near-term limits (i.e., AB32) are implemented; reductions will likely not be implemented equally across sectors. But while it may prove to be less expensive to reduce emissions from other sectors (e.g., power generation, industrial, agriculture and forestry, etc.), as the largest contributor of GHG emissions in the state, transportation must still play a major role if significant GHG emission reductions are to be achieved.

It is likely that between 1990 and 2050 relative emissions among subsectors will shift as large reductions in some subsectors make them less important, and vice-versa. For example, virtually all of the emission reduction strategies (biofuels, hydrogen, electricity, travel demand reduction) can be applied to the light-duty subsector, so this subsector might be one of the cleaner subsectors in the future and make up a small share of California's total transportation emissions, even though LDVs made up the largest share in 1990. In contrast, unless air travel demand is reduced and low-GHG biofuels are feasible, the aviation subsector could someday become the largest contributor to GHG emissions in the state.

The advantage of biofuels over other types of alternative fuels is that they are the most chemically similar to conventional petroleum-based fuels and can be used in conventional and advanced engines. As a result, they can be used in a greater number of subsectors—in particular, long-distance aviation and large marine vehicles, where other alternative fuels (hydrogen and electricity) may face challenges to their use. However, it should be noted that bio-based jet fuels currently face technical challenges. In addition, biofuels must overcome several significant hurdles before they are able meet the total demands of California or the U.S. (e.g., producing them at low cost and with low lifecycle GHG emissions and minimal food, water, and land-use impacts). Also, and very importantly, resource constraints could be a problem if biofuels are to play a significant role in powering transportation.

Though this analysis focuses mainly on the *Instate* emissions (emissions generated from trips taking place entirely within California), the results of all of the scenarios show that meeting an 80% reduction for *Overall* emissions (*Instate* emissions + those resulting from half of all trips that either originate in, or are destined for, California) is more challenging. The main issue stems from the greater importance of the aviation and marine subsectors in out-of-state travel and the inherent challenge of decarbonizing these two subsectors relative to other subsectors.

8.3 Future work and research needs

As previously mentioned, the purpose of this project was to paint snapshot pictures of what the transportation sector might look like in California in the year 2050 and how an 80% reduction in emissions could be structured. This analysis, which is meant to begin the discussion about the primary drivers and sectoral components of long-term transportation emissions in California, is the first step in a series of steps needed to improve the understanding of how to reduce GHG emissions. More research is needed to better understand what technologies and fuels and structural and behavioral changes can be used in each of the transportation subsectors. Further research is also needed to address policy gaps and the long timescales associated with vehicles and the built environment. Finally, the interaction of the transportation sector and other energy sectors must be better understood if GHG emissions reductions are to be reduced efficiently.

As a simple scenario analysis, this study does not include a number of important factors, such as the proper timing of technologies, policies, and other emission reduction strategies estimated. Also missing from the current analysis is economics (i.e., costs and prices of technologies, fuels, resources, etc.). Future analytical work that will extend this analysis will incorporate economics and dynamics using an energy systems optimization model, TIMES (The Integrated Markal Efom System), to conduct scenario and policy analysis and understand how its energy system (including all energy sectors) might evolve over time in the most economically efficient (least cost) way possible, subject to constraints on technologies, policies, resources, etc.

9. References

1. IPCC, *Climate Change 2007 - Fourth Assessment Report*. 2007, Intergovernmental Panel on Climate Change: Geneva.
2. Cayan, D.R., E.P. Maurer, M.D. Dettinger, M. Tyree, and K. Hayhoe, *Climate change scenarios for the California region.* CLIMATIC CHANGE, 2008. **87**: p. S21-S42.
3. Hayhoe, K., D. Cayan, C. Field, P. Frumhoff, E. Maurer, N. Miller, S. Moser, S. Schneider, K. Cahill, E. Cleland, L. Dale, R. Drapek, R. Hanemann, L. Kalkstein, J. Lenihan, C. Lunch, R. Neilson, S. Sheridan, and J. Verville, *Emissions pathways, climate change, and impacts on California.* Proceedings of the National Academy of Sciences, 2004. **101**(34): p. 12422-12427.
4. CalEPA, *Climate Action Team Report to Governor Schwarzenegger and the California Legislature*. 2006, California Climate Action Team.
5. Hu, P.S. and T.R. Reuscher, *Summary of Travel Trends, 2001 National Household Travel Survey*. 2004, US Department of Transportation, Federal Highway Administration. p. 135.
6. Kaya, Y. *Impact of Carbon Dioxide Emission Control on GNP Growth: Interpretation of Proposed Scenarios*. in *Paper presented to the IPCC Energy and Industry Subgroup, Response Strategies Working Group*. 1990. Paris.
7. Ehrlich, P.R. and J.P. Holdren, *Impact of Population Growth.* Science, 1971. **171**: p. 1212-17.
8. Yang, C. and S. Schneider, *Global Carbon Dioxide Emissions Scenarios: Sensitivity to Social and Technological Factors in Three Regions.* Mitigation and Adaptation Strategies for Global Change, 1997. **2**(4): p. 373-404.
9. Bongaarts, J., *Population growth and global warming.* Population and Development Review, 1992. **18**: p. 299-319.
10. IPCC, *Special Report on Emissions Scenarios*, ed. N. Nakicenovic and R. Swart. 2000, Cambridge, UK: Cambridge University Press. 612.
11. CA DOF. *Population Projections by Race / Ethnicity, Gender and Age for California and Its Counties 2000–2050*. 2007 July 2007 [cited; Available from: http://www.dof.ca.gov/html/DEMOGRAP/ReportsPapers/Projections/P3/P3.php.
12. Greene, D.L. and A. Schafer, *Reducing Greenhouse Gas Emissions from U.S. Transportation*. 2003, Pew Center on Global Climate Change. p. 68.
13. Kahn Ribeiro, S., S. Kobayashi, M. Beuthe, J. Gasca, D.L. Greene, D.S. Lee, Y. Muromachi, P.J. Newton, S. Plotkin, D. Sperling, R. Wit, and P.J. Zhou, *Transport and its infrastructure*, in *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, B. Metz, et al., Editors. 2007, Cambridge University Press: Cambridge, England.
14. Leighty, W., C. Yang, J. Ogden, *Advanced ICE Vehicles: An Assessment of the Technologies for Next Generation Vehicles*, in *Advanced Energy Pathways (AEP) Project, Task 4.1 Technology Assessments of Vehicle Fuels and Technologies*. 2008, Public Interest Energy Research (PIER) Program, California Energy Commission.

15. Kromer, M.A. and J.B. Heywood, *Electric Powertrains: Opportunities and Challenges in the US Light-Duty Vehicle Fleet*, S.A. Laboratory, Editor. 2007, MIT: Cambridge, MA. p. 153.
16. Wang, M.Q., *GREET 1.8a*. 2007, Argonne National Lab. p. Greenhouse gases, Regulated Emissions and Energy Use for Transportation (GREET) Model.
17. NRC, *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards*, N.A. Press, Editor. 2002, National Research Council: Washington DC.
18. EPA, *Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2006*. 2006, Office of Transportation and Air Quality, US Environmental Protection Agency.
19. Greszler, A. *Heavy Duty Vehicle Technology* in *Asilomar 2007: Transportation and Climate Policy* 2007. Pacific Grove, CA.
20. Ang-Olson, J. and W. Schroeer. *Energy Efficiency Strategies for Freight Trucking: Potential Impact on Fuel Use and Greenhouse Gas Emissions*. in *81st Annual Meeting of the Transportation Research Board*. 2003.
21. Frey, C., and Po-Yao Kuo, *Best Practices Guidebook for Greenhouse Gas Reductions in Freight Transportation*. 2007, North Carolina State University.
22. IUR. *Energy Efficiency Technologies for Railways*. 2008 [cited; Available from: http://www.railway-energy.org/tfee/index.php.
23. Greener by Design, *Mitigating the Environmental Impact of Aviation: Opportunities and Priorities*. 2005, Royal Aeronautical Society.
24. DOT, U.S., *Table 4-21: Energy Intensity of Certified Air Carriers, All Services*, N.T. Statistics, Editor. 2007, Research and Innovative Technology Administration, Bureau of Transportation Statistics.
25. DOT, U.S., *Air Carrier Profile*, N.T. Statistics, Editor. 2007, Research and Innovative Technology Administration, Bureau of Transportation Statistics.
26. Kroo, I., *Future Technology and Aircraft Types*, Stanford University.
27. NRC, *Securing the Future of U.S. Air Transportation: A System in Peril*. 2003: National Research Council.
28. Marintek, *Study of Greenhouse Gas Emissions from Ships*. 2000, International Maritime Organization. p. 169.
29. ARB, *California GREET Model* 2007.
30. Brandt, A., and Alexander Farrell, *Dynamics of the Oil Transition: Modeling Capacity, Costs, and Emissions*, U.o.C.E.I. (UCEI), Editor. 2008, Energy and Resources Group, University of California, Berkeley.
31. Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T. Yu, *Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change.* Sciencexpress, 2008.
32. Delucchi, M. *Lifecycle Analysis of GHG Emissions from Biofuels*. in *STEPS Research Symposium*. 2008. University of California, Davis.
33. Jenkins, B.M., *A roadmap for the development of biomass in California*, C.E. Commission, Editor. 2006, California Biomass Collaborative: Davis, CA.
34. Ewing, R., K. Bartholomew, S. Winkelman, J. Walters, and D. Chen, *Growing Cooler: The Evidence on Urban Development and Climate Change* 2007, Chicago, IL: Urban Land Institute.

35. Perlak, R., L. Wright, A. Turhollow, R. Graham, B. Stokes, and D. Erbach, *Biomass as a Feedstock for a Bioenergy and Bioprocessing Industry: The Technical Feasibility of a Billion-Ton Annual Supply*, in *Joint Study sponsored by USDOE and USDA*. 2005, Oak Ridge National Laboratory.
36. NRDC, *Growing Energy: How Biofuels Can Help End America's Oil Dependence*. 2004, National Resources Defense Council.
37. NRC, *Transitions to Alternative Transportation Technologies—a Focus on Hydrogen*, in *Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies*. 2008, National Research Council.
38. CA DOF. *Top Countries Ranked by its Gross Domestic Product, California's World Ranking*. 2008 [cited; Available from: http://www.dof.ca.gov/HTML/FS_DATA/LatestEconData/FS_Misc.htm.
39. CEC, *Energy Almanac - Statistics and Data on Ethanol and E85 as Transportation Fuels*. 2008, California Energy Commission.
40. DOT, *National Transportation Statistics*. 2007, Bureau of Transportation Statistics (BTS), US Department of Transportation.
41. EIA, *Annual Energy Outlook 2007 with Projections to 2030*. 2007, US Department of Energy (DOE), Energy Information Administration (EIA).
42. US Census Bureau. *U.S. Interim Projections by Age, Sex, Race, and Hispanic Origin: 2000-2050*. 2008 [cited Table 1a Available from: http://www.census.gov/population/www/projections/usinterimproj/.
43. IEA, *Biofuels for Transport: An International Perspective.* 2004, International Energy Agency.

APPENDIX A. DETAILED SCENARIO ASSUMPTIONS

A.1 Transport intensity (T) assumptions by scenario and sector

Units = miles/person (unless specified otherwise)	**1990 Historical Values**	**2050 Scenarios**									
		Reference	***Moderate efficiency SB***	***High efficiency SB***	***Hydrogen -intensive SB***	***Electricity -intensive SB***	***Biofuel-intensive SB***	***PMT SB***	***Efficient Biofuels 80in50***	***Electric-drive 80in50***	***Actor-based 80in50***
LDVs											
Gasoline ICEs	13,685	16,559	16,559	16,559	4,140	0	6,624	8,121	0	0	0
Biofuel ICEs	0	0	0	0	0	0	9,935	0	12,419	0	0
Diesel ICEs	0	0	0	0	0	0	0	183	0	0	0
Gasoline PHEVs	0	0	0	0	0	8,279	0	0	0	4,140	5,137
Biofuel PHEVs	0	0	0	0	0	0	0	0	4,140	0	0
Diesel PHEVs	0	0	0	0	0	0	0	0	0	0	3,082
H2FCVs	0	0	0	0	12,419	0	0	0	0	8,279	1,027
Battery EVs	0	0	0	0	0	8,279	0	0	0	4,140	1,027
Total LDV PMT per capita	**13,685**	**16,559**	**16,559**	**16,559**	**16,559**	**16,559**	**16,559**	**8,304**	**16,559**	**16,559**	**10,273**
LDV passengers per vehicle	1.66	1.66	1.66	1.66	1.66	1.66	1.66	2.49	1.66	1.66	2.08
LDV VMT per capita	8,244	9,975	9,975	9,975	9,975	9,975	9,975	3,325	9,975	9,975	4,948
HDVs											
Buses	**530**	**393**	**393**	**393**	**393**	**393**	**393**	**2,053**	**393**	**393**	**1,651**
Diesel, Gasoline, and Other ICE/HEV	530	393	393	393	79	0	393	2,053	294	0	165
Diesel & Gasoline PHEVs	0	0	0	0	0	157	0	0	0	0	413
Biofuel PHEVs	0	0	0	0	0	0	0	0	98	0	83
H2FCVs	0	0	0	0	314	0	0	0	0	196	165
Battery EVs	0	0	0	0	0	236	0	0	0	196	826
Heavy Trucks	**394**	**612**	**612**	**612**	**612**	**612**	**612**	**398**	**612**	**612**	**398**
Diesel	394	612	612	122	61	0	245	398	0	0	0
Diesel HEV	0	0	0	489	0	551	0	0	0	0	278
Biofuel HEVs	0	0	0	0	0	0	367	0	612	0	40
H2FCVs	0	0	0	0	551	0	0	0	0	550	40
Battery EVs	0	0	0	0	0	61	0	0	0	61	40
Total HDV PMT per capita	**925**	**1,004**	**1,004**	**1,004**	**1,004**	**1,004**	**1,004**	**2,450**	**1,004**	**1,004**	**2,049**

Units = miles/person (unless specified otherwise)	**1990 Historical Values**	**2050 Scenarios**									
		Reference	***Moderate efficiency SB***	***High efficiency SB***	***Hydrogen -intensive SB***	***Electricity -intensive SB***	***Biofuel-intensive SB***	***PMT SB***	***Efficient Biofuels 80in50***	***Electric-drive 80in50***	***Actor-based 80in50***
Bus passengers per vehicle	21	21	21	21	21	21	21	32	21	21	27
Aircraft											
Passenger Aviation - Instate	**190**	**165**	**165**	**165**	**165**	**165**	**165**	**82**	**165**	**165**	**132**
Gasoline	61	33	33	33	33	33	0	16	8	16	13
Jet Fuel (kerosene)	129	132	132	132	124	132	66	66	33	66	26
Biofuels	0	0	0	0	0	0	99	0	124	82	92
Hydrogen	0	0	0	0	8	0	0	0	0	0	0
Passenger Aviation - Overall	**2,797**	**4,248**	**4,248**	**4,248**	**4,248**	**4,248**	**4,248**	**3,186**	**4,248**	**4,248**	**3,823**
Gasoline	900	850	850	850	850	850	0	637	212	425	382
Jet Fuel (kerosene)	1,896	3,399	3,399	3,399	3,186	3,399	1,699	2,549	850	1,699	765
Biofuels	0	0	0	0	0	0	2,549	0	3,186	2,124	2,676
Hydrogen	0	0	0	0	212	0	0	0	0	0	0
Freight - Instate	**23**	**353**	**353**	**353**	**353**	**353**	**353**	**212**	**353**	**353**	**282**
Gasoline	7	71	71	71	71	71	0	42	18	35	28
Jet Fuel (kerosene)	16	282	282	282	265	282	141	169	71	141	56
Biofuels	0	0	0	0	0	0	212	0	265	177	198
Hydrogen	0	0	0	0	18	0	0	0	0	0	0
Freight - Overall	**3,174**	**18,930**	**18,930**	**18,930**	**18,930**	**18,930**	**18,930**	**13,251**	**18,930**	**18,930**	**17,037**
Gasoline	1,022	3,786	3,786	3,786	3,786	3,786	0	2,650	946	1,893	1,704
Jet Fuel (kerosene)	2,152	15,144	15,144	15,144	14,197	15,144	7,572	10,601	3,786	7,572	3,407
Biofuels	0	0	0	0	0	0	11,358	0	14,197	9,465	11,926
Hydrogen	0	0	0	0	946	0	0	0	0	0	0
General Aviation - Instate	**13**	**22**	**22**	**22**	**22**	**22**	**22**	**8**	**22**	**22**	**14**
Gasoline	4	4	4	4	4	4	0	2	1	2	1
Jet Fuel (kerosene)	9	18	18	18	17	18	9	6	4	9	3
Biofuels	0	0	0	0	0	0	13	0	17	11	10
Hydrogen	0	0	0	0	1	0	0	0	0	0	0
General Aviation - Overall	**26**	**44**	**44**	**44**	**44**	**44**	**44**	**23**	**44**	**44**	**20**

Units = miles/person (unless specified otherwise)	**1990 Historical Values**	**2050 Scenarios**									
		Reference	***Moderate efficiency SB***	***High efficiency SB***	***Hydrogen -intensive SB***	***Electricity -intensive SB***	***Biofuel-intensive SB***	***PMT SB***	***Efficient Biofuels 80in50***	***Electric-drive 80in50***	***Actor-based 80in50***
Gasoline	9	9	9	9	9	9	0	5	2	4	2
Jet Fuel (kerosene)	18	35	35	35	33	35	18	19	9	18	4
Biofuels	0	0	0	0	0	0	26	0	33	22	14
Hydrogen	0	0	0	0	2	0	0	0	0	0	0
Total Aircraft PMT per capita - Instate	226	540	540	540	540	540	540	302	540	540	428
Total Aircraft PMT per capita - Overall	5,997	23,222	23,222	23,222	23,222	23,222	23,222	16,460	23,222	23,222	20,880
Rail											
Passenger Rail	**98**	**65**	**65**	**65**	**65**	**65**	**65**	**1,753**	**65**	**65**	**1,330**
Intercity Rail	37	19	19	19	19	19	19	502	19	19	381
Diesel Hybrid	28	19	19	19	0	0	7	502	0	0	0
Biofuel Hybrid	0	0	0	0	0	0	11	0	19	0	0
H2FC	0	0	0	0	19	0	0	0	0	0	0
Electric	9	0	0	0	0	19	0	0	0	19	381
Commuter Rail	15	11	11	11	11	11	11	290	11	11	220
Diesel Hybrid	5	2	2	2	0	0	4	290	0	0	0
Biofuel Hybrid	0	0	0	0	0	0	6	0	11	0	0
H2FC	0	0	0	0	11	0	0	0	0	0	0
Electric	9	9	9	9	0	11	0	0	0	11	220
Heavy Rail	38	24	24	24	24	24	24	652	24	24	494
Diesel Hybrid	0	0	0	0	0	0	0	0	0	0	0
Biofuel Hybrid	0	0	0	0	0	0	0	0	0	0	0
H2FC	0	0	0	0	0	0	0	0	0	0	0
Electric	38	24	24	24	24	24	24	652	24	24	494
Light Rail	8	11	11	11	11	11	11	310	11	11	235
Diesel Hybrid	0	0	0	0	0	0	0	0	0	0	0
Biofuel Hybrid	0	0	0	0	0	0	0	0	0	0	0
H2FC	0	0	0	0	0	0	0	0	0	0	0
Electric	8	11	11	11	11	11	11	310	11	11	235
Freight Rail	**249**	**443**	**443**	**443**	**443**	**443**	**443**	**443**	**443**	**443**	**443**
Diesel Hybrid	249	443	443	443	0	0	177	443	0	0	266
Biofuel Hybrid	0	0	0	0	0	0	266	0	443	0	0

Units = miles/person (unless specified otherwise)	**1990 Historical Values**	**2050 Scenarios**									
		Reference	***Moderate efficiency SB***	***High efficiency SB***	***Hydrogen -intensive SB***	***Electricity -intensive SB***	***Biofuel-intensive SB***	***PMT SB***	***Efficient Biofuels 80in50***	***Electric-drive 80in50***	***Actor-based 80in50***
H2FC	0	0	0	0	443	0	0	0	0	0	0
Electric	0	0	0	0	0	443	0	0	0	443	177
Total Rail PMT per capita	**347**	**507**	**507**	**507**	**507**	**507**	**507**	**2,196**	**507**	**507**	**1,772**
Intercity Rail passengers per vehicle	184	275	275	275	275	275	275	367	184	184	229
Commuter Rail passengers per vehicle	38	57	57	57	57	57	57	75	38	38	47
Heavy Rail passengers per vehicle	22	33	33	33	33	33	33	44	22	22	27
Light Rail passengers per vehicle	26	39	39	39	39	39	39	52	26	26	33
Freight Rail load factor	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	125%
Marine, Agriculture, and Off-Road **Marine - Instate**	**43**	**46**	**46**	**46**	**46**	**46**	**46**	**46**	**46**	**46**	**37**
Marine - Overall	**44**	**47**	**47**	**47**	**47**	**47**	**47**	**47**	**47**	**47**	**38**
Large Marine Vehicles - Overall	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Gasoline	0	0	0	0	0	0	0	0	0	0	0
Diesel and Distillate Fuel Oil	0	1	1	1	0	1	0	1	0	0	0
Biofuels	0	0	0	0	0	0	1	0	1	0	0
Hydrogen	0	0	0	0	1	0	0	0	0	0	0
Residual Fuel Oil (Marine Bunker Fuel)	1	1	1	1	0	1	0	1	1	0	0
Harbor Craft	**8**	**8**	**8**	**8**	**8**	**8**	**8**	**8**	**8**	**8**	**6**
Gasoline	0	3	3	3	2	2	0	3	0	1	2
Diesel and Distillate Fuel Oil	8	5	5	5	2	6	3	5	0	1	3
Biofuels	0	0	0	0	0	0	5	0	8	4	1
Hydrogen	0	0	0	0	4	0	0	0	0	2	1
Residual Fuel Oil (Marine Bunker Fuel)	0	0	0	0	0	0	0	0	0	0	0
Personal Boats	**35**	**38**	**38**	**38**	**38**	**38**	**38**	**38**	**38**	**38**	**31**

Units = miles/person (unless specified otherwise)	1990 Historical Values	2050 Scenarios									
		Reference	*Moderate efficiency SB*	*High efficiency SB*	*Hydrogen-intensive SB*	*Electricity-intensive SB*	*Biofuel-intensive SB*	*PMT SB*	*Efficient Biofuels 80in50*	*Electric-drive 80in50*	*Actor-based 80in50*
Gasoline	35	19	19	19	29	35	0	19	0	17	18
Diesel and Distillate Fuel Oil	0	19	19	19	0	4	15	19	0	2	9
Biofuels	0	0	0	0	0	0	23	0	38	19	3
Hydrogen	0	0	0	0	10	0	0	0	0	0	0
Residual Fuel Oil (Marine Bunker Fuel)	0	0	0	0	0	0	0	0	0	0	0
Agriculture	**51**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**12**
Gasoline	6	5	5	5	5	5	0	5	0	0	2
Diesel	45	19	19	19	14	17	9	19	6	7	4
Biofuels	0	0	0	0	0	0	14	0	18	9	4
Hydrogen	0	0	0	0	5	0	0	0	0	5	1
Electricity	0	0	0	0	0	2	0	0	0	2	1
Off-Road	**364**	**583**	**583**	**583**	**583**	**583**	**583**	**466**	**583**	**583**	**466**
Gasoline	275	466	466	466	146	146	117	373	0	0	47
Diesel	69	117	117	117	146	146	117	93	146	0	140
Biofuels	0	0	0	0	0	0	350	0	437	175	93
Hydrogen	0	0	0	0	292	0	0	0	0	233	47
Electricity	0	0	0	0	0	292	0	0	0	175	140
Natural Gas	20	0	0	0	0	0	0	0	0	0	0
Total Marine, Ag, and Off-Road PMT per capita - Instate	**458**	**653**	**653**	**653**	**653**	**653**	**653**	**536**	**653**	**653**	**515**
Total Marine, Ag, and Off-Road PMT per capita - Overall	**458**	**654**	**654**	**654**	**654**	**654**	**654**	**537**	**654**	**654**	**516**
All Transport PMT per capita - Instate	**15,641**	**19,263**	**19,263**	**19,263**	**19,263**	**19,263**	**19,263**	**13,789**	**19,263**	**19,263**	**15,038**
All Transport PMT per capita - Overall	**21,412**	**41,946**	**41,946**	**41,946**	**41,946**	**41,946**	**41,946**	**29,948**	**41,946**	**41,946**	**35,490**
PMT Changes - Instate											
Total PMT per capita	14,504	17,181	17,181	17,181	17,181	17,181	17,181	12,192	17,181	17,181	13,386

Units = miles/person (unless specified otherwise)	**1990 Historical Values**	**2050 Scenarios**									
		Reference	***Moderate efficiency SB***	***High efficiency SB***	***Hydrogen -intensive SB***	***Electricity -intensive SB***	***Biofuel-intensive SB***	***PMT SB***	***Efficient Biofuels 80in50***	***Electric-drive 80in50***	***Actor-based 80in50***
Total PMT change from 2050 Ref. case	---	---	0	0	0	0	0	-4,988	0	0	-3,795
LDVs	---	---	0	0	0	0	0	-8,255	0	0	-6,286
Buses	---	---	0	0	0	0	0	1,660	0	0	1,258
Rail	---	---	0	0	0	0	0	1,689	0	0	1,265
Aircraft	---	---	0	0	0	0	0	-82	0	0	-33
PMT Changes - Overall											
Total PMT per capita	17,110	21,264	21,264	21,264	21,264	21,264	21,264	15,296	21,264	21,264	17,077
PMT change from 2050 Reference case	---	---	0	0	0	0	0	-5,968	0	0	-4,187
LDVs	---	---	0	0	0	0	0	-8,255	0	0	-6,286
Buses	---	---	0	0	0	0	0	1,660	0	0	1,258
Rail	---	---	0	0	0	0	0	1,689	0	0	1,265
Aircraft	---	---	0	0	0	0	0	-1,062	0	0	-425

A.2 Vehicle energy intensity (E) assumptions by scenario and sector

<u>Scenarios</u>: Reference and Moderate efficiency SB

Various units	**1990 Historical Values**			**2050 Scenarios**					
				Reference			**Moderate efficiency SB**		
LDVs	*MJ/mile*	*miles/gge*	*Fleet Share*	*MJ/pass.-mile*	*miles/gge*	*Fleet Share*	*MJ/pass.-mile*	*miles/gge*	*Fleet Share*
Gasoline ICEs	3.88	19.81	100%	2.04	35.3	100%	1.41	51.1	100%
Biofuel ICEs	0.00	---	0%	2.04	35.3	0%	1.41	51.1	0%
Diesel ICEs	2.44	---	0%	1.92	37.4	0%	1.12	64.5	0%
Gasoline PHEVs	0.00	---	0%	1.80	55.5	0%	1.01	71.2	0%
Biofuel PHEVs	0.00	---	0%	1.80	55.5	0%	1.01	71.2	0%
Diesel PHEVs	0.00	---	0%	1.73	64.5	0%	0.87	82.7	0%
H2FCVs	0.00	---	0%	1.40	59.6	0%	0.94	76.4	0%
Battery EVs	0.00	---	0%	0.82	88.3	0%	0.64	111.8	0%
LDV average	**3.88**	**19.8**	**---**	**2.04**	**35.3**	**---**	**1.41**	**51.1**	**---**
Car fleet share						60%			60%
Truck fleet share						40%			40%
HDVs	*MJ/mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
Buses	**3.93**	**3,723**	**---**	**2.93**	**3,703**	**---**	**2.20**	**2,083**	**---**
Diesel, Gasoline, and Other ICE/HEV	3.93	3,723	100%	2.93	3,703	100%	2.20	2,083	100%
Diesel & Gasoline PHEVs	0.00	---	0%	2.63	3,320	0%	1.97	1,867	0%
Biofuel PHEVs	0.00	---	0%	2.63	3,320	0%	1.97	1,867	0%
H2FCVs	0.00	---	0%	2.34	2,962	0%	1.76	1,666	0%
Battery EVs	0.00	---	0%	2.09	2,638	0%	1.57	1,484	0%
	MJ/mile	*miles/gge*	*Fleet Share*	*MJ/vehicle-mile*	*miles/gge*	*Fleet Share*	*MJ/vehicle-mile*	*miles/gge*	*Fleet Share*
Heavy Trucks	**23.05**	**5.9**	**---**	**24.58**	**5.5**	**---**	**18.44**	**7.4**	**---**
Diesel	23.05	5.9	100%	24.58	5.5	100%	18.44	7.4	100%
Diesel HEV	0.00	---	0%	18.44	7.4	0%	13.83	9.8	0%
Biofuel HEVs	0.00	---	0%	18.44	7.4	0%	13.83	9.8	0%
H2FCVs	0.00	---	0%	12.29	11.0	0%	9.22	14.7	0%

Various units	**1990 Historical Values**			**2050 Scenarios**					
				Reference			**Moderate efficiency SB**		
Battery EVs	0.00	---	0%	16.39	11.0	0%	9.22	14.7	0%
HDV average	**12.08**	**---**	**---**	**16.12**	**---**	**---**	**12.09**	**---**	**---**
Aircraft									
	MJ/mile	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
Passenger Aviation - Instate	**4.02**	**3,811**	**---**	**1.71**	**1,616**	**---**	**1.28**	**1,212**	**---**
Gasoline	4.02	3,811	---	1.71	1,616	20%	1.28	1,212	20%
Jet Fuel (kerosene)	4.02	3,811	---	1.71	1,616	80%	1.28	1,212	80%
Biofuels	---	---	---	1.71	1,616	0%	1.28	1,212	0%
Hydrogen	---	---	---	1.71	1,616	0%	1.28	1,212	0%
Passenger Aviation - Overall	**3.62**	**3,435**	**---**	**1.51**	**1,428**	**---**	**1.13**	**1,071**	**---**
Gasoline	3.62	3,435	---	1.51	1,428	20%	1.13	1,071	20%
Jet Fuel (kerosene)	3.62	3,435	---	1.51	1,428	80%	1.13	1,071	80%
Biofuels	---	---	---	1.51	1,428	0%	1.13	1,071	0%
Hydrogen	---	---	---	1.51	1,428	0%	1.13	1,071	0%
	MJ/person-mile	*Btu/person-mile*	*Fleet Share*	*MJ/person-mile*	*Btu/person-mile*	*Fleet Share*	*MJ/person-mile*	*Btu/person-mile*	*Fleet Share*
Freight - Instate	**1.06**	**1,000**	**---**	**0.45**	**424**	**---**	**0.34**	**318**	**---**
Gasoline	1.06	1,000	---	0.45	424	20%	0.34	318	20%
Jet Fuel (kerosene)	1.06	1,000	---	0.45	424	80%	0.34	318	80%
Biofuels	---	---	---	0.45	424	0%	0.34	318	0%
Hydrogen	---	---	---	0.45	424	0%	0.34	318	0%
Freight - Overall	**0.89**	**841**	**---**	**0.39**	**368**	**---**	**0.29**	**276**	**---**
Gasoline	0.89	841	---	0.39	368	20%	0.29	276	20%
Jet Fuel (kerosene)	0.89	841	---	0.39	368	80%	0.29	276	80%
Biofuels	---	---	---	0.39	368	0%	0.29	276	0%
Hydrogen	---	---	---	0.39	368	0%	0.29	276	0%
	MJ/pass.-mile	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
General Aviation - Instate	**19.45**	**18,435**	**---**	**74.89**	**70,982**	**---**	**56.17**	**53,236**	**---**
Gasoline	19.45	18,435	---	74.89	70,982	20%	56.17	53,236	20%

Various units	**1990** **Historical Values**			**2050 Scenarios**					
				Reference			**Moderate efficiency SB**		
Jet Fuel (kerosene)	19.45	18,435	---	74.89	70,982	80%	56.17	53,236	80%
Biofuels	---	---	---	74.89	70,982	0%	56.17	53,236	0%
Hydrogen	---	---	---	74.89	70,982	0%	56.17	53,236	0%
General Aviation - Overall	**19.45**	**18,435**	**---**	**74.89**	**70,982**	**---**	**56.17**	**53,236**	**---**
Gasoline	19.45	18,435	---	74.89	70,982	20%	56.17	53,236	20%
Jet Fuel (kerosene)	19.45	18,435	---	74.89	70,982	80%	56.17	53,236	80%
Biofuels	---	---	---	74.89	70,982	0%	56.17	53,236	0%
Hydrogen	---	---	---	74.89	70,982	0%	56.17	53,236	0%
Aircraft average - Instate	**4.62**	**---**	**---**	**3.87**	**---**	**---**	**2.91**	**---**	**---**
Aircraft average - Overall	**2.25**	**---**	**---**	**0.73**	**---**	**---**	**0.55**	**---**	**---**

Rail	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
Passenger Rail	**2.99**	**2,835**	**---**	**2.02**	**1,917**	**---**	**1.52**	**1,438**	**---**
Intercity Rail	2.64	2,505	---	2.16	2,047	---	1.62	1,535	---
Diesel Hybrid	2.64	2,505	100%	2.16	2,047	100%	1.62	1,535	100%
Biofuel Hybrid	2.64	---	0%	2.16	2,047	0%	1.62	1,535	0%
H2FC	2.64	---	0%	1.73	1,637	0%	1.30	1,228	0%
Electric	2.64	---	0%	---	---	0%	---	---	0%
Commuter Rail	3.24	3,068	---	1.57	1,485	---	1.18	1,114	---
Diesel Hybrid	3.24	3,068	37%	2.39	2,264	20%	1.79	1,698	20%
Biofuel Hybrid	3.24	---	0%	2.39	2,264	0%	1.79	1,698	0%
H2FC	3.24	---	0%	1.91	1,811	0%	1.43	1,358	0%
Electric	3.24	---	63%	1.36	1,290	80%	1.02	968	80%
Heavy Rail	3.19	3,024	---	2.09	1,980	---	1.57	1,485	---
Diesel Hybrid	3.19	---	0%	---	---	0%	---	---	0%
Biofuel Hybrid	3.19	---	0%	---	---	0%	---	---	0%
H2FC	3.19	---	0%	---	---	0%	---	---	0%
Electric	3.19	3,024	100%	2.09	1,980	100%	1.57	1,485	100%
Light Rail	3.19	3,024	---	2.09	1,980	---	1.57	1,485	---

Various units	**1990 Historical Values**			**2050 Scenarios**					
				Reference			**Moderate efficiency SB**		
Diesel Hybrid	3.19	---	0%	---	---	0%	---	---	0%
Biofuel Hybrid	3.19	---	0%	---	---	0%	---	---	0%
H2FC	3.19	---	0%	---	---	0%	---	---	0%
Electric	3.19	3,024	100%	2.09	1,980	100%	1.57	1,485	100%
	MJ/car-mile	*Btu/ton-mile*	*Fleet Share*	*MJ/car-mile*	*Btu/ton-mile*	*Fleet Share*	*MJ/car-mile*	*Btu/ton-mile*	*Fleet Share*
Freight Rail	**2.61**	**420**	**---**	**2.37**	**382**	**---**	**1.78**	**286**	**---**
Diesel Hybrid	2.61	420	100%	2.37	382	100%	1.78	286	100%
Biofuel Hybrid	2.61	---	0%	2.37	382	0%	1.78	286	0%
H2FC	2.61	---	0%	1.90	306	0%	1.42	229	0%
Electric	2.61	---	0%	---	218	0%	---	163	0%
Rail average	**2.72**	**---**	**---**	**2.33**	**---**	**---**	**1.74**	**---**	**---**
Marine, Agriculture, and Off-Road	*MJ/vehicle-mile*	*gal fuel/veh.-mile*	*Fleet Share*	*MJ/vehicle-mile*	*gal fuel/veh.-mile*	*Fleet Share*	*MJ/vehicle-mile*	*gal fuel/veh.-mile*	*Fleet Share*
Marine - Instate	**18.64**	**---**	**---**	**16.24**	**---**	**---**	**12.18**	**---**	**---**
Marine - Overall	**153.68**	**---**	**---**	**89.78**	**---**	**---**	**67.33**	**---**	**---**
Large Marine Vehicles - Overall	**7,908.54**	**53.4**	**---**	**3,416.49**	**23.1**	**---**	**2,562.37**	**17.3**	**---**
Gasoline	---	---	0%	3,416.49	23.1	0%	2,562.37	17.3	0%
Diesel and Distillate Fuel Oil	---	---	0%	3,416.49	23.1	50%	2,562.37	17.3	50%
Biofuels	---	---	0%	3,416.49	23.1	0%	2,562.37	17.3	0%
Hydrogen	---	---	0%	3,416.49	23.1	0%	2,562.37	17.3	0%
Residual Fuel Oil (Marine Bunker Fuel)	7,908.54	53.4	100%	3,416.49	23.1	50%	2,562.37	17.3	50%
Harbor Craft	**9.43**	**1.4**	**---**	**9.42**	**1.4**	**---**	**7.07**	**1.0**	**---**
Gasoline	---	---	0%	9.42	1.4	40%	7.07	1.0	40%
Diesel and Distillate Fuel Oil	9.43	1.4	100%	9.42	1.4	60%	7.07	1.0	60%
Biofuels	---	---	0%	9.42	1.4	0%	7.07	1.0	0%
Hydrogen	---	---	0%	9.42	1.4	0%	7.07	1.0	0%
Residual Fuel Oil (Marine Bunker Fuel)	---	---	0%	9.42	1.4	0%	7.07	1.0	0%

Various units	**1990** **Historical Values**			**2050 Scenarios**					
				Reference			**Moderate efficiency SB**		
Personal Boats	**20.66**	**3.5**	**---**	**17.66**	**2.9**	**---**	**13.25**	**2.2**	**---**
Gasoline	20.56	3.4	99%	17.66	2.9	50%	13.25	2.2	50%
Diesel and Distillate Fuel Oil	29.07	4.3	1%	17.66	2.9	50%	13.25	2.2	50%
Biofuels	---	---	0%	17.66	2.9	0%	13.25	2.2	0%
Hydrogen	---	---	0%	17.66	2.9	0%	13.25	2.2	0%
Residual Fuel Oil (Marine Bunker Fuel)	---	---	0%	17.66	2.9	0%	13.25	2.2	0%
	MJ/vehicle-mile	*gal fuel/hour*	*Fleet Share*	*MJ/vehicle-mile*	*gal fuel/hour*	*Fleet Share*	*MJ/vehicle-mile*	*gal fuel/hour*	*Fleet Share*
Agriculture	**28.68**	**0.6**	**---**	**24.89**	**2.8**	**---**	**18.67**	**2.1**	**---**
Gasoline	8.61	1.1	12%	24.89	2.8	20%	18.67	2.1	20%
Diesel	31.35	0.5	88%	24.89	2.8	80%	18.67	2.1	80%
Biofuels	---	---	0%	24.89	2.8	0%	18.67	2.1	0%
Hydrogen	---	---	0%	24.89	2.8	0%	18.67	2.1	0%
Electricity	---	---	0%	24.89	2.8	0%	18.67	2.1	0%
Off-Road	**8.60**	**0.2**	**---**	**4.47**	**0.6**	**---**	**4.02**	**0.5**	**---**
Gasoline	1.91	0.24	76%	4.47	0.6	80%	4.02	0.5	80%
Diesel	37.94	0.07	19%	4.47	0.6	20%	4.02	0.5	20%
Biofuels	---	---	0%	4.47	0.6	0%	4.02	0.5	0%
Hydrogen	---	---	0%	4.47	0.6	0%	4.02	0.5	0%
Electricity	---	---	0%	4.47	0.6	0%	4.02	0.5	0%
Natural Gas	0.02	3.11	6%	4.47	0.6	0%	4.02	0.5	0%
Marine, Ag, and Off-Road average - Instate	**11.78**	**---**	**---**	**6.04**	**---**	**---**	**5.13**	**---**	**---**
Marine, Ag, and Off-Road average - Overall	**24.66**	**---**	**---**	**11.38**	**---**	**---**	**9.14**	**---**	**---**
All Transport - Instate	**4.58**	**---**	**---**	**2.97**	**---**	**---**	**2.14**	**---**	**---**
All Transport - Overall	**4.20**	**---**	**---**	**2.49**	**---**	**---**	**1.80**	**---**	**---**

Scenarios: High efficiency SB and Hydrogen-intensive SB

Various units	**2050 Scenarios**					
	High efficiency SB			**Hydrogen-intensive SB**		
LDVs	*MJ/pass.-mile*	*miles/gge*	*Fleet Share*	*MJ/pass.-mile*	*miles/gge*	*Fleet Share*
Gasoline ICEs	1.17	61.3	100%	2.04	35.3	25%
Biofuel ICEs	1.17	61.3	0%	2.04	35.3	0%
Diesel ICEs	0.93	77.4	0%	1.92	37.4	0%
Gasoline PHEVs	0.70	85.4	0%	1.55	63.2	0%
Biofuel PHEVs	0.70	85.4	0%	1.55	63.2	0%
Diesel PHEVs	0.60	99.3	0%	1.50	70.6	0%
H2FCVs	0.71	91.7	0%	0.94	76.4	75%
Battery EVs	0.54	134.2	0%	0.82	88.3	0%
LDV average	**1.17**	**61.3**	**---**	**1.22**	**59.2**	**---**
Car fleet share			60%			60%
Truck fleet share			40%			40%
HDVs	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
Buses	**1.83**	**1,447**	**---**	**1.99**	**2,073**	**---**
Diesel, Gasoline, and Other ICE/HEV	1.83	1,447	100%	2.93	3,703	20%
Diesel & Gasoline PHEVs	1.64	1,297	0%	2.63	3,320	0%
Biofuel PHEVs	1.64	1,297	0%	2.63	3,320	0%
H2FCVs	1.46	1,157	0%	1.76	1,666	80%
Battery EVs	1.30	1,031	0%	2.09	2,638	0%
	MJ/vehicle-mile	*miles/gge*	*Fleet Share*	*MJ/vehicle-mile*	*miles/gge*	*Fleet Share*
Heavy Trucks	**12.29**	**11.0**	**---**	**10.75**	**12.6**	**---**
Diesel	15.36	8.8	20%	24.58	5.5	10%
Diesel HEV	11.52	11.8	80%	18.44	7.4	0%
Biofuel HEVs	11.52	11.8	0%	18.44	7.4	0%
H2FCVs	7.68	17.6	0%	9.22	14.7	90%
Battery EVs	6.40	17.6	0%	16.39	11.0	0%

Various units	**2050 Scenarios**					
	High efficiency SB			**Hydrogen-intensive SB**		
HDV average	**8.20**	**---**	**---**	**7.33**	**---**	**---**
Aircraft						
	MJ/pass.-mile	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
Passenger Aviation - Instate	**1.07**	**1,010**	**---**	**1.71**	**1,616**	**---**
Gasoline	1.07	1,010	20%	1.71	1,616	20%
Jet Fuel (kerosene)	1.07	1,010	80%	1.71	1,616	75%
Biofuels	1.07	1,010	0%	1.71	1,616	0%
Hydrogen	1.07	1,010	0%	1.71	1,616	5%
Passenger Aviation - Overall	**0.94**	**893**	**---**	**1.51**	**1,428**	**---**
Gasoline	0.94	893	20%	1.51	1,428	20%
Jet Fuel (kerosene)	0.94	893	80%	1.51	1,428	75%
Biofuels	0.94	893	0%	1.51	1,428	0%
Hydrogen	0.94	893	0%	1.51	1,428	5%
	MJ/person-mile	*Btu/person-mile*	*Fleet Share*	*MJ/person-mile*	*Btu/person-mile*	*Fleet Share*
Freight - Instate	**0.28**	**265**	**---**	**0.45**	**424**	**---**
Gasoline	0.28	265	20%	0.45	424	20%
Jet Fuel (kerosene)	0.28	265	80%	0.45	424	75%
Biofuels	0.28	265	0%	0.45	424	0%
Hydrogen	0.28	265	0%	0.45	424	5%
Freight - Overall	**0.24**	**230**	**---**	**0.39**	**368**	**---**
Gasoline	0.24	230	20%	0.39	368	20%
Jet Fuel (kerosene)	0.24	230	80%	0.39	368	75%
Biofuels	0.24	230	0%	0.39	368	0%
Hydrogen	0.24	230	0%	0.39	368	5%
	MJ/pass.-mile	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
General Aviation - Instate	**46.81**	**44,364**	**---**	**74.89**	**70,982**	**---**
Gasoline	46.81	44,364	20%	74.89	70,982	20%
Jet Fuel (kerosene)	46.81	44,364	80%	74.89	70,982	75%
Biofuels	46.81	44,364	0%	74.89	70,982	0%

Various units	2050 Scenarios					
	High efficiency SB			Hydrogen-intensive SB		
Hydrogen	46.81	44,364	0%	74.89	70,982	5%
General Aviation - Overall	**46.81**	**44,364**	**---**	**74.89**	**70,982**	**---**
Gasoline	46.81	44,364	20%	74.89	70,982	20%
Jet Fuel (kerosene)	46.81	44,364	80%	74.89	70,982	75%
Biofuels	46.81	44,364	0%	74.89	70,982	0%
Hydrogen	46.81	44,364	0%	74.89	70,982	5%
Aircraft average - Instate	**2.42**	**---**	**---**	**3.87**	**---**	**---**
Aircraft average - Overall	**0.46**	**---**	**---**	**0.73**	**---**	**---**
Rail	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
Passenger Rail	**1.26**	**1,198**	**---**	**1.75**	**1,662**	**---**
Intercity Rail	1.35	1,279	---	1.30	1,228	---
Diesel Hybrid	1.35	1,279	100%	2.16	2,047	0%
Biofuel Hybrid	1.35	1,279	0%	2.16	2,047	0%
H2FC	1.08	1,023	0%	1.30	1,228	100%
Electric	---	---	0%	---	---	0%
Commuter Rail	0.98	928	---	1.43	1,358	---
Diesel Hybrid	1.49	1,415	20%	2.39	2,264	0%
Biofuel Hybrid	1.49	1,415	0%	2.39	2,264	0%
H2FC	1.19	1,132	0%	1.43	1,358	100%
Electric	0.85	806	80%	---	1,290	0%
Heavy Rail	1.31	1,237	---	2.09	1,980	---
Diesel Hybrid	---	---	0%	---	---	0%
Biofuel Hybrid	---	---	0%	---	---	0%
H2FC	---	---	0%	---	---	0%
Electric	1.31	1,237	100%	2.09	1,980	100%
Light Rail	1.31	1,237	---	2.09	1,980	---
Diesel Hybrid	---	---	0%	---	---	0%

Various units	**2050 Scenarios**					
	High efficiency SB			**Hydrogen-intensive SB**		
Biofuel Hybrid	---	---	0%	---	---	0%
H2FC	---	---	0%	---	---	0%
Electric	1.31	1,237	100%	2.09	1,980	100%
	MJ/car-mile	*Btu/ton-mile*	*Fleet Share*	*MJ/person-mile*	*Btu/ton-mile*	*Fleet Share*
Freight Rail	**1.48**	**239**	**---**	**1.42**	**229**	**---**
Diesel Hybrid	1.48	239	100%	2.37	382	0%
Biofuel Hybrid	1.48	239	0%	2.37	382	0%
H2FC	1.19	191	0%	1.42	229	100%
Electric	---	136	0%	---	218	0%
Rail average	**1.45**	**---**	**---**	**1.46**	**---**	**---**
Marine, Agriculture, and Off-Road	*MJ/vehicle-mile*	*gal fuel/veh.-mile*	*Fleet Share*	*MJ/vehicle-mile*	*gal fuel/veh.-mile*	*Fleet Share*
Marine - Instate	**12.18**	**---**	**---**	**16.24**	**---**	**---**
Marine - Overall	**67.33**	**---**	**---**	**89.78**	**---**	**---**
Large Marine Vehicles - Overall	**2,562.37**	**17.3**	**---**	**3,416.49**	**23.1**	**---**
Gasoline	2,562.37	17.3	0%	3,416.49	23.1	0%
Diesel and Distillate Fuel Oil	2,562.37	17.3	50%	3,416.49	23.1	25%
Biofuels	2,562.37	17.3	0%	3,416.49	23.1	0%
Hydrogen	2,562.37	17.3	0%	3,416.49	23.1	50%
Residual Fuel Oil (Marine Bunker Fuel)	2,562.37	17.3	50%	3,416.49	23.1	25%
Harbor Craft	**7.07**	**1.0**	**---**	**9.42**	**1.4**	**---**
Gasoline	7.07	1.0	40%	9.42	1.4	25%
Diesel and Distillate Fuel Oil	7.07	1.0	60%	9.42	1.4	25%
Biofuels	7.07	1.0	0%	9.42	1.4	0%
Hydrogen	7.07	1.0	0%	9.42	1.4	50%
Residual Fuel Oil (Marine Bunker Fuel)	7.07	1.0	0%	9.42	1.4	0%
Personal Boats	**13.25**	**2.2**	**---**	**17.66**	**2.9**	**---**
Gasoline	13.25	2.2	50%	17.66	2.9	75%

Various units	2050 Scenarios					
	High efficiency SB			Hydrogen-intensive SB		
Diesel and Distillate Fuel Oil	13.25	2.2	50%	17.66	2.9	0%
Biofuels	13.25	2.2	0%	17.66	2.9	0%
Hydrogen	13.25	2.2	0%	17.66	2.9	25%
Residual Fuel Oil (Marine Bunker Fuel)	13.25	2.2	0%	17.66	2.9	0%
	MJ/vehicle-mile	*gal fuel/hour*	*Fleet Share*	*MJ/vehicle-mile*	*gal fuel/hour*	*Fleet Share*
Agriculture	**15.56**	**1.7**	**---**	**24.89**	**2.8**	**---**
Gasoline	15.56	1.7	20%	24.89	2.8	20%
Diesel	15.56	1.7	80%	24.89	2.8	60%
Biofuels	15.56	1.7	0%	24.89	2.8	0%
Hydrogen	15.56	1.7	0%	24.89	2.8	20%
Electricity	15.56	1.7	0%	24.89	2.8	0%
Off-Road	**3.35**	**0.4**	**---**	**4.47**	**0.6**	**---**
Gasoline	3.35	0.4	80%	4.47	0.6	25%
Diesel	3.35	0.4	20%	4.47	0.6	25%
Biofuels	3.35	0.4	0%	4.47	0.6	0%
Hydrogen	3.35	0.4	0%	4.47	0.6	50%
Electricity	3.35	0.4	0%	4.47	0.6	0%
Natural Gas	3.35	0.4	0%	4.47	0.6	0%
Marine, Ag, and Off-Road average - Instate	**4.42**	**---**	**---**	**6.04**	**---**	**---**
Marine, Ag, and Off-Road average - Overall	**8.43**	**---**	**---**	**11.38**	**---**	**---**
All Transport - Instate	**1.69**	**---**	**---**	**1.78**	**---**	**---**
All Transport - Overall	**1.44**	**---**	**---**	**1.57**	**---**	**---**

Scenarios: Electricity-intensive SB and Biofuel-intensive SB

Various units	2050 Scenarios					
	Electricity-intensive SB			Biofuel-intensive SB		
LDVs	*MJ/pass.-mile*	*miles/gge*	*Fleet Share*	*MJ/pass.-mile*	*miles/gge*	*Fleet Share*
Gasoline ICEs	2.04	35.3	0%	2.04	35.3	40%
Biofuel ICEs	2.04	35.3	0%	2.04	35.3	60%
Diesel ICEs	1.92	37.4	0%	1.92	37.4	0%
Gasoline PHEVs	1.55	63.2	50%	1.55	63.2	0%
Biofuel PHEVs	1.55	63.2	0%	1.55	63.2	0%
Diesel PHEVs	1.50	70.6	0%	1.50	70.6	0%
H2FCVs	1.40	59.6	0%	1.40	59.6	0%
Battery EVs	0.82	88.3	50%	0.82	88.3	0%
LDV average	**1.18**	**73.7**	**---**	**2.04**	**35.3**	**---**
Car fleet share			60%			60%
Truck fleet share			40%			40%
HDVs	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
Buses	**2.30**	**2,911**	**---**	**2.93**	**3,703**	**---**
Diesel, Gasoline, and Other ICE/HEV	2.93	3,703	0%	2.93	3,703	100%
Diesel & Gasoline PHEVs	2.63	3,320	40%	2.63	3,320	0%
Biofuel PHEVs	2.63	3,320	0%	2.63	3,320	0%
H2FCVs	2.34	2,962	0%	2.34	2,962	0%
Battery EVs	2.09	2,638	60%	2.09	2,638	0%
	MJ/vehicle-mile	*miles/gge*	*Fleet Share*	*MJ/vehicle-mile*	*miles/gge*	*Fleet Share*
Heavy Trucks	**18.23**	**7.6**	**---**	**20.89**	**6.5**	**---**
Diesel	24.58	5.5	0%	24.58	5.5	40%
Diesel HEV	18.44	7.4	90%	18.44	7.4	0%
Biofuel HEVs	18.44	7.4	0%	18.44	7.4	60%
H2FCVs	12.29	11.0	0%	12.29	11.0	0%
Battery EVs	16.39	11.0	10%	16.39	11.0	0%

Various units	**2050 Scenarios**					
	Electricity-intensive SB			**Biofuel-intensive SB**		
HDV average	**12.01**	**---**	**---**	**13.87**	**---**	**---**
Aircraft	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
Passenger Aviation - Instate	**1.71**	**1,616**	**---**	**1.71**	**1,616**	**---**
Gasoline	1.71	1,616	20%	1.71	1,616	0%
Jet Fuel (kerosene)	1.71	1,616	80%	1.71	1,616	40%
Biofuels	1.71	1,616	0%	1.71	1,616	60%
Hydrogen	1.71	1,616	0%	1.71	1,616	0%
Passenger Aviation - Overall	**1.51**	**1,428**	**---**	**1.51**	**1,428**	**---**
Gasoline	1.51	1,428	20%	1.51	1,428	0%
Jet Fuel (kerosene)	1.51	1,428	80%	1.51	1,428	40%
Biofuels	1.51	1,428	0%	1.51	1,428	60%
Hydrogen	1.51	1,428	0%	1.51	1,428	0%
	MJ/person-mile	*Btu/person-mile*	*Fleet Share*	*MJ/person-mile*	*Btu/person-mile*	*Fleet Share*
Freight - Instate	**0.45**	**424**	**---**	**0.45**	**424**	**---**
Gasoline	0.45	424	20%	0.45	424	0%
Jet Fuel (kerosene)	0.45	424	80%	0.45	424	40%
Biofuels	0.45	424	0%	0.45	424	60%
Hydrogen	0.45	424	0%	0.45	424	0%
Freight - Overall	**0.39**	**368**	**---**	**0.39**	**368**	**---**
Gasoline	0.39	368	20%	0.39	368	0%
Jet Fuel (kerosene)	0.39	368	80%	0.39	368	40%
Biofuels	0.39	368	0%	0.39	368	60%
Hydrogen	0.39	368	0%	0.39	368	0%
	MJ/pass.-mile	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
General Aviation - Instate	**74.89**	**70,982**	**---**	**74.89**	**70,982**	**---**
Gasoline	74.89	70,982	20%	74.89	70,982	0%
Jet Fuel (kerosene)	74.89	70,982	80%	74.89	70,982	40%
Biofuels	74.89	70,982	0%	74.89	70,982	60%

Various units	**2050 Scenarios**					
	Electricity-intensive SB			**Biofuel-intensive SB**		
Hydrogen	74.89	70,982	0%	74.89	70,982	0%
General Aviation - Overall	**74.89**	**70,982**	**---**	**74.89**	**70,982**	**---**
Gasoline	74.89	70,982	20%	74.89	70,982	0%
Jet Fuel (kerosene)	74.89	70,982	80%	74.89	70,982	40%
Biofuels	74.89	70,982	0%	74.89	70,982	60%
Hydrogen	74.89	70,982	0%	74.89	70,982	0%
Aircraft average - Instate	**3.87**	**---**	**---**	**3.87**	**---**	**---**
Aircraft average - Overall	**0.73**	**---**	**---**	**0.73**	**---**	**---**
Rail	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
Passenger Rail	**1.72**	**1,633**	**---**	**2.16**	**2,046**	**---**
Intercity Rail	1.23	1,167	---	2.16	2,047	---
Diesel Hybrid	2.16	2,047	0%	2.16	2,047	40%
Biofuel Hybrid	2.16	2,047	0%	2.16	2,047	60%
H2FC	1.73	1,637	0%	1.73	1,637	0%
Electric	1.23	1,167	100%	---	---	0%
Commuter Rail	1.36	1,290	---	2.39	2,264	---
Diesel Hybrid	2.39	2,264	0%	2.39	2,264	40%
Biofuel Hybrid	2.39	2,264	0%	2.39	2,264	60%
H2FC	1.91	1,811	0%	1.91	1,811	0%
Electric	1.36	1,290	100%	---	1,290	0%
Heavy Rail	2.09	1,980	---	2.09	1,980	---
Diesel Hybrid	---	---	0%	---	---	0%
Biofuel Hybrid	---	---	0%	---	---	0%
H2FC	---	---	0%	---	---	0%
Electric	2.09	1,980	100%	2.09	1,980	100%
Light Rail	2.09	1,980	---	2.09	1,980	---
Diesel Hybrid	---	---	0%	---	---	0%

Various units	**2050 Scenarios**					
	Electricity-intensive SB			**Biofuel-intensive SB**		
Biofuel Hybrid	---	---	0%	---	---	0%
H2FC	---	---	0%	---	---	0%
Electric	2.09	1,980	100%	2.09	1,980	100%
	MJ/person-mile	*Btu/ton-mile*	*Fleet Share*	*MJ/person-mile*	*Btu/ton-mile*	*Fleet Share*
Freight Rail	**1.35**	**218**	**---**	**2.37**	**382**	**---**
Diesel Hybrid	2.37	382	0%	2.37	382	40%
Biofuel Hybrid	2.37	382	0%	2.37	382	60%
H2FC	1.90	306	0%	1.90	306	0%
Electric	1.35	218	100%	---	218	0%
Rail average	**1.40**	**---**	**---**	**2.34**	**---**	**---**
Marine, Agriculture, and Off-Road						
	MJ/vehicle-mile	*gal fuel/veh.-mile*	*Fleet Share*	*MJ/vehicle-mile*	*gal fuel/veh.-mile*	*Fleet Share*
Marine - Instate	**16.24**	**---**	**---**	**16.24**	**---**	**---**
Marine - Overall	**89.78**	**---**	**---**	**89.78**	**---**	**---**
Large Marine Vehicles - Overall	**3,416.49**	**17.3**	**---**	**3,416.49**	**23.1**	**---**
Gasoline	3,416.49	17.3	0%	3,416.49	23.1	0%
Diesel and Distillate Fuel Oil	3,416.49	17.3	50%	3,416.49	23.1	40%
Biofuels	3,416.49	17.3	0%	3,416.49	23.1	60%
Hydrogen	3,416.49	17.3	0%	3,416.49	23.1	0%
Residual Fuel Oil (Marine Bunker Fuel)	3,416.49	17.3	50%	3,416.49	23.1	0%
Harbor Craft	**9.42**	**1.0**	**---**	**9.42**	**1.4**	**---**
Gasoline	9.42	1.0	30%	9.42	1.4	0%
Diesel and Distillate Fuel Oil	9.42	1.0	70%	9.42	1.4	40%
Biofuels	9.42	1.0	0%	9.42	1.4	60%
Hydrogen	9.42	1.0	0%	9.42	1.4	0%
Residual Fuel Oil (Marine Bunker Fuel)	9.42	1.0	0%	9.42	1.4	0%
Personal Boats	**17.66**	**2.9**	**---**	**17.66**	**2.9**	**---**
Gasoline	17.66	2.9	90%	17.66	2.9	0%

Various units	2050 Scenarios					
	Electricity-intensive SB			Biofuel-intensive SB		
Diesel and Distillate Fuel Oil	17.66	2.9	10%	17.66	2.9	40%
Biofuels	17.66	2.9	0%	17.66	2.9	60%
Hydrogen	17.66	2.9	0%	17.66	2.9	0%
Residual Fuel Oil (Marine Bunker Fuel)	17.66	2.9	0%	17.66	2.9	0%
	MJ/vehicle-mile	*gal fuel/hour*	*Fleet Share*	*MJ/vehicle-mile*	*gal fuel/hour*	*Fleet Share*
Agriculture	**18.67**	**2.1**	**---**	**24.89**	**2.8**	**---**
Gasoline	18.67	2.1	20%	24.89	2.8	0%
Diesel	18.67	2.1	70%	24.89	2.8	40%
Biofuels	18.67	2.1	0%	24.89	2.8	60%
Hydrogen	18.67	2.1	0%	24.89	2.8	0%
Electricity	18.67	2.1	10%	24.89	2.8	0%
Off-Road	**4.47**	**0.6**	**---**	**4.47**	**0.6**	**---**
Gasoline	4.47	0.6	25%	4.47	0.6	20%
Diesel	4.47	0.6	25%	4.47	0.6	20%
Biofuels	4.47	0.6	0%	4.47	0.6	60%
Hydrogen	4.47	0.6	0%	4.47	0.6	0%
Electricity	4.47	0.6	50%	4.47	0.6	0%
Natural Gas	4.47	0.6	0%	4.47	0.6	0%
Marine, Ag, and Off-Road average - Instate	**5.82**	**---**	**---**	**6.04**	**---**	**---**
Marine, Ag, and Off-Road average - Overall	**11.16**	**---**	**---**	**11.38**	**---**	**---**
All Transport - Instate	**1.98**	**---**	**---**	**2.85**	**---**	**---**
All Transport - Overall	**1.74**	**---**	**---**	**2.39**	**---**	**---**

Scenarios: **PMT SB and Efficient Biofuels 80in50**

Various units	**2050 Scenarios**					
	PMT SB			**Efficient Biofuels 80in50**		
LDVs	*MJ/pass.-mile*	*miles/gge*	*Fleet Share*	*MJ/pass.-mile*	*miles/gge*	*Fleet Share*
Gasoline ICEs	1.36	35.3	98%	1.41	51.1	0%
Biofuel ICEs	1.36	35.3	0%	1.41	51.1	75%
Diesel ICEs	1.28	37.4	2%	1.12	64.5	0%
Gasoline PHEVs	1.20	55.5	0%	0.89	81.0	0%
Biofuel PHEVs	1.20	55.5	0%	0.89	81.0	25%
Diesel PHEVs	1.15	64.5	0%	0.80	90.6	0%
H2FCVs	0.93	59.6	0%	0.94	76.4	0%
Battery EVs	0.54	88.3	0%	0.64	111.8	0%
LDV average	**1.36**	**35.3**	**---**	**1.28**	**56.3**	**---**
Car fleet share			60%			60%
Truck fleet share			40%			40%
HDVs	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
Buses	**1.95**	**2,469**	**---**	**2.14**	**2,029**	**---**
Diesel, Gasoline, and Other ICE/HEV	1.95	2,469	100%	2.20	2,083	75%
Diesel & Gasoline PHEVs	2.63	3,320	0%	1.97	1,867	0%
Biofuel PHEVs	2.63	3,320	0%	1.97	1,867	25%
H2FCVs	1.56	1,975	0%	1.76	1,666	0%
Battery EVs	1.39	1,759	0%	1.57	1,484	0%
	MJ/vehicle-mile	*miles/gge*	*Fleet Share*	*MJ/vehicle-mile*	*miles/gge*	*Fleet Share*
Heavy Trucks	**24.58**	**5.5**	**---**	**13.83**	**9.8**	**---**
Diesel	24.58	5.5	100%	18.44	7.4	0%
Diesel HEV	18.44	7.4	0%	13.83	9.8	0%
Biofuel HEVs	18.44	7.4	0%	13.83	9.8	100%
H2FCVs	12.29	11.0	0%	9.22	14.7	0%
Battery EVs	16.39	11.0	0%	9.22	14.7	0%

Various units	**2050 Scenarios**					
	PMT SB			**Efficient Biofuels 80in50**		
HDV average	**5.63**	**---**	**---**	**9.26**	**---**	**---**
Aircraft	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
Passenger Aviation - Instate	**1.71**	**1,616**	**---**	**1.28**	**1,212**	**---**
Gasoline	1.71	1,616	20%	1.28	1,212	5%
Jet Fuel (kerosene)	1.71	1,616	80%	1.28	1,212	20%
Biofuels	1.71	1,616	0%	1.28	1,212	75%
Hydrogen	1.71	1,616	0%	1.28	1,212	0%
Passenger Aviation - Overall	**1.51**	**1,428**	**---**	**1.13**	**1,071**	**---**
Gasoline	1.51	1,428	20%	1.13	1,071	5%
Jet Fuel (kerosene)	1.51	1,428	80%	1.13	1,071	20%
Biofuels	1.51	1,428	0%	1.13	1,071	75%
Hydrogen	1.51	1,428	0%	1.13	1,071	0%
	MJ/person-mile	*Btu/person-mile*	*Fleet Share*	*MJ/person-mile*	*Btu/person-mile*	*Fleet Share*
Freight - Instate	**0.45**	**424**	**---**	**0.34**	**318**	**---**
Gasoline	0.45	424	20%	0.34	318	5%
Jet Fuel (kerosene)	0.45	424	80%	0.34	318	20%
Biofuels	0.45	424	0%	0.34	318	75%
Hydrogen	0.45	424	0%	0.34	318	0%
Freight - Overall	**0.39**	**368**	**---**	**0.29**	**276**	**---**
Gasoline	0.39	368	20%	0.29	276	5%
Jet Fuel (kerosene)	0.39	368	80%	0.29	276	20%
Biofuels	0.39	368	0%	0.29	276	75%
Hydrogen	0.39	368	0%	0.29	276	0%
	MJ/pass.-mile	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
General Aviation - Instate	**74.89**	**70,982**	**---**	**56.17**	**53,236**	**---**
Gasoline	74.89	70,982	20%	56.17	53,236	5%
Jet Fuel (kerosene)	74.89	70,982	80%	56.17	53,236	20%
Biofuels	74.89	70,982	0%	56.17	53,236	75%

Various units	**2050 Scenarios**					
	PMT SB			**Efficient Biofuels 80in50**		
Hydrogen	74.89	70,982	0%	56.17	53,236	0%
General Aviation - Overall	**74.89**	**70,982**	**---**	**56.17**	**53,236**	**---**
Gasoline	74.89	70,982	20%	56.17	53,236	5%
Jet Fuel (kerosene)	74.89	70,982	80%	56.17	53,236	20%
Biofuels	74.89	70,982	0%	56.17	53,236	75%
Hydrogen	74.89	70,982	0%	56.17	53,236	0%
Aircraft average - Instate	**2.69**	**---**	**---**	**2.91**	**---**	**---**
Aircraft average - Overall	**0.71**	**---**	**---**	**0.55**	**---**	**---**
Rail	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
Passenger Rail	**1.62**	**1,534**	**---**	**2.43**	**2,302**	**---**
Intercity Rail	1.62	1,535	---	2.43	2,303	---
Diesel Hybrid	1.62	1,535	100%	2.43	2,303	0%
Biofuel Hybrid	1.62	1,535	0%	2.43	2,303	100%
H2FC	1.30	1,228	0%	1.94	1,842	0%
Electric	---	---	0%	---	---	0%
Commuter Rail	1.79	1,698	---	2.69	2,547	---
Diesel Hybrid	1.79	1,698	100%	2.69	2,547	0%
Biofuel Hybrid	1.79	1,698	0%	2.69	2,547	100%
H2FC	1.43	1,358	0%	2.15	2,037	0%
Electric	---	968	0%	---	1,452	0%
Heavy Rail	1.57	1,485	---	2.35	2,227	---
Diesel Hybrid	---	---	0%	---	---	0%
Biofuel Hybrid	---	---	0%	---	---	0%
H2FC	---	---	0%	---	---	0%
Electric	1.57	1,485	100%	2.35	2,227	100%
Light Rail	1.57	1,485	---	2.35	2,227	---
Diesel Hybrid	---	---	0%	---	---	0%

Various units	**2050 Scenarios**					
	PMT SB			**Efficient Biofuels 80in50**		
Biofuel Hybrid	---	---	0%	---	---	0%
H2FC	---	---	0%	---	---	0%
Electric	1.57	1,485	100%	2.35	2,227	100%
	MJ/person-mile	*Btu/ton-mile*	*Fleet Share*	*MJ/person-mile*	*Btu/ton-mile*	*Fleet Share*
Freight Rail	**2.37**	**382**	**---**	**1.78**	**286**	**---**
Diesel Hybrid	2.37	382	100%	1.78	286	0%
Biofuel Hybrid	2.37	382	0%	1.78	286	100%
H2FC	1.90	306	0%	1.42	229	0%
Electric	---	218	0%	---	163	0%
Rail average	**1.77**	**---**	**---**	**1.86**	**---**	**---**
Marine, Agriculture, and Off-Road	*MJ/vehicle-mile*	*gal fuel/veh.-mile*	*Fleet Share*	*MJ/vehicle-mile*	*gal fuel/veh.-mile*	*Fleet Share*
Marine - Instate	**16.24**	**---**	**---**	**12.18**	**---**	**---**
Marine - Overall	**89.78**	**---**	**---**	**67.33**	**---**	**---**
Large Marine Vehicles - Overall	**3,416.49**	**23.1**	**---**	**2,562.37**	**17.3**	**---**
Gasoline	3,416.49	23.1	0%	2,562.37	17.3	0%
Diesel and Distillate Fuel Oil	3,416.49	23.1	50%	2,562.37	17.3	0%
Biofuels	3,416.49	23.1	0%	2,562.37	17.3	50%
Hydrogen	3,416.49	23.1	0%	2,562.37	17.3	0%
Residual Fuel Oil (Marine Bunker Fuel)	3,416.49	23.1	50%	2,562.37	17.3	50%
Harbor Craft	**9.42**	**1.4**	**---**	**7.07**	**1.0**	**---**
Gasoline	9.42	1.4	40%	7.07	1.0	0%
Diesel and Distillate Fuel Oil	9.42	1.4	60%	7.07	1.0	0%
Biofuels	9.42	1.4	0%	7.07	1.0	100%
Hydrogen	9.42	1.4	0%	7.07	1.0	0%
Residual Fuel Oil (Marine Bunker Fuel)	9.42	1.4	0%	7.07	1.0	0%
Personal Boats	**17.66**	**2.9**	**---**	**13.25**	**2.2**	**---**
Gasoline	17.66	2.9	50%	13.25	2.2	0%

Various units	2050 Scenarios					
	PMT SB			Efficient Biofuels 80in50		
Diesel and Distillate Fuel Oil	17.66	2.9	50%	13.25	2.2	0%
Biofuels	17.66	2.9	0%	13.25	2.2	100%
Hydrogen	17.66	2.9	0%	13.25	2.2	0%
Residual Fuel Oil (Marine Bunker Fuel)	17.66	2.9	0%	13.25	2.2	0%
	MJ/vehicle-mile	*gal fuel/hour*	*Fleet Share*	*MJ/vehicle-mile*	*gal fuel/hour*	*Fleet Share*
Agriculture	**24.89**	**2.8**	**---**	**18.67**	**2.1**	**---**
Gasoline	24.89	2.8	20%	18.67	2.1	0%
Diesel	24.89	2.8	80%	18.67	2.1	25%
Biofuels	24.89	2.8	0%	18.67	2.1	75%
Hydrogen	24.89	2.8	0%	18.67	2.1	0%
Electricity	24.89	2.8	0%	18.67	2.1	0%
Off-Road	**4.47**	**0.6**	**---**	**4.02**	**0.5**	**---**
Gasoline	4.47	0.6	80%	4.02	0.5	0%
Diesel	4.47	0.6	20%	4.02	0.5	25%
Biofuels	4.47	0.6	0%	4.02	0.5	75%
Hydrogen	4.47	0.6	0%	4.02	0.5	0%
Electricity	4.47	0.6	0%	4.02	0.5	0%
Natural Gas	4.47	0.6	0%	4.02	0.5	0%
Marine, Ag, and Off-Road average - Instate	**6.39**	**---**	**---**	**5.13**	**---**	**---**
Marine, Ag, and Off-Road average - Overall	**12.89**	**---**	**---**	**9.14**	**---**	**---**
All Transport - Instate	**2.41**	**---**	**---**	**1.89**	**---**	**---**
All Transport - Overall	**1.62**	**---**	**---**	**1.60**	**---**	**---**

Scenarios: Electric-drive 80in50 and Actor-based 80in50

Various units	**2050 Scenarios**					
	Electric-drive 80in50			**Actor-based 80in50**		
LDVs	*MJ/pass.-mile*	*miles/gge*	*Fleet Share*	*MJ/pass.-mile*	*miles/gge*	*Fleet Share*
Gasoline ICEs	1.41	51.1	0%	0.75	76.9	0%
Biofuel ICEs	1.41	51.1	0%	0.75	76.9	0%
Diesel ICEs	1.12	64.5	0%	0.57	101.4	0%
Gasoline PHEVs	0.89	81.0	25%	0.41	117.4	50%
Biofuel PHEVs	0.89	81.0	0%	0.41	117.4	0%
Diesel PHEVs	0.80	90.6	0%	0.36	133.2	30%
H2FCVs	0.94	76.4	50%	0.49	114.4	10%
Battery EVs	0.64	111.8	25%	0.37	156.3	10%
LDV average	**0.85**	**84.3**	**---**	**0.40**	**124.6**	**---**
Car fleet share			60%			90%
Truck fleet share			40%			10%
HDVs	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
Buses	**1.66**	**1,575**	**---**	**1.25**	**990**	**---**
Diesel, Gasoline, and Other ICE/HEV	2.20	2,083	0%	1.47	1,157	10%
Diesel & Gasoline PHEVs	1.97	1,867	0%	1.56	1,230	25%
Biofuel PHEVs	1.97	1,867	0%	1.56	1,230	5%
H2FCVs	1.76	1,666	50%	1.17	926	10%
Battery EVs	1.57	1,484	50%	1.04	824	50%
	MJ/vehicle-mile	*miles/gge*	*Fleet Share*	*MJ/vehicle-mile*	*miles/gge*	*Fleet Share*
Heavy Trucks	**9.22**	**14.7**	**---**	**10.63**	**12.6**	**---**
Diesel	18.44	7.4	0%	15.36	8.8	0%
Diesel HEV	13.83	9.8	0%	11.52	11.8	70%
Biofuel HEVs	13.83	9.8	0%	11.52	11.8	10%
H2FCVs	9.22	14.7	90%	7.68	17.6	10%
Battery EVs	9.22	14.7	10%	6.40	17.6	10%

Various units	**2050 Scenarios**					
	Electric-drive 80in50			**Actor-based 80in50**		
HDV average	**6.26**	**---**	**---**	**3.07**	**---**	**---**
Aircraft						
	MJ/pass.-mile	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
Passenger Aviation - Instate	**1.28**	**1,212**	**---**	**1.07**	**1,010**	**---**
Gasoline	1.28	1,212	10%	1.07	1,010	10%
Jet Fuel (kerosene)	1.28	1,212	40%	1.07	1,010	20%
Biofuels	1.28	1,212	50%	1.07	1,010	70%
Hydrogen	1.28	1,212	0%	1.07	1,010	0%
Passenger Aviation - Overall	**1.13**	**1,071**	**---**	**0.94**	**893**	**---**
Gasoline	1.13	1,071	10%	0.94	893	10%
Jet Fuel (kerosene)	1.13	1,071	40%	0.94	893	20%
Biofuels	1.13	1,071	50%	0.94	893	70%
Hydrogen	1.13	1,071	0%	0.94	893	0%
	MJ/person-mile	*Btu/person-mile*	*Fleet Share*	*MJ/person-mile*	*Btu/person-mile*	*Fleet Share*
Freight - Instate	**0.34**	**318**	**---**	**0.28**	**265**	**---**
Gasoline	0.34	318	10%	0.28	265	10%
Jet Fuel (kerosene)	0.34	318	40%	0.28	265	20%
Biofuels	0.34	318	50%	0.28	265	70%
Hydrogen	0.34	318	0%	0.28	265	0%
Freight - Overall	**0.29**	**276**	**---**	**0.24**	**230**	**---**
Gasoline	0.29	276	10%	0.24	230	10%
Jet Fuel (kerosene)	0.29	276	40%	0.24	230	20%
Biofuels	0.29	276	50%	0.24	230	70%
Hydrogen	0.29	276	0%	0.24	230	0%
	MJ/pass.-mile	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
General Aviation - Instate	**56.17**	**53,236**	**---**	**46.81**	**44,364**	**---**
Gasoline	56.17	53,236	10%	46.81	44,364	10%
Jet Fuel (kerosene)	56.17	53,236	40%	46.81	44,364	20%
Biofuels	56.17	53,236	50%	46.81	44,364	70%

Various units	**2050 Scenarios**					
	Electric-drive 80in50			**Actor-based 80in50**		
Hydrogen	56.17	53,236	0%	46.81	44,364	0%
General Aviation - Overall	**56.17**	**53,236**	**---**	**46.81**	**44,364**	**---**
Gasoline	56.17	53,236	10%	46.81	44,364	10%
Jet Fuel (kerosene)	56.17	53,236	40%	46.81	44,364	20%
Biofuels	56.17	53,236	50%	46.81	44,364	70%
Hydrogen	56.17	53,236	0%	46.81	44,364	0%
Aircraft average - Instate	**2.91**	**---**	**---**	**2.06**	**---**	**---**
Aircraft average - Overall	**0.55**	**---**	**---**	**0.42**	**---**	**---**
Rail	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*	*MJ/pass.-mile*	*Btu/pass.-mile*	*Fleet Share*
Passenger Rail	**1.94**	**1,837**	**---**	**1.29**	**1,225**	**---**
Intercity Rail	1.38	1,313	---	0.92	875	---
Diesel Hybrid	2.43	2,303	0%	1.62	1,535	0%
Biofuel Hybrid	2.43	2,303	0%	1.62	1,535	0%
H2FC	1.94	1,842	0%	1.30	1,228	0%
Electric	1.38	1,313	100%	0.92	875	100%
Commuter Rail	1.53	1,452	---	1.02	968	---
Diesel Hybrid	2.69	2,547	0%	1.79	0	0%
Biofuel Hybrid	2.69	2,547	0%	1.79	1,698	0%
H2FC	2.15	2,037	0%	1.43	1,698	0%
Electric	1.53	1,452	100%	1.02	1,358	100%
Heavy Rail	2.35	2,227	---	1.57	1,485	---
Diesel Hybrid	---	---	0%	---	0	0%
Biofuel Hybrid	---	---	0%	---	---	0%
H2FC	---	---	0%	---	---	0%
Electric	2.35	2,227	100%	1.57	1,485	100%
Light Rail	2.35	2,227	---	1.57	1,485	---
Diesel Hybrid	---	---	0%	---	0	0%

Various units	2050 Scenarios					
	Electric-drive 80in50			Actor-based 80in50		
Biofuel Hybrid	---	---	0%	---	---	0%
H2FC	---	---	0%	---	---	0%
Electric	2.35	2,227	100%	1.57	1,485	100%
	MJ/person-mile	*Btu/ton-mile*	*Fleet Share*	*MJ/person-mile*	*Btu/ton-mile*	*Fleet Share*
Freight Rail	**1.01**	**163**	**---**	**0.98**	**61**	**---**
Diesel Hybrid	1.78	286	0%	1.19	0	60%
Biofuel Hybrid	1.78	286	0%	1.19	191	0%
H2FC	1.42	229	0%	0.95	191	0%
Electric	1.01	163	100%	0.68	153	40%
Rail average	**1.13**	**---**	**---**	**1.21**	**---**	**---**
Marine, Agriculture, and Off-Road						
	MJ/vehicle-mile	*gal fuel/veh.-mile*	*Fleet Share*	*MJ/vehicle-mile*	*gal fuel/veh.-mile*	*Fleet Share*
Marine - Instate	**12.18**	**---**	**---**	**10.15**	**---**	**---**
Marine - Overall	**67.33**	**---**	**---**	**56.11**	**---**	**---**
Large Marine Vehicles - Overall	**2,562.37**	**17.3**	**---**	**2,135.31**	**17.3**	**---**
Gasoline	2,562.37	17.3	0%	2,135.31	17.3	0%
Diesel and Distillate Fuel Oil	2,562.37	17.3	0%	2,135.31	17.3	30%
Biofuels	2,562.37	17.3	45%	2,135.31	17.3	20%
Hydrogen	2,562.37	17.3	25%	2,135.31	17.3	10%
Residual Fuel Oil (Marine Bunker Fuel)	2,562.37	17.3	30%	2,135.31	17.3	40%
Harbor Craft	**7.07**	**1.0**	**---**	**5.89**	**1.0**	**---**
Gasoline	7.07	1.0	15%	5.89	1.0	30%
Diesel and Distillate Fuel Oil	7.07	1.0	10%	5.89	1.0	40%
Biofuels	7.07	1.0	50%	5.89	1.0	20%
Hydrogen	7.07	1.0	25%	5.89	1.0	10%
Residual Fuel Oil (Marine Bunker Fuel)	7.07	1.0	0%	5.89	1.0	0%
Personal Boats	**13.25**	**2.2**	**---**	**11.04**	**1.8**	**---**
Gasoline	13.25	2.2	45%	11.04	1.8	60%

Various units	**2050 Scenarios**					
	Electric-drive 80in50			**Actor-based 80in50**		
Diesel and Distillate Fuel Oil	13.25	2.2	5%	11.04	1.8	30%
Biofuels	13.25	2.2	50%	11.04	1.8	10%
Hydrogen	13.25	2.2	0%	11.04	1.8	0%
Residual Fuel Oil (Marine Bunker Fuel)	13.25	2.2	0%	11.04	1.8	0%
	MJ/vehicle-mile	*gal fuel/hour*	*Fleet Share*	*MJ/vehicle-mile*	*gal fuel/hour*	*Fleet Share*
Agriculture	**18.67**	**2.1**	**---**	**15.56**	**1.7**	**---**
Gasoline	18.67	2.1	0%	15.56	1.7	20%
Diesel	18.67	2.1	30%	15.56	1.7	30%
Biofuels	18.67	2.1	40%	15.56	1.7	30%
Hydrogen	18.67	2.1	20%	15.56	1.7	10%
Electricity	18.67	2.1	10%	15.56	1.7	10%
Off-Road	**4.02**	**0.5**	**---**	**3.35**	**0.4**	**---**
Gasoline	4.02	0.5	0%	3.35	0.4	10%
Diesel	4.02	0.5	0%	3.35	0.4	30%
Biofuels	4.02	0.5	30%	3.35	0.4	20%
Hydrogen	4.02	0.5	40%	3.35	0.4	10%
Electricity	4.02	0.5	30%	3.35	0.4	30%
Natural Gas	4.02	0.5	0%	3.35	0.4	0%
Marine, Ag, and Off-Road average - Instate	**5.13**	**---**	**---**	**4.12**	**---**	**---**
Marine, Ag, and Off-Road average - Overall	**9.14**	**---**	**---**	**7.50**	**---**	**---**
All Transport - Instate	**1.35**	**---**	**---**	**1.03**	**---**	**---**
All Transport - Overall	**1.18**	**---**	**---**	**0.68**	**---**	**---**

A.3 Fuel carbon intensity (C) assumptions by scenario and sector

Units = gCO_2e/MJ (unless specified otherwise)	**1990 Historical Values**	**2050 Scenarios**									
		Reference	**Moderate efficiency SB**	**High efficiency SB**	**Hydrogen-intensive SB**	**Electricity-intensive SB**	**Biofuel-intensive SB**	**PMT SB**	**Efficient Biofuels 80in50**	**Electric-drive 80in50**	**Actor-based 80in50**
LDVs											
Gasoline ICEs	92	92	92	92	92	92	96	92	92	92	81
Biofuel ICEs	---	16	16	16	16	16	16	16	18	24	18
Diesel ICEs	90	91	91	91	91	91	95	91	90	90	80
Gasoline PHEVs	75	55	55	55	34	34	46	55	34	34	30
Biofuel PHEVs	75	19	19	19	10	10	20	19	10	12	10
Diesel PHEVs	75	55	55	55	33	33	45	55	33	33	30
H2FCVs	112	64	64	64	10	24	64	64	24	24	48
Battery EVs	112	22	22	22	7	7	22	22	7	7	7
Total LDVs	**92**	**92**	**92**	**92**	**44**	**24**	**48**	**92**	**16**	**23**	**30**
Biofuels share of gasoline and diesel (blend level)	0.0%	5.7%	5.7%	5.7%	5.7%	5.7%	0.0%	5.7%	0.0%	0.0%	20.0%
PHEVs: Share of miles driven in different modes											
All-electric (EV)	---	52%	52%	52%	68%	68%	68%	52%	68%	68%	68%
Hybrid-Electric (HEV)	---	48%	48%	48%	32%	32%	32%	48%	32%	32%	32%
HDVs											
Buses	**90**	**95**	**95**	**95**	**35**	**32**	**80**	**95**	**17**	**16**	**30**
Diesel, Gasoline, and Other ICE/HEV	90	95	95	95	95	95	80	95	18	90	80
Diesel & Gasoline PHEVs	---	69	69	69	63	63	59	69	14	60	42
Biofuel PHEVs	---	18	18	18	13	13	18	18	14	18	12
H2FCVs	---	64	64	64	10	24	64	64	24	24	48
Battery EVs	---	22	22	22	7	7	22	22	7	7	7
PHEVs: Share of miles driven in different modes											
All-electric (EV)	---	36%	36%	36%	36%	36%	36%	36%	36%	36%	52%
Hybrid-Electric (HEV)	---	64%	64%	64%	64%	64%	64%	64%	64%	64%	48%
Heavy Trucks	**90**	**95**	**95**	**95**	**29**	**87**	**47**	**95**	**14**	**23**	**66**
Diesel	90	95	95	95	95	95	80	95	18	90	80
Diesel HEV	---	95	95	95	95	95	80	95	18	90	80

Units = gCO_2e/MJ (unless specified otherwise)	**1990 Historical Values**	**2050 Scenarios**									
		Reference	**Moderate efficiency SB**	**High efficiency SB**	**Hydrogen-intensive SB**	**Electricity-intensive SB**	**Biofuel-intensive SB**	**PMT SB**	**Efficient Biofuels 80in50**	**Electric-drive 80in50**	**Actor-based 80in50**
Biofuel HEVs	---	18	18	18	13	13	18	18	14	18	12
H2FCVs	---	64	64	64	10	24	64	64	24	24	48
Battery EVs	---	22	22	22	7	7	22	22	7	7	7
Biofuels share of diesel (blend level)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	20.0%	0.0%	100.0%	0.0%	20.0%
Total HDV	**90**	**95**	**95**	**95**	**30**	**83**	**50**	**95**	**14**	**22**	**54**
Aircraft											
Passenger Aviation - Instate	**91**	**96**	**96**	**96**	**91**	**96**	**48**	**96**	**36**	**57**	**41**
Gasoline	92	96	96	96	96	96	96	96	92	92	96
Jet Fuel (kerosene)	90	95	95	95	95	95	95	95	90	90	95
Biofuels	---	16	16	16	16	16	16	16	18	24	18
Hydrogen	---	64	64	64	10	24	64	64	24	24	48
Passenger Aviation - Overall	**91**	**96**	**96**	**96**	**91**	**96**	**48**	**96**	**36**	**57**	**41**
Gasoline	92	96	96	96	96	96	96	96	92	92	96
Jet Fuel (kerosene)	90	95	95	95	95	95	95	95	90	90	95
Biofuels	---	16	16	16	16	16	16	16	18	24	18
Hydrogen	---	64	64	64	10	24	64	64	24	24	48
Freight - Instate	**91**	**96**	**96**	**96**	**91**	**96**	**48**	**96**	**36**	**57**	**41**
Gasoline	92	96	96	96	96	96	96	96	92	92	96
Jet Fuel (kerosene)	90	95	95	95	95	95	95	95	90	90	95
Biofuels	---	16	16	16	16	16	16	16	18	24	18
Hydrogen	---	64	64	64	10	24	64	64	24	24	48
Freight - Overall	**91**	**96**	**96**	**96**	**91**	**96**	**48**	**96**	**36**	**57**	**41**
Gasoline	92	96	96	96	96	96	96	96	92	92	96
Jet Fuel (kerosene)	90	95	95	95	95	95	95	95	90	90	95
Biofuels	---	16	16	16	16	16	16	16	18	24	18
Hydrogen	---	64	64	64	10	24	64	64	24	24	48
General Aviation - Instate	**91**	**96**	**96**	**96**	**91**	**96**	**48**	**96**	**36**	**57**	**41**
Gasoline	92	96	96	96	96	96	96	96	92	92	96
Jet Fuel (kerosene)	90	95	95	95	95	95	95	95	90	90	95

Units = gCO$_2$e/MJ (unless specified otherwise)	1990 Historical Values	2050 Scenarios									
		Reference	Moderate efficiency SB	High efficiency SB	Hydrogen-intensive SB	Electricity-intensive SB	Biofuel-intensive SB	PMT SB	Efficient Biofuels 80in50	Electric-drive 80in50	Actor-based 80in50
Biofuels	---	16	16	16	16	16	16	16	18	24	18
Hydrogen	---	64	64	64	10	24	64	64	24	24	48
General Aviation - Overall	**91**	**96**	**96**	**96**	**91**	**96**	**48**	**96**	**36**	**57**	**41**
Gasoline	92	96	96	96	96	96	96	96	92	92	96
Jet Fuel (kerosene)	90	95	95	95	95	95	95	95	90	90	95
Biofuels	---	16	16	16	16	16	16	16	18	24	18
Hydrogen	---	64	64	64	10	24	64	64	24	24	48
Total Aircraft - Instate	**91**	**96**	**96**	**96**	**91**	**96**	**48**	**96**	**36**	**57**	**41**
Total Aircraft - Overall	**91**	**96**	**96**	**96**	**91**	**96**	**48**	**96**	**36**	**57**	**41**
Rail											
Passenger Rail	**129**	**47**	**47**	**47**	**8**	**7**	**31**	**56**	**12**	**7**	**7**
Intercity Rail	104	95	95	95	10	7	42	95	18	7	7
Diesel Hybrid	90	95	95	95	80	80	80	95	90	90	80
Biofuel Hybrid	75	16	16	16	16	16	16	16	18	24	18
H2FC	112	64	64	64	10	24	64	64	24	24	48
Electric	147	22	22	22	7	7	22	22	7	7	7
Commuter Rail	126	44	44	44	10	7	42	95	18	7	7
Diesel Hybrid	90	95	95	95	80	80	80	95	90	90	80
Biofuel Hybrid	75	16	16	16	16	16	16	16	18	24	18
H2FC	112	64	64	64	10	24	64	64	24	24	48
Electric	147	22	22	22	7	7	22	22	7	7	7
Heavy Rail	147	22	22	22	7	7	22	22	7	7	7
Diesel Hybrid	90	95	95	95	80	80	80	95	90	90	80
Biofuel Hybrid	75	16	16	16	16	16	16	16	18	24	18
H2FC	112	64	64	64	10	24	64	64	24	24	48
Electric	147	22	22	22	7	7	22	22	7	7	7
Light Rail	147	22	22	22	7	7	22	22	7	7	7
Diesel Hybrid	90	95	95	95	80	80	80	95	90	90	80
Biofuel Hybrid	75	16	16	16	16	16	16	16	18	24	18
H2FC	112	64	64	64	10	24	64	64	24	24	48
Electric	147	22	22	22	7	7	22	22	7	7	7

Units = gCO$_2$e/MJ (unless specified otherwise)	**1990 Historical Values**	**2050 Scenarios**									
		Reference	**Moderate efficiency SB**	**High efficiency SB**	**Hydrogen-intensive SB**	**Electricity-intensive SB**	**Biofuel-intensive SB**	**PMT SB**	**Efficient Biofuels 80in50**	**Electric-drive 80in50**	**Actor-based 80in50**
Freight Rail	**90**	**95**	**95**	**95**	**10**	**7**	**42**	**95**	**18**	**7**	**60**
Diesel Hybrid	90	95	95	95	80	80	80	95	90	90	80
Biofuel Hybrid	75	16	16	16	16	16	16	16	18	24	18
H2FC	112	64	64	64	10	24	64	64	24	24	48
Electric	147	22	22	22	7	7	22	22	7	7	7
Biofuels share of diesel (blend level)	0.0%	0.0%	0.0%	0.0%	20.0%	20.0%	20.0%	0.0%	0.0%	0.0%	20.0%
Total Rail	**102**	**90**	**90**	**90**	**9**	**7**	**40**	**67**	**17**	**7**	**17**
Marine, Agriculture, and Off-Road											
Marine - Instate	**92**	**96**	**96**	**96**	**72**	**96**	**48**	**96**	**18**	**56**	**87**
Marine - Overall	**96**	**95**	**95**	**95**	**56**	**95**	**48**	**95**	**47**	**46**	**77**
Large Marine Vehicles - Overall	**96**	**95**	**95**	**95**	**52**	**95**	**48**	**95**	**54**	**44**	**75**
Gasoline	92	96	96	96	96	96	96	96	92	92	96
Diesel and Distillate Fuel Oil	90	95	95	95	95	95	95	95	90	90	95
Biofuels	---	16	16	16	16	16	16	16	18	24	18
Hydrogen	---	64	64	64	10	24	64	64	24	24	48
Residual Fuel Oil (Marine Bunker Fuel)	96	95	95	95	95	95	95	95	90	90	95
Harbor Craft	**90**	**96**	**96**	**96**	**53**	**96**	**48**	**96**	**18**	**41**	**75**
Gasoline	---	96	96	96	96	96	96	96	92	92	96
Diesel and Distillate Fuel Oil	90	95	95	95	95	95	95	95	90	90	95
Biofuels	---	16	16	16	16	16	16	16	18	24	18
Hydrogen	---	64	64	64	10	24	64	64	24	24	48
Residual Fuel Oil (Marine Bunker Fuel)	---	95	95	95	95	95	95	95	90	90	95
Personal Boats	**92**	**96**	**96**	**96**	**75**	**96**	**48**	**96**	**18**	**58**	**88**
Gasoline	92	96	96	96	96	96	96	96	92	92	96
Diesel and Distillate Fuel Oil	90	95	95	95	95	95	95	95	90	90	95
Biofuels	---	16	16	16	16	16	16	16	18	24	18

Units = gCO$_2$e/MJ (unless specified otherwise)	**1990 Historical Values**	**2050 Scenarios**									
		Reference	**Moderate efficiency SB**	**High efficiency SB**	**Hydrogen-intensive SB**	**Electricity-intensive SB**	**Biofuel-intensive SB**	**PMT SB**	**Efficient Biofuels 80in50**	**Electric-drive 80in50**	**Actor-based 80in50**
Hydrogen	---	64	64	64	10	24	64	64	24	24	48
Residual Fuel Oil (Marine Bunker Fuel)	---	95	95	95	95	95	95	95	90	90	95
Agriculture	**90**	**96**	**96**	**96**	**78**	**87**	**48**	**96**	**36**	**42**	**59**
Gasoline	92	96	96	96	96	96	96	96	92	92	96
Diesel	90	95	95	95	95	95	95	95	90	90	95
Biofuels	---	16	16	16	16	16	16	16	18	24	18
Hydrogen	---	64	64	64	10	24	64	64	24	24	48
Electricity	---	22	22	22	7	7	22	22	7	7	7
Off-Road	**90**	**96**	**96**	**96**	**53**	**51**	**48**	**96**	**36**	**19**	**49**
Gasoline	92	96	96	96	96	96	96	96	92	92	96
Diesel	90	95	95	95	95	95	95	95	90	90	95
Biofuels	---	16	16	16	16	16	16	16	18	24	18
Hydrogen	---	64	64	64	10	24	64	64	24	24	48
Electricity	---	22	22	22	7	7	22	22	7	7	7
Natural Gas	66	67	67	67	67	67	67	67	67	67	67
Total Marine, Agriculture, and Off-Road - Instate	**90**	**96**	**96**	**96**	**60**	**64**	**48**	**96**	**33**	**28**	**56**
Total Marine, Agriculture, and Off-Road - Overall	**94**	**96**	**96**	**96**	**57**	**79**	**48**	**96**	**42**	**35**	**65**
All Transport - Instate	**92**	**93**	**93**	**93**	**45**	**50**	**49**	**91**	**18**	**25**	**42**
All Transport - Overall	**92**	**94**	**94**	**94**	**59**	**65**	**48**	**92**	**24**	**35**	**44**
Unconventional oil resources (coal, NG, oil shale, tar sands) used in producing gasoline and diesel?	NO	YES	YES	YES	YES	YES	YES	YES	NO	NO	YES
Biofuels Mix (across all sectors)											
Ethanol	---	40%	40%	40%	40%	40%	40%	40%	30%	5%	30%
Biodiesel	---	30%	30%	30%	30%	30%	30%	30%	40%	85%	40%
Bio-butanol	---	30%	30%	30%	30%	30%	30%	30%	30%	10%	30%

Units = gCO_2e/MJ (unless specified otherwise)	1990 Historical Values	2050 Scenarios									
		Reference	Moderate efficiency SB	High efficiency SB	Hydrogen-intensive SB	Electricity-intensive SB	Biofuel-intensive SB	PMT SB	Efficient Biofuels 80in50	Electric-drive 80in50	Actor-based 80in50
Methanol	---	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
DME	---	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ethanol Production Shares by Technology											
Corn and Sugar Cane	---	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Cellulosic Biomass	---	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Indirect land use change (LUC) GHG impacts considered for biofuels production?	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Hydrogen Production Mix											
Natural Gas, pipeline, w/o or w/ CCS	---	10%	10%	10%	40%	30%	10%	10%	30%	30%	0%
Natural Gas, on-site	---	40%	40%	40%	0%	0%	40%	40%	0%	0%	50%
Natural Gas, liquid H2 truck, w/o or w/ CCS	---	0%	0%	0%	0%	0%	0%	0%	0%	0%	20%
Biomass, pipeline	---	30%	30%	30%	20%	35%	30%	30%	35%	35%	0%
Coal, pipeline, w/o or w/ CCS	---	0%	0%	0%	0%	30%	0%	0%	30%	30%	0%
Hydrogen (Electrolysis, onsite, CA grid mix)	---	10%	10%	10%	0%	0%	10%	10%	0%	0%	0%
Hydrogen (Electrolysis, onsite, 70% renewable grid mix)	---	10%	10%	10%	0%	0%	10%	10%	0%	0%	0%
Hydrogen (Electrolysis, onsite, 100% renewable grid mix)	---	0%	0%	0%	40%	5%	0%	0%	5%	5%	30%
Carbon Intensity of Hydrogen (gCO_2-eq/MJ)	---	64	64	64	10	24	64	64	24	24	48
Change from 1990 gasoline	---	-30%	-30%	-30%	-90%	-74%	-30%	-30%	-74%	-74%	-47%
Electricity Production Mix											
Electricity (NG CC, w/o or w/ CCS)	---	40%	40%	40%	30%	30%	40%	40%	30%	30%	30%
Electricity (Nuclear)	---	15%	15%	15%	30%	30%	15%	15%	30%	30%	30%
Electricity (Wind, Solar, Other renewables)	---	20%	20%	20%	40%	40%	20%	20%	40%	40%	40%

Units = gCO_2e/MJ (unless specified otherwise)	**1990 Historical Values**	**2050 Scenarios**									
		Reference	**Moderate efficiency SB**	**High efficiency SB**	**Hydrogen-intensive SB**	**Electricity-intensive SB**	**Biofuel-intensive SB**	**PMT SB**	**Efficient Biofuels 80in50**	**Electric-drive 80in50**	**Actor-based 80in50**
Electricity (Biomass)	---	5%	5%	5%	0%	0%	5%	5%	0%	0%	0%
Electricity (Coal, IGCC, w/o or w/ CCS)	---	20%	20%	20%	0%	0%	20%	20%	0%	0%	0%
Carbon Intensity of Electricity (gCO2-eq/MJ)	112	22	22	22	7	7	22	22	7	7	7
Change from 1990 electricity	---	-81%	-81%	-81%	-94%	-94%	-81%	-81%	-94%	-94%	-94%
Change from 1990 gasoline	---	-76%	-76%	-76%	-93%	-93%	-76%	-76%	-93%	-93%	-93%
Carbon Capture & Storage (CCS) Utilization											
Gasoline (Coal-to-Liquids)	---	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Diesel (Coal-to-Liquids)	---	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Hydrogen (Natural Gas, pipeline)	---	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Hydrogen (Natural Gas, liquid H2 truck)	---	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Hydrogen (Coal, pipeline)	---	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Electricity (Natural Gas Combined Cycle)	---	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Electricity (Coal, IGCC)	---	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES