tas00 | ACSJCA | JCA10.0.1465/W Unicode | research.3f (R3.6.i11:4432 | 2.0 alpha 39) 2015/07/15 14:30:00 | PROD-JCA1 | rq_6086854 | 9/19/2016 09:38:09 | 10 | JCA-DEFAULT

Environmental Science & Technology

Policy Analysis

pubs.acs.org/est

Personal Vehicles Evaluated against Climate Change Mitigation Targets

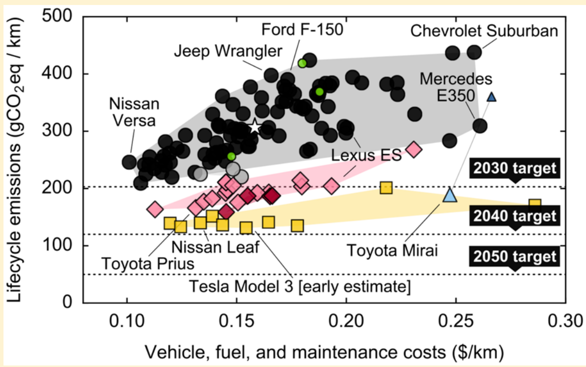
Marco Miotti,[†,⊥] Geoffrey J. Supran,[‡,⊥] Ella J. Kim,[§] and Jessika E. Trancik*[,†,∥]

[†]Institute for Data, Systems, and Society, [‡]Department of Materials Science & Engineering, and [§]Department of Urban Studies & Planning, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, United States

[∥]Santa Fe Institute, Santa Fe, New Mexico 87501, United States

Supporting Information

ABSTRACT: Meeting global climate change mitigation goals will likely require that transportation-related greenhouse gas emissions begin to decline within the next two decades and then continue to fall. A variety of vehicle technologies and fuels are commercially available to consumers today that can reduce the emissions of the transportation sector. Yet what are the best options, and do any suffice to meet climate policy targets? Here, we examine the costs and carbon intensities of 125 light-duty vehicle models on the U.S. market today and evaluate these models against U.S. emission-reduction targets for 2030, 2040, and 2050 that are compatible with the goal of limiting mean global temperature rise to 2 °C above preindustrial levels. Our results show that consumers are not required to pay more for a low-carbon-emitting vehicle. Across the diverse set of vehicle models and powertrain technologies examined, a clean vehicle is usually a low-cost vehicle. Although the average carbon intensity of vehicles sold in 2014 exceeds the climate target for 2030 by more than 50%, we find that most hybrid and battery electric vehicles available today meet this target. By 2050, only electric vehicles supplied with almost completely carbon-free electric power will meet climate-policy targets.



INTRODUCTION

The transportation sector accounts for 28% of U.S. greenhouse gas (GHG) emissions through vehicle fuel combustion, and 13% worldwide.[1,2] Light-duty vehicles (LDVs), which are defined by the U.S. Environmental Protection Agency (EPA) as passenger cars and light trucks with 12 seats or fewer and a gross vehicle weight rating below 8500 lbs (10 000 lbs for SUVs and passenger vans),[3] contribute about 61% of emissions from the U.S. transportation sector.[2] LDVs are therefore a crucial element of any comprehensive strategy to reduce U.S. and global GHG emissions, particularly under growing transportation demands.[1,4−6]

Alternative powertrain technologies, such as battery electric and fuel-cell powertrains, are potential mitigation technologies for personal LDVs, and a variety of studies have evaluated their capacity to contribute to the reduction of transportation emissions.[7−25] Most of these studies focus on the comparison of powertrain technologies implemented in a car of a single size and body style.[7−9,11−15,17−20,23,25] Among those studies that consider different vehicle sizes and styles,[10,16,21,24] none considers more than three different options. In aggregate, these studies cover a limited set of available vehicles, and direct comparisons across studies are complicated by differences in assumed system boundaries, fuel-production pathways, and lifetime driving distance, as well as data sources for lifecycle inventories and fuel-consumption values.

Here, we address two missing elements in the literature by reflecting the diversity of personal vehicle models available to consumers and by assessing these options against climate change mitigation targets. When comparing personal vehicles against climate targets, it is important to understand the wide range of models available for purchase because consumer choices are defined by this available set.

In particular, we focus on the trade-offs between costs and emissions that consumers face in selecting a vehicle model. Although cost is not the sole influence on consumer purchasing decisions,[26−31] low-carbon vehicles will only achieve a dominant market share if they are affordable to a majority of the driving population. (Our proxy for affordability is the relative cost of low-carbon vehicles versus popular, conventional vehicles on the market.) Here, we address these issues by examining a comprehensive set of 125 vehicle models on sale today, covering all prominent powertrain technology options: internal-combustion-engine vehicles (ICEVs); hybrid electric vehicles (HEVs); plug-in hybrid electric vehicles (PHEVs); and battery electric vehicles (BEVs). Our analysis also includes the

Received: January 13, 2016
Revised: May 30, 2016
Accepted: May 31, 2016

DOI: 10.1021/acs.est.6b00177
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

2016 Toyota Mirai, one of the first commercially available fuel-cell vehicles (FCVs).

We evaluate vehicle models on a cost-carbon plot[32] to answer the overarching questions: How do the costs and carbon intensities of vehicle models compare across the full diversity of today's LDV market, and what is the potential for various LDV technologies to close the gap between the current fleet and future GHG emission targets? Specifically, we ask: Do consumers face a cost-carbon trade-off today? Which models, if any, meet 2030 GHG emissions reduction targets? Finally, in the longer term, which vehicle technologies would enable emissions targets for 2040 and 2050, designed around a 2 °C limit, to be met? What role can advancements in the carbon intensity of electricity generation, powertrain efficiencies, and production pathways for liquid fuels play? The insights and choices identified in this study may be of interest to car owners, cars manufacturers, and transportation policymakers alike.

This paper is organized as follows. In the next section, we describe the methods used for our analysis. We then present a comparison of vehicle models spanning today's LDV market against carbon intensity targets on a cost-carbon curve before investigating what factors may enable the future decarbonization of this sector. Finally, we discuss the significance of our results for key decision-makers.

■ MATERIALS AND METHODS

Key steps in our analysis include: (1) estimating LDV lifecycle GHG emission targets (gCO_2eq/km) for the years 2030, 2040, and 2050 consistent with 2 °C climate policy targets; (2) identifying 125 of the most popular LDV models on the market today across all powertrain technologies; (3) estimating the lifecycle costs and carbon intensities of these vehicles on the basis of today's costs and energy mixes and comparing these results against the GHG targets; and (4) assessing the potential of different vehicle models and powertrain technologies to meet GHG targets under a number of vehicle-improvement and energy-market scenarios. Further details are given in the Supporting Information.

Estimating Carbon Intensity Targets. On the basis of overall GHG reduction targets, we estimate carbon intensity targets for emissions from personal LDVs, quantified as GHG emissions per unit distance traveled (gCO_2eq/km). The targets are calculated in three steps: (1) define the overall annual U.S. GHG emission targets in 2030, 2040, and 2050; (2) allocate a fraction of these emissions to LDVs; and (3) divide these numbers by the total vehicle distance expected to be traveled by LDVs.

In step 1, the U.S. emissions reduction targets correspond to a proposed equitable allocation of GHG emissions across nations to limit global warming to less than 2 °C above preindustrial temperatures.[33] Under these targets, total U.S. GHG emissions would be reduced by 32% below 1990 levels by 2030 and 80% below 1990 levels by 2050. We also calculate an emission target for 2040 using linear interpolation (56% below 1990 levels). The U.S. had outlined an equivalent emission reduction goal of 42% below 2005 levels (corresponding to 32% below 1990 levels) by 2030 prior to the United Nations Climate Change Conference in Copenhagen. More recently, the U.S. has made less stringent commitments to reduce overall GHG emissions 26−28% below 2005 levels by 2025 as part of the 2014 U.S.−China Joint Announcement on Climate Change.[34]

In step 2, we apply equal-percentage GHG emissions reductions across all end-use sectors. (This is in contrast to the approach applied in step 1, of a differentiated allocation across nations, and is an approach suggested by current policy proposals in the U.S. targeting electricity and transportation end-use sectors. Below, we briefly discuss circumstances under which different percentage emissions reductions might be applied across end-use sectors.) We define the share of emissions represented by the LDV end-use sector to include emissions from (a) fuel combustion; (b) the production, distribution, and storage of the fuel; and (c) the production, shipping, and disposal of the vehicles. Using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model,[35] discussed further in the Estimating Vehicle GHG Emissions section, we estimate that, on average, (a) represents 70.8% of lifecycle emissions while (b) and (c) represent 18.5% and 10.7%, respectively. Including lifecycle emissions numbers based on these estimates raises the share of overall U.S. GHG emissions represented by LDVs from 17% to 24%. (The transportation sector's 28% share of overall GHG emissions cited in this paper's introduction includes only emissions from fuel combustion in vehicles).[2] The 24% estimate does not account for the fact that a portion of the vehicle and fuel production emissions may have occurred outside the U.S.

In step 3, we use forecasts of the total vehicle miles traveled (VMT) by personal vehicles from the Annual Energy Outlook.[5] In 2011, the VMT by LDV were 2623 billion miles (4220 billion km) and are projected to grow by 0.9% per year until 2040.[5] The emissions intensity targets (emissions per km) estimated here assume a continuation of this growth rate until 2050. The effect of varying this assumption is shown in Figures S1−S2.

The resulting targets are 203 gCO_2eq/km for the average vehicle on the road in 2030, 121 gCO_2eq/km in 2040, and 50 gCO_2eq/km in 2050. Emission targets are shown as dotted lines in Figures 1−5. The targets are raised relative to a case in which only vehicle fuel combustion emissions are included or to a case in which only raw test-cycle fuel-economy data is considered, for two reasons: (1) we include well-to-tank emissions of fuel production and distribution, as well as emissions from the production and disposal of the vehicles; and (2) we base fuel-consumption estimates on U.S. EPA ratings, which have been adjusted for the use of auxiliaries, driving in cold and hot conditions, aggressive driving patterns, and charging losses of PHEVs and BEVs.[3]

Emissions intensity targets are subject to various uncertainties in future demand for LDV travel (or VMT) and the allocation of emissions reductions across sectors (for a quantitative description of the effect of uncertainty, see ref 37). The latter is a policy decision and economic efficiency arguments could be used to justify different percentage emissions reductions across sectors. A potential shortcoming of "segmental" policies is that they determine this allocation at the outset rather than letting the market do so.[37] Segmental policies do have advantages, however, and they are the current policy format of choice in the U.S.

Uncertainties in VMT will emerge from the decisions of individuals in the population, and are more difficult to estimate *ex ante*. A stagnation of VMT has been observed since 2006, meaning that these targets may be somewhat too stringent (although VMT rose again in 2015).[36] However, an increase in travel by some modes of transportation for which decarbon-

DOI: 10.1021/acs.est.6b00177
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

ization is particularly difficult (such as air travel) may call for the increased decarbonization of others (such as LDVs), offsetting the relaxation of targets due to any long-term reduction in the growth of VMT.

These two sources of uncertainty and the effect that they can have on the GHG intensity targets are further discussed in the Supporting Information, with the effect of the uncertainty in future VMT estimated in Figures S1−S2. Our findings regarding which powertrain technologies can meet midcentury climate targets are robust to these VMT uncertainties, due to the dominant effect of aggressive emissions-reduction targets.

Selecting Vehicle Models. We report the lifecycle carbon intensities and costs to the consumer of a total of 125 LDVs. We define LDVs as all four-wheeled vehicles that are captured by the EPA regulations on LDV vehicle fuel economy. This includes all passenger cars and light trucks with 12 seats or less and a gross vehicle weight rating below 8500 lbs (10 000 lbs for SUVs and passenger vans).[3] We include all internal-combustion-engine vehicle (ICEV) models that sold more than 50 000 units in 2014 (93 models[38]), all non-plug-in hybrid electric vehicles (HEVs) that sold more than 5000 units in 2014 (16 models[39]), and all plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) that sold more than 1000 units in 2014 (four and eight models[39]). Combined, these vehicles account for 83% of all personal LDVs sold in 2014.[38] In addition, we include the recently released Toyota Mirai as the only fuel-cell vehicle (FCV), and added diesel and E85 flex-fuel versions for three of the ICEV models. The Mirai is shown for two different hydrogen production pathways: steam methane reforming of natural gas (SMR) and electrolysis using electricity. We also include early estimates of the costs and carbon intensities of the Tesla Model 3 and the Chevrolet Bolt. Except for the Mirai, Model 3, and Bolt, all data used to calculate emissions and costs are based on the respective 2014 models.

Estimating Vehicle GHG Emissions. Lifecycle GHG emission intensities are calculated using GREET 1 and 2.[35] GREET is a widely used, publicly available full-vehicle-lifecycle model developed by Argonne National Laboratory.[35] GREET 1 models the lifecycle emissions of fuels and of electricity, and GREET 2 models the lifecycle emissions of the vehicles themselves. For each powertrain technology and model, the vehicle class (car, SUV, or pickup), curb weight, fuel consumption, battery power (for HEVs), battery capacity (for PHEVs and BEVs), and fuel-cell power (for FCVs) are determined. These parameters are obtained from manufacturers' web sites and a car-information web portal.[40] The carbon intensity of electricity is modeled as the average U.S. mix, including emissions from infrastructure construction (623 gCO_2eq/kWh). We use a consistent lifetime of 169 400 miles (272 600 km) for all vehicle types, corresponding to the approximate averages for LDVs in the U.S.[41] Other GREET parameters are left at their defaults. Because consistent information could not be obtained for all models, the use of light-weighting materials is not considered; that is, all vehicles are assumed to have the "baseline" material mix of their respective powertrain technology and vehicle class.

We determine the fuel consumption of each car from the official fuel economy value recorded by the U.S. government (EPA), based on a standardized test procedure specified by federal law, using the combined city (55%) and highway (45%) rating.[3] These fuel-economy ratings are adjusted for the use of air conditioning in warm weather, efficiency losses in cold weather, and driving patterns.[3]

Although there is public skepticism about the accuracy of these ratings,[42] the EPA holds that they are relatively accurate on average[43] and updates test procedures regularly to mitigate biases. Tests found that large cars and diesel cars may yield somewhat higher (better) real-world fuel economies on average than their ratings suggest,[42] and certain hybrid models may result in lower fuel economies.[44] Notably, however, these results could be partially explained by biases in driving behavior rather than unrealistic test ratings: hybrids may more often be driven in urban environments with dense traffic (which can detrimentally impact fuel economy), while large trucks may more often be driven under steady, efficient highway conditions.

For those models for which several trims and engine sizes are available, the basic (most affordable) trim is analyzed. An exception is made for models that are offered with more than one powertrain technology. In these cases, the trims and feature sets of all technology options for that model are matched by upgrading trims to the lowest common feature set, allowing like-for-like comparison of these models. Details can be found in Table S5 in the Supporting Information. Although tires are included in the vehicle cycle (three sets per lifetime for cars, four for SUVs and pickups), the GHG emissions of maintenance are not modeled, and it is assumed that all components (including the battery) last for a vehicle's entire lifetime. The results' sensitivity to this assumption is provided in Figure S3. Further sensitivity analyses, details on how GHG emissions were calculated, and the specific parameters obtained for each of the 125 analyzed vehicle models can be found in sections S2 and S3 in the Supporting Information.

Estimating Vehicle Costs. The costs of ownership are calculated as the present value of the costs of purchasing the vehicle, paying for fuel and electricity, tire replacements, and regular maintenance, and are presented in 2014 U.S. dollars. As with the calculation of GHG emissions, we assume that each vehicle is driven a total distance of 169 400 miles at 12 100 miles (19 470 km) per year for 14 years of ownership. A discount rate of 8% is applied to future cash flows. The average reported lifetime is slightly longer (15 years), and the average annual driving distance is slightly lower (11 300 miles per year) but decreases with increasing car age.[41] Using a lifetime of 14 years at a constant 12 100 miles per year yields the same discounted cash flows and the same total lifetime distance driven as would using the reported lifetime and vehicle-age-specific annual driving distances. Insurance costs, as well as taxes on vehicle acquisition and ownership, are not included. They depend strongly on the location of the customer and on additional complicating factors that are specific to each vehicle model. Each vehicle's price is based on its official manufacturer's suggested retail price (MSRP) without tax. In addition, we evaluate the impact of federal tax refunds on the lifecycle costs of PHEVs, BEVs, and FCVs. The federal refund scales with the capacity of the battery up to a maximum value of \$7500.[45] Finally, we inspect the added effect of a best-case state tax refund. Assessed for the case of California, this contributes \$1500 for PHEVs, \$2500 for BEVs, and \$5000 for FCVs.[46] Some other states have similar programs, but they were not analyzed in detail.

Fuel and electricity prices are based on the 10 year average of 2004-2013 inflation-adjusted prices in the U.S.[47] The resulting prices are \$3.14/gal for gasoline, \$3.41/gal for premium

DOI: 10.1021/acs.est.6b00177
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

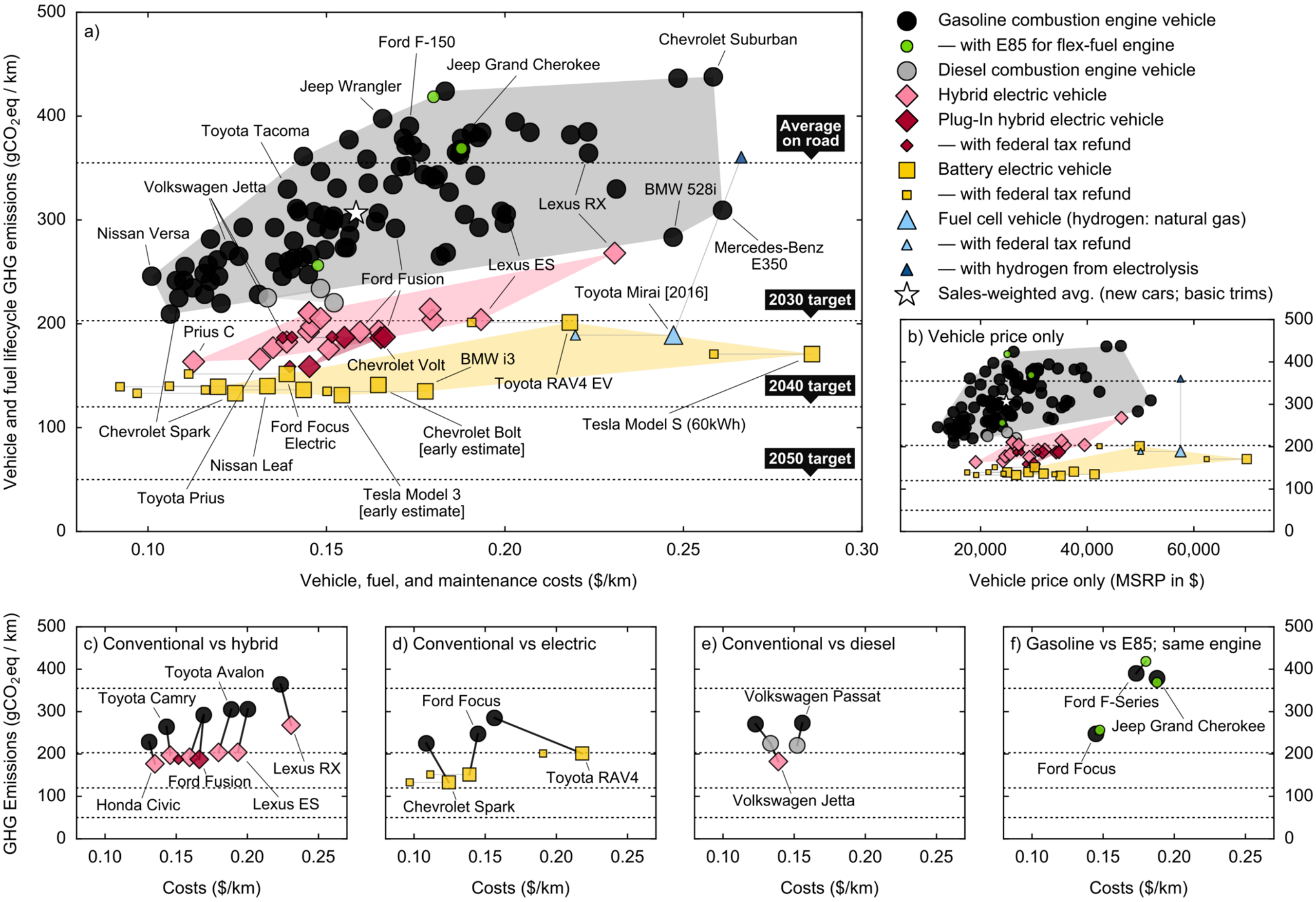


Figure 1. (a) Cost-carbon space for light-duty vehicles, assuming a 14 year lifetime, 12 100 miles driven annually, and an 8% discount rate. Data points show the most popular internal-combustion-engine vehicles (ICEVs; including standard, diesel, and E85 corn-ethanol combustion), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs) in 2014, as well as one of the first fully commercial fuel-cell vehicles (FCVs). For most models, the most affordable trim is analyzed. For models that are offered with different powertrain technologies, the trims are adjusted to match feature sets. The shaded areas are a visual approximation of the space covered by these models. The emission intensity of electricity used assumes the average U.S. electricity mix (623 gCO_2eq/kWh). The FCV is modeled for hydrogen produced either by electrolysis or by steam methane reforming. Horizontal dotted lines indicate GHG emission targets in 2030, 2040, and 2050 intended to be consistent with holding global warming below 2 °C. Panel b shows the same as panel a but for upfront vehicle prices only, based on MSRPs. (c−f) Comparisons of different powertrain technologies used in the same car models ("conventional" powertrains include gasoline and diesel combustion engines). Because trims of these comparisons are harmonized, some models (mostly ICEVs) would be available in more affordable versions with fewer features. For PHEVs and BEVs, the impact of the federal tax refund is also shown. Costs are given in 2014 U.S. dollars.

gasoline, $3.39/gal for diesel, $2.51/gal for E85, and $0.121/kWh for electricity. Hydrogen prices are estimated to be $4.00/kg for hydrogen from methane and $7.37/kg for hydrogen from electrolysis, estimated based on average industrial electricity and natural gas prices. A more detailed description of how these values were determined can be found in the Supporting Information. We also investigate the effect of variability in these prices over time and across locations within the U.S.

The costs of tires and regular maintenance are modeled in a simplified manner, assuming a total of $895 per year for sedan ICEVs and HEVs and $1013 per year for SUVs and pickups.[48] A German study found that regular maintenance costs of BEVs may be a third lower than those of ICEVs;[49] this reduction is applied to BEVs and FCVs. For PHEVs, maintenance costs are lowered by one-sixth. Batteries and fuel cells are assumed to last the entire lifetime of every vehicle, and fuel economies are assumed to stay constant. The sensitivity of the cost estimates and the results to these assumptions is presented in sections S2 and S3 in the Supporting Information.

Evaluating Vehicle GHG Emission-Reduction Pathways. Future prospects for reducing vehicle GHG emission intensities are assessed on the basis of potential improvements in powertrain efficiency, aerodynamic drag, tire rolling resistance, and weight (without decreasing vehicle size, which is evaluated separately). We base estimates of potential fuel consumption reductions by 2050 on a recent comprehensive report.[50] However, we do not use the projected values for 2050. Rather, we use the arithmetic mean of projections for 2030 and 2050. We do this because some vehicles today may already include some of the projected improvements; and we limit the curb weight reductions (which are also taken into account in calculating vehicle cycle emissions) to 15%, whereas the authors in ref 50 assume 15% by 2030 and 30% by 2050. On the basis of this analysis, we apply estimates of maximum possible fuel consumption reductions by 2050 of 40% for ICEVs, 45% for HEVs and PHEVs in charge-sustaining mode, 30% for BEVs and PHEVs in charge-depleting mode, and 35% for FCVs.

We also examine the effect of changing production pathways for electricity and fuels. We consider changes to lifecycle GHG

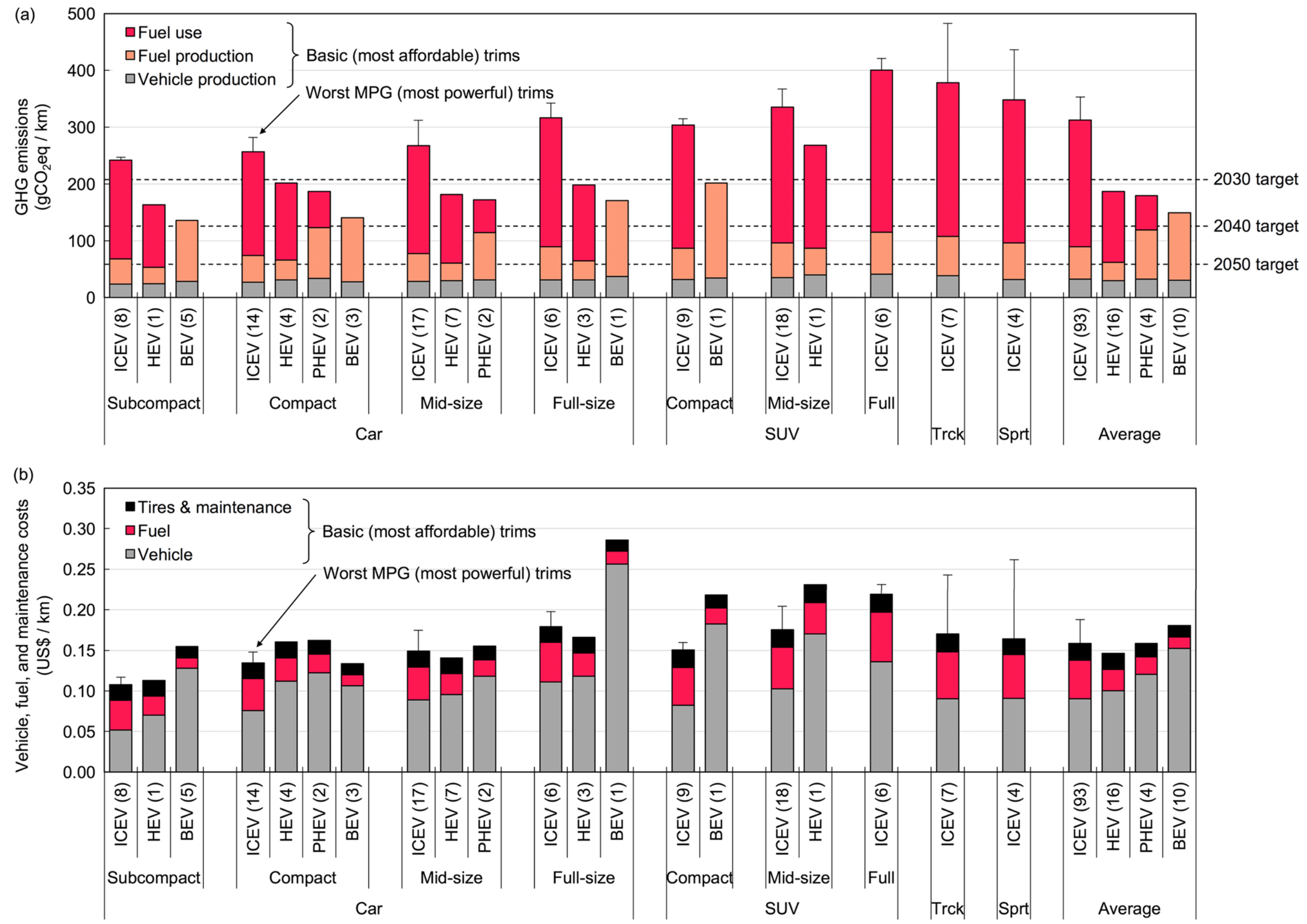


Figure 2. Sales-weighted averages by vehicle class, size, and technology of (a) GHG emissions and (b) costs for the data shown in Figure 1. The shaded bars represent the averages when the most affordable trim is analyzed, as in Figure 1. The error bars represent the averages when analyzing the trim with the worst fuel economy for each model (only ICEVs have trims with substantially different fuel economies for each model). The numbers in brackets represent the number of vehicle models considered for each group. SUV = sport utility vehicle; Trck = pickup truck; Sprt = sports car.

emissions when a low-carbon electricity mix is used to charge electric vehicles and when biofuels are used to fuel combustion engines. For the low-carbon electricity mix, we assume a hypothetical energy-supply portfolio composed of 50% wind and 12.5% each of hydro, solar photovoltaic, biomass, and nuclear energy. Using GREET 2014, this mix results in emissions of 24 g CO_2 eq/kWh, including the indirect effects of reducing carbon emissions from manufacturing and constructing power-generation equipment. The electricity mix not only affects the GHG emissions of BEVs and PHEVs (due to charging) but also the carbon intensity of the production of vehicles and fuels for all powertrain technologies.

RESULTS

GHG Emissions and Costs of 125 Popular Cars in the United States. We find that GHG emissions and costs vary considerably across popular vehicle models, both within and across powertrain technologies, with lower emissions generally corresponding to lower costs. Alternative powertrain technologies (HEVs, PHEVs, and BEVs) exhibit systematically lower lifecycle GHG emissions than ICEVs but do not necessarily cost the consumer more (Figure 1a). As one example, the most popular BEV, the Nissan Leaf, costs 20% less than the sales-weighted average ICEV in 2014 when vehicle, fuel, and maintenance costs are considered. Even before including tax refunds, the compact version of the Nissan Leaf matches the cost of the average compact ICEV sold in 2014 (Figures 1 and 2). At the same time, the Leaf has half the GHG emissions intensity of the average ICEV sold in 2014 and 38% less than the average compact ICEV. In contrast to the trade-off between costs and GHG emissions reported for electricity,[32] where electric utilities are the consumers of energy conversion technologies and fuels, there is no such trade-off faced by consumers of vehicles.

Among alternative powertrain technologies and fuels, BEVs offer the lowest emissions, followed by PHEVs and HEVs, and then diesel engines and FCVs. Vehicles fueled by diesel are among the lowest-emitting ICEVs in the set examined here, while those using E85 (assuming corn-based ethanol) do not reduce emissions relative to gasoline (Figure 1f); the CO_2eq emissions per gallon of E85 fuel are 22% lower than those of gasoline (determined based on GREET data), but this advantage is offset by the lower fuel economies achieved with E85 in flex-fuel engines. For the one FCV model examined (Toyota Mirai), emissions reductions are only achieved when hydrogen is producing using SMR. When hydrogen from electrolysis is used, the Toyota Mirai's emissions are almost

DOI: 10.1021/acs.est.6b00177
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

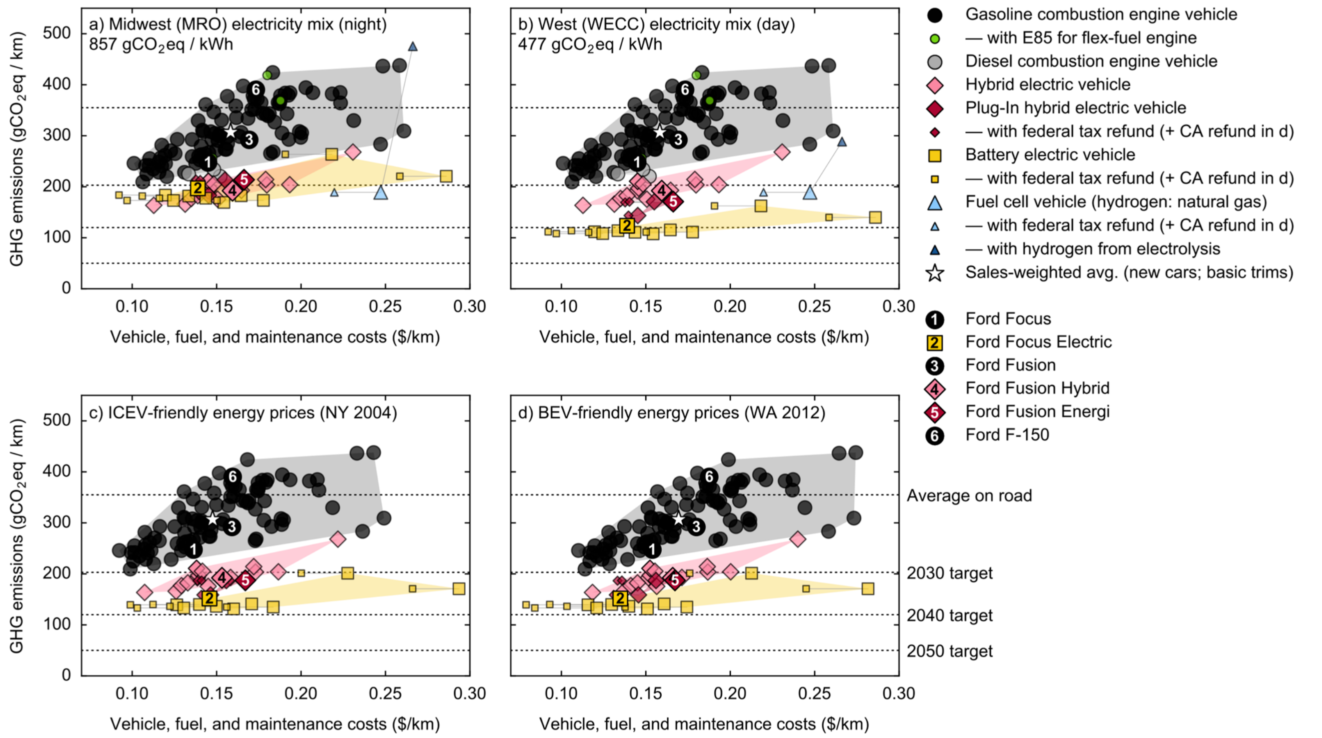


Figure 3. Cost-carbon space of light-duty vehicles as in Figure 1a, shown for four different cases: (a) a lower carbon intensity electricity mix, using the emissions intensity of electricity of the Midwest during nighttime charging;[51] (b) a higher carbon intensity electricity mix, using the emissions intensity of electricity of the West during daytime charging (note that the region has a larger impact on the emission intensity of electricity generation than the time of day of charging);[51] (c) an ICEV-friendly energy price scenario, using average inflation-adjusted prices from New York State in 2004 ($2.43/gal for gasoline and $0.178/kWh and federal tax refunds only; and (d) a BEV-friendly energy price scenario, using average inflation-adjusted prices from Washington State in 2012 ($3.88/gal for gasoline and $0.086/kWh for electricity) and combined federal and state (CA) tax refunds.

almost at the same level as some of the highest-emitting ICEVs on the market.

The regional variability of the electricity mix has a considerable impact on the emissions reduction potential of BEVs and PHEVs (Figure 3a,b). Based on a calculation of regionalized marginal emission factors of electricity,[51] we find that under relatively low carbon intensity electricity conditions, such as the Western Electricity Coordinating Council (WECC) with daytime charging (477 gCO_2eq/kWh, Figure 3b), emissions from today's BEVs are reduced by about 50% compared to ICEVs and by about 25% compared to HEVs. In regions with high carbon intensities of electricity, for example the Midwest Reliability Organization (MRO) with nighttime charging (857 gCO_2eq/kWh, Figure 3a), BEVs do not outperform (P)HEVs, and they emit only about 25% less than comparable ICEVs.

A comparison of the costs and GHG emissions of various powertrain technology and fuel options for the same vehicle model provides further perspective. We find that alternative powertrain technologies often do not cost more for the same vehicle model (Figure 1c–f). About half of the HEVs result in lower costs to the consumer than their ICEV counterparts (Figure 1c). For two BEV models, there is a substantial cost penalty on the order of 20-40%. The Ford Focus BEV and the Ford Fusion PHEV, however, were found to be cheaper overall than the combustion engine version (Figure 1c,d). Moreover, the federal tax refund currently offered means that most PHEV and BEV models come at a considerable cost advantage compared to their equivalent ICEV models. This is especially the case when combined with state tax refunds also available in some regions (Figure 3d).

When only the purchasing prices (upfront costs) of the vehicles are considered, the comparison, based on current costs, shifts in favor of ICEVs (Figure 1b). If consumers are more sensitive to the vehicle purchasing price than to overall lifecycle costs, due to a limited budget for purchasing a vehicle and limited access to financing, they may perceive ICEVs to be more affordable. In addition, some studies suggest that consumers do not fully account for fuel costs when making vehicle purchasing decisions.[52]

One consequence of the higher up-front costs and lower fuel costs of alternative powertrains, particularly BEVs, can be a more stable driving cost over time. Because of the higher fuel cost contribution to the per-distance lifetime cost of driving an ICEV (Figure 2), a changing fuel price can cause the cost of driving to fluctuate more, leaving consumers with a less-predictable driving cost over the lifetime of the vehicle. The difference can be considerable, with fuel costs contributing 31% to total costs in the case of ICEVs and only 9% in the case of BEVs, determined based on a sales-weighted average (Figure 2). The effect can be amplified by the fact that gasoline prices tend to vary more than (consumer) electricity prices over time. Across geographical locations, however, electricity prices vary more than gasoline prices. In Figure 3c,d, we examine the combined impact of spatial and temporal variation in fuel costs by comparing a strongly ICEV-friendly price scenario (Figure 3c) against a strongly BEV-friendly price scenario (Figure 3d) based on inflation-adjusted annual average prices in the lower 48 U.S. states between 2003 and 2015.[47] Also, whereas the

DOI: 10.1021/acs.est.6b00177
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

ICEV-friendly scenario shows the effect of only federal tax refunds, the BEV-friendly scenario shows the effect of combined federal and state (CA) refunds. We find that in going from the ICEV-friendly to the BEV-friendly scenario, the average ICEV becomes 15% more expensive, the average HEV becomes 9% more expensive, the average PHEV stays the same, and the average BEV becomes 6% less expensive. Although these changes do not substantially shift the relative positions of the different technologies in the cost-carbon space, they can have a considerable impact on the cost-competitiveness of specific models.

Vehicles Evaluated against Climate Targets. Several currently available vehicles meet the 2030 average GHG intensity target, although none meet the more stringent 2040 and 2050 targets (Figures 1 and 2). Those vehicles meeting the 2030 target include several HEVs, PHEVs, and BEVs, as well as the Toyota Mirai FCV when operated with hydrogen from SMR (Figure 1a). None of the ICEV vehicles meet the 2030 target, although some come very close. Meeting the 2030 target would therefore require that consumer powertrain choices change well in advance of 2030 (likely by 2025 or earlier) given the time required for the operating fleet to mirror the average carbon intensity of new vehicles. Alternatively, major improvements to ICEV efficiencies and substantial downsizing could allow gasoline-fueled ICEVs to fall below the 2030 target, though not the 2040 and 2050 targets (Figure 4).

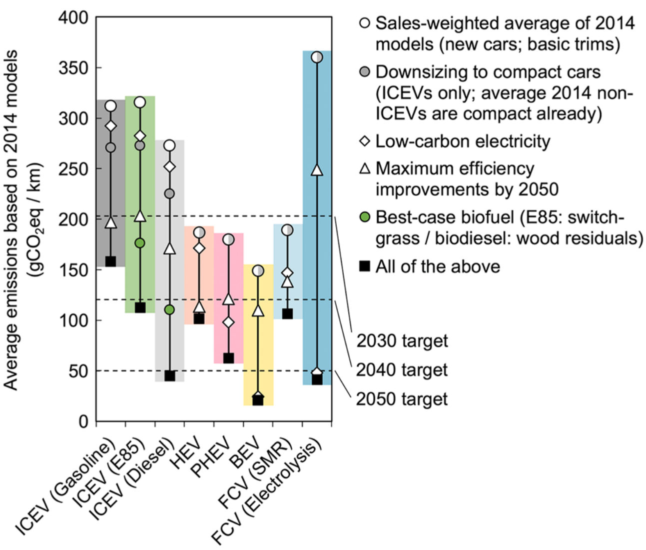


Figure 4. Average GHG emissions intensities of each powertrain technology in response to vehicle downsizing, a low-carbon (zero-fossil-fuel) electricity supply mix (24 gCO_2eq/kWh), efficiency improvements, the use of future biofuels (for ICEVs), and the combination of all factors. Efficiency improvements include a 15% weight reduction and reduced fuel consumptions of 40% (ICEVs), 45% (HEV and PHEVs in charge-sustaining mode), 30% (BEV and PHEVs in charge-depleting mode), and 35% (FCV).[50]

As shown in Figure 4, emission reductions due to estimated improvement potentials of fuel economies[50] are higher for combustion-engine vehicles (ICEVs and HEVs) than for electric vehicles (PHEVs, BEVs, and FCVs). Even if these fuel-economy improvements and other emissions-reducing changes are achieved, however, gasoline-powered non-hybrid ICEVs may never be able to drop below the emission intensities of today's BEVs (charged with electricity at the current U.S. average GHG emissions intensity).

Some of the "best-case" second-generation biofuels promise greater emission reductions for ICEVs. The average 2014 ICEV, equipped with an E85-capable combustion engine and operated with E85 from switchgrass, would reach the 2040 target. The same average car, equipped with a diesel engine and operated with biodiesel from wood residuals, would surpass it.

The greatest emissions savings, however, are expected from decarbonizing the electricity mix, and only technologies that can benefit most from this are able to reach the 2050 GHG emissions intensity target (Figure 4). The lowest GHG emissions are achieved by BEVs, at 32 gCO_2eq/km. The Toyota Mirai FCV operated with hydrogen from electrolysis results in GHG emissions that are nearly comparable to BEVs under this scenario. However, the overall electricity consumption per distance driven is almost three times higher for the Mirai. This is the reason why the GHG emissions of the Mirai, when driven with hydrogen from electrolysis, are so sensitive to the carbon intensity of the electricity mix.

To illustrate a possible scenario for reaching the 2040 and 2050 targets, we consider the effects of the electrification of transportation and the simultaneous decarbonization of electricity. Figure 5a depicts the average emission intensity of

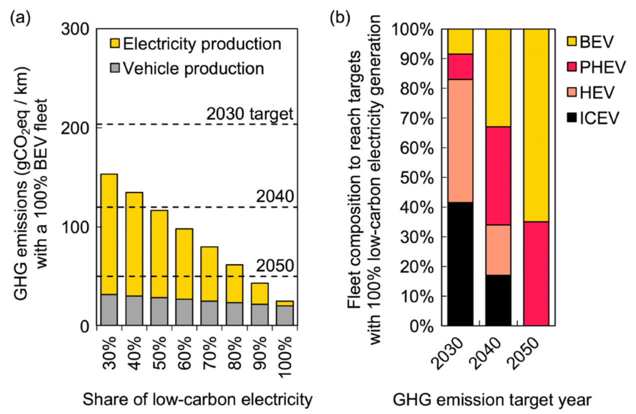


Figure 5. (a) GHG emissions as a function of the share of low-carbon electricity (24 gCO_2eq/kWh) if the entire fleet consists of the average 2014 BEV model (see Figure 4). The low-carbon share ranges from 30% (close to the 32% current share) to 100%. (b) Examples of powertrain technology shares that meet the GHG emission targets if electricity is generated from 100% low-carbon sources, using the average emissions of the 2014 models (see Figure 4).

a hypothetical LDV fleet consisting entirely of BEVs, based on the sales-weighted average of 2014's BEV models. Under this scenario, no improvements to the carbon intensity of electricity production would be necessary to meet the 2030 target because the average 2014 BEV surpasses that target with the current average U.S. electricity mix. In fact, as Figure 3a shows, even in regions of the U.S. with very high carbon intensities of electricity, many BEVs and (P)HEVs meet the 2030 target. Later targets do require reductions, however. To meet the 2040 target, the share of low-carbon electricity generation technologies would need to reach about 50%. To meet the 2050 target, a share of more than 80% would be necessary. In section S2.1 of the Supporting Information, we show the vehicle cost-carbon space when using a fully decarbonized electricity mix, considering different electricity-price scenarios.

DOI: 10.1021/acs.est.6b00177
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

Interestingly, these emissions-reduction targets for electricity are less stringent than they would be for the electricity sector when applying a similar approach to that used here.[32] This is in part because electric vehicles have a higher efficiency of conversion from primary energy to energy at the wheel than the dominant vehicle technologies used today. The implication is that if the electricity end-use sector meets its targets, the decarbonization would be more than enough to achieve LDV transportation targets under a full electrification of transportation.

Another scenario that meets the 2050 target is a partial electrification of transportation but a full decarbonization of electricity. In Figure 5b, we analyze the powertrain technology mix required to meet a target if electricity were to be generated using low-carbon technologies only. The 2030 target could be reached with a fleet consisting almost entirely of ICEVs and HEVs, even if no improvements in efficiency are assumed. To meet the 2040 target, however, a considerable share of PHEVs and BEVs would be necessary. The 2050 target is likely to require a virtually ICEV-free fleet consisting almost entirely of BEVs and PHEVs.

■ DISCUSSION

This paper presents an approach to quantify the diversity of carbon emissions across the U.S. LDV market against climate mitigation targets, with the goal of better informing three categories of decision-makers: car owners, car manufacturers, and transportation policymakers. Our analysis identifies choices available to consumers of vehicles and insights that can inform directed innovation efforts by policymakers and car manufacturers. Together, these stakeholders will dictate progress in decarbonizing the transportation sector and whether a transition occurs at a speed and scale commensurate with climate-policy goals.

Despite the broad spectrum of vehicle costs and carbon intensities offered (within the 125 vehicles examined, there is a 400% spread between the lowest- and highest-emitting cars and a 250% spread between the cheapest and most expensive), several clear patterns emerge. We find that the least-emitting cars also tend to be the most affordable ones within and, in many cases, even across different powertrain technologies. Although the average carbon intensity of vehicles sold in 2014 exceeds the 2030 climate target by more than 50%, most available (P)HEVs and BEVs meet this goal.

A primary takeaway for car buyers is that vehicle decarbonization compatible with future climate targets can only be achieved by transitioning away from ICEVs, principally to (P)HEVs and BEVs. We find that with today's options, the average consumer is able to choose (P)HEVs and BEVs at little to no additional cost over similarly sized ICEVs once the existing tax refunds for PHEVs and BEVs are taken into account. Our analysis helps highlight the extent of cost-carbon savings that car buyers forego by opting for traditional ICEVs over alternative lower-cost, lower-carbon technologies.

Meeting the 2030 climate target requires that by well before 2030, the emissions intensity of the average new car must be as low as that of today's average HEVs and PHEVs. Thereafter, sufficient vehicle-emissions reductions will likely require both the electrification of the vehicle fleet and a large and rapid decarbonization of the electricity generation sector (40% by 2040 and 80% by 2050). This finding corroborates previously proposed climate-mitigation scenarios at state,[53−55] national,[56] and global scales.[57] However, by examining technology choices from the perspective of consumers (key decisionmakers in any future low-carbon transition), our study goes a step further in illuminating technological development and policy pathways that might reach these goals.

An all-electric fleet would increase 2050 electricity consumption in the U.S. by an estimated 1315 TWh per year, or about 28%, if all cars were replaced by today's Ford Focus Electric, for example. This figure would increase to 73% if all cars were replaced by a Toyota Mirai FCV (with an efficiency of electrolysis, compression, and storage of 62%).[35] Accordingly, it will be important for public and private actors to address infrastructure integration challenges such as charging stations and demands on the electricity-supply system,[29,58,59] monitor materials scalability,[60−62] avoid environmental-burden shifting,[16,63,64] and identify alternative road infrastructure revenue streams to today's per-gallon taxes on liquid fuels like gasoline and diesel.[65] One of the most important technological developments may be an increase in the vehicle range of affordable BEVs, although recent research has shown that the typical daily transportation energy needs of most drivers in the U.S. would be met by the relatively low-cost electric vehicles available on the market today.[66]

In addressing the GHG emission challenge of the personal transportation sector, consumer behavior should be taken into account when designing government policies. Policies designed to nudge car buyers toward carbon-saving powertrain technologies and vehicle sizes and classes will likely be important. Additionally, strategies for reducing travel demand can play a critical role and might include discouraging rebound effects,[67] implementing road pricing[68,69] and information-feedback traffic-management systems,[70,71] and ensuring that any eventual proliferation of autonomous vehicles helps lower, rather than raise, miles traveled.[72,73]

Even with the most beneficial behavioral changes, however, a fundamental transition away from ICEVs will be required to meet future GHG emission targets. Overall, we conclude that there are already cost incentives in many contexts for consumers to begin this transition. Further reducing costs (especially vehicle manufacturing costs) of BEVs and other low-carbon technologies (for example, through learning-by-doing, research and development, and economies of scale),[74−76] providing favorable financing, and better informing consumers of the lifecycle cost benefits of more efficient technologies, will likely all be important measures. Given the unprecedented speed and scale of the simultaneous transformations in energy and transportation needed, the joint support of government energy and climate policy, manufacturing innovation, and conscientious consumer decision-making will be key.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b00177.

An expanded discussion of GHG emission targets, cost-carbon space of current LDVs under varying conditions, sensitivities of costs and emissions subject to various parameter uncertainties, and the calculation of emissions and costs. Figures showing sensitivity analysis for the GHG emission targets for personal LDVs, a cost-carbon plot showing a low-carbon electricity mix, and the results of sensitivity analyses. Tables showing parameter values for sensitivity analyses, GHG emissions and cost factors

DOI: 10.1021/acs.est.6b00177
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

of the fuel and vehicle cycles, and input data for all vehicles analyzed. (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: trancik@mit.edu.

Author Contributions

⊥M.M. and G.J.S. contributed equally.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors thank Senator Jeff Bingaman of New Mexico for a discussion of consumers' perspectives and the importance of comparing powertrain technologies within vehicle models. We thank the New England University Transportation Center at MIT under DOT grant No. DTRT13-G-UTC31, the Singapore National Research Foundation (NRF) through the Singapore MIT Alliance for Research and Technology (SMART) Centre, the Reed Foundation, the MIT Leading Technology and Policy Initiative, and the MIT Leading Technology and Policy Initiative for funding this research.

■ REFERENCES

(1) Sims, R. et al. Chapter 8. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Edenhofer, O. et al., Eds.; Cambridge University Press: Cambridge, United Kingdom, 2014.

(2) EPA. *Inventory of U.S. Greenhouse gas emissions and sinks: 1990–2012*; EPA: Washington, D.C., 2014.

(3) U.S. Department of Energy. Fuel Economy home page; http://www.fueleconomy.gov/feg/how_tested.shtml (accessed 2015-12-04).

(4) Creutzig, F.; Mcglynn, E.; Minx, J.; Edenhofer, O. Climate policies for road transport revisited (I): Evaluation of the current framework. *Energy Policy* **2011**, *39*, 2396–2406.

(5) IEA. *World Energy Outlook 2012*; IEA: Paris, France, 2012.

(6) Chu, S.; Majumdar, A. Opportunities and challenges for a sustainable energy future. *Nature* **2012**, *488*, 294–303.

(7) Maclean, H. L.; Lave, L. B.; Lankey, R.; Joshi, S. A Life-Cycle Comparison of Alternative Automobile Fuels. *J. Air Waste Manage. Assoc.* **2000**, *50*, 1769–1779.

(8) Brinkman, N.; Wang, M.; Weber, T.; Darlington, T. *Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems: A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions* **2005**, DOI: 10.2172/1218344.

(9) Schafer, A.; Heywood, J.; Weiss, M. Future fuel cell and internal combustion engine automobile technologies: A 25-year life cycle and fleet impact assessment. *Energy* **2006**, *31*, 2064–2087.

(10) Bandivadekar, A.; Bodek, K.; Cheah, L.; Evans, C.; Groode, T.; Heywood, J.; Kasseris, E.; Kromer, M.; Weiss, M.. *On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions*. Report for the Laboratory for Energy and the Environment. MIT: Cambridge, MA, 2008.

(11) Elgowainy, A.; Burnham, A.; Wang, M.; Molburg, J.; Rousseau, A. *Well-to-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-in Hybrid Electric Vehicles* **2009**, DOI: 10.2172/951259.

(12) Edwards, R.; Larivé, J.; Beziat, J.*Well-to-wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*. Report for Well-to-Wheels; EC Joint Research Center: Petten, The Netherlands, 2011

(13) Van Vliet, O.; Brouwer, A. S.; Kuramochi, T.; Van Den Broek, M.; Faaij, A. Energy use, cost and CO_2 emissions of electric cars. *J. Power Sources* **2011**, *196*, 2298–2310.

(14) Gao, L.; Winfield, Z. C. Life cycle assessment of environmental and economic impacts of advanced vehicles. *Energies* **2012**, *5*, 605–620.

(15) Faria, R.; Marques, P.; Moura, P.; Freire, F.; Delgado, J.; De Almeida, A. T. Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. *Renewable Sustainable Energy Rev.* **2013**, *24*, 271–287.

(16) Hawkins, T. R.; Gausen, O. M.; Strømman, A. H. Environmental impacts of hybrid and electric vehicles-a review. *Int. J. Life Cycle Assess.* **2012**, *17*, 997–1014.

(17) Hawkins, T. R.; Singh, B.; Majeau-Bettez, G.; Strømman, A. H. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *J. Ind. Ecol.* **2013**, *17*, 53–64.

(18) Wang, D.; Zamel, N.; Jiao, K.; Zhou, Y.; Yu, S.; Du, Q.; Yin, Y. Life cycle analysis of internal combustion engine, electric and fuel cell vehicles for China. *Energy* **2013**, *59*, 402–412.

(19) Bartolozzi, I.; Rizzi, F.; Frey, M. Comparison between hydrogen and electric vehicles by life cycle assessment: A case study in Tuscany, Italy. *Appl. Energy* **2013**, *101*, 103–111.

(20) Nanaki, E. A.; Koroneos, C. J. Comparative economic and environmental analysis of conventional, hybrid and electric vehicles - The case study of Greece. *J. Cleaner Prod.* **2013**, *53*, 261–266.

(21) Messagie, M.; Boureima, F. S.; Coosemans, T.; Macharis, C.; Mierlo, J. V. A range-based vehicle life cycle assessment incorporating variability in the environmental assessment of different vehicle technologies and fuels. *Energies* **2014**, *7*, 1467–1482.

(22) Nordelöf, A.; Messagie, M.; Tillman, A. M.; Ljunggren Söderman, M.; Van Mierlo, J. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles-what can we learn from life cycle assessment? *Int. J. Life Cycle Assess.* **2014**, *19*, 1866.

(23) Bauer, C.; Hofer, J.; Althaus, H.-J.; Del Duce, A.; Simons, A. The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework. *Appl. Energy* **2015**, *157*, 871–883.

(24) Miotti, M.; Hofer, J.; Bauer, C. Integrated environmental and economic assessment of current and future fuel cell vehicles. *Int. J. Life Cycle Assess.* **2015**, DOI: 10.1007/s11367-015-0986-4.

(25) Winkler, S. L.; Wallington, T. J.; Maas, H.; Hass, H. Light-duty vehicle CO_2 targets consistent with 450 ppm CO_2 stabilization. *Environ. Sci. Technol.* **2014**, *48*, 6453–60.

(26) Brownstone, D.; Bunch, D. S.; Train, K. Joint mixed logit models of stated and revealed preferences for alternative-fuel vehicles. *Transportation Research Part B: Methodological* **2000**, *34*, 315–338.

(27) Ozaki, R.; Sevastyanova, K. Going hybrid: An analysis of consumer purchase motivations. *Energy Policy* **2011**, *39*, 2217–2227.

(28) De Haan, P.; Mueller, M. G.; Scholz, R. W. How much do incentives affect car purchase? Agent-based microsimulation of consumer choice of new cars. Part I: Model structure, simulation of bounded rationality, and model validation. *Energy Policy* **2009**, *37*, 1072–1082.

(29) Hackbarth, A.; Madlener, R. Consumer preferences for alternative fuel vehicles: A discrete choice analysis. *Transportation Research Part D: Transport and Environment* **2013**, *25*, 5–17.

(30) Sierzchula, W.; Bakker, S.; Maat, K.; Van Wee, B. The influence of financial incentives and other socio-economic factors on electric vehicle adoption. *Energy Policy* **2014**, *68*, 183–194.

(31) Helveston, J. P.; Liu, Y.; Feit, E. M.; Fuchs, E.; Klampfl, E.; Michalek, J. J. Will subsidies drive electric vehicle adoption? Measuring consumer preferences in the U.S. and China. *Transportation Research Part A: Policy and Practice* **2015**, *73*, 96–112.

(32) Trancik, J. E.; Cross-Call, D. Energy technologies evaluated against climate targets using a cost and carbon trade-off curve. *Environ. Sci. Technol.* **2013**, *47*, 6673–6680.

(33) den Elzen, M.; Höhne, N. Reductions of greenhouse gas emissions in Annex I and non-Annex I countries for meeting concentration stabilisation targets. *Clim. Change* **2008**, *91*, 249–274.

(34) The White House Office of the Press Secretary. FACT SHEET: U.S.-China Joint Announcement on Climate Change and Clean Energy Cooperation. https://www.whitehouse.gov/the-press-office/

2014/11/11/fact-sheet-us-china-joint-announcement-climate-change-and-clean-energy-c (accessed 2015-08-27).

(35) ANL. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. https://greet.es.anl.gov/ (accessed 2014-12-20).

(36) FHWA Office of Highway Policy Information Policy: Federal Highway 548 Administration. http://www.fhwa.dot.gov/policyinformation/travel_monitoring/tvt.cfm (accessed 2015-12-14).

(37) Trancik, J. E.; Chang, M. T.; Karapataki, C.; Stokes, L. C. Effectiveness of a Segmental Approach to Climate Policy. *Environ. Sci. Technol.* **2014**, *48*, 27−35.

(38) Cain, T. 2013 U.S. Vehicle Sales Rankings By Model - Top 270 Best-Selling Vehicles In America - Every Vehicle Ranked. http://www.goodcarbadcar.net/2014/01/usa-vehicle-sales-rankings-by-model-december-2013-year-end.html (accessed 2015-08-27).

(39) Cobb, J. December 2013 Dashboard. http://www.hybridcars.com/december-2013-dashboard/ (accessed 2014-12-20).

(40) New Cars, Used Cars, 2015 Car Reviews. http://www.cars.com/ (accessed 2014-12-18).

(41) Davis, S. C.; Diegel, S. W.; Boundy, R. G. *Transportation Energy Data Book Edition 34*; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2015. http://cta.ornl.gov/data .

(42) Stepp, E. One-in-Three Americans Doubt Accuracy of Fuel Economy Ratings. http://newsroom.aaa.com/2015/06/one-in-three-americans-doubt-accuracy-of-fuel-economy-ratings/ (accessed 2016-05-19).

(43) Nelson, G. EPA says its mpg test holds up for hybrids. http://www.autonews.com/article/20130826/OEM11/308269980/epa-says-its-mpg-test-holds-up-for-hybrids (accessed 2016-05-19).

(44) Consumer Reports. Why You Might Not Be Getting the Efficiency Promised: Some window stickers promise too much. *Consumer Reports*, August 2013 (accessed 2016-05-19).

(45) IRS. Qualified Vehicles Acquired after 12-31-2009. http://www.irs.gov/Businesses/Qualified-Vehicles-Acquired-after-12-31-2009 (accessed 2015-02-20).

(46) DriveClean home page. http://driveclean.ca.gov (accessed 2015-02-20).

(47) EIA. U.S. Energy Information Administration (EIA) Website. https://www.eia.gov/ (accessed 2016-05-28).

(48) AAA. *Your Driving Costs: How Much Are You Really Paying to Drive?*; AAA: Aurora, IL, 2013.

(49) Institut für Automobilwirtschaft. *Elektroautos mit deutlich niedrigeren Unterhaltskosten*. Institut für Automobilwirtschaft: Braunschweig, Germany, 2012.

(50) Heywood, J.; MacKenzie, D.; Akerlind, I. B.; Bastani, P.; Berry, I.; Bhatt, K.; Chao, A.; Chow, E.; Karplus, V.; Keith, D.; Khusid, M.; Nishimura, E.; Zoepf, S. *On the Road toward 2050 Potential for Substantial Reductions in Light-Duty Vehicle Energy Use and Greenhouse Gas Emissions*; MIT: Cambridge, MA, 2015; p 286

(51) Siler-Evans, K.; Azevedo, I. L.; Morgan, M. G. Marginal Emissions Factors for the U.S. Electricity System. *Environ. Sci. Technol.* **2012**, *46*, 4742−4748.

(52) Greene, D. *How Consumers Value Fuel Economy: A Literature Review*. EPA: Washington, D.C., 2010

(53) Williams, J. H.; DeBenedictis, A.; Ghanadan, R.; Mahone, A.; Moore, J.; Morrow, W. R.; Price, S.; Torn, M. S. The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity. *Science* **2012**, *335*, 53−59.

(54) Wei, M.; Nelson, J. H.; Greenblatt, J. B.; Mileva, A.; Johnston, J.; Ting, M.; Yang, C.; Jones, C.; McMahon, J. E.; Kammen, D. M. Deep carbon reductions in California require electrification and integration across economic sectors. *Environ. Res. Lett.* **2013**, *8*, 014038.

(55) Jacobson, M. Z.; DeLucchi, M.; Bazouin, G.; Bauer, Z. A. F.; Heavey, C. C.; Fisher, E.; Morris, S. B.; Piekutowski, D. J.; Vencill, T. A.; Yeskoo, T. W. 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. *Energy Environ. Sci.* **2015**, *8*, 2093−2117.

(56) Williams, J. H.; Haley, B.; Kahrl, F.; Moore, J.; Jones, A. D.; Torn, M. S.; McJeon, H. *Pathways to Deep Decarbonization in the United States*; E3: San Francisco, CA, 2014

(57) Sachs, J.; Tubiana, L.; Guerin, E.; Waisman, H.; Mas, C.; Colombier, M.; Schmidt-Traub, G. *Pathways to Deep Decarbonization*; SDSN/IDDRI: New York, 2014

(58) Traut, E.; Hendrickson, C.; Klampfl, E.; Liu, Y.; Michalek, J. J. Optimal design and allocation of electrified vehicles and dedicated charging infrastructure for minimum life cycle greenhouse gas emissions and cost. *Energy Policy* **2012**, *51*, 524−534.

(59) Richardson, D. B. Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration. *Renewable Sustainable Energy Rev.* **2013**, *19*, 247−254.

(60) Wadia, C.; Albertus, P.; Srinivasan, V. Resource constraints on the battery energy storage potential for grid and transportation applications. *J. Power Sources* **2011**, *196*, 1593−1598.

(61) Larcher, D.; Tarascon, J.-M. Towards greener and more sustainable batteries for electrical energy storage. *Nat. Chem.* **2014**, *7*, 19−29.

(62) Kavlak, G.; McNerney, J.; Jaffe, R. L.; Trancik, J. E. Metal production requirements for rapid photovoltaics deployment. *Energy Environ. Sci.* **2015**, *8*, 1651−1659.

(63) Michalek, J. J.; Chester, M.; Jaramillo, P.; Samaras, C.; Shiau, C.-S. N.; Lave, L. B. Valuation of plug-in vehicle life-cycle air emissions and oil displacement benefits. *Proc. Natl. Acad. Sci. U. S. A.* **2011**, *108*, 16554−16558.

(64) Denholm, P.; Kuss, M.; Margolis, R. M. Co-benefits of large scale plug-in hybrid electric vehicle and solar PV deployment. *J. Power Sources* **2013**, *236*, 350−356.

(65) Jenn, A.; Azevedo, I. L.; Fischbeck, P. How will we fund our roads? A case of decreasing revenue from electric vehicles. *Transportation Research Part A: Policy and Practice* **2015**, *74*, 136−147.

(66) Needell, Z. A.; McNerney, J.; Chang, M. T.; Trancik, J. E. Potential for widespread electrification of personal vehicle travel in the United States. *Nature Energy* **2016**, *1*, 16112.

(67) Chitnis, M.; Sorrell, S.; Druckman, A.; Firth, S. K.; Jackson, T. Who rebounds most? Estimating direct and indirect rebound effects for different UK socioeconomic groups. *Ecological Economics* **2014**, *106*, 12−32.

(68) Johansson, O. Optimal road-pricing: Simultaneous treatment of time losses, increased fuel consumption, and emissions. *Transportation Research Part D: Transport and Environment* **1997**, *2*, 77−87.

(69) Anas, A.; Lindsey, R. Reducing Urban Road Transportation Externalities: Road Pricing in Theory and in Practice. *Review of Environmental Economics and Policy* **2011**, *5*, 66−88.

(70) Frey, H. C.; Rouphail, N. M.; Unal, A.; Colyar, J. D. Emissions Reduction Through Better Traffic Management: An Empirical Evaluation Based Upon On-Road Measurements. *Prepared by NC State University for NC Department of Transportation, Raleigh* **2001**, *28*.

(71) Zhang, L.; Yin, Y.; Chen, S. Robust signal timing optimization with environmental concerns. *Transportation Research Part C: Emerging Technologies* **2013**, *29*, 55−71.

(72) Wu, C.; Zhao, G.; Ou, B. A fuel economy optimization system with applications in vehicles with human drivers and autonomous vehicles. *Transportation Research Part D: Transport and Environment* **2011**, *16*, 515−524.

(73) Greenblatt, J. B.; Saxena, S. Autonomous taxis could greatly reduce greenhouse-gas emissions of US light-duty vehicles. *Nat. Clim. Change* **2015**, *5*, 860−863.

(74) Nagy, B.; Farmer, J. D.; Bui, Q. M.; Trancik, J. E. Statistical Basis for Predicting Technological Progress. *PLoS One* **2013**, *8*, e52669.

(75) Farmer, J. D.; Trancik, J. E. Dynamics of technological development in the energy sector. *The London Accord*; **2007**, 1−24

(76) Bettencourt, L. M. A.; Trancik, J. E.; Kaur, J. Determinants of the Pace of Global Innovation in Energy Technologies. *PLoS One* **2013**, *8*, e67864.

DOI: 10.1021/acs.est.6b00177
Environ. Sci. Technol. XXXX, XXX, XXX−XXX