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Meeting an 80% reduction in greenhouse gas emissions from transportation by 2050: A case study in California

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ABSTRACT

This paper investigates how California may reduce transportation greenhouse gas emissions 80% below 1990 levels by 2050 (i.e., *80in50*). A Kaya framework that decomposes greenhouse gas emissions into the product of population, transport intensity, energy intensity, and carbon intensity is used to analyze emissions and mitigation options. Each transportation subsector, including light-duty, heavy-duty, aviation, rail, marine, agriculture, and off-road vehicles, is analyzed to identify specific mitigation options and understand its potential for reducing greenhouse gas emissions. Scenario analysis shows that, while California's 2050 target is ambitious, it can be achieved in transport if a concerted effort is made to change travel behavior and the vehicles and fuels that provide mobility. While no individual "*Silver Bullet*" strategy exists that can achieve the goals, a portfolio approach that combines strategies could yield success. The *80in50* scenarios show the impacts of advanced vehicle and fuels technologies as well as the role of travel demand reduction, which can significantly reduce energy and resource requirements and the level of technology development needed to meet the target.

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 (California Department of Environmental Protection, 2006). As a result, Governor Arnold Schwarzenegger announced aggressive greenhouse gas (GHG) reduction targets (Executive Order S-3-05) that call for reducing emissions to 1990 levels by 2020 and to 80% below 1990 levels by 2050 (also called "*80in50*" in this paper). These targets are among the most ambitious by a major world economy and since then, the state has passed landmark legislation, the Global Warming Solutions Act (i.e., AB32), in 2006 that makes the 2020 targets in the Executive Order binding, taking a lead role in regulating GHG emissions. The near-term (2020) 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 GHG and climate before catastrophic changes occur (California Department of Environmental Protection, 2006). 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 paper explores how California can meet this target in the transportation sector.

This paper explores options for reducing emissions in the transportation sector by 80% in the year 2050 using a scenario approach. These scenarios look across all transportation subsectors (light-duty vehicles, heavy-duty vehicles (buses and trucks), rail, aviation, marine, agriculture, and off-road), and includes strategies for reducing travel demand, improving

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Table 1
1990 California transportation energy use and lifecycle emissions by subsector and vehicle type.

Subsector	Vehicle type	Energy use				GHG emissions			
		Instate		Overall		Instate		Overall	
		(PJ)	%	(PJ)	%	MMT CO_2e	%	MMT CO_2e	%
Light-duty	Cars and trucks	1,460	69.4	1,460	50.8	134.3	69.7	134.3	50.9
Heavy-duty	Buses	77	3.7	77	2.7	6.9	3.6	6.9	2.6
	Heavy Trucks	318	15.1	318	11.1	28.7	14.9	28.7	10.9
Aviation	Passenger	56	2.6	386	13.4	5.0	2.6	34.8	13.2
	Freight	5	0.2	118	4.1	0.4	0.2	10.6	4.0
	General	5	0.2	10	0.3	0.4	0.2	0.9	0.3
Rail	Passenger	9	0.4	9	0.3	0.9	0.5	0.9	0.3
	Freight	19	0.9	19	0.7	1.7	0.9	1.7	0.7
Marine	Large marine	–	0.0	321	11.2	–	0.0	31.0	11.7
	Harbor craft	2	0.1	2	0.1	0.2	0.1	0.2	0.1
	Personal boats	25	1.2	25	0.9	2.3	1.2	2.3	0.9
Agriculture	Agriculture	53	2.5	53	1.8	4.7	2.5	4.7	1.8
Off-road	Off-road	76	3.6	76	2.7	6.9	3.6	6.9	2.6
All subsectors		2,105		2,874		192.6		264.0	

efficiency and using advanced technologies with alternative fuels. To keep the scenario analysis simple and transparent, this paper 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. Instead, scenarios are presented with explicit assumptions, representing snapshots of potential futures around which decision-makers and stakeholders can begin discussions about the feasibility of reaching the targets, and the necessary trajectories and challenges for developing and implementing technologies and policy.

In California, the transportation sector is the largest contributor of GHG emissions, making up over 40% of the state's total in 2006 (California Air Resources Board, 2008). As a result, the transportation sector must play a major role if significant statewide emission reductions are to be achieved. In this study, two categories of emissions are defined: *Instate* emissions, which are produced from vehicle trips that take place entirely within California's borders; and *Overall* emissions, which include instate trips as well as half of all out-of-state trips (both domestic and international) that originate or terminate in California. Table 1 gives a breakdown of transportation energy use and "well-to-wheels" lifecycle emissions by subsector and vehicle type in California in 1990 for both the *Instate* and *Overall* cases. Light-duty vehicles (LDV; i.e., passenger cars and trucks) account for approximately two-thirds of the state's *Instate* transportation energy use and emissions and approximately half of *Overall* transportation energy use and emissions. The similarity between energy use and emissions is a result of the ubiquitous use of petroleum fuels. Aviation and marine make up just 3% and 1%, respectively, of all transportation emissions in the *Instate* emissions case but 18% and 13%, respectively, of all transportation emissions in the *Overall* emissions case. Note that, according to the definitions of the California Air Resources Board (2008), fuel consumption (and thus GHG emissions) from interstate trucking and rail are included in the *Instate* emissions category.

2. Methods

This paper uses a spreadsheet model, the Long-term Evaluation of Vehicle Emission Reduction Strategies (LEVERS) model, which is built around a transportation-variant of the Kaya identity, to analyze GHG emissions. The Kaya identity (Kaya, 1990) decomposes CO_2 emissions into the product of several important parameters. Decomposition analysis has become a popular energy and environmental analysis tool in recent years (Ang and Zhang, 2000; Schipper et al., 2001) and several studies have used decomposition analysis to study historical energy use and GHG emissions in US transport by subsector (Lakshmanan and Han, 1997; Scholl et al., 1996). While the original Kaya identity defines activity in terms of GDP, this variation of the Kaya equation (see Eqs. (1) and (2)) focuses on transport intensity as the main activity driver in the transportation sector. Transportation CO_2 emissions[1] are decomposed into four main drivers: population, travel demand, vehicle fuel consumption, and fuel carbon intensity. These independent parameters are multiplied together to determine GHG emissions, making it straightforward to understand the impact of changes to a single parameter on GHG emissions (i.e. reducing one parameter by 50% will lower GHG emissions by 50%, all other terms being equal).

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[1] The terms carbon, CO_2, and greenhouse gases are used interchangeably in this paper, as calculations are based upon equivalent carbon dioxide emissions (CO_2e) using global warming potentials of different GHGs.

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$$\mathrm{CO}_{2,\mathit{Transport}} \equiv (\mathit{Population})\left(\frac{\mathit{Transport}}{\mathit{Person}}\right)\left(\frac{\mathit{Energy}}{\mathit{Transport}}\right)\left(\frac{\mathit{Carbon}}{\mathit{Energy}}\right) \tag{1}$$

$$\mathrm{CO}_{2,\mathit{Transport}} \equiv P \times T \times E \times C. \tag{2}$$

Transport intensity (T) is defined as individual passenger, vehicle or freight miles per capita (e.g., miles/person), depending on the particular subsector. A key challenge for meeting the *80in50* goal is that the first two terms (P and T) are projected to increase by 2050. The latter two parameters in the identity are energy intensity (E), which describes the energy use per-mile (e.g., MJ/mile) of transport, and carbon intensity (C), which describes the carbon emissions per unit of fuel energy (e.g., $\mathrm{gCO_2e/MJ}$).

The LEVERS model organizes scenario assumptions (i.e., Kaya parameters for the different mitigation options for each subsector and vehicle category listed in Table 1) and calculates aggregate transportation GHG emissions and fuel and resource usage. Specifying these options involves numerous assumptions about the mix of technologies and fuels used, the levels of optimism in the development of those technologies and structural and behavioral changes.

Three of the Kaya parameters correspond with three main ‘‘levers” for reducing emissions: reducing transport intensity (T), energy intensity (E) and fuel carbon intensity (C). Population is not considered in this analysis as a means of reducing emissions; California’s population is expected to double between 1990 and 2050 (California Department of Finance, 2007). Important considerations for determining how effective a strategy will be in reducing emissions include the following: what mitigation options are used, how broadly they are applied, and the degree of improvement they provide. Some mitigation options cannot be implemented in all subsectors. A number of literature sources were investigated (e.g., Greene and Schafer, 2003; Kahn Ribeiro et al., 2007) to bound the extent to which specific mitigation options could be applied and their impact on emissions in each of the transportation subsectors. Combinations of these options are used in the scenarios developed and presented in Section 3.

Transport intensity may be reduced by several means. Better land-use planning, higher-density developments, telecommuting and increased co-location of jobs and housing can reduce travel demand even while maintaining or improving the ability of people to access their desired destinations. Another method is mode-switching from private cars to mass transit (buses, trains, etc.), which has the capacity to carry a large number of people at a given time (see Kahn Ribeiro et al., 2007; Ewing et al., 2007 for a good review). Changes in consumer and industrial purchasing behavior can reduce activity in the freight sector.

Vehicle energy use (i.e. energy intensity) can be reduced by either reducing weight and dissipative losses or increasing the drivetrain efficiency. A number of advanced on-road vehicle technologies including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell vehicles (FCVs) can greatly improve vehicle drivetrain efficiency. Different options exist for reducing the energy intensities of other vehicle types as well (Greene and Schafer, 2003; Kahn Ribeiro et al., 2007).

Reducing the carbon intensity of vehicle fuels is accomplished by replacing higher-carbon content petroleum fuels with lower-carbon fuels (e.g. biofuels, hydrogen, or electricity). Because there are several different feedstocks and production methods for each alternative fuel, the carbon content of an alternative fuel can vary dramatically depending on how it is produced. In this study, the carbon content of fuels is estimated on a lifecycle GHG-basis, using a version of Argonne National Laboratory’s GREET model developed for California (California Air Resources Board, 2007a).

3. Results

Scenarios are used to investigate the GHG reduction impacts associated with of the adoption of advanced technologies and fuels and changes in transport intensity. Three sets of scenarios were developed for this project and are presented and discussed below: (1) a *Reference* scenario to establish a business-as-usual baseline for comparison, (2) *Silver Bullet* scenarios to examine the potential for individual solutions, and (3) *80in50* scenarios to illustrate several distinct approaches to achieve the *80in50* goal. These scenarios should not be taken as predictions of the future; rather, they are used to calculate the emissions impacts of adopting optimistic, yet plausible assumptions about the utilization of specific mitigation strategies.

Table 2
Change in transport intensity, energy intensity, and carbon intensity between 1990 and 2050 by subsector in the *Reference* scenario.

		LDV (%)	HDV (%)	Aviation (%)	Rail (%)	Marine/Ag/Off-road (%)	All subsectors (%)
T	Domestic	+21	+55	+34	+46	+42	+24
	Overall	+21	+55	+288	+46	+42	+103
E	Domestic	−47	0	−39	−14	−47	−35
	Overall	−47	0	−56	−14	−65	−46
C	Domestic	0	+6	+6	−4	+6	+2
	Overall	0	+6	+6	−4	+1	+2

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Table 3
Brief description of the *Reference* and *Silver Bullet* (*SB*) scenarios.

Scenario name	Scenario summary
Reference scenario	Doubling of population, modest increase (21%) in transport intensity, slight efficiency improvement (35%) and similar carbon intensity relative to 1990.
Moderate efficiency SB	No breakthrough technological advances, but applies all advances in conventional technologies towards improving vehicle efficiency to achieve doubling of average vehicle efficiency from 1990. Same carbon intensity as Reference, except for some electrified rail.
High efficiency SB	Significant breakthroughs in conventional technologies to achieve nearly triple (265%) vehicle efficiency from 1990. Same carbon intensity as Reference, except for some electrified rail.
Hydrogen-intensive SB	Applies FCV and low-carbon hydrogen fuels (9.5 gCO_2e/MJ) aggressively across most subsectors, except aviation, and provides 58% of all transport miles. Fleet market share of on-road H2 vehicles is limited to 60% in 2050 per (Greene et al., 2007; National Research Council, 2008). Assumes that the obstacles to use of hydrogen in heavy-duty trucks are overcome.
Electricity-intensive SB	Electric vehicles (BEVs and PHEVs) and very low-carbon electricity are applied across many subsectors except marine and aviation, providing 77% of all transport miles. Electricity carbon intensity (6.5 gCO_2e/MJ) is 94% below the 1990 value.
Biofuel-intensive SB	Low-carbon biofuels (16.3 gCO_2e/MJ) are the primary fuels used in conventional vehicles (low efficiency) in all transport subsectors, providing 59% of all transport miles. Biofuels are limited to 15–20% of future US supply[a].
PMT SB	About 25–50% reductions in passenger travel demand for LDVs and aviation relative to *Reference* scenario, through better land use, smart growth, transit and high-speed rail (Ewing et al., 2007). No alternative fuels; same carbon intensity as Reference. Improved energy intensities due to increased vehicle load factors.

[a] The USDA and DOE's "Billion-Ton Study" estimates 1.18 billion metric tonnes of dry biomass available in the US, which can be converted to approximately 85–92 billion gge of biofuels based upon reasonable conversion rates (Perlack et al., 2005). California currently accounts for nearly 18% of US ethanol consumption, 11% of US VMT and transportation fuels consumption and 13% of US GDP; and California's population is expected to grow faster than the country as a whole (12% in 1990 growing to 14% in 2050; California Department of Finance, 2007, 2008; US Department of Transportation, 2007; California Energy Commission, 2008; US Census Bureau, 2008).

3.1. Reference scenario

The *Reference* scenario describes a future where transportation activity and technology development continues to follow historical trends[2] (Table 2). In each of the scenarios presented in this study, the state population (P) is expected to double – from 29.8 million in 1990 to 59.5 million in 2050 (California Department of Finance, 2007). In this business-as-usual scenario, transport intensity (T) is expected to increase moderately by 21% and vehicle load factors are assumed to be the same as in 1990. As a result, travel demand ($P \times T$) in the *Instate* case is nearly 2.5 times the 1990 value and nearly four times the 1990 value in the *Overall* case, primarily due to rapid growth in air travel. Conventional vehicles and fuels continue to be employed. The only expected improvement in this scenario is a modest sector-wide reduction (35%) in energy intensity associated with continued evolutionary improvements in engine efficiency. In the light-duty sector, this corresponds to a 50% improvement in average vehicle efficiency from 1990 and is consistent with the recent CAFE standards of 2007 in the light-duty sector[3]. The average carbon intensity of all transportation fuels in 2050 is roughly the same as in 1990 (approx. 92 gCO_2e/MJ), since petroleum-based fuels are assumed to remain dominant, with some blending of biofuels and use of unconventional oil sources.

The *Reference* scenario leads to a 61% increase in *Instate* emissions from 1990 to 2050. *Instate* emissions reach 311 $MMTCO_2e$ in 2050 while in the *Overall* emissions case, they reach 492 $MMTCO_2e$. Despite increases in aircraft efficiency, rapid growth in air travel demands leads to significant increases in emissions from the aviation sector. 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.

3.2. 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 feasible extent from a technology perspective in 2050[4]. The emissions are calculated to gain an understanding of the aggregate GHG reduction potential of a particular mitigation option. The *SB* scenarios each modify only one element of the *Reference* scenario, such as the application of biofuels or high-efficiency vehicles. Table 3 provides a brief summary of the *Silver Bullet* scenarios.

Fig. 1 shows the reduction in GHG emissions for each of the *Silver Bullet* scenarios relative to the 1990 level and the 2050 *Reference* scenario. None of the *Silver Bullet* scenarios achieve the *80in50* goal. Both of the efficiency scenarios show that improving vehicle technologies can help to reduce emissions relative to business-as-usual, but the gains are largely negated by significant increases in travel demand inherent in the *Reference* scenario. The *Biofuel-intensive SB* scenario achieves a small (19%) reduction in emissions relative to 1990. The availability of low-carbon biofuels is limited (60% of fuel usage in this scenario or 16.1 billion gallons of gasoline equivalent (gge)). If additional biofuel lifecycle emissions associated with land-use

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[2] A range of sources were used to develop the Reference scenario including several national and state projections of transportation activity (California Air Resources Board, 2005, 2007b; Energy Information Administration, 2007; California Department of Transportation, 2006).

[3] Average on-road fuel economy of the entire California vehicle fleet in 1990 was 19.4 mpg (California Department of Transportation 2006).

[4] This assessment is subjective. As a result, the same level of optimism may not be exhibited about each individual technology in all scenarios.

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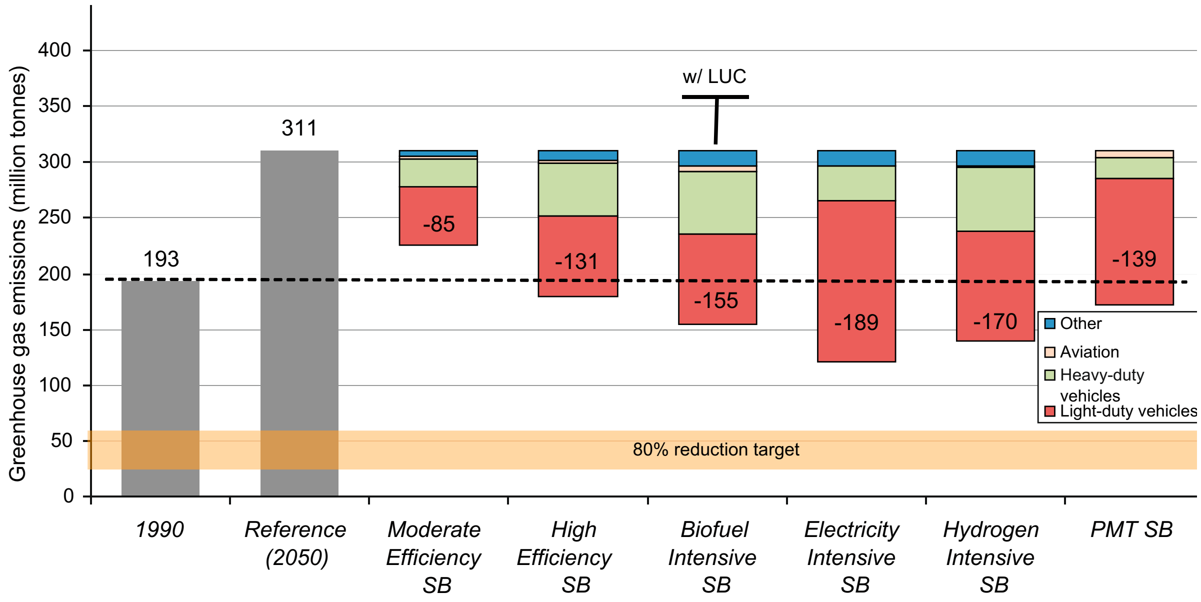

Fig. 1. Greenhouse gas emission reductions for *Silver Bullet* scenarios relative to *Reference* scenario for *Instate* emissions.

change (LUC) are included, as discussed in Searchinger et al. (2008), the benefits of biofuels could disappear. Though there is considerable uncertainty over the LUC impacts of biofuels, using Searchinger's estimates, LUC impacts would increase GHGs by an *additional* 79% over 1990 values.

Other alternative-fuel-intensive scenarios (*Hydrogen-intensive SB* and *Electricity-intensive SB*) do not achieve the *80in50* goal, either. Even though they can achieve significant emission reductions in the light-duty and heavy-duty sectors, these technologies are not applied across all subsectors, and as a result, they yield moderate reductions from 1990 emissions (53% and 41%, respectively). The extent of alternative fuel usage drops significantly in the *Overall* case (as these technologies cannot be applied as much in the aviation and marine sectors). Reducing per capita travel demand can also lead to GHG reductions relative to the *Reference* scenario, but population growth in the *PMT SB* still leads to a 72% increase in travel demand (PxT) relative to 1990, and only an 8% reduction from 1990 emissions.

3.3. *80in50 scenarios*

None of the individual mitigation strategies examined in the *Silver Bullet* scenarios can achieve the ambitious *80in50* goal, even under some aggressive assumptions about the development and implementation of advanced technologies and fuels, changes in travel demand and resource availability. However, many of the options examined are complementary and can be combined in a portfolio approach. Three *80in50* scenarios are presented that represent different futures in California in which 80% reductions in *Instate* GHG emissions are realized. The first two scenarios focus mainly on technology (*Efficient Biofuels 80in50 and Electric-drive 80in50*), and they assume that technology development can reduce the carbon emissions from transportation and eliminate the need for behavioral changes (i.e., reducing transportation activity) as transportation activity ($P \times T$) follows the *Reference* scenario. 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.

3.4. *Scenario descriptions*

The *Efficient Biofuels 80in50* scenario relies heavily on advanced technologies for biofuels production entirely from cellulosic sources with negligible LUC impacts (C = 16.3 gCO_2e/MJ). There are no major technical limitations to the use of biofuels in any subsector, so each transportation subsector comes to depend heavily on them. As seen in Table 4, biofuels provide the vast majority of fuel in every subsector (83%) with some contributions from electricity (mostly PHEVs in LDV subsector) and petroleum. By 2050, continual improvements in efficiency have reduced the transportation sector-wide average energy intensity by 58% compared to 1990 levels (LDV fleet-average fuel economy reaches 56 mpgge). Carbon intensity of fuels across the entire transportation sector is reduced by 80% compared to 1990 levels. These changes in energy and carbon intensity and the fuels used by subsector are shown in Table 4.

The *Electric-drive 80in50* scenario relies heavily on advanced electric-drive technologies (PHEVs, BEVs and FCVs) and low-carbon hydrogen and electricity. Limited availability of low-carbon biofuels constrains their use (only 1 billion gge is

Table 4
Description of the *80in50* scenarios.

	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	60	15
Aviation	25	75	0	0	50	40
Rail	0	93	0	7	69	18
Marine/Ag/Off-road	23	77	0	0	45	36
All subsectors combined	2	83	0	15	42	20
Total # of miles	1,083.8	billion				
Electric-drive 80in50						
LDV	0	0	60	40	21	9
HDV	21	0	56	23	47	47
Aviation	50	50	0	0	50	63
Rail	0	0	0	100	42	7
Marine/Ag/Off-road	4	32	37	27	45	26
All subsectors combined	3	3	55	39	31	26
Total # of miles	1,082.9	billion				
Actor-based 80in50						
LDV	20	5	10	64	10	32
HDV	25	13	9	53	48	56
Aviation	30	70	0	0	42	46
Rail	11	3	0	87	44	17
Marine/Ag/Off-road	42	21	9	27	36	59
All subsectors combined	21	9	8	62	24	45
Total # of miles	843.4	billion				

used in the *Instate* case). Electric-drive technologies are used extensively in all subsectors except aviation, marine, agriculture, and off-road. vehicle sectors also use a significant amount (32%) of biofuels.

Hydrogen is used in applications where longer range and weight are important concerns, such as heavy-duty trucks; this assumes that the challenges in using hydrogen in heavy-duty trucks (storage cost and density, vehicle range, and refueling time) are overcome. Rail becomes entirely electrified. Table 4 provides a breakdown of miles in each subsector by fuel type. All low-carbon biofuels are directed toward the aviation, marine, agricultural, and off-road subsectors, where it is more challenging to use either hydrogen or electricity. Over all subsectors, hydrogen accounts for 55% and electricity accounts for 39% of *Instate* miles. By 2050, the average energy intensity is reduced by 69% compared to 1990 levels (LDV fuel economy reaches 88 mpgge). Hydrogen is produced by large central fossil production of hydrogen with CCS (60%) and renewable production. Altogether, carbon intensity of transportation fuels is reduced by 74% compared to 1990 levels (H_2 carbon intensity = 9.5 gCO$_2$e/MJ; electricity = 6.5 gCO$_2$e/MJ).

Unlike the other two scenarios, the *Actor-based 80in50* scenario presents a world where, because of much high energy prices, all *actors* (companies, governments, and individuals) are motivated to reduce energy consumption and GHG emissions, mainly through smaller, more efficient vehicles, reduced per-capita transportation activity, and increased vehicle occupancy load factors. High gasoline prices, effective integration of transportation and land-use planning, and increased use of carpools and telecommuting only lead to a 20% increase light-duty VMT compared to 1990 levels, even when accounting for population growth. Actors respond to high prices through the use of higher efficiency vehicles and greater vehicle occupancies in each subsector. The LDV fleet shifts from trucks and SUVs to cars, and on-road vehicles are increasingly electrified using PHEV technology. There are limited roles for hydrogen and electricity in subsectors such as aviation; in these, biofuels play a larger role. By 2050, a shift towards smaller vehicles and an emphasis on efficiency have reduced average energy intensity in the transportation sector by 76% compared to 1990 levels (LDV fuel economy reaches 125 mpgge). Even though electricity is essentially decarbonized, the continued use of petroleum (21% of miles) leads to a smaller reduction (55%) in carbon intensity of fuels than the two other *80in50* scenarios, which had *C* reductions of 80% and 74%, respectively.

3.5. 80in50 scenario results and comparison

Fig. 2 shows a comparison of the distribution of emissions among the various subsectors and emission reductions among the three mitigation approaches (*T*, *E*, and *C*) for the three *80in50* scenarios. The *Actor-based 80in50* scenario provides the most diverse solution, drawing on all three strategies (travel demand, vehicle efficiency and low-carbon fuels) to reduce emissions. *Electric-drive 80in50* exhibits very high efficiency and low-carbon intensity, while *Efficient Biofuels 80in50* relies on low-carbon biofuels to meet the *80in50* goals. Reductions in travel demand in the two technology-based scenarios would lessen the requisite adoption levels of the advanced vehicle and fuel technologies, while still meeting the 80% target.

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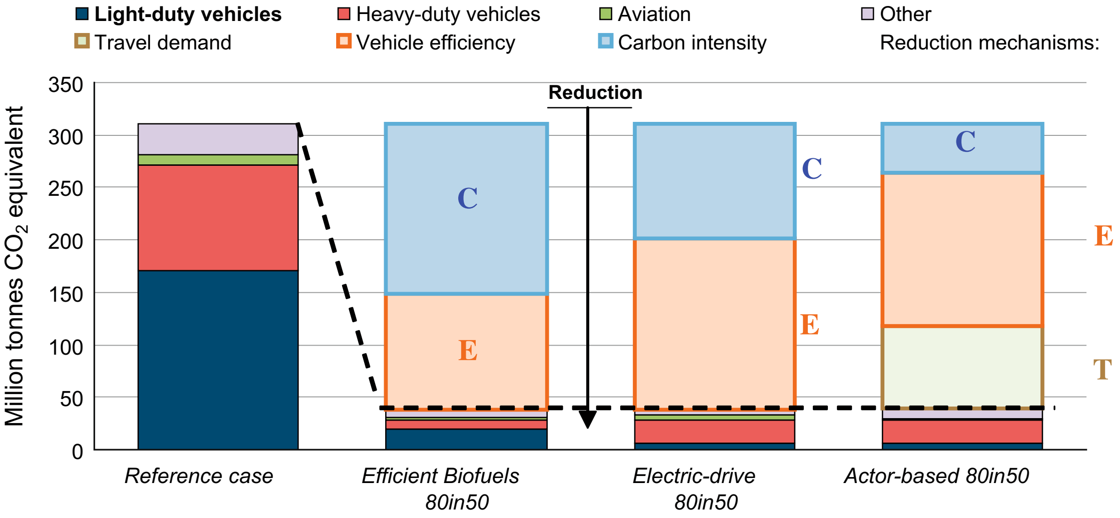

Fig. 2. *80in50* scenario comparison: final emissions by vehicle type and emission reductions by strategy.

Fig. 3 shows how GHG emissions are reduced in the three *80in50* scenarios, compared to the *Reference* scenario, for different activity, fuel, and technology options. In the *Efficient Biofuels 80in50* scenario, biofuels are responsible for 229 MMTCO$_2$e of the emission reductions, and electricity for 37 MMTCO$_2$e. As seen in the figure, most of the reductions from the use of biofuels (146 MMTCO$_2$e) can be attributed to their lower carbon intensity (relative to conventional fuels in the *Reference* scenario). For electricity, vehicle-efficiency improvements (mostly through PHEV penetration in the LDV subsector) account for nearly two-thirds of the emission reductions (25 MMTCO$_2$e) while the lower carbon content of electricity as a fuel makes up the remainder (13 MMTCO$_2$e). Because of their broad applicability and use in conventional combustion engines, reductions in GHG emissions from the use of biofuels are seen across multiple sectors.

The *Efficient Biofuels 80in50* scenario demands a very large quantity of low-carbon biofuels (16.2 billion gge). This is significant considering current US ethanol consumption and future mandates (3.7 billion gge in 2006 (Energy Information Administration, 2008b) and a requirement of 36 billion gallons of renewable fuel (approximately 24 billion gge) by 2022). As discussed in Section 3.2, 16 billion gge of biofuels could conceivably be available in California if optimistic estimates of US biofuels prove accurate (85–92 billion gge) and California is able to use 15–20% of the US total (Perlack et al., 2005). World biofuel production capacity is estimated to be 443–536 billion gge according to the International Energy Agency (2004). Because of competition for food and land-use impacts, this quantity of low-carbon biofuels production may not be feasible. Biomass residues (from agriculture, forestry and municipal waste) are resources that are less likely to cause these negative effects, but studies of biomass residues available in California estimate the state is capable of producing just 2.3 billion gge (Jenkins, 2006).

In the *Electric-drive 80in50* scenario (see Fig. 3), the largest contributor to emissions reduction occurs from the use of FCVs and hydrogen fuel (161 MMTCO$_2$e) and is split relatively evenly between the LDV and HDV subsectors. Electric vehicles also contribute to emission reductions (85 MMTCO$_2$e) 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 associated with electric-drive vehicles (FCVs, EVs, and PHEVs), while the remainder can be attributed to the use of low-carbon intensity hydrogen and electricity. Biofuels are responsible for emission reductions in other sectors where hydrogen and electric vehicles are ill-suited.

The two largest contributors to GHG reductions for the *Actor-based 80in50* scenario (see Fig. 3) are reductions in overall travel demand and the use of electricity in high-efficiency vehicles mainly in the LDV and HDV subsectors. Of the technology-related GHG emission reductions (192 MMTCO$_2$e), vehicle efficiency is responsible for the vast majority, 147 MMTCO$_2$e (77%). Biofuels consumption in this scenario is 1.7 billion gge in 2050, dramatically less than the level in the *Efficient Biofuels 80in50* scenario.

Since the three *80in50* scenarios rely heavily on very low-carbon intensity fuels to achieve the GHG target, they are sensitive to assumptions about fuels production. Production methods for biofuels, hydrogen or electricity that result in higher-carbon-intensity fuels would eliminate much of the emission reductions gained in these scenarios. The *Actor-based 80in50* is less sensitive to increases in carbon intensity since reductions in travel demand and greater vehicle efficiencies contribute more towards emission reductions.

When *Overall* emissions for these scenarios are analyzed, the *80in50* target is not met. To meet the targets for *Overall* emissions, dramatic changes are needed in the aviation and large marine subsectors, including reductions in passenger and freight travel demand and carbon and energy intensity. The *Actor-based 80in50* scenario addresses *Overall* emissions

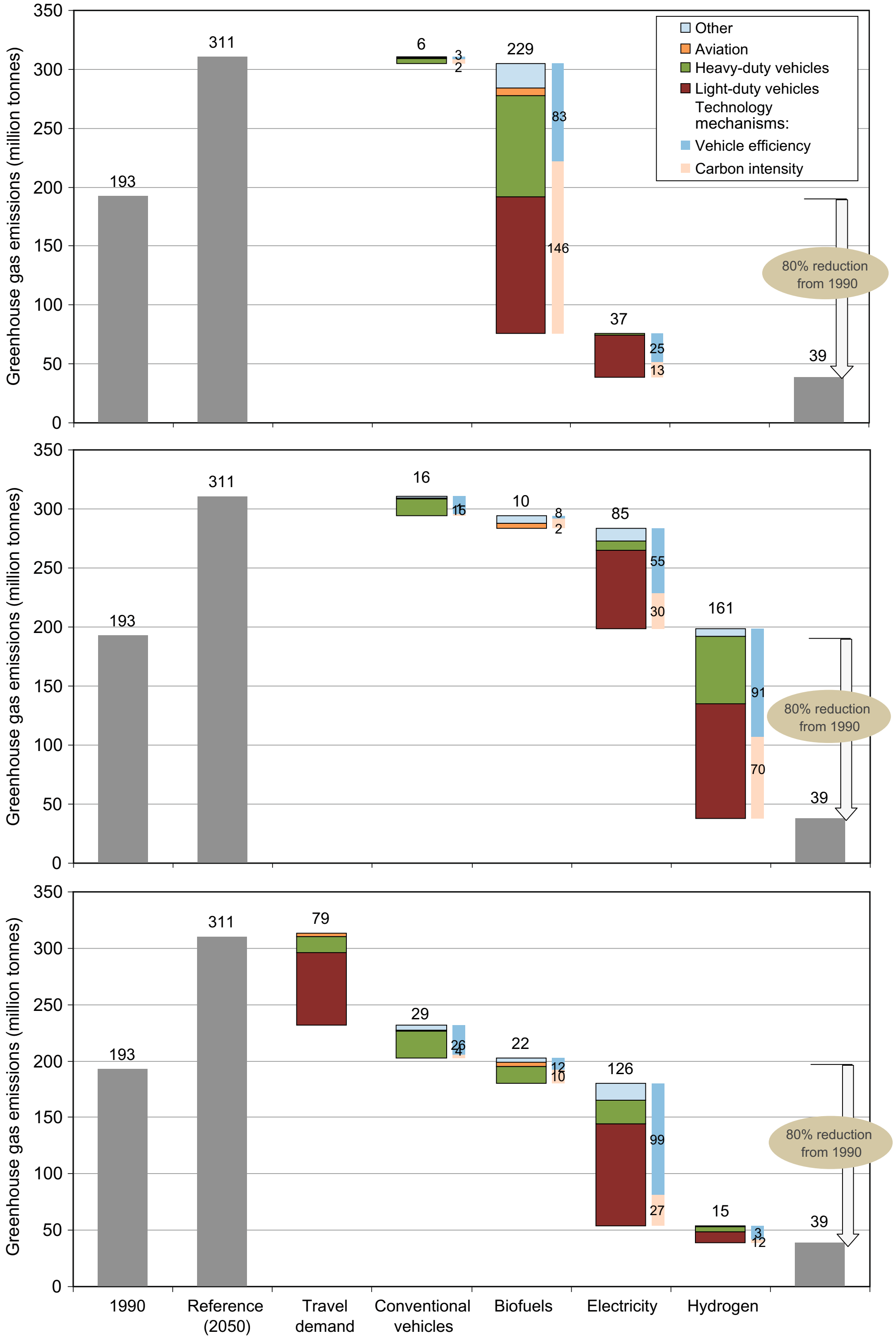

Fig. 3. Instate GHG reductions by mitigation strategy for three *80in50* scenarios.

better than the other scenarios because it has the lowest travel demand and highest efficiency, particularly in aviation and marine. The other two scenarios highlight the consequences of increased travel demand in the aviation and large marine subsectors where technology challenges or biofuel resource availability limits their use.

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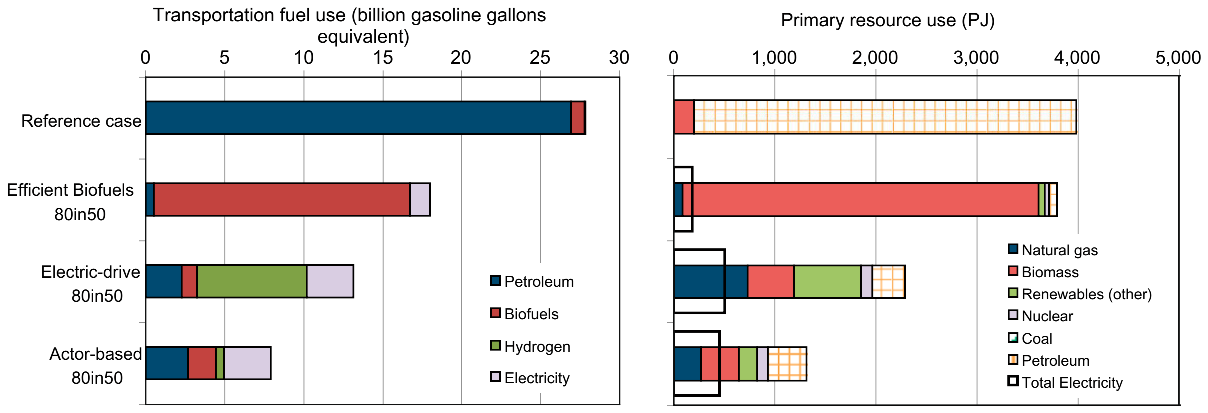

Fig. 4. Transportation fuel use and primary resource consumption in 2050 by scenario (*Instate* emissions).

Clear distinctions between the two technology scenarios appear when comparing fuel consumption and primary resource requirements (Fig. 4). Increased fleet-average vehicle efficiency in *Electric-drive 80in50* reduces fuel use by over 13 billion gge, or 53% from the *Reference* scenario. The higher drivetrain efficiencies utilized in *Electric-drive 80in50* lead to lower fuel and primary energy resource usage than in the *Efficient Biofuels 80in50* scenario. The *Electric-drive 80in50* scenario also leads to a greater diversity of primary energy resources because of the numerous options available for hydrogen and electricity production, while for *Efficient Biofuels 80in50*, biomass is, by far, the most important feedstock. The *Actor-based 80in50* scenario, with the highest vehicle efficiencies and greatest reduction in travel demand, has the lowest scenario fuel use and primary resource requirements. Fuel requirements for the *Actor-based 80in50* scenario are reduced by almost 20 billion gge (72%) from the *Reference* scenario, and similar reductions hold for primary resource consumption as well. The magnitude of primary energy use in these scenarios, though significant, is still well below the Energy Information Administration's (EIA) business-as-usual projections for US production of energy resources in 2030[5] (EIA, 2008a). This implies that the demands of the *80in50* scenarios can be met by projected potential supply of domestic resources. For biomass and renewable electricity generation, the *untapped* supply potential is much larger than the numbers shown here (Perlack et al., 2005; National Renewable Energy Laboratory, 2004).

4. Conclusions

The development of durable and robust policies can help to address the challenges associated with reducing GHG emissions from transportation. A review of California transportation policies has identified a number of policy gaps that may impede the state's ability to meet its GHG emission reductions target. The vehicle-efficiency related emissions regulations (AB1493 and CAFE) in California apply to LDVs only and the state's Low-Carbon Fuels Standard (LCFS) and other alternative fuels regulations apply only to on-road vehicles. While tackling emissions in the LDV subsector is important, regulations that address emissions in other subsectors, like aviation and heavy-duty vehicles, are also important, as the GHG target is not likely to be met by focusing on LDVs alone. SB375 is the first regulation to focus on travel demand's contribution to GHG emissions. Addressing transport intensity in all transport subsectors through urban planning and transportation demand management is inherently complicated, involving many factors such as land-use planning, and personal choices and preferences.

If biofuels are the primary means of reducing carbon intensity, the quantity of these fuels demanded in California will be substantial. Because of the potential conflict between food and fuel production, more advanced non-agricultural biofuels (e.g. algae) may be needed. Robust biofuels policies can incentivize these technologies and the production of biofuels with little or no associated direct and indirect land-use change, as well as address the significant uncertainty surrounding this topic.

The time-scales required for changing the transportation system are long. An important near-term approach is to identify mitigation strategies in key subsectors, including attempts to bring highly efficient, alternative fuel vehicles to market and increased funding and policy support for transportation research (for vehicle technologies and fuels, urban planning and transportation demand management strategies).

This paper investigates three scenarios in which California reduces transportation GHG emissions 80% below 1990 levels by 2050 using a Kaya framework. Numerous GHG mitigation options in each of these subsectors examined were identified but with a focus on three areas: improving vehicle efficiency, reducing fuel carbon intensity, and reducing travel demand.

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[5] EIA estimates the following energy supply in 2030: crude oil (12,699 PJ), natural gas (21,099 PJ), coal (30,202 PJ), biomass (8,570 PJ), electric generation (17,599 PJ), nuclear power (10,093 PJ), and renewable power (1,991 PJ).

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The scenarios presented in the paper illustrate the enormous challenge associated with meeting the target reductions in the transportation sector. The *Silver Bullet* scenarios show that no mitigation option can singlehandedly meet the target goal because travel demand is expected to increase significantly by 2050 and advanced technologies and fuels may not be suitable for use in all subsectors or may be limited in availability. The *80in50* scenarios illustrate that the 80% reduction goal could potentially be met in multiple ways. The *Efficient Biofuels 80in50* and *Electric-drive 80in50* scenarios show that if vehicle and fuels technologies become clean enough, California can preserve its current levels of mobility. The former requires more primary energy and relies heavily on biomass, while the latter uses fuel more efficiently and has the potential for a significantly more diverse resource mix. The *Actor-based 80in50* scenario shows that large shifts in social and travel behavior are valuable mitigation options, especially if technology is not as successful. This scenario has the lowest energy resource requirements.

Though we focus mainly on *In state* emissions, the results of looking at the scenarios show that meeting an 80% reduction for *Overall* emissions is more challenging, in part because of the greater importance of the aviation and marine subsectors in out-of-state travel and the inherent challenge of decarbonizing for these modes.

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