Supporting Information

Personal vehicles evaluated against climate change mitigation targets

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S1 Discussion of uncertainties in greenhouse gas emission targets

The greenhouse gas (GHG) emission targets shown in Figures 1, 3 and 4 in the main article are subject to uncertainties, and sensitive to climate change policy choices. This chapter briefly discusses the major uncertainties and choices.

First, climate change mitigation targets (in terms of maximum average global warming compared to pre-industrial temperature levels) as well as the corresponding maximum globally allowed GHG emissions are subject to both scientific uncertainties and political debate. Less stringent climate change targets would lead to higher (less stringent) GHG emission targets for light-duty vehicles (LDVs).

Second, the allocation of globally permitted GHG emissions to specific countries is subject to debate as well. If fewer emissions are allocated to industrialized or Annex I countries, targets for LDVs in the U.S. would need to be lower.

Third, our derivation assumed that all GHGs associated with the materials supply chain for vehicle and fuel production are emitted within the U.S. In reality, this is not the case. For instance, a fraction of the emissions due to the production and distribution of each vehicle occur outside of the U.S., even if the final manufacturing process takes places within the U.S. Our U.S. emission targets are therefore somewhat conservative; that is, they are more stringent than they might in reality need to be. However, in terms of global climate change mitigation, this simplification in our method does not lessen the challenge of decarbonization; ultimately, it is the global carbon budget that counts, and production- and consumer-based emission schemes are only accounting devices. If domestic decarbonization efforts are measured in such a way as to neglect emissions embodied in trade, one must be careful not to overestimate apparent progress and underestimate the need for more stringent emissions reductions. Embodied carbon leakage has been estimated to constitute more than 25% of global emissions [1, 2].

Fourth, the vehicle miles travelled (VMT) were assumed to follow the U.S. Energy Information Administration (EIA)-projected 0.9% increase per year [3]. If VMT are higher, the targets would need to be lower by the reciprocal of the same factor, and vice-versa. The trajectory of VMT by light-duty vehicles is linked to the development of VMT in other transportation sectors (see next point).

Finally, our targets assume that the shares of emissions allocated to each end-use sector do not change with time. If, as one example, VMT by passenger air travel increase significantly, and the carbon intensity per mile of air traffic cannot be mitigated considerably, other sectors may have to compensate by further reducing their GHG emissions so as to reach overall emissions targets. A modal shift from cars to air travel may decrease the VMT for cars as well, but not necessarily enough to compensate for the increase in air travel.

Combined, these factors can have a substantial impact on the GHG emission intensities of LDVs that will be required to meet climate change policy goals. The allocations of emissions across time, regions, and sectors are policy choices that have to be made. The future growth in VMT, on the other hand, cannot be controlled directly by GHG emission policies. Therefore, we conducted a sensitivity analysis for the targets with respect to the annual growth of VMT, assuming that the sectoral allocations stay constant. The results are depicted in Figures S1 and S2.

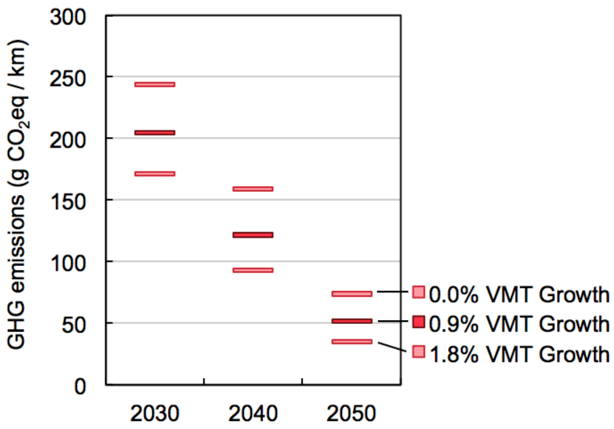

Figure S1: Sensitivity analysis for the GHG emission targets for personal LDVs with respect to the annual growth rate of vehicle miles traveled (VMT) between 2012 and the year of the target. 0.9% is the baseline case used in the main article.

S2 Cost-carbon space of current light-duty vehicles under varying conditions

In Section S2.1, we map out the cost-carbon space under a low-carbon electricity scenario for different electricity prices. In Section S2.2, we map out the cost-carbon space considering uncertainties in five parameters: the lifetime of lithium-ion batteries; the discount rate; the drive cycles (driving patterns); the vehicle life in years; and the vehicle lifetime driving distance.

S2.1 Costs and emissions under a low-carbon electricity scenario

Figure S2 shows the same information as Figure 1a in the main article, but under a scenario where electricity is produced from low-carbon sources only, resulting in a GHG emission intensity of electricity production and distribution of 24.3 gCO_2eq/kWh (as opposed to the baseline case of 623 gCO_2eq/kWh).

We observe that with a fully decarbonized electricity mix, BEVs are able to meet the 2050 target, while PHEVs are located in between the 2040 and the 2050 target (assuming that the fraction of the distance in which PHEVs are driven in charge depleting and charge sustaining modes remains constant at 57% and 43%, respectively).

The costs to the consumer of BEVs and PHEVs are fairly insensitive to electricity costs. We find that even a doubling of the electricity price does not change the cost comparison between BEVs and ICEVs substantially. This is because the cost of electricity for charging BEVs and PHEVs represents a relatively small fraction of total costs (see Figure 2 in the main article).

Finally, Figure S2 shows the GHG target ranges resulting from the uncertainty in future annual vehicle miles traveled by light-duty vehicles (see Figure S1). We note that our conclusions as to which technologies are able to meet what targets, and under what conditions, are robust to these uncertainties.

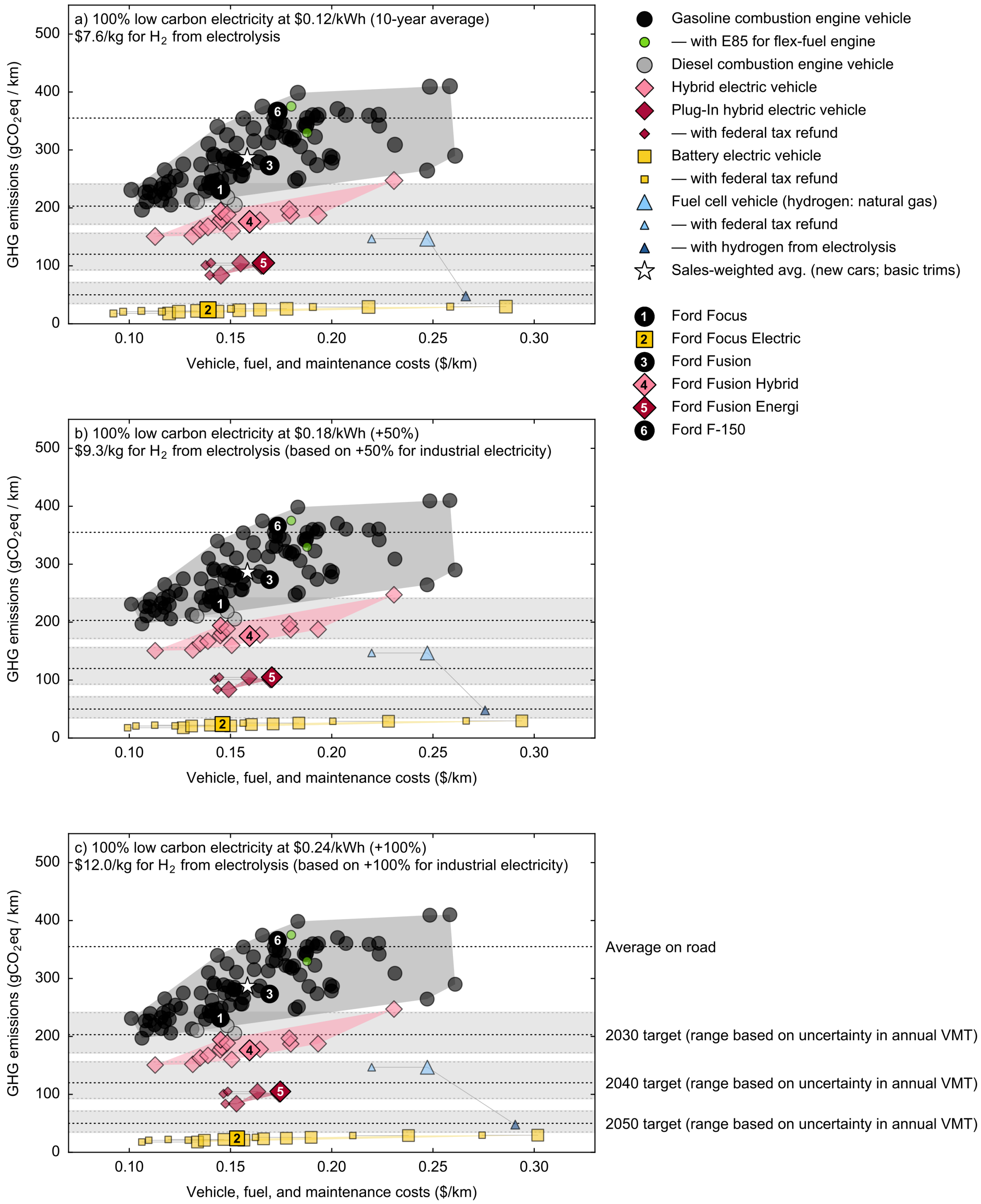

Figure S2: Same cost-carbon plot as Figure 1a in the main article, but with a low-carbon electricity mix (24 gCO_2eq/kWh instead of 623 gCO_2eq/kWh). Plots (a) - (c) represent different scenarios for the increase in electricity price for this electricity mix: (a) 0% (no increase); (b) 50% increase; and (c) 100% increase. The electricity price increases are also applied to industrial electricity prices that are used to calculate the costs of hydrogen (H_2) produced with electrolysis. The uncertainty bands (shaded areas) for the targets reflect the uncertainties in future growth in annual vehicle miles traveled (VMT) shown in Figure S1.

S2.2 Sensitivities of costs and emissions subject to various parameter uncertainties

Here we show the results of sensitivity analyses with respect to the multiple parameters shown in Table S1. The results are shown in Figure S3.

Our sensitivity analysis shows that a full replacement of the lithium-ion batteries in BEVs and PHEVs does not have a major effect on the lifecycle GHG emissions of BEVs and PHEVs (Figure S3b). In terms of costs, the impact is larger (assuming a battery price corresponding to \$200/kWh): on average, the total vehicle, fuel, and maintenance costs to the consumer of BEVs increase by about 7.5% when considering the battery replacement at the beginning of year 8. This implies that if a full battery replacement is necessary, and it has to be paid by the consumer, PHEVs, and especially BEVs, become, in some cases, less financially attractive.

We also show that a low discount rate benefits alternative-fuel vehicles, especially BEVs and PHEVs (Figure S3c and d). This is because the upfront costs (vehicle prices) are particularly large compared to the operating costs (fuel and maintenance) for these vehicle types. If consumers act myopically — that is, perceive future costs as relatively unimportant when making their purchasing decisions — ICEVs can be considerably more attractive than HEVs, PHEVs, and BEVs compared to a case where consumers evaluate costs with greater long-term financial focus. Of course, this is not always an option due to limited budget flexibility.

The drive cycle has a larger impact on the GHG emissions of ICEVs than on those of other powertrain technologies. This is because ICEV technology is the only technology that does not recuperate braking energy. Therefore, ICEV fuel economies are substantially worse in the city drive cycle than in the highway drive cycle. HEVs, PHEVs, and FCVs, on the other hand, have similar fuel economies in both drive cycles. Most BEVs even perform slightly better in the city cycle. For these reasons, the powertrain technologies are much closer together in terms of emissions when only highway driving is considered (Figure S3f) than when only city driving is considered (Figure S3e).

We also find that a shorter lifetime (with the same total lifetime distance driven) results in lower relative costs of alternative-fuel vehicles such as PHEVs and BEVs, because the high operating costs of ICEVs are discounted less strongly (Figure S3g and h). This may be relevant for fleet managers (as opposed to private vehicle owners) whose cars may have a shorter lifetime, at a higher annual driving distance, than privately owned cars.

While the costs of PHEVs and BEVs profit from a shorter lifetime for a given total lifetime distance driven, they profit from a longer lifetime distance (Figure S3i and j). This, again, may be relevant for fleet managers of taxi or car sharing services, as those vehicles tend to be driven for distances significantly above average. It should be noted, however, that reliability concerns for PHEVs, BEVs, and FCVs (in particular the batteries and the fuel cells) are particularly relevant for very long lifetime driving distances such as those shown in Figure S3j.

Table S1: Parameter values for sensitivity analyses described in section S2.2 and shown in Figure S3. The sensitivity analysis investigates the effect of varying each parameter between three different values (Default, Case 1, and Case 2) while holding all other parameters constant at their Default values. For each parameter, Case 1 is shown in the left plot of Figure S3 and Case 2 is shown in the right plot.

Parameter	Default	Case 1 (left)	Case 2 (right)	Notes
Lithium-Ion battery replacement	No replacement	No replacement	1 replacement	We assume replacement costs of $200/kWh. The replacement costs for the Nissan Leaf are currently $230/kWh ($5,500 for a 24 kWh battery [4]), those for the 60 kWh Tesla Model S are $167/kWh ($10,000 for a 60 kWh battery [5]). The costs are discounted, assuming that the replacement takes place after half the car's lifetime (beginning of year 8). Emissions for the production of the additional battery are calculated the same way as for the first battery.
Discount rate	8%	0%	16%	Some studies have found that consumers behave myopically when it comes to considering future fuel prices in their purchasing decisions for cars [6]. This can be described with a high discount rate.
Driving pattern	Combined (55% city and 45% highway)	City only	Highway only	We analyze two extreme cases of driving patterns: 100% city cycle (FTP-75) driving, and 100% highway cycle (HWFET) driving. We use the official reported adjusted fuel economy ratings to determine the fuel economies of the different models under these cycles.
Lifetime in years	14 years	7 years	21 years	The lifetime distance driven (see parameter below) is assumed to be constant at 272,000 km. Therefore, the annual distance driven changes.
Lifetime distance driven	272,600 km (169,400 miles)	136,000 km (84,500 miles)	408,800 km (254,000 miles)	The assumed lifetime (see row above) is 14 years in each case, however the annual driving distance changes.

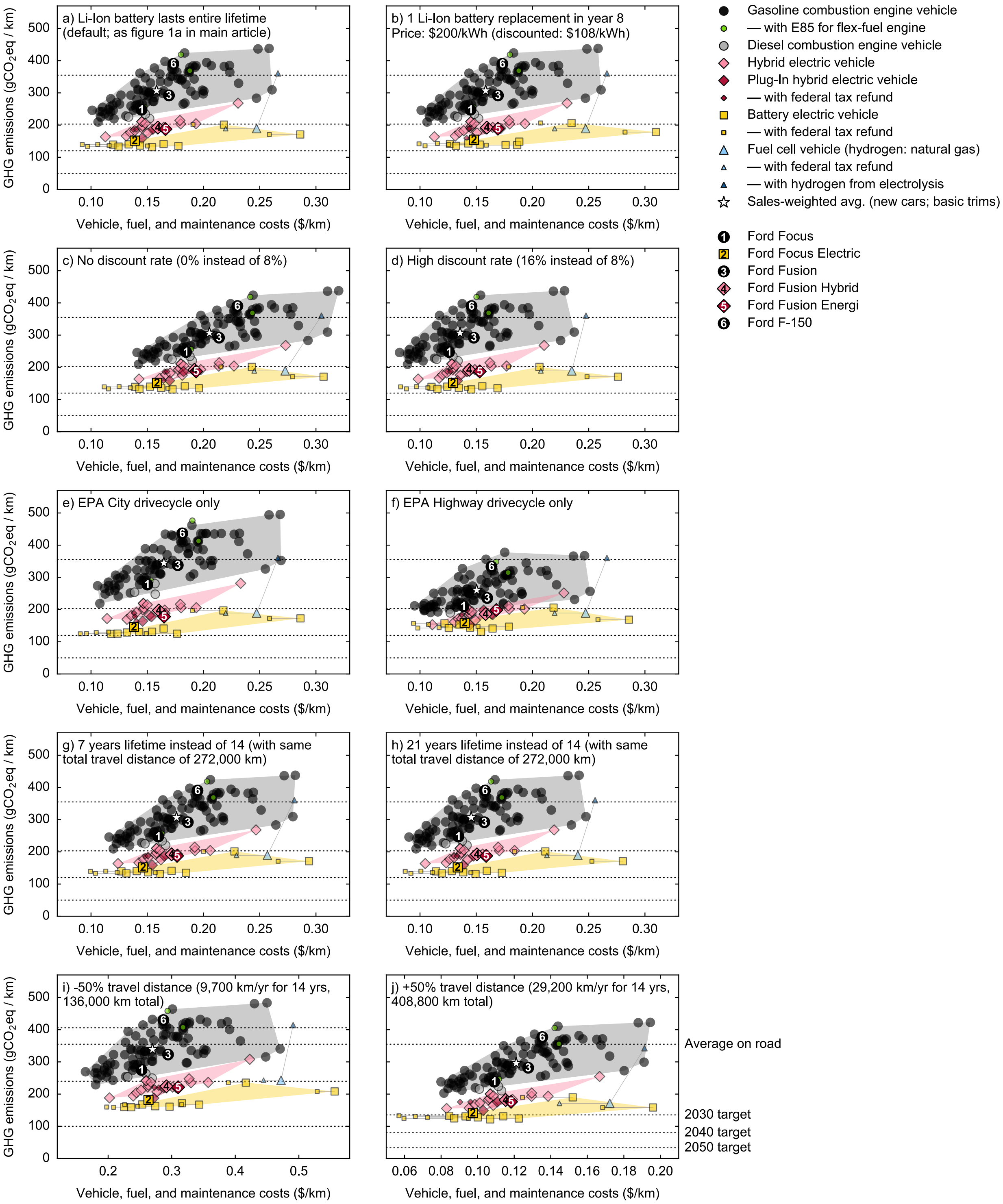

Figure S3: Results of the sensitivity analyses described in section S2.2. The parameters that are changed in each subfigure are shown in Table S1. The changes in lifetime travel distances (plots i and j) change the emission targets: the lower the lifetime driving distance, the higher (less stringent) the emission targets per mile driven. Therefore, the 2030 target is located above the current average emissions of cars on the road in plot i).

S3 Calculation of emissions and costs

Emissions and costs were calculated using parametrized formulas. For GHG emissions, these formulas consist of a set of vehicle parameters (such as curb weight and fuel economy), and a set of intensity coefficients X_i that we derived from GREET, the lifecycle assessment (LCA) model we used [7]. These coefficients can represent emission intensities (amount of emission per amount of material), energy intensities (amount of electricity per amount of material), or mass intensities (amount of component mass per functional unit of that component).

Cost calculations are simpler, as they only consist of the vehicle purchasing price, the fuel costs (which is a product of fuel price and fuel consumption), and some annual maintenance cost rate. Future costs are discounted. The following section discusses these calculations in more detail.

S3.1 Emissions and costs of the fuel cycle

Generally, it was assumed that vehicles are fueled with regular gasoline; premium gasoline was only used if the manufacturer explicitly recommends or requires the use of premium gasoline for even the most basic trim. For PHEVs, we further assume that 57% of the distance is driven in charge depleting mode (using mostly electricity as a fuel), and 43% is driven in charge sustaining mode (using gasoline as a fuel, and electricity only from recuperation of braking energy). These values are consistent with GREET's default settings. For PHEVs with a serial-parallel powertrain configuration, 14% of the energy used during charge depleting mode comes from gasoline, and 86% from electricity in the battery. For PHEVs with a strictly serial configuration (only the Chevrolet Volt), we assume that all energy comes from the battery during charge depleting mode. We also note that the charging efficiency of PHEVs and BEVs is already included in the EPA fuel economy estimates for these vehicle types.

For gasoline, diesel, and electricity prices, we used a constant fuel price, based on a 10-year average of the inflation-adjusted monthly price in the U.S. between 2004 and 2013. This resulted in a regular gasoline price of \$3.14/gallon (averaged over all formulations), a premium gasoline price of \$3.41/gallon, a diesel price of \$3.39/gallon, and a residential electricity price of \$0.121/kWh or \$4.10/gallon-equivalent [8]. The E85 (corn ethanol) price was set to 20% below the regular gasoline price, resulting in \$2.51/gallon. We note that this is an estimated difference [9], which in reality varies considerably with time and region. The price of hydrogen was derived from a cost study by the National Renewable Energy Laboratory (NREL) [10]. Using linear interpolation of NREL's sensitivity analysis, we first adjusted hydrogen prices so that they were based on a 10-year average of industrial natural gas and electricity prices. We then added 0.40 cents per MJ_{eq} of taxes, or 48 cents per kg, to the hydrogen prices. This is the same as the current average tax on gasoline with respect to its lower heating value (48.5 cents per gallon, or 0.40 cents per MJ_{eq}). The resulting hydrogen prices are \$4.11/kg (\$4.17/gallon-equivalent) for hydrogen from steam methane reforming (SMR), and \$7.59/kg (\$7.70/gallon-equivalent) for hydrogen from electrolysis, including pressurization and storage.

The carbon emissions of the fuel cycle per mile (not km) driven, $E_{fuelcycle}$ (in gCO_2eq/mile), are calculated as a function of the fuel consumption in miles per gallon (or miles per gallon-equivalent of gasoline), and the carbon intensity of electricity generation, as follows:

$$E_{fuelcycle} = C_1 + C_2 \cdot \frac{1}{FE} + C_3 \cdot \frac{1}{FE} \cdot E_{electricity} + C_4 + C_5 \cdot \frac{1}{FE} + C_6 \cdot \frac{1}{FE} \cdot E_{electricity} \quad (1)$$

where FE is the fuel economy in miles per gallon of gasoline-equivalent, and $E_{electricity}$ is the carbon intensity of electricity generation and distribution in gCO_2eq/kWh. The intensity coefficients $C1$ to $C6$ are extracted empirically from GREET and shown in Table S2. The fuel economies (FE) of all vehicles analyzed are shown in Table S4.

For PHEVs, the calculation is more complicated. There are two fuel economy values, and thus two emission intensities $E_{fuelcycle}$: One for the charge sustaining cycle (CS), when the car is driven in its 'combustion-mode', and one for the charge depleting cycle (CD), when the car is (mainly) driven in electric mode. Following GREET's split, we calculate the GHG emissions of PHEVs assuming that 57% of the distance is driven in CD, and 43% in CS. In addition, there are two types of PHEV drivetrain configurations: Serial (also called extended range), and serial-parallel. While serial hybrids use only electricity as a power source in CD mode, serial-parallel hybrids typically use a certain amount of gasoline as well. This implies that the fuel economy rating for their CD mode does not exclusively refer to electricity consumption. For serial-parallel hybrids, we therefore assumed that 14% of the energy per mile used during CD comes from gasoline, and 86% from electricity, following GREET's default values. The classification of each PHEV as either series or serial-parallel can be found in Table S4.

The costs of the different fuels are shown in Table S2 as well. The costs (average, minimum, and maximum) refer to the mean, minimum, and maximum monthly average of the respective fuel price, when adjusted for inflation, in 2013 dollars, observed between 2004 and 2013. The hydrogen prices are derived from the respective (industrial) natural gas and electricity prices.

S3.2 Emissions and costs of the vehicle cycle

The carbon emissions of the vehicle cycle, $E_{vehiclecycle}$ (in gCO_2eq), are calculated as follows:

$$E_{vehiclecycle} = X_2 + X_3 \cdot E_{electricity} + m_{scaling} \cdot (X_4 + X_5 \cdot E_{electricity}) + P_{batt} \cdot (X_7 + X_8 \cdot E_{electricity}) + C_{batt} \cdot (X_{10} + X_{11} \cdot E_{electricity}) + P_{fc} \cdot (X_{13} + X_{14} \cdot E_{electricity}) \quad (2)$$

where $E_{electricity}$ is the carbon intensity of electricity generation and distribution in gCO_2eq/kWh, P_{batt} is the power in kW of the power battery (for HEVs and FCVs), E_{batt} is the capacity in kWh of the energy battery (for PHEVs and BEVs), and P_{fc} is the nominal power of the fuel cell system (for FCVs). The corresponding values for all vehicles are shown in Table S4. $m_{scaling}$ is the remaining mass after subtracting from the curb weight the mass of the fixed components (tires, fluids, etc.), the battery, and the fuel cell system:

$$m_{scaling} = m_{curbweight} - X_1 - X_6 \cdot P_{batt} - X_9 \cdot E_{batt} - X_{12} \cdot P_{fc} \quad (3)$$

The curb weights for all vehicles analyzed are shown in Table S4. All the coefficients (X_1 to X_{14}) are extracted from GREET, as shown in Table S3. For all vehicles but FCVs, this approach reproduces the exact results of GREET with the corresponding inputs. For FCVs, our results are only an approximation of GREET's results. This is because in GREET, the power of the fuel cell (P_{fc}) has interdependencies with some of the coefficients X_i due to how the materials mix is calculated. The X_i would therefore, in theory, be a function of P_{fc}. However, this only has a minor effect on the final GHG emissions (error in $E_{vehiclecycle} \ll 1\%$), and can be neglected.

The vehicle costs are determined by the purchasing price and the costs for tires and regular maintenance. The purchasing price was assumed to be the manufacturer's suggested retail prices (MSRPs, Table S4), while the annual tire and maintenance costs can be found in Table S3.

S3.3 Total emissions and costs per mile driven

The lifecycle costs per mile (not km) driven, C (in US$/mile), are calculated as follows:

$$C = \frac{C_{MSRP}}{L \cdot D} + \sum_{y=1}^{L} \frac{C_{fuel} \cdot FE^{-1} + C_{maintenance} \cdot D^{-1}}{(1+r)^{y-1}} \quad (4)$$

where C_{MSRP} is the purchasing price of the vehicle, L is the lifetime in years, D is the annual distance driven with each car, r is the discount rate, C_{fuel} is the fuel price in US$ per gallon-equivalent of fuel, FE is the fuel consumption in gallon-equivalents per mile, and $C_{maintenance}$ are the costs for tires and regular maintenance in US$ per year.

Total greenhouse gas emissions per mile driven, E, are calculated as:

$$E = \frac{E_{vehiclecycle}}{L \cdot D} + E_{fuelcycle} \quad (5)$$

S3.4 Parameters of each vehicle model

Table S4 displays the inputs used in Equations 1-3 for each individual vehicle analyzed, as well as the number of units sold in 2014, which was used to calculate sales-weighted averages. The vehicle data was obtained from Cars.com [11], and the sales data from goodcarbadcar.net for model-level sales data [12] and hybridcars.com for sales data specific to HEV, PHEV, and BEV trims [13]. 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 different powertrain technologies (such as the Toyota Camry ICEV and the Toyota Camry HEV). In these cases, the trim of the technology with the smaller feature set is upgraded to match the basic trim of the technology with the more extensive feature set, allowing for a direct comparison of these models. An overview of these cases can be found in table S5.

The data for all vehicle models and their trims was gathered using an automated process. However, it was necessary to approximate the weight of each chosen trim, as only a range of lowest and highest curb weights was available, but not the weight of each specific trim. The curb weight was therefore calculated using a linear interpolation with respect to the MSRP: The lowest curb weight (lower end of range) was assigned to the trim with the lowest MSRP, the highest curb weight to the trim with the highest MSRP. The resulting curb weight was then assumed to scale linearly with the increase in MSRP. For vehicles where the trim with the lowest MSRP corresponds to the trim with the best fuel economy (about 80% of all vehicles), the chosen curb weight was therefore simply the lower end of the range. The error in curb weight due to this approximation is smaller than 50 kg ($< 5\%$) for almost all vehicles.

The fuel economy ratings represent the official combined ratings assigned by the EPA (55% city and 45% highway driving). These are adjusted ratings that take into account the use of auxiliaries, driving in cold and hot conditions, aggressive driving patterns, and charging losses of PHEVs and BEVs. [14]

Table S2: Greenhouse gas emission and cost factors of the fuel cycle. gGHG in the units of factors C_1, C_2, C_4, and C_5 refers to greenhouse gas emissions in gCO_2eq *without* emissions from electricity use, since the impact of electricity is accounted for separately by factors C_3 and C_6 in Eq. 1. $/gal$_{eq}$ refers to the price per one gallon-equivalent of gasoline; that is, the price per 121.9 MJ of lower heating value.

	Carbon Intensity Coefficients						Costs		
	Feedstock			Combustion					
Fuel	C_1 gGHG/mile	C_2 gGHG/gal	C_3 kWh/gal	C_4 gGHG/mile	C_5 gGHG/gal	C_6 kWh/gal	Average $/gal$_{eq}$	Monthly min. $/gal$_{eq}$	Monthly max. $/gal$_{eq}$
Biodiesel (Forest-Based Residue Biooil)	0.00	-6157	1.52	0.00	0	8596			
Bioethanol (E85 Corn Ethanol)	0.00	-755	1.14	2.18	8456	0	2.51	1.49	3.56
Biogasoline (Forest-Based Residue Biooil)	0.00	-5869	1.64	0.00	2	8432			
Diesel	0.00	1709	0.49	0.20	8871	0	3.39	1.94	5.17
Electricity for charging BEV and PHEV	0.00	0	32.88	0.00	0	0	4.10	3.48	4.50
Gasoline Premium	0.00	1857	0.59	2.18	8607	0	3.41	2.14	4.73
Gasoline Regular	0.00	1857	0.59	2.18	8607	0	3.14	1.86	4.47
H2 from Electrolysis	0.00	0	52.29	0.00	0	0	7.47	7.11	7.77
H2 from Natural Gas	0.00	11478	4.30	3.27	0	0	4.05	3.62	6.03

Table S3: Greenhouse gas emission and cost factors of the vehicle cycle. gGHG in the units of factors X2, X4, X7, X10, and X13 refer to greenhouse gas emissions in gCO_2eq *without* emissions from electricity use, since the impact of electricity is accounted for separately by factors X3, X5, X8, X11, and X14.

	Carbon Intensity Coefficients														Costs
	Fixed parts (Tires, Fluids, etc)			Scaling Parts		Power Battery			Energy Battery			Fuel Cell System			Tires/Main.
	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	
Class	kg	gGHG	kWh	gGHG/kg	kWh/kg	kg/kW	gGHG/kW	kWh/kW	kg/kWh	gGHG/kWh	kWh/kWh	kg/kW	gGHG/kW	kWh/kW	$/yr
Car (ICEV)	58.76	1,716	1,120	2.40	2.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	895.50
SUV (ICEV)	80.51	2,301	1,244	2.36	2.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1,012.50
PickUp (ICEV)	80.51	2,301	1,244	2.38	2.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1,012.50
Car (HEV)	42.39	1,640	1,106	2.40	2.37	1.25	5.01	6.22	0.00	0.00	0.00	0.00	0.00	0.00	895.50
SUV (HEV)	59.38	2,203	1,226	2.39	2.36	1.25	5.01	6.22	0.00	0.00	0.00	0.00	0.00	0.00	1,012.50
PickUp (HEV)	59.38	2,203	1,226	2.39	2.37	1.25	5.01	6.22	0.00	0.00	0.00	0.00	0.00	0.00	1,012.50
Car (PHEV)	42.39	1,656	1,174	2.41	2.38	0.00	0.00	0.00	9.43	33.62	24.69	0.00	0.00	0.00	771.25
SUV (PHEV)	59.38	2,219	1,294	2.40	2.37	0.00	0.00	0.00	9.43	33.62	24.69	0.00	0.00	0.00	873.75
PickUp (PHEV)	59.38	2,219	1,294	2.40	2.39	0.00	0.00	0.00	9.43	33.62	24.69	0.00	0.00	0.00	873.75
Car (BEV)	35.25	1,140	1,141	2.40	2.41	0.00	0.00	0.00	7.52	24.50	14.77	0.00	0.00	0.00	647.00
SUV (BEV)	50.30	1,471	1,246	2.38	2.39	0.00	0.00	0.00	7.52	24.50	14.77	0.00	0.00	0.00	735.00
PickUp (BEV)	50.30	1,471	1,246	2.37	2.40	0.00	0.00	0.00	7.52	24.50	14.77	0.00	0.00	0.00	735.00
Car (FCV)	35.25	1,124	1,074	2.41	2.43	1.25	5.01	6.22	0.00	0.00	0.00	5.00	56.48	40.89	647.00
SUV (FCV)	50.30	1,455	1,179	2.39	2.42	1.25	5.01	6.22	0.00	0.00	0.00	5.00	56.48	40.89	735.00
PickUp (FCV)	50.30	1,455	1,179	2.38	2.43	1.25	5.01	6.22	0.00	0.00	0.00	5.00	56.48	40.89	735.00

Table S4: Input data for basic trims of all vehicles analyzed [11–13]. For each model, the most basic (affordable) trim is chosen, except for the models shown in Table S5. Cweight = curb weight; FE = Fuel Economy; FE/2 = Fuel Economy in charge depleting (CD) mode for PHEVs; MPG = miles per gallon; MRSP = Manufacturer Recommended Selling Price; Ftax = federal tax refund; PBatt = power battery (HEV and FCV); Ebatt = energy battery (PHEVs and BEVs); FC = fuel cell power; PCon = Plug-in Hybrid (PHEV) drivetrain configuration (ser = serial, s-p = serial-parallel); Grs = number of gears; Pwr = nominal engine/motor power in hp (horsepower). Within 'fuel' column: Prem. Gas. = premium gasoline; SMR = steam methane reforming; Elysis = electrolysis; AS manual = auto-shift manual.

Description		Input													Trim Information		
Model	Trim	# Sold	Class	Type	Fuel	Cweight kg	FE MPG	FE/2 MPG	MSRP US$	Ftax US$	Pbatt kW	Ebatt kWh	FC kW	PCon	Transmission	Grs	Pwr hp
Acura MDX	3.5L	65,603	Mid-size SUV	ICEV	Prem. Gas.	1826	23		$42,290						6-spd automatic	6	290
BMW 3-Series & 4-Series	i	142,232	Compact Car	ICEV	Prem. Gas.	1495	28		$32,750						8-spd automatic	4	180
BMW 5-Series	i	52,704	Mid-size Car	ICEV	Prem. Gas.	1730	27		$49,500						8-spd automatic	4	240
BMW i3	Base	6,092	Subcompact Car	BEV	Gasoline	1270	124		$41,350	$7,500		22			1-spd automatic	0	170
Buick Enclave	Convenience	62,300	Full-size SUV	ICEV	Gasoline	2143	20		$38,890						6-spd automatic	6	288
Buick LaCrosse	Base	51,468	Mid-size Car	ICEV	Gasoline	1704	29		$33,535						6-spd automatic	4	182
Cadillac SRX	Base	53,578	Mid-size SUV	ICEV	Gasoline	1940	20		$37,605						6-spd automatic	6	308
Chevrolet Bolt***	0	0	Subcompact Car	BEV	Gasoline	1624	115		$37,500			60			1-spd automatic	0	201
Chevrolet Camaro	LS w/1LS	86,297	Sports Car	ICEV	Gasoline	1679	21		$23,555						6-spd manual	6	323
Chevrolet Cruze	2LT Auto	273,060	Compact Car	ICEV	Gasoline	1533	30		$22,580						6-spd automatic	4	138
Chevrolet Cruze Diesel	Diesel	0	Compact Car	ICEV	Diesel	1574	33		$24,985						6-spd automatic	4	151
Chevrolet Equinox	LS	242,242	Mid-size SUV	ICEV	Gasoline	1705	26		$24,440						6-spd automatic	4	182
Chevrolet Impala	LS w/1LS	140,280	Full-size Car	ICEV	Gasoline	1669	25		$26,860						6-spd automatic	4	195
Chevrolet Malibu	LS w/1LS	188,519	Mid-size Car	ICEV	Gasoline	1539	29		$22,340						6-spd automatic	4	196
Chevrolet Silverado	w/1WT	529,755	Pickup	ICEV	Gasoline	2072	20		$25,575						6-spd automatic	6	285
Chevrolet Sonic	LS Manual	93,518	Subcompact Car	ICEV	Gasoline	1220	29		$14,170						5-spd manual	4	138
Chevrolet Spark	1LT Auto	38,014	Subcompact Car	ICEV	Gasoline	1059	33		$14,995						2-spd CVT	4	84
Chevrolet Spark EV	1LT	1,145	Subcompact Car	BEV	Gasoline	1356	119		$26,685	$7,500		19			1-spd automatic	0	130
Chevrolet Suburban	LS	55,009	Full-size SUV	ICEV	Gasoline	2574	17		$46,300						6-spd automatic	8	320
Chevrolet Tahoe	LS	97,726	Full-size SUV	ICEV	Gasoline	2480	17		$43,600						6-spd automatic	8	320
Chevrolet Traverse	LS	103,943	Full-size SUV	ICEV	Gasoline	2108	20		$30,795						6-spd automatic	6	281
Chevrolet Volt	Base	18,805	Compact Car	PHEV	Prem. Gas.	1717	37	97	$34,185	$7,500		17		ser	1-spd automatic	0	149
Chrysler 200	LX	117,363	Mid-size Car	ICEV	Gasoline	1543	24		$21,795						4-spd automatic	4	173
Chrysler 300	Base	53,382	Full-size Car	ICEV	Gasoline	1797	23		$31,395						8-spd automatic	6	292
Chrysler Town & Country	Touring	138,040	Car	ICEV	Gasoline	2110	20		$30,765						6-spd automatic	6	283
Dodge Avenger	SE	51,705	Mid-size Car	ICEV	Gasoline	1542	24		$20,595						4-spd automatic	4	173
Dodge Challenger	SXT	51,611	Sports Car	ICEV	Gasoline	1739	21		$26,495						5-spd automatic	6	305
Dodge Charger	SE	94,099	Sports Car	ICEV	Gasoline	1797	21		$26,995						5-spd automatic	6	292
Dodge Dart	SE	83,858	Compact Car	ICEV	Gasoline	1445	29		$16,495						6-spd manual	4	160
Dodge Durango	SXT	64,398	Full-size SUV	ICEV	Gasoline	2157	21		$29,995						8-spd automatic	6	290

Table S4 Continued: Input data for all vehicles analyzed

Description		Input													Trim Information		
Model	Trim	# Sold	Class	Type	Fuel	Cweight	FE	FE/2	MSRP	Ftax	Pbatt	Ebatt	FC	PCon	Transmission	Grs	Pwr
Dodge Grand Caravan	AVP/SE	134,152	Car	ICEV	Gasoline	1960	20		$20,895						6-spd automatic	6	283
Dodge Journey	SE	93,572	Mid-size SUV	ICEV	Gasoline	1732	22		$19,995						4-spd automatic	4	173
Fiat 500	Lounge	32,205	Subcompact Car	ICEV	Gasoline	1096	34		$18,500		40				5-spd manual	4	101
Fiat 500E	Base	1,503	Subcompact Car	BEV	Gasoline	1352	115		$31,800	$7,500		24			1-spd automatic	0	111
Ford C-Max Energi	SEL	8,433	Compact Car	PHEV	Gasoline	1750	38	88	$31,635	$4,007		8		s-p	2-spd CVT	4	141
Ford C-Max Hybrid	SEL	19,162	Compact Car	HEV	Gasoline	1636	39		$27,170		40				2-spd CVT	4	141
Ford Edge	SE	108,864	Mid-size SUV	ICEV	Gasoline	1840	22		$28,100						6-spd automatic	6	285
Ford Escape	S	306,212	Compact SUV	ICEV	Gasoline	1588	25		$23,100						6-spd automatic	4	168
Ford Explorer	Base	189,339	Mid-size SUV	ICEV	Gasoline	2057	20		$30,015						6-spd automatic	6	290
Ford F-Series	XL	753,851	Pickup	ICEV	Gas/E85	2125	19		$25,025						6-spd automatic	6	302
Ford Fiesta	S	63,192	Subcompact Car	ICEV	Gasoline	1151	31		$14,100						5-spd manual	4	120
Ford Focus	Titanium	217,670	Compact Car	ICEV	Gasoline	1386	31		$24,065						6-spd AS manual	4	160
Ford Focus Electric	Base**	1,964	Compact Car	BEV	Gas/E85	1651	105		$30,165	$7,500		23			1-spd automatic	0	143
Ford Fusion	Titanium**	259,905	Mid-size Car	ICEV	Gasoline	1577	26		$23,935						6-spd automatic	4	175
Ford Fusion Energi	SE Luxury	11,550	Mid-size Car	PHEV	Gasoline	1775	38	88	$32,590	$4,007		8		s-p	2-spd CVT	4	141
Ford Fusion Hybrid	Titanium**	35,405	Mid-size Car	HEV	Gasoline	1640	42		$27,280		40				2-spd CVT	4	141
Ford Mustang	V6	82,635	Sports Car	ICEV	Gasoline	1588	22		$22,510						6-spd manual	6	305
Ford Taurus	SE	52,395	Full-size Car	ICEV	Gasoline	1830	22		$26,780						6-spd automatic	6	288
GMC Acadia	SLE-1	83,972	Full-size SUV	ICEV	Gasoline	2112	20		$34,485						6-spd automatic	6	288
GMC Sierra	Base	211,833	Pickup	ICEV	Gasoline	2072	20		$26,075						6-spd automatic	6	285
GMC Terrain	SLE-1	105,016	Mid-size SUV	ICEV	Gasoline	1748	26		$26,465						6-spd automatic	4	182
Honda Accord	EX**	374,397	Mid-size Car	ICEV	Gasoline	1500	28		$25,680						2-spd CVT	4	185
Honda Accord Hybrid	Base	13,977	Mid-size Car	HEV	Gasoline	1610	47		$29,155		40				1-spd CVT	4	141
Honda Civic	EX	320,911	Mid-size Car	ICEV	Gasoline	1288	33		$21,090						2-spd CVT	4	143
Honda Civic Hybrid	Base	5,070	Mid-size Car	HEV	Gasoline	1306	45		$24,635		40				2-spd CVT	4	90
Honda CR-V	LX	335,019	Compact SUV	ICEV	Gasoline	1499	26		$23,120						5-spd automatic	4	185
Honda Fit [2015]	LX	59,340	Subcompact Car	ICEV	Gasoline	1140	32		$15,650						6-spd manual	4	130
Honda Odyssey	LX	122,738	Car	ICEV	Gasoline	1994	22		$28,825						6-spd automatic	6	248
Honda Pilot	LX	108,857	Mid-size SUV	ICEV	Gasoline	1950	21		$29,670						5-spd automatic	6	250
Hyundai Accent	GLS	63,309	Subcompact Car	ICEV	Gasoline	1125	31		$14,645						6-spd manual	4	138
Hyundai Elantra	SE	222,023	Compact Car	ICEV	Gasoline	1258	31		$17,200						6-spd manual	4	145
Hyundai Santa Fe	GLS	107,906	Mid-size SUV	ICEV	Gasoline	1771	21		$29,900						6-spd automatic	6	290
Hyundai Sonata	SE	195,884	Mid-size Car	ICEV	Gasoline	1523	28		$24,300						6-spd automatic	4	192
Hyundai Sonata Hybrid	Base	21,052	Mid-size Car	HEV	Gasoline	1568	38		$26,000		40				6-spd automatic	4	159
Jeep Cherokee	Sport	178,508	Mid-size SUV	ICEV	Gasoline	1669	25		$22,995						9-spd automatic	4	184

Table S4 Continued: Input data for all vehicles analyzed

Description		Input													Trim Information		
Model	Trim	# Sold	Class	Type	Fuel	Cweight	FE	FE/2	MSRP	Ftax	Pbatt	Ebatt	FC	PCon	Transmission	Grs	Pwr
Jeep Compass	Sport	61,264	Compact SUV	ICEV	Gasoline	1405	26		$18,795						5-spd manual	4	158
Jeep Grand Cherokee	Laredo	183,786	Mid-size SUV	ICEV	Gas/E85	2062	20		$29,495						8-spd automatic	6	290
Jeep Patriot	Sport	93,462	Compact SUV	ICEV	Gasoline	1422	26		$16,395						5-spd manual	4	158
Jeep Wrangler	Sport	175,328	Compact SUV	ICEV	Gasoline	1760	19		$22,395						6-spd manual	6	285
Kia Forte	LX	69,336	Compact Car	ICEV	Gasoline	1241	29		$15,900						6-spd manual	4	148
Kia Optima	LX	145,244	Mid-size Car	ICEV	Gasoline	1468	27		$21,500						6-spd automatic	4	192
Kia Optima Hybrid	LX	13,776	Mid-size Car	HEV	Gasoline	1586	38		$25,995		40				6-spd automatic	4	159
Kia Sorento	LX	102,520	Mid-size SUV	ICEV	Gasoline	1630	22		$24,100						6-spd automatic	4	191
Kia Soul	Base	145,316	Compact Car	ICEV	Gasoline	1231	26		$14,900						6-spd manual	4	130
Lexus CT 200h	Premium	17,673	Compact Car	HEV	Gasoline	1420	41		$32,050		40				2-spd CVT	4	98
Lexus ES 300h	Base	14,837	Full-size Car	HEV	Gasoline	1660	39		$39,500		40				2-spd CVT	4	156
Lexus ES 350	Base	57,671	Full-size Car	ICEV	Gasoline	1610	25		$36,620						6-spd automatic	6	268
Lexus IS	Base	51,358	Compact Car	ICEV	Gasoline	1570	24		$36,100						6-spd automatic	6	204
Lexus RX 350	Base	98,139	Mid-size SUV	ICEV	Gasoline	1895	21		$39,760						6-spd automatic	6	270
Lexus RX 450h	Base	9,351	Mid-size SUV	HEV	Gasoline	2050	30		$46,410		60				2-spd CVT	6	245
Lincoln MKZ	Base	23,976	Compact Car	ICEV	Gasoline	1687	26		$35,190						6-spd automatic	4	240
Lincoln MKZ Hybrid	Base	10,033	Compact Car	HEV	Gasoline	1736	37		$35,190		40				2-spd CVT	4	141
Mazda 3	i SV	104,985	Compact Car	ICEV	Gasoline	1261	33		$16,945						6-spd manual	4	155
Mazda 6	i Sport	53,224	Mid-size Car	ICEV	Gasoline	1444	29		$20,990						6-spd manual	4	184
Mazda CX-5	Sport	99,122	Compact SUV	ICEV	Gasoline	1449	29		$21,395						6-spd manual	4	155
Mercedes-Benz C-Class	Sport	75,065	Compact Car	ICEV	Prem. Gas.	1555	25		$35,800						7-spd automatic	4	201
Mercedes-Benz E-Class	Base	66,400	Mid-size Car	ICEV	Prem. Gas.	1642	24		$51,900						7-spd automatic	6	302
Nissan Altima	2.5	335,644	Mid-size Car	ICEV	Gasoline	1410	31		$22,170						2-spd CVT	4	182
Nissan Frontier	S	74,323	Pickup	ICEV	Gasoline	1682	21		$17,990						5-spd manual	4	152
Nissan Leaf	S	30,200	Compact Car	BEV	Gasoline	1477	113		$28,980	$7,500		24			1-spd automatic	0	107
Nissan Maxima	3.5 S	50,401	Full-size Car	ICEV	Prem. Gas.	1613	22		$31,290						2-spd CVT	6	290
Nissan Pathfinder	S	79,111	Mid-size SUV	ICEV	Gasoline	1891	22		$29,210						2-spd CVT	6	260
Nissan Rogue	S	199,199	Mid-size SUV	ICEV	Gasoline	1539	29		$22,790						2-spd CVT	4	170
Nissan Sentra	S	183,268	Mid-size Car	ICEV	Gasoline	1285	30		$15,990						6-spd manual	4	130
Nissan Versa	1.6 S	139,781	Subcompact Car	ICEV	Gasoline	1105	30		$11,990						5-spd manual	4	109
Ram P/U	Tradesman	439,789	Pickup	ICEV	Gasoline	2048	20		$25,060						8-spd automatic	6	305
Smart Fortwo	passion	7,859	Subcompact Car	ICEV	Gasoline	827	36		$14,930						5-spd AS manual	3	70
Smart Fortwo electric drive	passion	2,594	Subcompact Car	BEV	Gasoline	970	107		$25,000	$7,500		18			1-spd automatic	0	74
Subaru Forester	2.5i	159,953	Compact SUV	ICEV	Gasoline	1490	25		$21,995						6-spd manual	4	170
Subaru Impreza	2.0i	57,996	Compact Car	ICEV	Gasoline	1335	28		$17,895						5-spd manual	4	148

Table S4 Continued: Input data for all vehicles analyzed

Description		Input														Trim Information		
Model	Trim	# Sold	Class	Type	Fuel	Cweight	FE	FE/2	MSRP	Ftax	Pbatt	Ebatt	FC	PCon	Transmission	Grs	Pwr
Subaru Legacy	2.5i	52,270	Mid-size Car	ICEV	Gasoline	1504	24		$20,295						6-spd manual	4	173
Subaru Outback	2.5i	138,790	Mid-size SUV	ICEV	Gasoline	1553	25		$23,495						6-spd manual	4	173
Subaru XV Crosstrek	2.0i Premium	70,956	Compact SUV	ICEV	Gasoline	1405	26		$21,995						5-spd manual	4	148
Tesla Model 3***	0	0	Compact Car	BEV	Gasoline	1565	125		$35,000			55			1-spd automatic	0	201
Tesla Model S	Base (60kWh)	16,550	Full-size Car	BEV	Gasoline	2108	95		$69,900	$7,500		60			1-spd automatic	0	302
Toyota 4Runner	SR5	76,906	Mid-size SUV	ICEV	Gasoline	1996	19		$32,820						5-spd automatic	6	270
Toyota Avalon	XLE Premium	50,135	Full-size Car	ICEV	Gasoline	1578	25		$33,445						6-spd automatic	6	268
Toyota Avalon Hybrid	XLE Premium	17,048	Full-size Car	HEV	Gasoline	1630	39		$35,805		40				2-spd CVT	4	156
Toyota Camry	LE	389,091	Mid-size Car	ICEV	Gasoline	1453	29		$22,870						6-spd automatic	4	178
Toyota Camry Hybrid	LE	39,515	Mid-size Car	HEV	Gasoline	1551	41		$26,790		40				2-spd CVT	4	156
Toyota Corolla/Matrix	L	339,498	Compact Car	ICEV	Gasoline	1270	31		$16,800						6-spd manual	4	132
Toyota Highlander	LE	146,127	Mid-size SUV	ICEV	Gasoline	1875	22		$29,215						6-spd automatic	4	185
Toyota Mirai	0	1	Mid-size Car	FCV	Hydrogen	1850	66		$57,500	$7,500	40		90		1-spd direct	0	151
Toyota Prius	Two	122,776	Mid-size Car	HEV	Gasoline	1380	49		$24,200		40				2-spd CVT	4	98
Toyota Prius C	One	40,570	Subcompact Car	HEV	Gasoline	1134	49		$19,080		40				2-spd CVT	4	73
Toyota Prius Plug-In	Base	13,264	Mid-size Car	PHEV	Gasoline	1436	50	95	$29,990	$1,500		4		s-p	2-spd CVT	4	98
Toyota Prius V	Two	30,762	Full-size Car	HEV	Gasoline	1485	42		$26,750		40				2-spd CVT	4	98
Toyota RAV4	XLE	266,514	Compact SUV	ICEV	Gasoline	1577	27		$25,000						6-spd automatic	4	176
Toyota RAV4 EV	Base	1,184	Compact SUV	BEV	Gasoline	1829	76		$49,800	$7,500		42			1-spd automatic	0	154
Toyota Sienna	L V6	124,502	Car	ICEV	Gasoline	1955	21		$26,920						6-spd automatic	6	266
Toyota Tacoma	Base	155,041	Pickup	ICEV	Gasoline	1508	23		$18,125						5-spd manual	4	159
Toyota Tundra	SR V6	118,493	Pickup	ICEV	Gasoline	2159	18		$26,200						5-spd automatic	6	270
Volkswagen Jetta Hybrid	Base	1,939	Compact Car	HEV	Gasoline	1502	45		$25,560		40				7-spd AS manual	4	150
Volkswagen Jetta Sedan	2.0L S	122,192	Compact Car	ICEV	Gasoline	1288	28		$16,895						5-spd manual	4	115
Volkswagen Jetta TDI	2.0L TDI Value	0	Compact Car	ICEV	Diesel	1470	34		$21,295						6-spd manual	4	140
Volkswagen Passat	1.8T SE	96,649	Mid-size Car	ICEV	Gasoline	1482	28		$25,875						6-spd automatic	4	170
Volkswagen Passat TDI	2.0L TDI SE	0	Mid-size Car	ICEV	Diesel	1539	35		$26,675						6-spd manual	4	140

* The BMW i3 was modeled with a lightweight material mix to account for the heavy use of carbon fiber within its chassis. Only 50% of the emission penalty (as modeled by GREET) was awarded, since BMW claims to use renewable electricity for the final production stages of the carbon fiber parts.

** These trims were modified further to correspond more closely to the respective HEV, PHEV, or BEV trims. See footnotes below Table S5 for details.

*** The curb weight, fuel economy, and (for the Tesla Model 3) battery size were estimated based on early projections and properties of models of similar size and shape.

Table S5: List of vehicle models for which a trim other than the most basic (most affordable) trim was chosen in order to match the feature set of the most basic HEV, PHEV, or BEV version of the same model.

Model	Basic trim			Chosen trim			Matched with
	Name	MSRP	Fuel economy	Name	MSRP	Fuel economy	
Chevrolet Cruze	LS Manual	$17,520	29	2LT Auto	$22,580	30	Cruze Diesel (Diesel ICEV)
Chevrolet Spark	LS Manual	$12,170	34	1LT Auto	$14,995	33	Spark EV 1LT (BEV)
FIAT 500	Pop	$16,445	34	Lounge	$18,500	34	500e Battery Electric (BEV)
Ford C-Max Hybrid	SE	$24,170	39	SEL	$27,170	39	C-Max Energi SEL (PHEV)
Ford Focus	S	$16,810	30	Titanium	$24,065	31	Focus Electric Base (BEV)
Ford Focus Electric	Base	$29,170	104	Base*	$30,165	104	Focus Titanium (ICEV)
Ford Fusion	S	$21,970	26	Titanium**	$28,800	26	Fusion Energi SE Luxury (PHEV)
Ford Fusion Hybrid	S	$26,270	42	Titanium**	$30,800	42	Fusion Energi SE Luxury (PHEV)
Honda Accord	LX	$21,955	28	EX***	$25,680	28	Accord Hybrid Base (HEV)
Honda Civic	LX	$18,190	31	EX	$21,090	33	Civic Hybrid Base (HEV)
Hyundai Sonata	GLS	$21,450	28	SE	$24,300	28	Sonata Hybrid Base (HEV)
smart fortwo	pure	$13,270	36	passion	$14,930	36	fortwo electric passion (BEV)
Toyota Avalon	XLE	$31,590	25	XLE Premium	$33,445	25	Avalon Hybrid XLE Premium (HEV)
Toyota Camry	L	$22,425	29	LE	$22,870	29	Camry Hybrid LE (HEV)
Toyota RAV4	LE	$23,550	27	XLE	$25,000	27	RAV4 EV Base (BEV)
Volkswagen Jetta	2.0L Base	$15,695	28	2.0L S	$16,895	28	Jetta Hybrid Base (HEV)
Volkswagen Passat	1.8T S	$22,095	28	1.8T SE	$25,875	28	Passat 2.0L TDI SE

* The leather seat option ($995) was added to this trim to match the seats of the Ford Focus Titanium.

** The price of this trim was decreased by $1800 to match the ‘SE Luxury’ (rather than the ‘Titanium’) feature set of the Ford Fusion Energi.

*** The CVT transmission option ($800) was added manually to this trim to match the transmission system of the Honda Accord Hybrid.

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