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Title: Assessment of the cost-effectiveness of vehicle efficiency and alternative fuel technologies for greenhouse gas emission reduction

Author: Nicholas Lutsey (corresponding author)
Institute of Transportation Studies
University of California, Davis
One Shields Ave.
Davis, CA 95616
nplutsey@gmail.com
Phone: 530-752-6548
Fax: 530-752-6572

ABSTRACT

Governments around the world are implementing programs to reduce greenhouse gas (GHG) emissions from the transportation sector. The targeted GHG emission reductions will require major transformations in the vehicle and fuel areas; however, little effort has been made to systematically compare the costs of efficiency and alternative fuel options under consistent assumptions. This paper analyzes the cost-effectiveness – or cost per tonne GHG emission reduction – of near-term technology options for vehicle efficiency, biofuel usage, battery electric vehicles, and hydrogen fuel cells for GHG reduction in the light duty vehicle sector within the 2020 timeframe. The costs and GHG impacts of emerging technologies are evaluated to develop a marginal GHG abatement cost curve for a technology deployment scenario that complies with the adopted vehicle regulation and low carbon fuel standard in California. The findings indicate large variation in cost-per-tonne estimations across technologies and high uncertainty based on the price of petroleum.

Keywords: climate change; cost-effectiveness; low-carbon fuel; vehicle efficiency

INTRODUCTION

The transportation sector is generally attributed with between 20% and 40% of major economies' overall greenhouse gas (GHG) footprints (*1-3*) and is therefore a fundamental component to any comprehensive long-term climate change mitigation strategy. As a result, governments around the world are enacting a diverse array of programs that would reduce GHG emissions from transportation by promoting vehicle efficiency, alternative transportation fuels, travel demand reduction, and lower-GHG travel modes.

Light duty automobiles have become the dominant starting point in government programs to reduce transportation GHG emissions. Statistics from the U.S. highlight the importance of specifically targeting light duty vehicle GHG emissions. Private automobiles in the U.S. represent about 85% of passengers' miles travelled, energy use, and GHG emissions. When also factoring in non-passenger road transportation, passenger automobiles make up about 75% of road transportation and 60% of all (i.e., including non-road, marine, and aviation) transportation energy and GHG emissions in the U.S. (*4*). As a result, much of the initial effort to control GHG emissions has focused on automobiles and their fuels.

Early GHG mitigation efforts acknowledge the links between conventional vehicles and dominant petroleum fuels by compelling both the automobile industry and fuel providers to deploy low-GHG transportation technologies. Nearly every major auto market now has some form of automobile GHG or fuel consumption reduction program. For example, the major automobile markets of the U.S., Europe, Japan, China, and Canada each have programs that would reduce exhaust carbon dioxide emissions by greater than 20% on a per-distance-travelled basis within ten years (*5*). Although the policies are diverse and continue to evolve, the indication is clear that there will be constant public pressure to improve the efficiency of new light duty vehicle for the foreseeable future. These policies promote incremental efficiency technologies (e.g., efficient engines and transmissions) as well as more long-term, advanced drivetrain options like battery electric and hydrogen fuel cell vehicles.

On the alternative fuel side, many efforts have revolved around regional industry strengths of the nation enacting the programs. For example, the U.S. has historically pushed biofuel blending volumetric mandates and offered tax incentives to support corn-based ethanol and soybean-based biodiesel. Brazil has developed its sugarcane-based ethanol industry into a viable alternative to motor gasoline in that country. Increasingly, those goals are being tied specifically to criteria about the impact of those fuels on GHG emissions (as in *6*). Another policy concept, the low carbon fuel standard, has been adopted in California (*7*) and Europe (*8*), has been explored by many U.S. states, and has been proposed in several major proposals for new federal U.S. climate legislation.

As these policies move forward, one of the major uncertainties in these GHG mitigation programs relates to the ensuing cost of these transformative technological changes in the fuels and automobile industry. Critical to an understanding of the overall costs of these programs are the relative costs of the alternative fuel options compared with conventional petroleum-based fuel options and the relative cost of the alternative vehicle drivetrain technologies as compared with conventional internal combustion engines. This analysis compares technology options in terms of their cost-effectiveness in order to inform on their relative viability in contributing toward California's climate mitigation goals.

BACKGROUND

There are myriad ways to assess GHG mitigation strategies' costs and benefits. The research and policy literature is populated with a variety of quantitative and qualitative methods using various technical, economic, and political feasibility criteria. Among the methods, many variations of cost-benefit analyses and cost-effectiveness evaluations are employed to help prioritize individual emission-reduction technology alternatives when costs can be approximated. Broad analyses involving economic equilibrium models impose carbon constraints to estimate the impacts on various sectors of the economy (see, e.g., *9,10*). "Bottom-up" technology cost analyses, such as this one, assess each technology's engineering costs and impacts to evaluate their GHG abatement cost-effectiveness – or cost-per-tonne CO_2e reduced – individually, and then are analytically combined to determine the impacts of a portfolio of technologies.

The marginal GHG abatement cost curve (or "supply curve") method is highly useful for GHG mitigation planning. Quantifiable criteria that are widely used for evaluating individual mitigation options include GHG emission reduction potential, initial implementation costs, and direct variable and ancillary costs and benefits. The method offers an ideal framework for evaluating individual technology

options by encapsulating these desired criteria into a cost-effectiveness value. Then with these cost-effectiveness evaluations, GHG mitigation technologies are ordered by their cost-per-tonne reduction and plotted cumulatively within constructed scenarios of the future. These abatement curves depict available GHG mitigation at estimated marginal technology costs.

Early related work in supply curves was directed at energy conservation in the electricity sector (*11,12*). Later studies expanded to include transportation options and shifted to focus on the objective of emission reductions. Concurrently, emission reduction cost-effectiveness, defined as the cost per tonne emission reduction, emerged as a comparative measure for evaluating options to reduce criteria pollutant emissions. For example, early transportation-specific cost-effectiveness work looked at vehicle and alternative fuel technologies to reduce criteria pollutant emissions (*13-15*). Since then, much of the vehicle pollution control efforts have shifted toward GHG emissions. Most recently the method has used to study technologies in transportation and other sectors for GHG abatement in the U.S. (*16,17*). These multi-sectoral studies tend to suffer from a lack of resolution into vehicle and fuel technologies. Other studies more narrowly delve into particular vehicle technologies (see, e.g., *18*) without consideration of the full span of available vehicle and fuel technologies. The objective of this analysis is to provide a detailed synthesis of the emerging technologies that will be fundamental to diverse portfolio strategies to achieve compliance with near-term GHG mitigation policies for vehicle efficiency and low-GHG fuels.

This study analyzes the particular case of California, which has now adopted two regulatory programs with potentially wide-reaching impacts. The fuel-related program, the Low Carbon Fuel Standard (LCFS) would reduce the GHG intensity (i.e., GHG emissions per energy unit of fuel) by 10% by the year 2020. The development of this concept was novel when developed in 2006 (*19,20*), has since been adopted by the state of California (*7*), and is being considered widely in the Europe, in federal U.S. climate legislation, and in other U.S. states. The light duty vehicle GHG emission regulation in California, referred to as "Pavley" after its original legislative author, was passed by the state legislature in 2002 and adopted by CARB in 2004, and it calls for a 30% reduction in GHG emissions per mile for new automobiles by model year 2016 (*21,22*). This vehicle GHG regulation was used as the basis for a federal U.S. rulemaking on fuel economy and GHG emissions for vehicles of model years 2012 to 2016 (*23*), and California currently has plans to extend a its vehicle GHG regulatory program toward increasingly stringent goals beyond model year 2016. Using these policies as a backdrop, this paper explores the cost-effectiveness of the technologies that could be deployed for industry compliance with the policy objectives.

ANALYSIS

This analysis analyzes the prospects for the use of known and emerging technologies to comply with California's LCFS and Pavley programs to reduce GHG emissions from 2010 to 2025. The technologies evaluated include improved gasoline vehicle efficiency, the use of various biofuels, and advanced electric drivetrains. We assess incremental vehicle costs, alternative fuel costs, GHG emission reductions impacts, lifetime energy cost impacts, and the cost-effectiveness of available near-term technologies for light-duty vehicles. Exploring these costs alongside expected levels of technology penetration for compliance with the California GHG regulations, we evaluate the overall GHG reductions and construct and GHG abatement cost curve. For a report with further discussion, data tables, technology descriptions, and underlying assumptions, see Lutsey, 2009 (*24*). This section summarizes key elements of the analysis. Note that the evaluated transportation strategies are all technology-based options for vehicles and fuels; GHG reductions that involve reductions in the use of vehicles are not considered here.

Vehicle and Alternative Fuel Technologies

The types of vehicle efficiency and alternative fuel technologies with potential GHG benefits are wide ranging. Available and emerging vehicle technology improvements that can contribute toward light duty vehicle GHG emission reductions can be categorized as "in-use" measures, gasoline vehicle efficiency, alternative fossil fuel (e.g., compressed natural gas, diesel), biofuel options from various fuel pathways (e.g., corn, sugarcane, soy, cellulosic), and advanced electrified vehicle drivetrains (e.g., grid-connected electric vehicles, hydrogen fuel cell vehicles). These technologies, their GHG impacts, their incremental vehicle costs, and data sources referred to are summarized in Table 1.

Relatively modest GHG reductions result from modifications to vehicle mobile air conditioning (MAC) and other improvements from "in-use" technologies (e.g., lower friction oils, lower rolling resistance tires) (*21,25,26*). Incremental improvements for GHG reductions from conventional gasoline include more efficient internal combustion (variable valve systems, gasoline direct injection, cylinder deactivation), more efficient transmissions (6-speed automatic, automated manual, continuously variable), and overall vehicle body advances (aerodynamics, light-weighting). GHG emissions rates of new vehicles can be reduced by about 20-30% with these technologies (see, e.g., *27-31*). Further efficiency improvements of 25-50% are possible, relative to today's vehicles, with the use of hybrid gasoline-electric vehicle technology (*27,28,32,33*). Diesel technology provides efficiency improvements of about 15-30% GHG-per-mile reductions over conventional gasoline vehicles (*27, 28, 34*). Compressed natural gas light duty vehicles do not necessarily have efficiency advantages, but due to the lower GHG intensity of natural gas, offer a 30% lifecycle GHG reduction compared to gasoline (*7*).

Biofuels from various pathways offer a wide range of GHG impacts when used in light duty vehicles. Gasoline fuel for conventional vehicles has most prominently been blended with biologically derived ethanol fuels, mainly from corn and sugarcane. Typically this blending has been done at small levels like "E10" (10% by volume ethanol in gasoline) or "B5" (5% by volume biodiesel in diesel). Modest benefits of 10-20% GHG reduction can be found in the literature for average new corn-derived ethanol fuel production practices (*35,36*), but improved corn ethanol practices can yield greater improvements (*37,38*), and sugarcane as a source of ethanol production can have the potential for far greater reductions (*39,40*). Gasoline-substitute biofuels, made from waste materials (agricultural and forestry residues and municipal solid waste) or cellulosic energy crops could have major life-cycle GHG benefits of 60-95% (*19,41,42*). A similar array of biofuel feedstocks can be used to produce biodiesel, which can be mixed into conventional diesel fuel. Studies of the GHG benefits of biomass-based diesel fuels range from 40-80% (*7,19,36,43,44*). These referenced studies do not include very recent but uncertain calculations of indirect land use effects (see *45-47*). However, the official LCFS GHG intensities (from *7*) used in this analysis do apply indirect land use effects for these alternative fuels.

Varying degrees of GHG reduction are possible with electric-drive propulsion technologies. Beyond the increasingly popular hybrid gasoline-electric vehicles, there are "plug-in" hybrids that can be fuelled by both electricity and petroleum fuels, full battery electric vehicles, and hydrogen-powered fuel cell vehicles. Though there can be wide differences based on different regions' primary energy sources for their electricity, GHG reductions from the utilization of California average or marginal grid electricity would result in a 57-64% reduction in life-cycle GHG reduction as compared to today' conventional gasoline vehicles (based on *7*). Naturally, grid-connection-capable plug-in hybrid electric vehicles (PHEVs) would achieve somewhere between their non-plug-in hybrid efficiency on gasoline (i.e., of approximately 35%) and these greater electricity GHG impacts – depending on how often they use electricity. Based on several sources, fuel cell vehicles, fuelled by natural gas-derived hydrogen, offer roughly 40-70% reductions in overall energy use and GHG emissions per distance traveled than conventional vehicles (*7, 48-51*). Greater reductions still would result from greater use of lower-GHG primary energy sources. Note that the cost attributes of EVs and HFCVs – which are relatively less mature and are likely to remain at lower volume and higher cost than the others in Table 1 – are discussed separately further below.

This assessment of the GHG emission reduction benefits of vehicle and fuel technologies is based on available engineering data and the official CARB regulatory accounting of alternative low-GHG fuels for the LCFS (*7*). Figure 1 shows the impact of the vehicle and fuel technology combinations from a vehicle and fuel use life-cycle GHG-per-mile perspective. The low-GHG technology combinations are compared with the reference average U.S. light duty vehicle of model year 2008, which achieved 26.8 miles per gallon on the composite federal certification test cycle (*52*), is estimated to have an 80% on-road degradation factor *(52),* and uses E10 gasoline with a 96 gCO_2e per megajoule of fuel life-cycle GHG intensity (*7*). CARB has adopted default GHG intensities for these major fuels, along with its initial draft values for indirect land use effects to be associated with the different pathways. The official California default GHG intensities (from *7)* are chosen as a framework for this policy analysis; however, we emphasize the uncertainty in those fuel GHG ratings and their potential to evolve over time.

TABLE 1 Summary of vehicle efficiency and alternative fuel technologies considered in this analysis for widespread near-term deployment to meet California GHG mitigation goals

Vehicle technology	Incremental vehicle price (2008$)[a]	Fuel price (2008$/gge)[b]	GHG reduction impact[c]	Technology description (*sources*)
Mobile air conditioning (MAC)	100 *60-140*	2.75 *2.00-4.00*	4%	Variable displacement compressor, lower leak system, low-GWP refrigerant, e.g., R-152a or CO_2 (*21,25*)
"In use" efficiency technologies	570 *460-680*	2.75 *2.00-4.00*	9%	Lower friction oils, lower rolling resistance tires, efficient accessories (*26*)
Incremental gasoline vehicle efficiency	1,500 *1000-2000*	2.75 *2.00-4.00*	25%	Emerging engine (gasoline direct injection, turbocharging, cylinder deactivation), transmission (AMT, 6-speed, CVT) and body technologies (*27-31*)
Biofuel flex-fuel (E85-capable, corn)	200 *0-400*	3.16 *2.66-3.17*	7%	Best current corn ethanol production practices, conventional gasoline technology, with modified fuel tank, pumps, lines, injectors, sensors (*7,37,38,52*)
Biofuel flex-fuel (E85-capable, sugar)	200 *0-400*	3.01 *2.76-3.45*	12%	Sugarcane-derived ethanol, conventional gasoline technology, with modified fuel tank, pumps, lines, injectors, sensors (*7,39,40,52*)
Biofuel flex-fuel (E85-capable, crop)	200 *0-400*	2.92 *2.40-3.44*	29%	Energy crop-derived ethanol, conventional gasoline technology, with modified fuel tank, pumps, lines, injectors, sensors (*7,19,41,42,52*)
Biofuel flex-fuel (E85-capable, residue)	200 *0-400*	2.92 *2.40-3.44*	38%	Agricultural residue and waste-derived ethanol, conventional gasoline technology, with modified fuel tank, pumps, lines, injectors, sensors (*7,19,41,42,52*)
Hybrid gasoline-electric vehicles (HEV)	2,750 *2000-3500*	2.75 *2.00-4.00*	35%	Regenerative braking, electric battery storage, electric motor propulsion, downsized combustion engine, electric accessories (*27,29,32,33*)
Diesel vehicle	2,400 *1800-3600*	2.75 *2.00-4.00*	24%	Turbo-charged, high-pressure common-rail compression ignition engine; emissions aftertreatment (*29,27,34*)
Biodiesel vehicle (B20, crop)	2,400 *1800-3600*	3.42 *2.95-3.90*	28%	Energy crop-based biodiesel, turbo-charged, high-pressure common-rail compression ignition engine; exhaust aftertreatment (*7,19,36,43,44*)
Biodiesel vehicle (B20, residue)	2,400 *1800-3600*	3.17 *2.71-3.63*	32%	Agricultural residue and waste-derived biodiesel, turbo-charged, high-pressure common-rail compression ignition engine; exhaust aftertreatment (*7,19,43*)
Compressed natural gas (CNG) vehicle	1,800 *1500-2000*	2.13 *1.84-2.41*	29%	Combustion engine with compressed (5000 psi) gas storage tank, fuel lines, fuel control valves, sensors (*7,42*)
Plug-in hybrid electric vehicle (PHEV10)	4,700 *4100-5300*	4.82 *3.21-6.41*	40%	Increased electrification from HEV (battery, motor, etc); electric grid charging, metering, equivalent 10-mile "all-electric" range, 10% miles electric (*7,29,32,53,54*)
Plug-in hybrid electric vehicle (PHEV20)	7,500 *6400-8600*	4.82 *3.21-6.41*	43%	Increased electrification from HEV (battery, motor, etc); electric grid charging, metering, equivalent 20-mile "all electric" range, 28% miles electric (*7,29,32,53,54*)
Plug-in hybrid electric vehicle (PHEV40)	13,000 *11000-15000*	4.82 *3.21-6.41*	50%	Increased electrification from HEV (battery, motor, etc); electric grid charging, metering, equivalent 40-mile "all electric" range, 50% miles electric (*7,29,32,53,54*)

[a] *based on range of on-vehicle cost estimates from references shown (ranges in italics)*
[b] *fuel prices shown in price per gasoline equivalent gallon of fuel delivered to vehicle; for flex-fuel vehicles (E85, PHEV), only alternative fuel cost is shown; see full analysis (24) for further discussion of assumptions and data*
[c] *based on percent vehicle and fuel use cycle GHG reductions on a gram GHG-per-mile basis; based on light-duty vehicle average fuel economy of 26.8 miles per gallon, 96 g CO_2e/megajoule GHG intensity; based on middle of engineering estimations from references; alternative fuel GHG intensities are based on CARB (2009) Low Carbon Fuel Standard default fuel ratings (7); Flexibly fuel vehicles (i.e., biofuels and PHEV) are partially fuelled by alternative fuel and partially by gasoline; Percents not additive, combinations of technologies not shown*

GHG Reduction Cost-Effectiveness of Technologies

Cost-effectiveness, defined here, is the cost-per-tonne-GHG-reduction as experienced by the consumer for low-GHG vehicle-fuel technology, in comparison to the conventional model year 2008 light duty vehicle. Included in this cost-effectiveness evaluation are upfront vehicle technology costs of efficiency technology, differential fuel prices of alternative fuel option as compared to conventional petroleum fuels, and discounted lifetime vehicle energy savings. Therefore, the cost in the numerator is the incremental vehicle investment cost for the technology plus the discounted lifetime energy cost impacts that result from the use of the technology over the vehicle lifetime. The estimated incremental vehicle costs associated with the low-GHG technologies are shown in Table 1. Technology costs for this assessment refer to "near-term" engineering cost estimates for emerging technologies produced at high production levels within the 2020 time horizon of this study.

Lifetime energy impacts from alternative fuel usage and reductions in energy use are valued with a 7% annual discount rate in years subsequent to the initial energy investment. We analyze the technology options with a range of assumed world petroleum prices: "low" $34/barrel ($2.00/gallon gasoline equivalent [gge] retail fuel in California), "middle" $64/barrel ($2.75/gge), and "high" $114/barrel ($4.00/gge). This span of petroleum prices was designed to cover the range of projected scenarios forecasted by US and California energy agencies (*55,56*). Therefore, for efficiency technologies (e.g., hybrid), overall energy impacts would be the discounted forgone consumer motor gasoline costs over the average vehicle lifetime. For alternative fuels, the lifetime energy impacts would be the differential costs to consumer of the new alternative fuel, as compared to the reference motor gasoline costs. Note that estimated alternative fuel costs are not depicted in the cost figures in Table 1.

For the denominator of the cost-per-tonne metric, the technology GHG emissions from the vehicle efficiency and low-GHG alternative fuel usage are converted into lifetime metric tonne of GHG reduction. For this step, assumptions about average California light duty vehicle usage over their lifetime were applied. Based on data from CARB 2007 data (*57*), the lifetime light duty vehicle mileage after accounting for vehicle survival is about 192,000 miles per vehicle over a median life of 20 years. The mileage-per-year over the vehicle age is approximately 20,000 miles/year in the first year and decreases on average at an average of 8% per year. Note that this differs from national average data (e.g., see *4*) which show the first year of vehicle use to be about 15,000 miles per year, with roughly a 5% decrease in miles per year. The reference average light duty vehicle contributes 99.5 tonnes CO_2e emissions over its lifetime, making the percent vehicle and fuel use GHG emission rate reduction (see Table 1) approximately equal to the average lifetime GHG reduction in tonnes for each technology.

Figure 1 shows the resulting evaluation of the GHG reduction cost-effectiveness of the vehicle and fuel technologies. These cost-effectiveness values include the uncertainty in the estimated initial cost of the alternative vehicle technology, the uncertainty in the average lifetime net present value of the fuel use impacts of the vehicle technology, and the lifetime GHG emission reduction of the vehicle technology. As shown in this figure the GHG reduction cost-effectiveness values, from technology to technology, vary greatly. Depicted by the shaded boxes in the figure is the magnitude of uncertainty associated with the technologies' costs; the lower technology costs (for alternative fuels and/or efficiency technologies) are represented by the left-most edge of the boxes.

Also shown in Figure 1, via the error bars in the figure, is the reality that all technologies have considerable GHG abatement cost uncertainty with respect to the variability of the world oil price. This comparison of the technology options reveals very different GHG abatement cost attributes. A number of efficiency technologies result in energy savings that outweigh the up-front technology costs over the vehicle lifetime and result in net beneficial (i.e., less than $0 per metric tonne GHG reduction). Current prominent biofuel options (e.g., corn and sugarcane ethanol) appear to be less attractive from a cost-per-tonne basis and have much higher cost variability depending on world oil prices. More advanced biofuel feedstocks with similar per-gallon costs to current biofuel options could be much more attractive from a cost-effectiveness perspective due to their lower GHG intensities. More advanced technologies with electrified drivetrains also have major equipment cost uncertainty (e.g., from the costs of battery packs, fuel cell stacks).

Figure 2 shows the scattering of GHG reduction cost-effectiveness values for the different vehicle and alternative fuel technologies versus their relative gram-per-mile life-cycle GHG reduction. Opposed to the previous figure with uncertainty ranges above, only middle petroleum prices and middle technology costs are shown in this figure. Here, technologies with potential mass deployment in the relative near-term are shown. Shown in the figure are options for vehicle efficiency, diesel with biodiesel, ethanol from different pathways, and plug-in hybrid vehicles. Full battery electric vehicle and hydrogen fuel cell vehicle technologies are excluded from the figure (see Figure 6 and related discussion below).

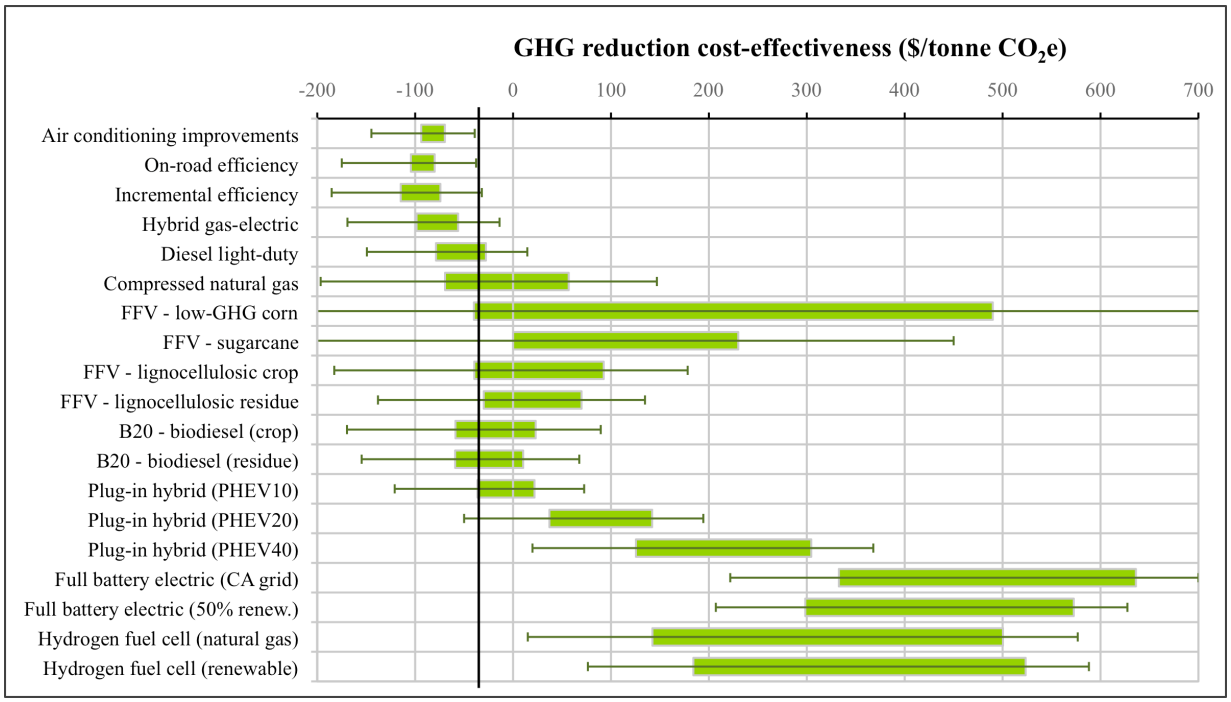

FIGURE 1 Greenhouse gas abatement "near-term" cost-effectiveness of technologies for light duty vehicles (shaded boxes represent technology uncertainty; error bars represent petroleum price uncertainty from $34 to $113 per barrel)

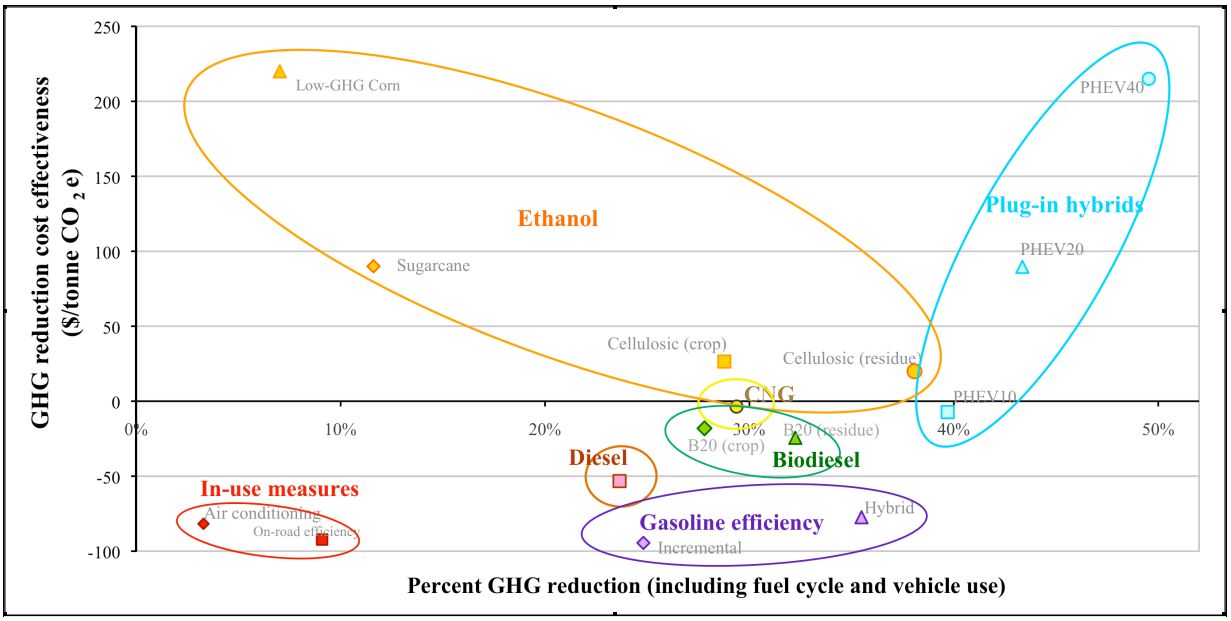

FIGURE 2 Greenhouse gas abatement cost-effectiveness versus GHG reduction for light duty vehicle technologies for middle estimate of technology "near-term" costs and middle petroleum price estimates ($64/barrel world oil price, $2.75/gallon retail in California)

Scenario for Vehicle Efficiency and Low GHG Alternative Fuel Use

With an integrated vehicle stock-turnover and use model, we analyze the impacts of the increased deployment of new vehicle efficiency technologies and their alternative fuel use in the California light duty fleet to meet the adopted GHG regulations. Reference data on vehicle sales, turnover, fuel economy,

and mileage, are calibrated to existing official California government agency estimations (*57,58*). The technology deployment scenario is specifically developed to simultaneously be consistent with the California Air Resources Board's expected compliance scenarios for the Pavley vehicle GHG standard (through vehicle model year 2016) for auto manufacturers and the proposed LCFS program for transportation fuel providers (through calendar year 2020) (see *7,21*).

The scenario applies logistical curves to gradually phase the technologies into the new vehicle fleet and the fuel supply. Figure 3 shows a summary of vehicle shares and alternative fuel use for the "Pavley and LCFS compliance scenario" through the year 2025. Note that these technology mixes (with above discussed GHG benefits) provide compliance with the gram-CO_2e-per-mile Pavley standard and the gram-CO_2e-per-megajoule LCFS. This scenario puts heavy focus in the near-term on relatively well known technologies that are already available in small numbers. As shown in the top pane of Figure 3, the near-term technologies of vehicle efficiency, hybrid technology, and E85-capable vehicles that can utilize available low-GHG intensity corn- and sugarcane-derived biofuels are considered for widespread deployment in the earliest years (2009-2015). Evolutionary technologies that build on those technologies, such as plug-in hybrid vehicles and increasingly lower GHG intensity biofuels, are phased into transportation fuels and the vehicle fleet somewhat later (2015-2025). More advanced vehicle drivetrain technologies, e.g., fuel cells and full battery electric vehicles are have lower penetrations with phase-in periods that are later and slower (2015-2035) and therefore make only small contributions to fleet GHG reductions within the time horizon of this analysis.

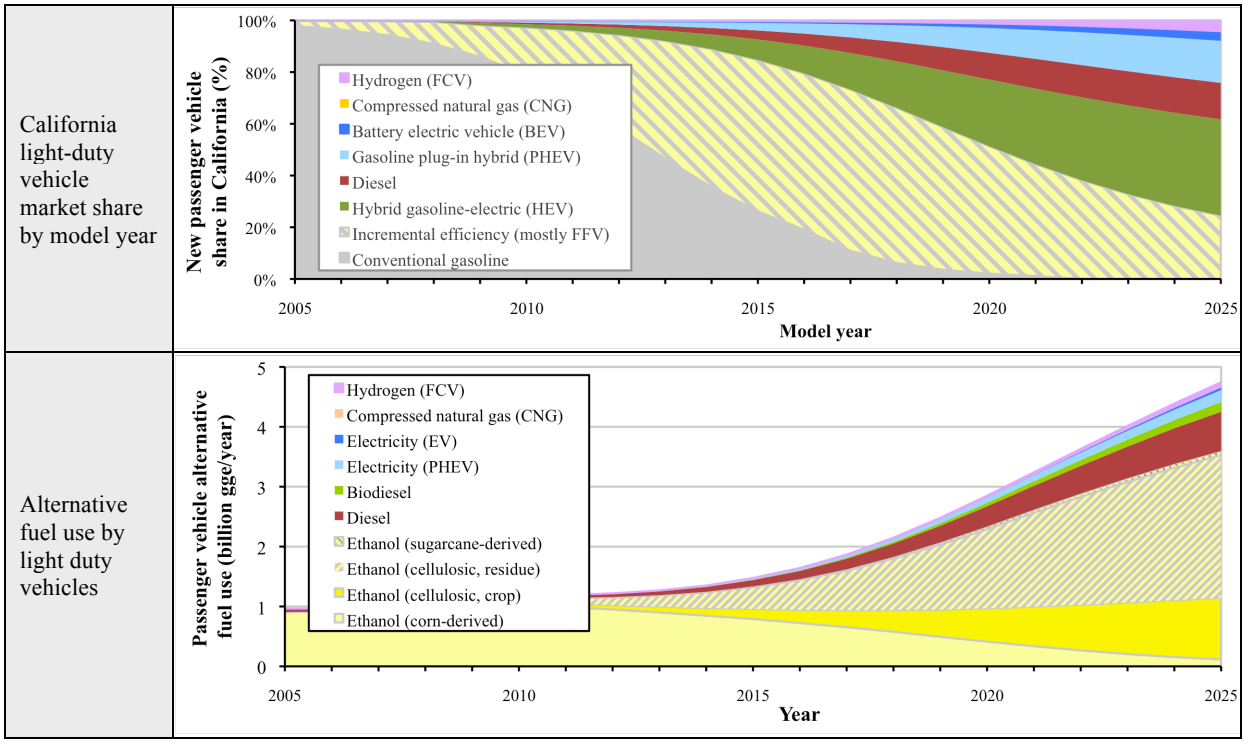

FIGURE 3 Vehicle, fuel, and GHG emissions for scenario for joint compliance with Pavley and LCFS programs in California

The resulting light duty vehicle alternative fuel consumption from the GHG compliance scenario is depicted in the second row of Figure 3. Biofuels such as ethanol and biodiesel can be blended into motor fuels and used on all vehicles at lower blend levels, and at much higher levels with relatively small vehicle changes (e.g., in fuel lines, injectors, and tanks) for E85-capable vehicles. As a result in this analysis, similar to the CARB staff LCFS ISOR analysis, compliance with the LCFS through year 2020 relies mainly on biofuel blending within conventional vehicles to achieve compliance with the LCFS. Only a small number of more advanced vehicles, representing less than 2% of the entire vehicle stock by

2020, are capable of using electricity or hydrogen and thereby make only a minor contribution toward LCFS compliance. The scenario results in 19% of light duty vehicle fuels being non-gasoline in 2020.

This California-based scenario would require about 4 billion gallons of gasoline equivalent energy from biomass feedstocks. If most of this biofuel use was in the form of ethanol (as is assumed for this analysis) then the volumetric equivalent biofuel use for this scenario would be greater than 5 billion gallons due to the lower volumetric energy density of ethanol. The major alternative fuels that are employed in this scenario for GHG reductions toward the LCFS are cellulosic biofuels (derived from various crops and residue types). With these assumptions and for ethanol being the dominant gasoline-substitute biofuel, the majority of new light duty vehicle sales by model year 2020 would have to be E85-capable vehicles. The corresponding cumulative deployment of E85-capable vehicles in California is over 5 million units by the year 2020 that are utilizing E85, and they would have to be fueled by the E85 fuel (rather than conventional gasoline) more than half of the time. Of course with greater use of more seamlessly blended biofuels (e.g., biobutanol, biologically derived hydrocarbons) – this cumulative E85 vehicle requirement would be lower.

IMPLICATIONS FOR GHG MITIGATION PROGRAMS

The objective of this analysis is to inform on the cost-effectiveness and GHG emission impacts of adopted California vehicle and fuel policies. The analytical scenario explored in this report is the result of the joint implementation of the Pavley (through model year 2016) and LCFS (through calendar year 2020) programs, and is roughly consistent with the proposed compliance scenarios put forth in California Air Resources Board staff rulemaking research for these two programs. However, this analysis also has ramifications for the much broader long-term climate mitigation goals.

Figure 4 shows the synthesis of the near-term cost-effectiveness evaluation and the amount of reduced GHG emissions resulting from each of those technologies from California vehicle use in the year 2020 to achieve the Pavley and LCFS goals. The GHG emission reductions follow from this analysis' modeled scenario for compliance with the Pavley and LCFS programs, and the resulting aggregate GHG emission reductions in the form of GHG reduction marginal abatement curves. The figure shows the GHG abatement costs for the use of the various vehicle and fuel technologies (y-axis) with respect to their cumulative GHG reduction in the light duty sector in California in year 2020 (x-axis). The figure applies the middle petroleum cost assumption (i.e., $64/barrel world oil price, $2.75/gge retail fuel). The error bars in the figure represent the cost uncertainty in the GHG reduction technology (i.e., the incremental lifetime costs of the vehicle technology or the alternative fuel usage). Note that there is greater abatement cost uncertainty when considering a range of potential petroleum prices (as shown in Figure 1) than is shown in Figure 4.

The relative near-term GHG reduction programs being considered today, in California, nationally, and internationally, are but near-term milestones toward the ultimate long-term climate policy goal of climate stabilization. Toward that goal, GHG mitigation targets, such as 80% reduction of GHG emissions by year 2050 (i.e., "80-in-50"), have been postulated in scientific circles and widely discussed in policy circles as a goal in an effort to avoid the worst of the potential climate change consequences. Several studies (see, e.g., *59*) now explore what such a goal would mean if it was subjected on each economic sector like transportation.

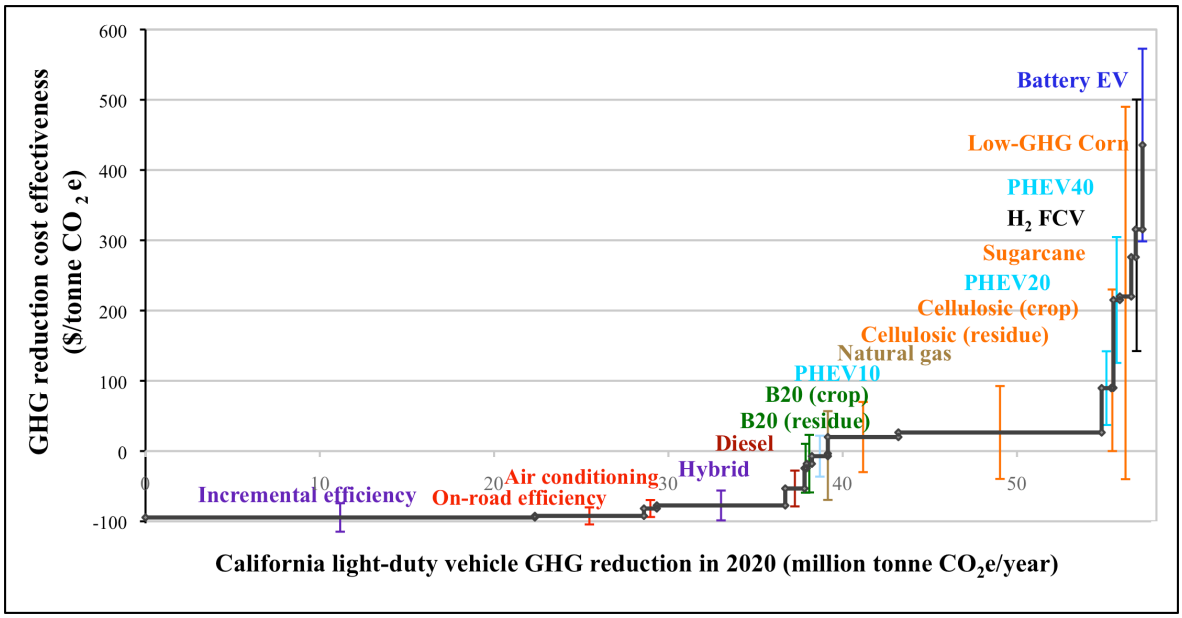

FIGURE 4 GHG abatement cost-effectiveness curve for light-duty vehicle technology use toward "Pavley and LCFS compliance scenario" for the year 2020, using estimated near-term technology costs and middle petroleum price estimates ($64/barrel)

As shown in Figure 5, the relative near-term (i.e, pre-2025) deployment of technologies to comply with the Pavley and LCFS programs would bring about substantial GHG reductions but would be inadequate in achieving the longer term goals. As shown by the percent GHG reductions above (Table 1), none of the near-term technologies looked at here are low enough in GHG-per-mile to approach an overall 80% reduction. However, combinations of vehicle and fuel technologies can achieve greater than 50% GHG reductions, and all of the biofuel, electricity, and hydrogen options can increasingly strive for lower GHG upstream effects. Nonetheless, baseline activity characteristics (e.g., projected population and vehicle mileage increases) make this challenge greater still. A combination of a new round of far lower GHG technologies, along with a series of travel demand measures that encourage lower-GHG modes and reduced overall travel activity would likely be required for the light duty vehicle sector to approach the ambitious 2050 goal.

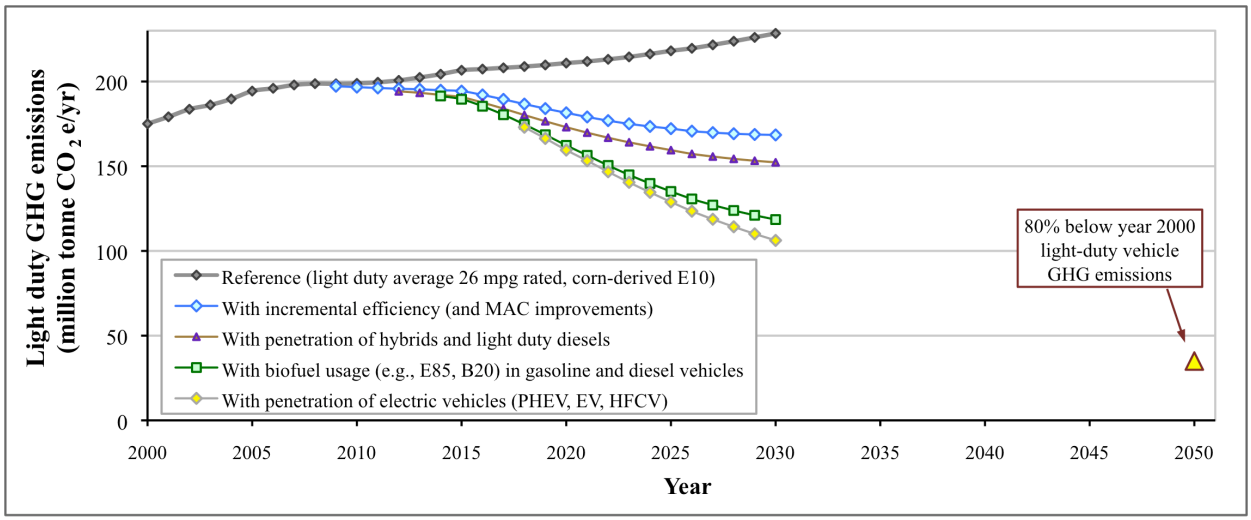

FIGURE 5 Light duty vehicle GHG emissions from the "Pavley and LCFS compliance scenario," in longer term context of 2050 climate mitigation goals

Of the technologies in this analysis that have the greatest potential (in terms of GHG impacts and cost reductions) are battery electric and hydrogen fuel cell vehicles (see, e.g.,*48,49,60*). Major potential cost reductions could result from technology breakthroughs in batteries, fuel cell stacks, and hydrogen storage. Other engineering cost reductions in these vehicles are likely from learning by-doing, economies of scale, and incremental improvements in the major components (e.g., motors, generators, power electronics, and transmissions). These two technology areas have the great advantage of being diverse energy carriers that can be derived from a whole range of low-GHG intensity primary energy sources.

For illustration purposes here, longer term post-2020 cost reductions for these electric vehicles are considered in Figure 6. The cost-effectiveness of electric and fuel cell vehicles with the "near-term" costs that were applied above are shown in the figure along with modified estimations for these technologies based on lower battery, fuel cell, and hydrogen storage costs. Whereas Figure 1 above applies a middle estimate "near-term" cost $500 per kWh of battery capacity (with a range from $400 to $600 per kWh), this longer-term estimation in Figure 6 considers costs of $200-340 per kWh (based on *29*). Fuel cell technology in Figure 1 uses a middle estimate for a "near-term" cost premium of $20,000 per vehicle, including fuel cell and hydrogen storage costs; the figure below depicts the resulting cost-effectiveness for a reduction of this cost premium to $10,000 per vehicle (based on $62 per kW of fuel cell capacity and $18/kWh of hydrogen storage). In cost-reduced cases, the overall reductions in cost-effectiveness that could result from a longer time horizon than used in this study would make electric and hydrogen vehicles considerably more attractive from a cost-effectiveness perspective. For example, the GHG reduction cost-effectiveness of fuel cell vehicles is reduced from about $300/tonne to less than $100/tonne, and full battery electric vehicles drop from over $400/tonne to about $200/tonne.

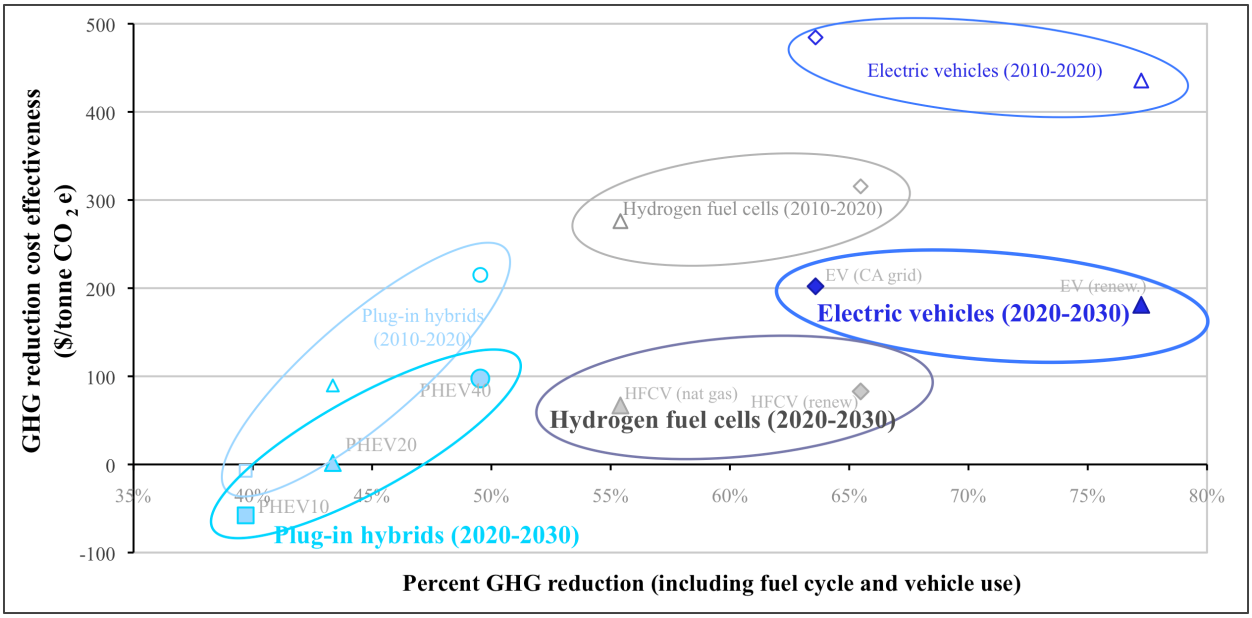

FIGURE 6 Potential greenhouse gas abatement cost reductions over longer term for more advanced electric vehicle drivetrain technologies

CONCLUSION

This analysis offers several findings related to the GHG reduction and cost impacts of vehicle and fuel GHG mitigation programs in California – and, by extension, for other jurisdictions considering comparable actions. Although other jurisdictions with different vehicle usage and retail fuel prices would have somewhat different cost-per-tonne evaluations, the technologies for vehicles and fuels analyzed here are nearly universally applicable for automakers and fuel providers worldwide.

California's vehicle and fuel programs were designed as performance standards that do not favor particular technologies and that allow sufficient flexibility to accommodate unforeseen technology, cost,

and market trends. Despite the inherent flexibility of the standards and technological uncertainty, the near-term nature of these programs makes the modeling and cost-effectiveness evaluation of emerging technologies a useful exercise. Even though any ability to forecast the ultimate future technological "winners" is speculative, and assessments of their estimated costs are even more speculative, the "best estimates" of cost-effectiveness (as in this analysis) can still be informative in assessing emerging technologies. This cost-effectiveness analysis, although far from a precise tool, illuminates the relative attractiveness of technologies in terms of differences in their sign (i.e., positive or negative), order of magnitude, and uncertainty due to technology cost advances and fluctuating fuel prices under the current regulatory conditions.

The cost-effectiveness evaluations suggest that a number of GHG-reduction technologies have high potential for net-benefits associated with them, on account of their lifetime energy savings to consumers outweighing the initial technology costs. The "no regrets" options include incremental gasoline vehicle improvements, hybrid gasoline-electric vehicles, and diesel compression-ignition technology for light duty vehicles. "In-use" technologies, like vehicle accessories (e.g., more efficient mobile air conditioning systems) and tire rolling resistance options, also have net-beneficial cost-per-tonne GHG reductions associated with them.

The blending of biofuels into traditional motor fuels for GHG reduction exhibited widely ranging cost-effectiveness values across different biofuel pathways and also had very high cost uncertainty under the parameters examined here. Best current corn and sugarcane ethanol production practices, under California's regulatory accounting for the LCFS, reveal relatively low GHG reductions, are among the higher estimated cost-per-tonne-GHG values, and show the greatest GHG abatement cost uncertainty with petroleum price fluctuations. However, biofuels from cellulosic feedstocks (either crop or residue based) that are the dominant expected compliance mechanism for the California LCFS, exhibit relatively attractive costs per tonne of GHG reduction, mainly on account of their far more advantageous GHG reductions, as credited under the California LCFS.

Although more advanced electric drivetrains (e.g., plug-in hybrids, full electric, and hydrogen fuel cell vehicles) were found to have some of the highest near-term cost-effectiveness values, there is some silver lining. First, the use of grid-connection plug-in hybrids can be relative low cost, while offering a bridge toward those more advanced, more electrified options in the future. For example, "PHEV10s" that are capable of 10 miles of all-electric driving per charge, offer a relatively modest incremental step toward full electric vehicles and could offer net energy savings for $2.75 retail gasoline (equivalent to $64/barrel world oil price) for technology costs of $500 per kilowatt hour of rated battery capacity. Second, these more advanced drivetrains offer great potential for cost reductions with research and development programs. Third, these technologies, in using electricity and hydrogen, offer the most diverse array of low-GHG upstream primary energy sources in the long term.

Based on the findings from this analysis, the types and magnitude of technology shifts that will be required for the pending GHG mitigation programs will require substantial transformations in vehicles, fuels, and infrastructure. Such shifts would be unprecedented for California, no stranger to its role as a pioneering experimental lab for new environmental policies. But considering similar efforts being developed on a national scale in the U.S. and elsewhere, analytical efforts such as this to continually assess technology costs take on greater importance in helping to direct research, development, and deployment incentives for low-GHG technologies.

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