Emissions Reductions from Electrifying High-Mileage Vehicles

TRB Paper No. 22-02767
Transportation Research Board 101st Annual Meeting
January, 2022

Zack Aemmer
Department of Civil and Environmental Engineering
University of Washington, Seattle, Washington, 98195
Email: zae5op@uw.edu

Daniel Malarkey
Department of Civil and Environmental Engineering
University of Washington, Seattle, Washington, 98195
Email: djmalark@uw.edu

Don MacKenzie
Department of Civil and Environmental Engineering
University of Washington, Seattle, Washington, 98195
Email: dwhm@uw.edu

Word Count: 5777 words + 4 tables (250 words per table) = 6,777 words

Submitted [July 31, 2021]

ABSTRACT

This paper evaluates the effects of a hypothetical policy targeting internal combustion vehicles with high annual miles for replacement with electric vehicles (EVs). We first characterize the distribution of the fleet of light-duty vehicles owned by households in 2017 by annual vehicle miles traveled (VMT) and emissions per mile. We use the 2017 National Household Travel Survey (NHTS) data to estimate the relationship between average annual VMT and vehicle lifetime mileage. We then estimate emission reductions from converting different segments of the fleet to electric vehicles using Argonne National Lab's Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model. We find that a policy targeting electric vehicle conversion in the top mileage quintile of the existing vehicle fleet would generate more than four times the annual reduction in certain criteria pollutants and twice the lifetime reduction in greenhouse gases compared to a policy that converts vehicles in the bottom mileage quintile. The effect on lifetime emissions savings per vehicle depends on the relationship between annual mileage, scrappage probability, and lifetime mileage - a dependence we explore through sensitivity analysis. A review of 81 policies related to electric vehicles in California finds no instance of a policy that targets high-mileage vehicles. We conclude that reforming the public subsidies for electric vehicles to target high-mileage vehicles could improve economic efficiency as measured in emissions reductions per dollar of subsidy. Such a program could also target low- and moderate-income households to improve equity.

Keywords: Electric Vehicles, Emissions, Lifetime, Annual Mileage, Subsidy Policy, Public Policy, Efficiency, Equity

INTRODUCTION

Internal combustion engine vehicles (ICEVs) produce emissions that damage human health and contribute to global warming (*1*). As part of a suite of policies to reduce these harmful emissions, the U.S. federal government and the state of California offer tax credits and cash subsidies to lower the cost of electric vehicles (EVs) and electric vehicle supply equipment (EVSE) (*2*,*3*). In 2019, EV purchasers received $1.4 billion in federal tax credits, and in 2020, California appropriated $2.7 billion in revenue generated by the state's cap and trade program for low carbon transportation and low carbon transit operations (*4*,*5*).

Prior studies fault the federal tax credit on equity and efficiency. Borenstein and Davis found that 90 percent of the credit went to households in the highest earning quintile (*6*). Xing et al. estimated 70 percent of the credit went to households that would have purchased an EV without the subsidy and that EVs typically replace relatively fuel-efficient vehicles, which lowers the emissions benefit by 39 percent compared with EVs replacing vehicles of average fuel efficiency (*7*). Burlig et al. used data from home chargers in California to calculate EVs were driven just 5,300 miles per year, less than half of the U.S. fleet average (*8*). Davis analyzed the 2017 National Highway Travel Survey and found EVs were driven 65 percent of the average for vehicles with gasoline engines (*9*). Both studies observe that lower annual mileage for EVs lowers the emissions benefits from vehicle electrification.

Chakraborty et al. disagree, presenting survey data that shows the new generation of electric vehicles with greater range are driven as much or more than gasoline-powered vehicles and will deliver on EVs' emissions benefits as the market grows (*10*). More generally, a static analysis of the efficiency of EV and EVSE subsidies at a single point in time will obscure the dynamics of how they accelerate learning by doing in manufacturing. Subsidies may allow the industry to scale faster and through innovation improve vehicle and equipment performance, lowering costs over time so EVs can compete with ICEVs without subsidy. Gerarden analyzed the impacts of consumer subsidies in the global market for solar panels and found they encouraged firms to innovate to reduce their costs. He also found that static analysis significantly underestimated the social benefits of the subsidy policies (*11*).

In contrast to the federal tax credit for EVs, California has targeted 63 percent of the aggregate public investment from its cap-and-trade revenue to census tracts identified as disadvantaged or low-income since 2017 (*5*). Notwithstanding these efforts to improve program equity with geographic targeting, most of the households that purchase new and used EVs in these target communities have high incomes (*12*).

One potential approach to improve the efficiency and equity of vehicle electrification policy would be to focus subsidies on replacing ICEVs with high-annual miles that are driven by moderate- and low-income drivers. Annual emissions reductions from converting to an EV scale with annual miles driven, so a high-mileage vehicle replacement program could deliver larger immediate annual emissions reductions per dollar of subsidy. Moreover, a program that targeted high-mileage vehicles could also include household income criteria to target moderate and low-income households. For the purposes of this paper, we define a shift in EV subsidies from high income households to moderate and low-income households as an improvement in equity.

However, larger annual emissions reductions will not necessarily translate into lower total greenhouse gas emissions in the long run. If electric vehicles are driven a fixed number of miles before retirement, putting them into high-mileage service could reduce annual emissions, but those benefits would be sustained over a proportionally shorter number of years. Put another way, if EVs last 150,000 miles regardless of whether they are driven 5,000 or 50,000 miles per year, then the lifetime greenhouse gas emissions would be the same for vehicles with low and high annual mileage.

In this paper, we use the 2017 NHTS data to analyze the relationship between annual miles of driving and the total miles a vehicle is driven before being retired. We also use NHTS data to characterize annual emissions of the vehicle fleet along two dimensions: annual miles driven per year and the average emissions per vehicle mile. We observe that 20 percent of the household vehicle fleet with the highest mileage generate more than 45 percent of the annual emissions. The 20 percent of the fleet with the lowest mileage generate less than 4 percent of the annual emissions.

We use Argonne National Lab's Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model to estimate the annual emissions and lifetime emissions reductions from converting different segments of the existing fleet after accounting for different potential relationships between annual miles and vehicle lifetime miles. We find that a policy targeting EV conversion in the top mileage quintile of the 2017 vehicle fleet would generate more than four times the reduction in certain criteria pollutants and twice the reduction in lifetime greenhouse gases compared to a policy that converts vehicles in the bottom mileage quintile.

We then undertake a comprehensive review of EV subsidy policies across federal, state, and local governments in California and find no instance of a policy that targets high-mileage vehicles. Given the potential efficiency and equity benefits of targeting high-mileage vehicles we discuss potential program design and areas for additional research.

METHODS

Characterizing Emissions from the U.S. Household Vehicle Fleet

The NHTS provides data from 2017 characterizing the emissions of vehicles driven by survey respondents, as well as their travel behavior. Using this data, we analyzed the distribution of annual vehicle miles traveled (VMT) and emissions per mile of the US passenger vehicle fleet. These distributions were used to segment the fleet for evaluating reductions in emissions from ICEV replacement with a subsidized EV purchase in the emissions modeling section. This analysis allows us to 1) characterize how each segment of the fleet contributes to the overall emissions, and 2) illustrate the potential benefits of targeting EV subsidies towards specific segments of the fleet.

Determining annual VMT from the NHTS data can be done in several ways. It is provided by NHTS directly through the ANNMILES and BESTMILE variables. The first is self-reported annual VMT for the year of the study, and may be subject to perceptual errors. The second is the best estimate of annual VMT based on a set of NHTS decision rules, and also provides estimates in cases where annual VMT was not reported (*13*). Alternatively, the OD READ and VEHAGE variables can be used to determine the average annual VMT over the lifetime of each vehicle. This approach may overstate the VMT in 2017 of the fleet given that many older vehicles were driven at a higher annual mileage early in their lifetimes (*14*). In characterizing the household vehicle fleet, we use the BESTMILE variable to calculate annual VMT.

Emissions Model

One salient yet often overlooked point of estimating EV emissions benefits is that if an electric vehicle is driven the same number of lifetime miles before being scrapped, regardless of its annual VMT, its lifetime greenhouse gas (GHG) emissions will remain static and make the same contribution to keeping society within the global GHG budget (*15–17*). Prior research has explored the depreciation effects of driver behavior that are indirectly related to annual mileage such as city and highway mileage, class of vehicle, depth of battery discharge and style of driving (*18–21*). We did not find any published work that directly quantifies the effects of annual VMT on lifetime mileage for ICEVs or EVs.

For this analysis, we allow for the possibility that a vehicle's lifetime is a function of its age and its annual mileage, not mileage alone. This could mean that vehicles driven at higher average annual VMT will achieve higher lifetime mileage, and thus greater lifetime reductions in GHG emissions if replaced with an EV. We estimate a linear relationship between annual VMT and lifetime mileage using data from the US vehicle fleet gathered by the NHTS. Although the relationship may differ between ICEVs and EVs, for our baseline and upper bound cases, we assume the impact of age on vehicle lifetime is the same between the two vehicle types. This relationship is shown in **Equation 1** below, where (β) indicates the magnitude of the effect of annual VMT on lifetime mileage. We apply this equation only between the mean of the first and fifth annual VMT quintiles constructed from the NHTS fleet data, given that it is unlikely to extend to extreme cases (e.g. a vehicle driven infinite miles will not obtain an infinite lifetime mileage):

$$Lifetime\ Mileage = \alpha + \beta \times Average\ Annual\ VMT \ni 2{,}100 \leq Average\ Annual\ VMT \leq 25{,}800, \quad \textbf{(1)}$$

To determine the constant for this relationship (α), we selected the oldest vehicles in the NHTS vehicle dataset (model years 1985-2000) that were on average driven less than 5,000 miles per year. This set of vehicles has an average cumulative mileage of 73,000 which is unlikely to increase significantly before they are scrapped. The National Highway Transportation Safety Administration (NHTSA) estimates the survival rate for vehicles older than 20 years at less than 2 percent (22). We use this mean cumulative mileage of 73,000 miles as an estimate for the constant term (α).

Then, to calculate a baseline magnitude for the effect of annual VMT on lifetime mileage in an average vehicle (β), we use NHTSA's estimates for average passenger car lifetime mileage (127,000 miles) and average annual VMT (6,400 miles/yr) across 20 years to solve **Equation 1** for (β), giving (127,000 - 73,000) / (6,400) = 8.4 additional lifetime miles per additional mile of annual VMT, or 8,400 additional lifetime miles per additional thousand miles annual VMT. The underlying data for the NHTSA estimates is also the NHTS vehicle data (*22*). Our baseline assumption therefore assumes the relationship in **Equation 1**, and that this relationship holds similarly for ICEVs and EVs.

For the lower bound of our sensitivity analysis, we assume the effect of age on lifetime mileage is zero. Therefore, all EVs that replace ICEVs have lifetime miles of 127,000 regardless of their annual miles. To determine a reasonable upper bound, we selected the vehicles from the NHTS vehicle dataset that have high cumulative mileage (more than 180,000 miles, or the 95th percentile). The average cumulative mileage and annual VMT for these vehicles were again used to solve **Equation 1** for (β), giving (224,000 - 73,000) / (14,700) = 10.3 additional lifetime miles per additional mile of annual VMT. Together, these two assumptions reasonably bound the potential magnitude of the effect of annual VMT on lifetime mileage for a typical vehicle.

For the emissions calculations, we used Argonne National Laboratory's GREET database, which provides well-to-wheel data on emissions rates per mile for various vehicle classes and fuels, to model changes in emissions from converting ICEVs to EVs (*23*). For determining the expected GHG and criteria pollutant emissions for an electric vehicle, we use the GREET data for a typical battery electric vehicle (BEV). Electricity generation fuel mix was taken at the national level (U.S. mix), and a target year of 2019 (latest available pre-pandemic energy consumption). The base assumptions for electricity mix in the GREET model rely on data from the Energy Information Administration's Annual Energy Outlook. Key assumptions related to vehicle manufacturing include the assumption of passenger cars (as opposed to SUVs or pick-up trucks), and conventional construction materials (as opposed to lightweight). For EVs, Li-Ion batteries were assumed. This data also incorporates the manufacturing costs of EVs and ICEVs, as estimated by prior research, vehicle tear-downs, and other automotive models. This allows the calculation of total lifetime emissions for a given vehicle based on the sum of its lifetime emissions and manufacturing costs, shown in **Equation 2** below:

$$Lifetime\ Emissions = Manufacturing\ Emissions + (Lifetime\ Mileage \times \frac{Emissions}{Mile}), \quad \textbf{(2)}$$

To determine the net lifetime savings of replacing an ICEV purchase with an EV purchase, the lifetime emissions of the EV are subtracted from those of an ICEV driven the same annual VMT as shown in **Equation 3**:

$$Lifetime\ GHG\ Emissions\ Savings = Lifetime\ Emissions_{ICEV} - Lifetime\ Emissions_{EV}, \quad \textbf{(3)}$$

Criteria pollutants are quantified in terms of annual emissions as their social harm is related to their concentration at a specific place and point in time in contrast to greenhouse gas emissions where the total stock of GHGs in the earth's atmosphere determines the amount of global warming. To determine the annual emission rate each vehicle's total emissions are divided by its expected lifespan calculated from its annual VMT and expected lifetime mileage. This is shown in **Equation 4** below:

$$Annual\ Pollutant\ Emissions = Lifetime\ Emissions \times \frac{Annual\ VMT}{Lifetime\ Mileage}, \qquad (4)$$

Policy Review

We evaluated the US Department of Energy's Alternative Fuels Data Center list of laws and incentives for California as of June 2021 to determine if any of the existing 156 programs included targets for high-mileage vehicles (*2*). We scored public and private utility EV and EVSE subsidy programs as to whether the program served four groups: households; private business; private non-profits; and local governments, school districts, tribes, and public transit agencies. We also evaluated whether the program had elements that favored or increased incentives for: low-income households, disadvantaged and low-income communities, school children, and high-mileage vehicles.

RESULTS

Annual Mileage and Emissions Characteristics of Household Vehicle Fleet

Analysis of the NHTS vehicle data revealed a right-skewed distribution of annual VMT and an approximately normal distribution of emissions per mile (**Figures 1-2**). In terms of annual VMT, 80 percent of vehicles are driven less than 16,000 miles per year with outliers up to 200,000 miles per year. With respect to emissions per mile, most vehicles emit between 300 and 600 grams of CO_2 per mile. In each figure, the red line indicates the top quintile of the distribution, above which an ICEV replaced with an EV would create the largest reduction in immediate and lifetime emissions.

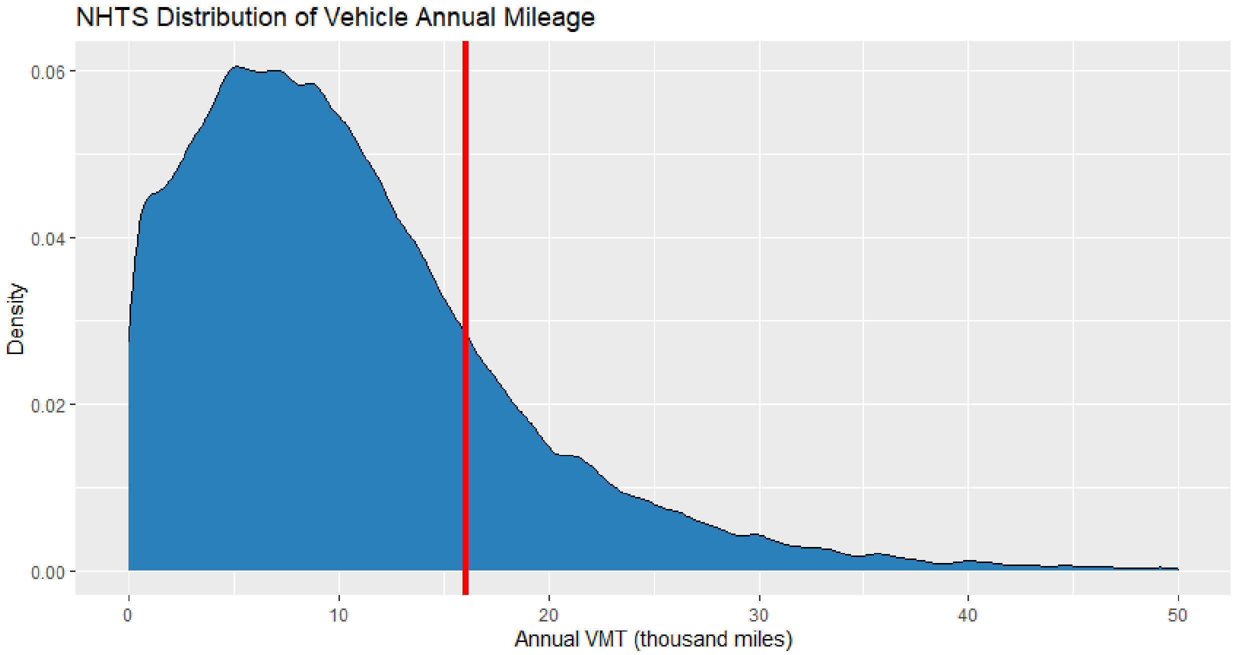


Figure 1 Weighted distribution of vehicle annual VMT according to the NHTS (Mean=11,131, SD=11,196). The red line indicates the start of the uppermost quintile, where electrification will achieve the largest emissions reductions. Upper bound for annual VMT is 200,000 miles per year.

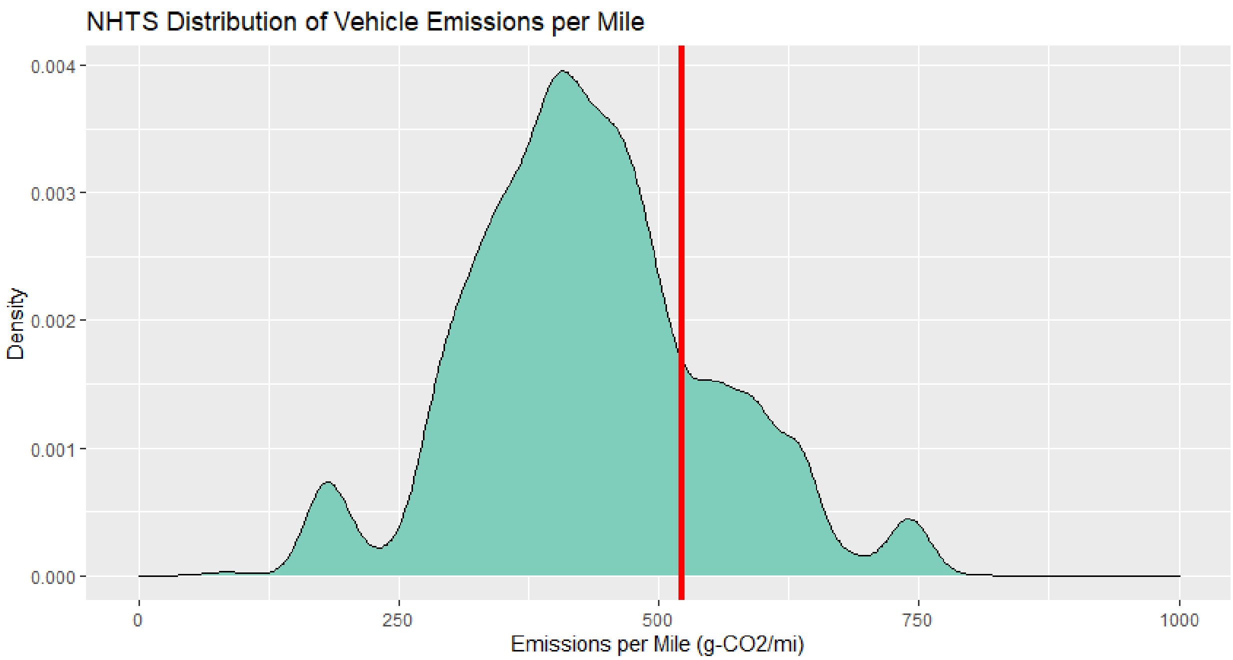


Figure 2 Weighted distribution of vehicle emissions per mile according to the NHTS (Mean=433, SD=120). The red line indicates the start of the uppermost quintile, where electrification will achieve the highest returns. Upper bound for emissions per mile is 1,400 g-CO_2 per mile.

The joint distribution of annual VMT and emissions per mile in the NHTS data is shown in **Figure 3**. In general, most of the fleet tends to fall in the center of the emissions per mile range, spread across 0-20,000 miles per year. One noteworthy component of this distribution is the spike of vehicles belonging to the lower left portion of the distribution, where emissions per mile is good, and annual VMT is extremely low. Although EVs are highly concentrated in this section of the market, it is difficult to say whether they are driven less than the highly efficient ICEVs that are also found in this part of the distribution.

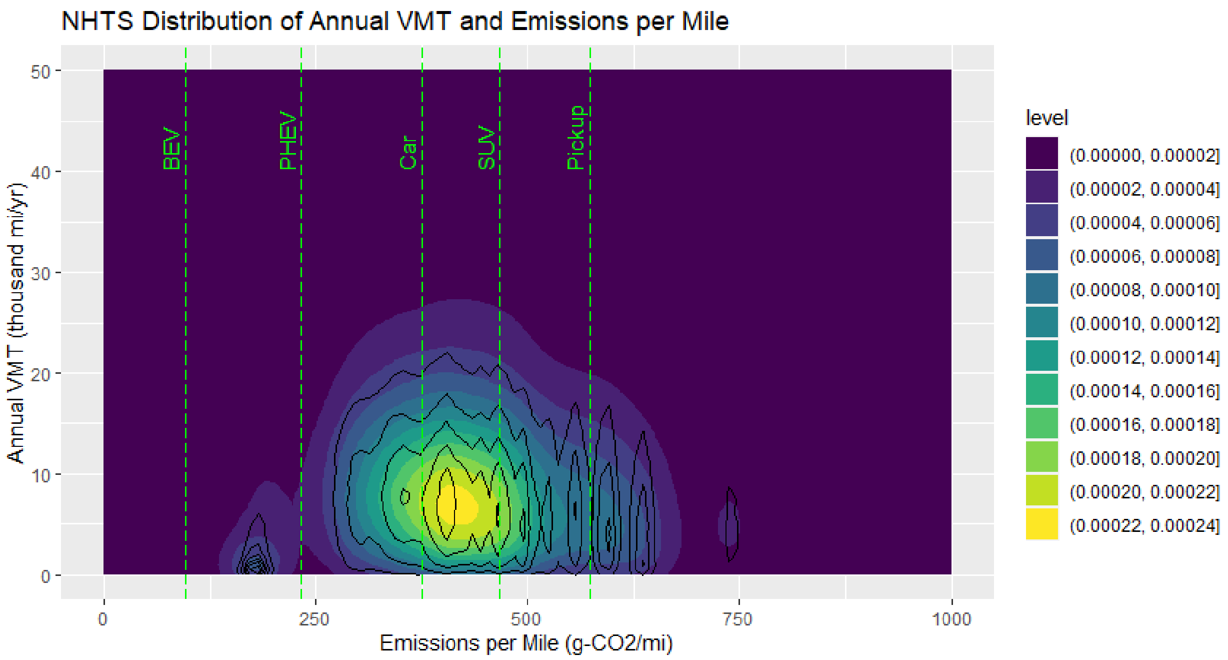
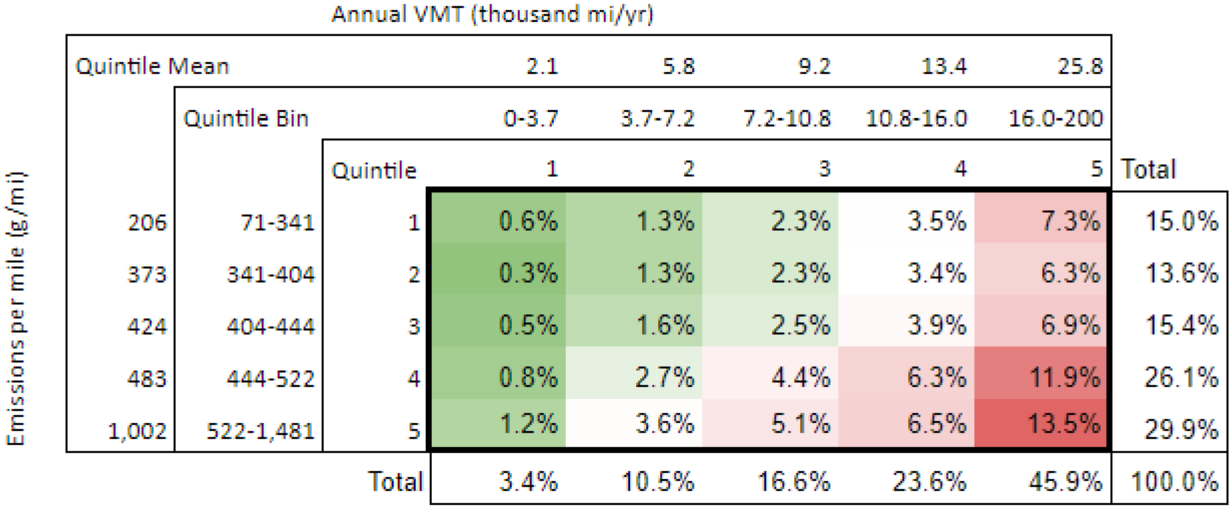


Figure 3 Density distribution of all vehicles in NHTS across annual VMT and emissions per mile with average emissions per mile shown for different classes of vehicles. EVs make up a very small portion of the dataset (~2 percent).

In contrast to this subset of efficient, low-mileage vehicles, the fleet also contains highly inefficient vehicles which are driven at high annual VMT. **Table 1** summarizes how the total annual GHG emissions of the fleet are distributed across market segments of annual VMT and emissions per mile. The 4 percent of the fleet in the cell in the lower right corner with the highest emissions per mile and highest annual VMT, generate nearly 14 percent of annual emissions. The top 20 percent of the fleet by annual VMT generate 45.9 percent of the emissions whereas the twenty percent of vehicles with the highest emissions per mile generate 29.9 percent of the emissions. The large share of emissions generated by high mileage vehicles means a program that targets the fifth quintile in annual VMT could deliver 50 percent more emissions reductions than a program that targets the fifth quintile in emissions per mile.

TABLE 1 Share of Annual GHG Emissions by 2017 Household Fleet Segment



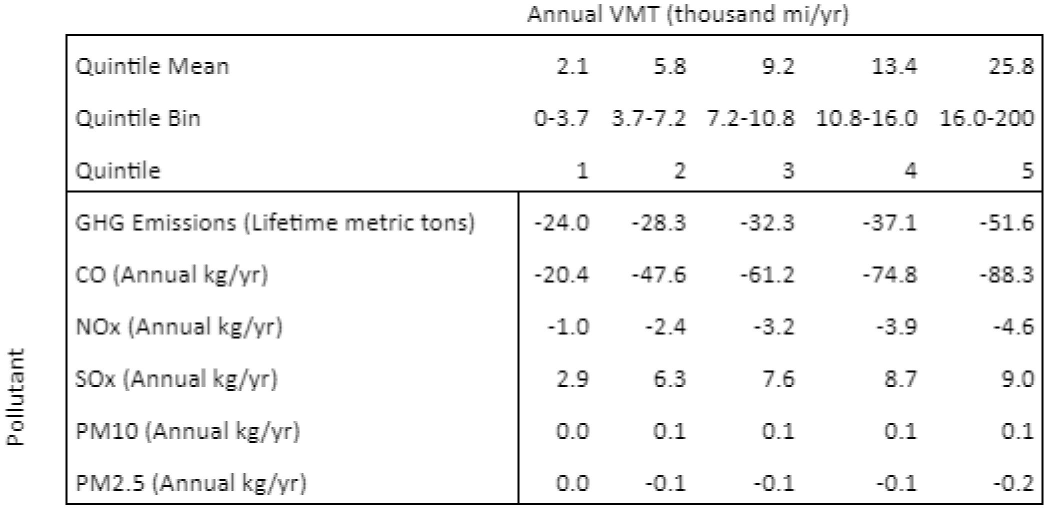
Annual VMT (thousand mi/yr)

	Quintile Mean			2.1	5.8	9.2	13.4	25.8	
		Quintile Bin		0-3.7	3.7-7.2	7.2-10.8	10.8-16.0	16.0-200	
			Quintile	1	2	3	4	5	Total
Emissions per mile (g/mi)	206	71-341	1	0.6%	1.3%	2.3%	3.5%	7.3%	15.0%
	373	341-404	2	0.3%	1.3%	2.3%	3.4%	6.3%	13.6%
	424	404-444	3	0.5%	1.6%	2.5%	3.9%	6.9%	15.4%
	483	444-522	4	0.8%	2.7%	4.4%	6.3%	11.9%	26.1%
	1,002	522-1,481	5	1.2%	3.6%	5.1%	6.5%	13.5%	29.9%
			Total	3.4%	10.5%	16.6%	23.6%	45.9%	100.0%

Greenhouse Gas Emissions Model

To determine the effects of replacing a given ICEV with an EV across the spectrum of annual VMT, we used the assumption that higher annual VMT results in higher lifetime mileage as described in **Equation 1**. Under this assumption, EVs with a higher annual VMT accumulate more emissions savings and higher returns on their initial manufacturing emissions investment. **Table 2** summarizes the results of this analysis on a per-vehicle basis. Each value provides the reduction from replacing a single ICEV with an EV, as calculated according to **Equations 2-4**. Results show that replacing an ICEV purchase with an EV creates a net decrease in lifetime GHG, annual CO, NOx, and PM2.5. It also creates an annual increase in SOx and PM10. In all cases, the magnitude of the effect is increased by replacing a vehicle with a higher annual VMT.

TABLE 2 Per-Vehicle Reduction in Emissions from Replacing an ICEV with an EV



Annual VMT (thousand mi/yr)

	Quintile Mean	2.1	5.8	9.2	13.4	25.8
	Quintile Bin	0-3.7	3.7-7.2	7.2-10.8	10.8-16.0	16.0-200
	Quintile	1	2	3	4	5
Pollutant	GHG Emissions (Lifetime metric tons)	-24.0	-28.3	-32.3	-37.1	-51.6
	CO (Annual kg/yr)	-20.4	-47.6	-61.2	-74.8	-88.3
	NOx (Annual kg/yr)	-1.0	-2.4	-3.2	-3.9	-4.6
	SOx (Annual kg/yr)	2.9	6.3	7.6	8.7	9.0
	PM10 (Annual kg/yr)	0.0	0.1	0.1	0.1	0.1
	PM2.5 (Annual kg/yr)	0.0	-0.1	-0.1	-0.1	-0.2

We tested the sensitivity of these results to changing the assumptions about how annual miles affect lifetime miles in **Figure 4**. As the effect of annual VMT on lifetime mileage decreases, the net emissions benefits of electrifying a high annual mileage vehicle drop to zero. In the limiting case, where the effect of annual mileage is not present and each EV has a fixed number of lifetime miles, we see no difference in lifetime GHG reductions between electrifying high annual mileage or low annual mileage vehicles.

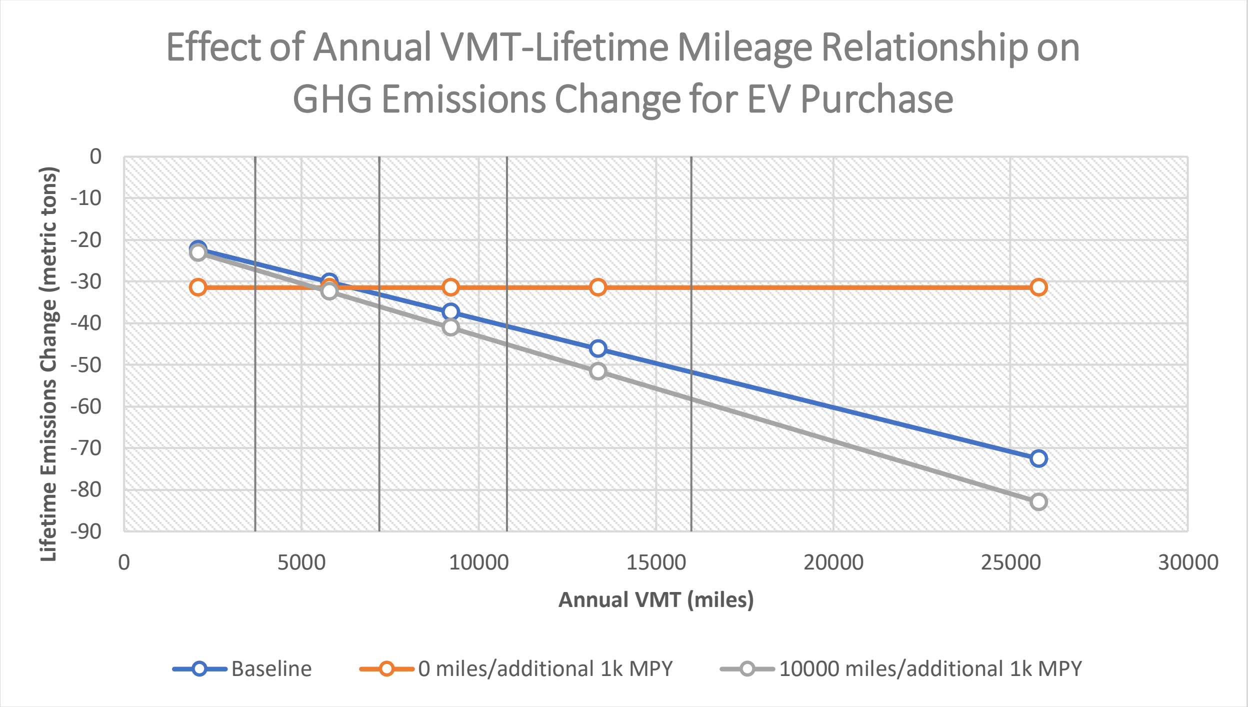


Figure 4 The effect of annual VMT on vehicle lifetime is represented as a coefficient determining the additional amount of miles added to a vehicle's lifetime mileage per 1,000 miles of additional annual VMT. This figure shows the effects of varying this coefficient relative to our baseline assumption.

Criteria Pollutants Emissions Model

Annual emissions across a vehicle's lifetime were calculated using **Equation 4** and the GREET data, and findings are summarized for the replacement of an ICEV with an EV in **Figure 5** below. Emissions of certain criteria pollutants (CO, NOx, PM2.5) are reduced through the replacement of ICEVs with EVs, while others (SOx, PM10) are increased. This is shown through the downward trend of the line for SOx emissions savings; as a vehicle with higher annual VMT is replaced, the net reduction increases in magnitude. Each pollutant is shown according to its potential annual emissions reduction across each annual VMT bin, to show how replacing an ICEV with an EV might vary depending on the annual VMT of the vehicle. Given that the benefits of criteria pollutant reduction scale directly with daily/annual VMT, reductions in these pollutants among high annual VMT vehicles would have an immediate effect on the well-being of society, as opposed to the GHG emissions benefits, which accumulate over the lifetime of the vehicle.

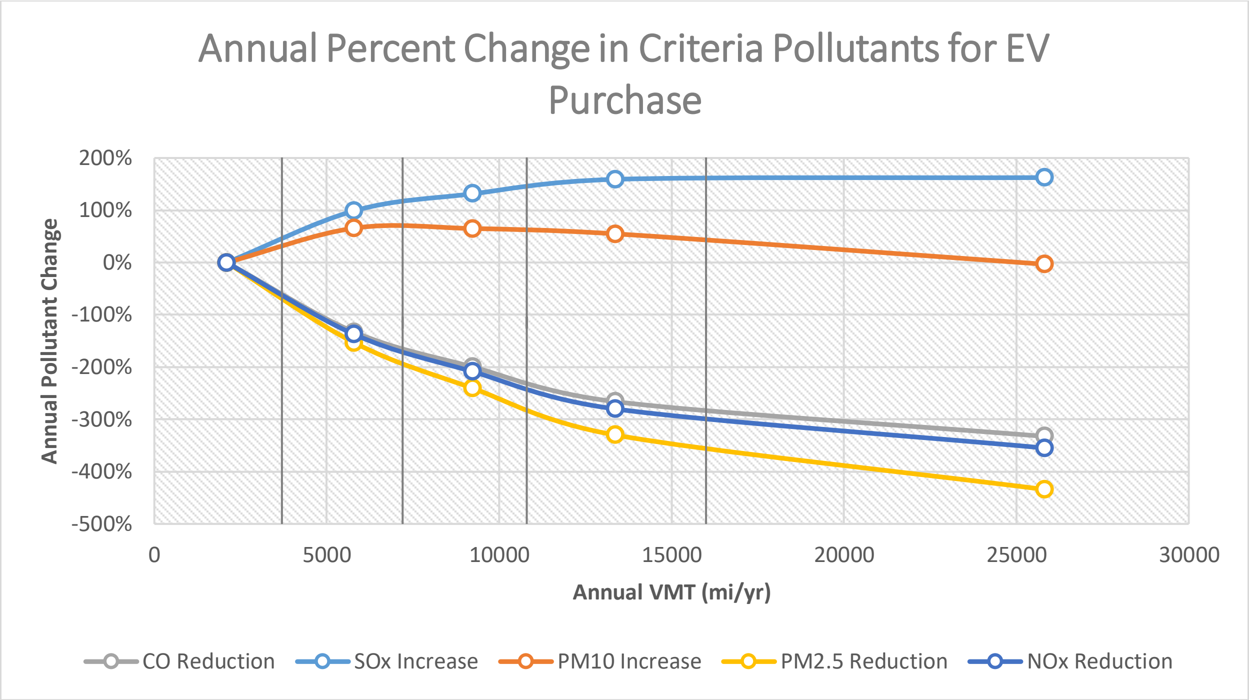


Figure 5 Criteria pollutant percent reductions for a single EV purchase relative to ICEV by annual VMT.

The net effect of replacing an ICEV with an EV is a reduction in three out of five criteria pollutants. This is true regardless of the annual VMT of the vehicle, but the annual emissions consistently decrease with the annual VMT of the vehicle being replaced. In the case of SOx and PM10 emissions, an increase in annual emissions is observed when replacing an ICEV with an EV due to emissions during lithium-ion battery production and electricity generation (*24*,*25*). This leads to increasingly higher annual emissions of SOx over the lifetime of the vehicle when a higher annual VMT vehicle is replaced. Depending on the relative damage per ton of each pollutant, this could create a net benefit to society. Should all pollutants create similar damages, the magnitude of the reductions in CO, PM2.5, and NOx will far outweigh the increases in SOx and PM10.

Policy Review

We used the US DOE Alternative Fuels Database for the state of California to identify 81 programs that subsize EVs and EVSE. These programs are operated by state agencies, counties, cities, air quality districts and electric utilities. They include EV and EVSE subsidies, access to HOV lanes, lower electric rates, low-cost financing, and sales tax exemptions. As shown in **Table 3**, none of the programs target high-mileage vehicles.

TABLE 3 Attributes of EV and EVSE Incentive Programs in California

Program targets or favors	Number of programs
Replacing high-mileage ICE vehicles	0
Disadvantaged & low-income communities	20
Low-income households	28
Residential households	35
Local government, transit, schools, & tribes	46
Commercial businesses	48

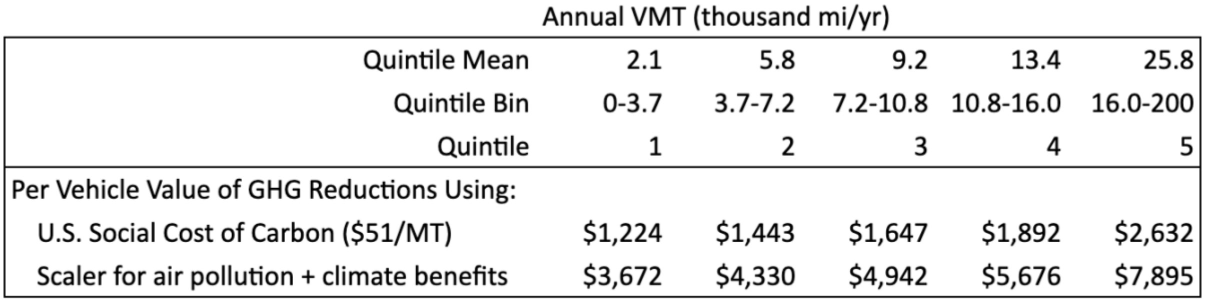
While 28 programs target low-income households and 20 target disadvantaged and low-income communities, we did not evaluate whether those intended groups actually made use of the subsidies. Indeed, recent studies suggest that programs targeting subsidies for vehicle electrification in disadvantaged census tracts have mostly gone to their higher income residents (*12*).

DISCUSSION

Current federal and state EV policy in California offer subsidies for vehicles and electric supply equipment without regard to the vehicle's prospective annual VMT. To increase the return on dollars spent per EV subsidy as measured in emissions reductions, federal or state policy could target the share of the market with high annual VMT. In **Figures 1-2**, this would be the segment of the vehicle fleet falling to the right of the red lines, making up the highest quintile of polluters. This portion of the population is found in the right side of the results in **Table 1**. Davis showed that a large portion of EVs in 2017 landed squarely among vehicles in the lowest portion of annual VMT distribution (*9*). Given the potential near-term benefits to human health of reducing CO and NOx as well as the potential long-term benefits of reducing the planet's stock of greenhouse gases, policymakers should consider new subsidy program designs that target high-mileage vehicles.

In 2021, the U.S government updated its central estimate of the social cost of carbon in 2020 to \$51 per ton of CO_2 with a discount rate of 3 percent (*26*). Applying this estimate to the GHG reductions in **Table 2**, shows the dollar value of the reduction in emissions from replacing an ICEV with an EV. In 2016, Silva et al. analyzed changes in mortality between a baseline forecast and a "clean transportation" forecast for 2030 for the U.S. from both the reduction in GHGs and criteria pollutants. Considering both the global warming and air pollution effects, their analysis yielded a central estimate of benefits at a 3% discount rate that was approximately three times the U.S. social cost of carbon (*27*). In **Table 4** we apply this scaler from Silva et al. as a rough estimate of the benefit of the emissions reductions with the understanding that magnitude of the benefits from reducing criteria pollutants vary with an area's population density, proximity to roadways, meteorological conditions, and other environmental factors (*28*).

TABLE 4 Per-Vehicle Value of Reduction in Emissions from Replacing an ICEV with an EV



	Annual VMT (thousand mi/yr)				
Quintile Mean	2.1	5.8	9.2	13.4	25.8
Quintile Bin	0-3.7	3.7-7.2	7.2-10.8	10.8-16.0	16.0-200
Quintile	1	2	3	4	5
Per Vehicle Value of GHG Reductions Using:					
U.S. Social Cost of Carbon ($51/MT)	$1,224	$1,443	$1,647	$1,892	$2,632
Scaler for air pollution + climate benefits	$3,672	$4,330	$4,942	$5,676	$7,895

Using this estimate of climate and air pollution benefits, the value to society of converting ICEVs in the top quintile of annual mileage approximately equals the federal EV subsidy of $7,500. This number does not include the potential benefits of EV subsidies accelerating learning by doing and driving innovation in the EV supply chain for lower costs and better performance. These results point towards some ways to improve EV subsidy program design:

- Target programs to buyers who would have purchased an ICEV but for the EV subsidy.
- Increase EV subsidies for vehicles with high annual VMT.
- Consider regional variation in EV subsidies to account for local air quality conditions and population densities.

One way to structure a subsidy program to target vehicles with high utilization would be for federal or state government to partner with companies that offer financing for EV purchases. So long as the vehicle was in high use, say more than 16,000 miles per year, subsidy dollars would go to reduce the monthly payment on the vehicle loan. Should the vehicle move out of the top quintile for VMT, then the subsidy could be reduced. A program built around EV financing could also target low- and moderate-income households since credit applications for vehicle financing would include information on income.

Although creating a financial incentive to maintain high mileage could encourage more driving, the policy's very purpose would be to encourage high utilization of zero emission vehicles rather than have them sit idle and deliver less mobility relative to their lifetime emissions. The magnitude of any incentive to increase driving will depend on program design and may be small given the low price elasticity of demand for auto travel (*29*).

Policymakers may also choose to target subsidies towards vehicle purchases in the highest pollutants per mile market segment. One challenge in program design is how best to validate that the buyer would have purchased a high emissions vehicle absent the incentive. In certain settings like commercial or public fleets, policymakers may develop high confidence that a new subsidy design could motivate a shift from ICEV to EV. For example, a program could target commercial fleets that operate pickup trucks with V8 engines. Our purpose here is not to flesh out comprehensive program designs but rather to show that more efficient and equitable EV subsidy programs are possible and deserve further consideration by researchers, policy analysts, and policymakers.

Our analysis shows a compelling case for targeting high-mileage vehicles to reduce the emissions of carbon monoxide and nitrogen oxides. Replacing vehicles in the top quintile of VMT with EVs will deliver four times the reduction in these emissions as replacing vehicles in the lowest quintile of VMT. The reported increases in sulfur oxides and larger particulates from the GREET model associated with electrification would be lower in those parts of the country with a cleaner electric grid, and should diminish over time as electricity production increasingly shifts away from coal and natural gas toward renewables and other low-carbon electricity sources.

While our base case shows that replacing ICEVs in the top quintile for VMT would deliver twice the lifetime GHG savings as replacing ICEVs from the bottom quintile, uncertainty remains about how average annual VMT affects lifetime mileage, and therefore the lifetime GHG emissions of an electric vehicle. The controlling factors behind vehicle scrappage may differ between ICEVs and EVs. In the case of an ICEV, the lifespan of the drivetrain may be the largest contributor, in which case stop-and-go conditions, or frequent cold starts may contribute to a decrease in lifespan. In the case of an EV, the battery lifespan may be the largest contributor, in which case the average depth of discharge, or ambient operating temperature may decrease lifespan of the vehicle (*18,30*). Each of these factors may correlate with a different driving environment (e.g. short city miles with frequent stops, readily accessible charging, vs. long highway commutes at high speeds with overnight recharging). Given the nascent state of electric vehicle production and the rapid improvement in batteries and other vehicle technologies, it will take time and more research before we can reach firm conclusions about how driver behavior and vehicle use will affect the lifetime mileage of EVs. A better understanding of the relationship between annual VMT and lifetime mileage for EVs will provide more confidence about the magnitude of greenhouse gas reductions from electrifying high annual mileage vehicles.

CONCLUSIONS

Our analysis of the NHTS vehicle and driving data, and application of the GREET model to different segments of the U.S. household vehicle fleet, indicate that federal and state policymakers could improve the equity and efficiency of EV subsidy programs by reforming them to target low- and moderate-income households that drive vehicles over 16,000 miles per year. Such a policy could increase the per vehicle reductions in annual carbon monoxide and oxides of nitrogen emissions by a factor of four. There is more uncertainty about the magnitude of GHG savings from such a policy, but plausible theories on the relationship between annual miles and lifetime mileage show a potential doubling in GHG emissions reductions by shifting EV conversions from the lowest annual VMT quintile to the highest.

ACKNOWLEDGMENTS

This research was supported by a grant from Uber to the University of Washington

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: Zack Aemmer: literature review, NHTS data and GREET model analysis, manuscript drafting and editing; Daniel Malarkey: literature review, California EV policy review, manuscript drafting and editing; Don MacKenzie: study conception and design, manuscript editing. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

1. Organization WH. Health Effects of Transport-related Air Pollution. WHO Regional Office Europe; 2005. 205 p.

2. Alternative Fuels Data Center: California Laws and Incentives [Internet]. [cited 2021 Jul 14]. Available from: https://afdc.energy.gov/laws/state_summary?state=CA

3. Federal Tax Credits for Electric and Plug-in Hybrid Cars [Internet]. [cited 2021 Jul 7]. Available from: https://www.fueleconomy.gov/feg/taxevb.shtml

4. JCX-55-19 | Joint Committee on Taxation [Internet]. [cited 2021 Jul 14]. Available from: https://www.jct.gov/publications/2019/jcx-55-19/

5. 2021_cci_annual_report.pdf [Internet]. [cited 2021 Jul 14]. Available from: https://ww2.arb.ca.gov/sites/default/files/classic//cc/capandtrade/auctionproceeds/2021_cci_annual_report.pdf

6. Borenstein S, Davis LW. The Distributional Effects of US Clean Energy Tax Credits. Tax Policy and the Economy. 2016 Jan 1;30(1):191–234.

7. Xing J, Leard B, Li S. What does an electric vehicle replace? Journal of Environmental Economics and Management. 2021 May 1;107:102432.

8. Burlig F, Bushnell J, Rapson D, Wolfram CD. Low Energy: Estimating Electric Vehicle Electricity Use [Internet]. Rochester, NY: Social Science Research Network; 2021 Feb [cited 2021 Jul 14]. Report No.: ID 3781971. Available from: https://papers.ssrn.com/abstract=3781971

9. Davis LW. How much are electric vehicles driven? Applied Economics Letters. 2019 Oct 15;26(18):1497–502.

10. No, electric vehicles aren't driven less than gas cars [Internet]. ITS. [cited 2021 Jul 14]. Available from: https://its.ucdavis.edu/blog-post/no-electric-vehicles-arent-driven-less-than-gas-cars/

11. Gerarden TD. Demanding Innovation: The Impact of Consumer Subsidies on Solar Panel Production Costs. Cambridge, MA: Harvard Environmental Economics Program; 2018. p. 1–62.

12. Canepa K, Hardman S, Tal G. An early look at plug-in electric vehicle adoption in disadvantaged communities in California. Transport Policy. 2019 Jun 1;78:19–30.

13. 2017BESTMILE_Documentation.pdf [Internet]. [cited 2021 Jul 27]. Available from: https://nhts.ornl.gov/assets/2017BESTMILE_Documentation.pdf

14. Davis S (ORCID:0000000188604535), Boundy RG. Transportation Energy Data Book: Edition 39 [Internet]. Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States); 2021 Feb [cited 2021 Jul 31]. Report No.: ORNL/TM-2020/1770. Available from: https://www.osti.gov/biblio/1767864/

15. Rajagopal D, Phadke A. Prioritizing electric miles over electric vehicles will deliver greater benefits at lower cost. Environ Res Lett. 2019 Sep 6;14(9):091001.

16. Slowik P, Pavlenko N, Lutsey N. Emerging Policy Approaches to Electrify Ride-Hailing in the United States. 2019 Jan [cited 2021 Jun 16]; Available from: https://trid.trb.org/view/1584765

17. Jenn A. Emissions benefits of electric vehicles in Uber and Lyft ride-hailing services. Nat Energy. 2020 Jul;5(7):520–5.

18. Neubauer J, Brooker A, Wood E. Sensitivity of battery electric vehicle economics to drive patterns, vehicle range, and charge strategies. Journal of Power Sources. 2012 Jul 1;209:269–77.

19. Weymar E, Finkbeiner M. Statistical analysis of empirical lifetime mileage data for automotive LCA. Int J Life Cycle Assess. 2016 Feb 1;21(2):215–23.

20. Plötz P, Funke SÁ, Jochem P. The impact of daily and annual driving on fuel economy and CO2 emissions of plug-in hybrid electric vehicles. Transportation Research Part A: Policy and Practice. 2018 Dec 1;118:331–40.

21. Karabasoglu O, Michalek J. Influence of driving patterns on life cycle cost and emissions of hybrid and plug-in electric vehicle powertrains. Energy Policy. 2013 Sep 1;60:445–61.

22. Vehicle Survivability and Travel Mileage Schedules [Internet]. [cited 2021 May 27]. Available from: https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/809952

23. Argonne GREET Model [Internet]. [cited 2021 Jul 9]. Available from: https://greet.es.anl.gov/

24. B. Dunn J, Gaines L, C. Kelly J, James C, G. Gallagher K. The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling’s role in its reduction. Energy & Environmental Science. 2015;8(1):158–68.

25. Mitropoulos LK, Prevedouros PD, Kopelias P. Total cost of ownership and externalities of conventional, hybrid and electric vehicle. Transportation Research Procedia. 2017 Jan 1;24:267–74.

26. Technical Support Document: Social Cost of Carbon, Methane,. :48.

27. Silva RA, West JJ, Lamarque J-F, Shindell DT, Collins WJ, Faluvegi G, et al. FUTURE GLOBAL MORTALITY FROM CHANGES IN AIR POLLUTION ATTRIBUTABLE TO CLIMATE CHANGE. Nat Clim Chang. 2017 Sep;7(9):647–51.

28. Fujita EM, Campbell DE, Arnott WP, Johnson T, Ollison W. Concentrations of mobile source air pollutants in urban microenvironments. Journal of the Air & Waste Management Association. 2014 Jul 3;64(7):743–58.

29. Office of Highway Policy Information - Policy | Federal Highway Administration [Internet]. [cited 2021 Jul 28]. Available from: https://www.fhwa.dot.gov/policyinformation/

30. Helmers E, Weiss M. Advances and critical aspects in the life-cycle assessment of battery electric cars. EECT. 2017 Feb 1;5:1–18.