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Targeted electric vehicle procurement incentives facilitate efficient abatement cost outcomes

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ABSTRACT

Electric vehicles (EVs) are one solution to creating a transportation system that is more energy efficient, fosters greater energy security, and is less polluting. Existing public policy reflects this sentiment. Over the last two decades, various government-sponsored policies have been adopted to stimulate EV sales. The most notable – and ubiquitous – of these are procurement incentives. However, the effectiveness of this policy as a pathway to emissions reductions depends on the cost-to-emissions advantage EVs offer over gasoline powered vehicles. Under what conditions is this advantage realized? Using publicly available data, we estimate the precursors – with foci on aggregate mileage and battery longevity - required for EVs to achieve an array of abatement cost thresholds. Our findings are fourfold. First, we illustrate that increased aggregate vehicle utilization – ceteris paribus – decreases implied abatement cost. Second, we find that, after accounting for battery replacements, requisite aggregate utilization for EV-incentive policies to achieve cost parity with alternatives can greatly exceed existing ownership trends, depending on the targeted abatement cost and vehicle ownership period. Third, we document that – owing to their sole emphasis on EV procurement rather than utilization – existing policy fails to accommodate these preconditions. Fourth, we demonstrate that electrical grid decarbonization may be insufficient to produce efficient abatement cost outcomes for EVs. Addressing these inefficiencies necessitates – we conclude – adopting procurement incentivize programs that reward utilization rather than acquisition alone. Doing so would also address longstanding distributional concerns surrounding such programs.

1. Introduction

Although private vehicle ownership facilitates improvements in economic mobility, negative externalities persist. Cars, vans, and sport utility vehicles produce – owing to their reliance on fossil fuel – nearly half of all transportation-related greenhouse gas emissions, making them significant contributors to climate change (United States Environmental Protection Agency, 2018; Axsen et al., 2020; Hoek et al., 2002).

Electric vehicles (EVs) promise relief. These vehicles present numerous advantages over their fossil fuel-powered counterparts, the most notable being improved fuel economy, reduced reliance on fossil fuel, and zero tailpipe emissions (Muratori et al., 2021). However widespread adoption of EVs is challenged, in part, by higher average up-front procurement costs. In 2020, the average starting price of an EV was $61,889, compared to $38,000 for fossil fuel powered vehicles (Hardman, 2021; Burnham et al., 2021). Many governments have responded to this challenge by offering EV procurement incentives. For example, the United States government provides tax credits – up to $7500 per vehicle – for qualified EV purchases (IRC 30d New Qualified, 2022). Similar programs are available in France, Germany, and Norway. Such programs aim to incentivize fleet turnover as a pathway towards reduced fossil fuel dependence and carbon emissions reduction.

How effective are these programs? EV procurement incentives offer the prospect of reduced carbon emissions via increased EV adoption. Such incentives may also represent an investment in future vehicle fleet electrification, fostering near-term EV demand that subsequently drives future economies of scale and technological advancements that improve EVs' long-run environmental prospects. However, the universal and long-term provision of these incentives is challenged by public

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resistance towards federal subsidies (Volcovici, 2019), limited capital, and projected growth of public debt (The, 2021; Nunes et al., 2022). This is also reflected in existing government policy which limits the magnitude of subsidy availability via budgetary caps (Plug-in Electric, 2021). Evidence also suggests that promoting future innovation is most efficiently achieved via supply-side – rather than demand-side – incentives (see Limitations for further discussion).

Given that good governance necessitates judicious disbursement of public funds, where EV procurement incentive policies are concerned, this entails not only that emission reductions be realized owing to such policies but also that emissions reductions be maximized per dollar spent. Our study – centered in a key auto market, the United States – examines this issue. First, we identify the preconditions necessary for EV subsidies to achieve economic efficiency. Second, we quantify the requisite magnitude of these subsidies. And third, we situate our findings within the context of outcomes produced by existing EV procurement incentive policy. Our efforts are judicious given the need to achieve meaningful reductions in carbon emissions using pathways that – given political and fiscal constraints – do not further exacerbate deficit spending concerns (Stocking et al., 2012).

1.1. Economic efficiency

Realizing economic efficiency requires equating the emissions reduction per dollar spent from incentivizing EV procurement with those of alternative CO_2 emissions-abating policy options (i.e., government policies that aim to mitigate CO_2 emissions, ranging from vehicle procurement incentives to subsidized wind and solar electrical generation) (Gillingham & Stock, 2018). We emphasize this definition over one that strictly compares the total level of policies' emissions reductions under the assumption that policymakers – as evidenced by their actions - desire reducing the largest amount of carbon emissions in the short run. Owing to finite capital constraints, achieving this goal demands prioritizing policies that offer the cheapest emissions reductions per dollar spent.

Per-dollar emissions expenditure depends in large measure on two factors: first, the emissions benefit (estimated via cradle-to-grave lifecycle emissions analyses) realized by replacing existing vehicles, namely internal combustion engine vehicles (ICEVs) with EVs; and second, the cost differential between EVs and ICEVs. Greater emissions benefits – ceteris paribus – suggest more emissions are reduced for the same cost, thereby raising emissions reduced per dollar spent. Conversely, larger cost differences suggest more financial resources are needed to induce the same volume of emissions reduction, thereby lowering emissions reductions per dollar spent.

Given that EVs impose higher manufacturing emissions and upfront costs but lower fuel use emissions and operating costs (MIT Energy Initiative, 2019; Lutsey & Nicholas, 2019), a key determinant of these differences is aggregate vehicle utilization. Existing work suggests EVs may offer an emissions advantage over ICEVs after approximately 13, 500 miles (The Greenhouse Gases, 2020) and become relatively cheaper to own after travelling approximately 65,000 miles (Mitropoulos et al., 2017). However, the former estimate fails to standardize across vehicle sizes, and existing literature largely overlooks the need for battery replacements, which levy large effects on both emissions and the total cost of ownership (TCO). Additionally, ambiguity persists over whether utilization parity between EVs and ICEVs is realized, persistence that impacts an EV's ability to deliver emissions and cost benefits over the status quo (Davis, 2019; Burlig et al., 2021; Chakraborty et al., 2022; Jia & Chen, 2022; Hawkins et al., 2013; Dillman et al., 2020; Marmiroli et al., 2018; Heywood et al., 2015).

1.2. Our study

We account for these parameters in our study. Using publicly available data on vehicle costs, resale value, and manufacturing and fuel emissions, as well as newly developed models of battery longevity, we estimate the cost and emissions differences between mid-sized EVs and ICEVs under an array of utilization patterns. We subsequently identify the aggregate utilization thresholds required for EV incentives to achieve abatement cost parity with alternative policy options, leveraging existing economic literature that provides estimated abatement costs for a comprehensive list of policies as benchmarks (Gillingham & Stock, 2018). We further assess whether existing policy levers support these preconditions and explore – as appropriate – how public policy can be reshaped to maximize such support. By emphasizing abatement cost targets (i.e., the "price" of reducing each ton of CO_2 emissions), we demonstrate the requisite preconditions for EV-incentive policies to become economically efficient uses of government capital compared to alternatives. Additionally, we document the impact of future improvements to electricity grids on such preconditions, scrutinizing the possibility that achieving economically efficient emissions reductions may require vehicle utilization patterns that diverge significantly from those seen today (Lu, 2006; Average, 2022; Maps & Data, 2020).

This study is, to our knowledge, one of the first to estimate abatement costs based on TCO differences, rather than the social cost of carbon (Muratori et al., 2021; Hawkins et al., 2013; Archsmith et al., 2015; Palmer et al., 2018; Wu et al., 2015; Qiao et al., 2020). This approach allows for cost-benefit analyses of policies that are aimed to make EVs financially competitive with ICEVs while remaining agnostic about the magnitude of carbon-based externalities (Creti et al., 2015). Considering TCO is also important as significant attention has – thus far – been placed on procurement price parity between EVs and ICEVs. However, consumers consider numerous factors when making vehicle procurement decisions. Although consideration of the totality of these factors is not the focus of our efforts (White & Sintov, 2017; Neumann et al., 2010), existing literature demonstrates that consumers consider total costs over purely upfront costs during purchasing decisions (Saccani et al., 2017). Our work reflects this reality.

Additionally, whereas understanding consumers' heterogenous motivations for EV procurement warrants scrutiny, we analyze whether – from the vantage point of public spending – EVs represent an economically efficient means of reducing CO_2 emissions. To the extent that EVs are designed primarily to reduce emissions (e.g., Walker & Roser, 2015), the realization of this goal depends critically on economic efficiency. If reducing emissions via EV adoption is a costlier approach to combating climate change than other alternatives, policies that incentivize EV procurement implicitly diminish potential emissions reductions. Put differently, to best mitigate future climate change, available capital must be utilized in the most efficient way, as defined – we argue - by the potential emissions reduction realized per dollar spent.

1.3. Novelty

Our study differs from previous efforts in four ways.

First, contrary to many existing efforts, our study leverages both lifecycle emissions analyses and TCO models simultaneously to estimate EV abatement costs, a necessary metric for policymakers to compare the economic efficiency of policy alternatives (Muratori et al., 2021; Nunes et al., 2022; Hawkins et al., 2013; Palmer et al., 2018; Wu et al., 2015; Qiao et al., 2020; Rasbash et al., 2023; Woody et al., 2022). Such a concurrent analysis offers nuanced improvements over previous work. Specifically, previous efforts often separately examine either emissions or TCO profiles of EVs versus ICEVs and leverage inconsistent (and thus, incomparable) vehicle assumptions. In doing so, researchers effectively compare different sets of vehicles' emissions and financial profiles, which may produce unreliable estimates of per-dollar emissions benefits. Moreover, existing work jointly examining emissions and financial profiles excludes upfront vehicle costs (Vega-Perkins et al., 2023), which can contribute the majority of EVs' and ICEVs' per-mile operating costs (Verma et al., 2022).

Our approach leverages models of both simultaneously using assumptions which facilitate an equivalent comparison of emissions benefit relative to cost differential (see Sections 2.1.1 and 2.2.1). By using consistent and comparable vehicle assumptions for both our emissions and TCO analyses, our work can – in contrast to many previous efforts – provide estimates of per-dollar emissions benefits for a representative EV. This allows for a more direct comparison of EV procurement incentives to alternative policy options and represents a distinct focus from our previous efforts which emphasize emissions advantage preconditions absent economic efficiency considerations (Nunes et al., 2022).

Second, unlike previous work, we estimate the requisite annual and aggregate utilization required for EVs to realize efficient abatement cost targets compared to the per-dollar emissions reductions offered by alternative policies. This approach withdraws the need to estimate a travel demand model that accounts for consumer heterogeneity and instead allows for direct comparisons of individual households to requisite utilization thresholds.

Third, our study accounts for requisite battery replacements. Although nascent literature finds that newer EV batteries effectively retain battery capacity through 100,000 miles (Wassiliadis et al., 2022), this omits consideration of calendar aging, a dominant source of capacity fade (De Gennaro et al., 2020). Leveraging capacity fade models based on real-world driving data and case studies (De Gennaro et al., 2020), we estimate battery longevity as a function of annual mileage. Doing so accounts for both vehicle utilization (relevant for cycle aging) and the duration over which utilization occurs (relevant for calendar aging).

Fourth and finally, whereas existing literature often compares EVs to ICEVs of different sizes or driving ranges (e.g., 30), we standardize our vehicle selection for both parameters, thereby facilitating a more accurate comparison across powertrain types (see Supplementary Information, Section I for more details).

Our efforts can inform climate change mitigation and adaptation efforts, particularly in cities. Densely and permanently settled locations are key contributors to climate change, as urban areas produce roughly 78% of carbon emissions that adversely affect over 50% of the world's population living in them (Liang & Gong, 2020; Cities & Climate Change, 2021). EV procurement incentive programs offer a pathway towards reducing these emissions. However, concerns persist over these programs' efficacy. Our results help address this concern by providing evidence-based guidance on the extent to which EV procurement programs represent a cost-effective approach to emissions reductions, compared to a one-size-fits-all approach. Finally, we emphasize this timeliness of our work as global urbanization trends are envisioned to continue, highlighting the need for resourceful carbon emissions reduction pathways (Urban Development, 2022).

2. Research plan

Our study examines the viability of EV-incentive policies as an economically efficient means of reducing emissions. To do so, we first quantify the lifecycle emissions of EVs compared to ICEVs given varying annual and aggregate utilization thresholds and – as appropriate – battery replacement. We subsequently estimate – by manipulating battery replacement - the TCO differences realized between EVs and ICEVs. Finally, we assess the requisite preconditions for EV incentives to achieve abatement cost parity with alternative policy options based on existing cost estimates (Gillingham & Stock, 2018).

Our model leverages – where possible – publicly available data to inform our estimates (see Table 1). Concerns over the precise figures leveraged are addressed by applying sensitivity testing (see Uncertainty Considerations). Details of our approach, data that inform our model and vehicle selection, and references justifying their use are available in the supplementary information section (Supplementary Information, Section I). We center our analysis on the United States, a key auto market in terms of both auto sales volume and global transportation emissions.[1]

To clarify our model's key parameters and terminology, emissions differences refer to CO_2 emissions differentials between ICEVs and EVs, measured on per-mile and total bases (expressed in g CO_2e/mile and tCO_2e/vehicle, respectively); TCO difference refers to the net present-day value differential between ICEVs and EVs (expressed in US dollars), considering ownership duration and aggregate utilization; abatement cost refers to the collective cost of reducing CO_2 emissions-related externalities borne by both the federal government and individual consumers; utilization refers to EV mileage (considered on annualized and aggregate bases); and battery longevity refers to how long an EV battery remains in service (expressed in miles).

2.1. Emissions estimation

To estimate emissions differences between ICEVs and EVs, we focus our analysis on lifecycle emissions. We define EVs as vehicles solely powered by electricity obtained from the power-generating electric grid (estimated to generate 436 gCO_2e/kWh (MIT Energy Initiative, 2019)). Given the ubiquity of existing EV procurement incentives across the nation (though state-level incentives exist), to evaluate the efficacy and efficiency of existing EV incentive programs, we leverage national estimates of the US electric grid's average emissions factor. The emissions profiles of EVs and ICEVs account for vehicle manufacturing, extraction, processing, and transportation, as well as fuel production, usage, and efficiency (Nunes et al., 2022; MIT Energy Initiative, 2019). Emissions from battery replacement – estimated using assumptions about battery architecture and chemistry, recharge strategies, and ambient temperatures (De Gennaro et al., 2020) – are also considered for EVs. Consistent with existing literature and original equipment manufacturer (OEM) recommendations, we assume batteries reach their end of life at 20% capacity loss, as batteries may demonstrate unstable behavior and rapid declines in available capacity beyond this threshold (Schoch et al., 2018; Spotnitz, 2003; Patil et al., 2023). Leveraging historical and current procurement choice data, and in the interests of minimizing emissions confounds, we standardize for vehicle size by choosing mid-sized vehicles with internal volumes between 110 and 120 ft^3 and assume usage of an 85-kWh battery to ensure comparable driving range to similarly-sized ICEVs (Nunes et al., 2022; MIT Energy Initiative, 2019; Bernau, 2021; Lorio et al., 11 Jan., 2022; Electric Vehicles & Fuel Economy, 2020).

Subject to these conditions, we estimate requisite aggregate utilization thresholds for EVs to achieve lifecycle emissions parity with ICEVs under four scenarios. In the first, we consider requisite aggregate utilization thresholds for an EV assuming the counterfactual ICEV travels 180,000 total miles over its lifespan (MIT Energy Initiative, 2019), without accounting for necessary EV battery replacements. Next, we relax our initial assumption and calculate the requisite aggregate utilization threshold given equivalent ICEV/EV aggregate utilization, absent battery replacements. In our third scenario, we estimate requisite aggregate utilization thresholds assuming an ICEV's aggregate utilization is 180,000 miles while allowing for requisite battery replacements. Finally, we relax both assumptions simultaneously and present requisite

[1] Our efforts exclude consideration of the 2022 Inflation Reduction Act's impact on EV procurement owing to ambiguity surrounding the legislation's manufacturing, critical mineral, and component assembly requirements. We emphasize however that passage of the legislation does not impact the primary provision of the $7500 procurement incentive.

Table 1
Emissions and TCO estimation parameters.

	EV	ICEV	Emissions Analysis	TCO Analysis	Sensitivity Range (EV)	Sensitivity Range (ICEV)
Fuel efficiency (MPGe)	114[a]	34[a]	Operating	–	114–125	34–48
Energy content of gasoline (kWh/gal.)	33.7[b]	33.7[b]	Operating	–	–	–
Fuel production emissions (gCO_2e/MJ)	121[b]	19[b]	Operating	–	72.6–121	17–19
Fuel use emissions (gCO_2e/MJ)	0[b]	73[b]	Operating	–	–	65–73
Vehicle manufacturing emissions (metric tons CO_2e)	13.6[c,d,e]	8[c]	Non-operating	–	0–13.6	0–8.0
Replacement battery manufacturing emissions (metric tons CO_2e)	4.25[f]	–	Non-operating	–	0–4.25	–
Vehicle purchase price ($)	36,620[g]	23,645[g]	–	Non-operating	24,818–36,620	21,280–23,645
Sales tax (%)	7.5[h]	7.5[h]	–	Non-operating	6.75–7.5	6.75–7.5
Title fee ($)	35[h]	35[h]	–	Non-operating	–	–
Tax credits ($)	7500[i]	0[i]	–	Non-operating	–	–
Annual taxes & fees ($)	668[j]	668[j]	–	Non-operating	–	–
Annual insurance cost ($)	2400[k]	1650[k]	–	Non-operating	2160–2400	1485–1650
Maintenance & repair costs ($/mile)	0.03[l]	0.06[l]	–	Operating	0.027–0.030	0.054–0.060
Average electricity price ($/kWh)	0.149[m]	–	–	Operating	0.134–0.149	–
Average gasoline price ($/gal.)	–	3.19[m]	–	Operating	–	2.87–3.19
Miles per kilowatt-hour	3.333[n]	–	–	Operating	3.333–3.666	–
Resale value (proportion of previous year's value)	0.95[h]	0.95[h]	–	Non-operating	0–1.0	0–1.0
Annual discount rate	0.07[p]	0.07[p]	–	Non-operating	0.070–0.077	0.070–0.077
Annual utilization (mi./year)	11,300[q]	11,300[q]	Operating	Operating	5300–90,000	5300–90,000
Aggregate utilization (mi./vehicle)	67,800[q]	67,800[q]	Operating	Operating	10,000–565,000	10,000–565,000
Battery lifespan (mi.)	82,750[r]	–	Non-operating	Non-operating	28,000–565,000	–

Note: – denotes "not applicable." Emissions estimates assume mid-size EVs and ICEVs (MIT Energy Initiative, 2019). Our data are from the following sources: fuel efficiency: [a] (MIT Energy Initiative, 2019; Compare Side-by-Side, 2018); energy content of gasoline (per-gallon): [b] (MIT Energy Initiative, 2019; Technology, 2016); emissions from fuel production and usage: [b] (MIT Energy Initiative, 2019); vehicle manufacturing emissions (including emissions from recycling processes): [c] (MIT Energy Initiative, 2019; Nealer et al., 2015), [d] (MIT Energy Initiative, 2019; Heywood et al., 2015), and [e] (MIT Energy Initiative, 2019; Qiao et al., 2017); manufacturing emissions for an 85-kWh replacement battery: [f] (MIT Energy Initiative, 2019; Dunn et al., 2016); [g] (MIT Energy Initiative, 2019; Compare Side-by-Side, 2018; Hummel et al., 2017); sales tax, title fees, and resale value: [h] (Breetz & Salon, 2018); tax credits: [i] (MIT Energy Initiative, 2019; Breetz & Salon, 2018; Federal Tax, 2022); annual taxes and fees: [j] (Cost of Car, 2021); annual insurance costs: [k] (MIT Energy Initiative, 2019; Brennan, 2022); per-mile maintenance and repair costs: [l] (Harto, 2020); average electricity and gasoline prices: [m] (Breetz & Salon, 2018; Average Energy, 2021); miles per kilowatt-hour: [n] (MIT Energy Initiative, 2019); miles per gallon: [o] (MIT Energy Initiative, 2019; Breetz & Salon, 2018); annual discount rate: [p] (Breetz & Salon, 2018; OMB Circular, 2015); annual and aggregate utilization: [q] (Mitropoulos et al., 2017; Vehicles Getting Older, 2016); and battery lifespan: [r] (De Gennaro et al., 2020).

aggregate utilization thresholds given parity in aggregate utilization between EVs and ICEVs while accounting for battery replacements.[2]

2.1.1. Emissions estimation equations

Leveraging existing methodology (Nunes et al., 2022; MIT Energy Initiative, 2019), we first estimate per-mile emissions, accounting for vehicle manufacturing emissions, fuel usage and production emissions, fuel efficiency, aggregate utilization, and energy per gallon of gasoline using Eq. (1.0):

$$E_{PM} = \frac{((e_{vm} * 1,000,000) + \ e_{vd} + e_{mr})}{au} + \left(\frac{1}{FE} * \left(\frac{e_{fp}}{MJ_E} + \ \frac{e_{fu}}{MJ_E}\right) * EC_G\right) \tag{1.0}$$

where E_{PM} = emissions per mile (g CO_2e/mi.); e_{vm} = vehicle manufacturing emissions (metric tons CO_2-equivalent (CO_2e)); e_{vd} = emissions from end-of-life vehicle disposal; e_{mr} = emissions from vehicle maintenance and repair; au = aggregate utilization (miles); FE = vehicle fuel efficiency (miles per gallon-equivalent (MPGe)); $\frac{e_{fp}}{MJ_E}$ = fuel production emissions (g CO_2e per megajoule of energy); $\frac{e_{fu}}{MJ_E}$ = fuel usage emissions (g CO_2e per megajoule of energy); and EC_G = energy content of gasoline (lower heating value) (Nunes et al., 2022; MIT Energy Initiative, 2019). Vehicle maintenance and end-of-life disposal emissions are assumed to approximate zero for ICEVs and EVs owing to their relative insignificance (Klemola, 2016).

After estimating EV and ICEV per-mile emissions, we subsequently calculate total emissions using Eq. (2.0):

$$E_{PV} = \frac{au}{1,000,000} * \ E_{PM} \tag{2.0}$$

where E_{PV} = emissions per vehicle (tons CO_2e); au = aggregate utilization (miles); and E_{PM} = per-mile emissions (g CO_2e/mi.), calculated using Eq. (1.0) (Nunes et al., 2022).

After estimating lifecycle emissions using Eqs. (1.0) and (2.0), we estimate the emissions benefit realized by purchasing an EV as a function of aggregate utilization. Initially, we do not account for battery replacements and assume the counterfactual ICEV travels a total of 180,000 miles (MIT Energy Initiative, 2019). To estimate the requisite aggregate utilization threshold for EVs to achieve equivalent per-mile emissions, we use the following equation:

$$ED = \ PME_{ICEV,c} - PME_{EV,\ t} \tag{3.0}$$

[2] This approach assumes EVs and ICEVs are purchased and operated as primary, rather than secondary, vehicles; a reflection of envisioned improvements in battery capacity and by consequence range, which may produce procurement patterns that differ from those observed today (10).

where ED = EV-versus-ICEV emissions difference (g CO_2e/mi.); $PME_{ICEV,c}$ = ICEV per-mile emissions (g CO_2e/mi.) given *c* miles travelled, calculated using Eq. (1.0), where *c* is held constant at 180,000; and $PME_{EV,t}$ = EV per-mile emissions (g CO_2e/mi.) given *t* miles travelled, calculated using Eq. (1.0). We define our requisite aggregate utilization threshold where ED = 0.

We then redefine Eq. (3.0) to assume aggregate utilization parity between EVs and ICEVs, which produces Eq. (3.1):

$$ED = PME_{ICEV,t} - PME_{EV,\ t} \tag{3.1}$$

where ED = EV-versus-ICEV emissions difference (g CO_2e/mi.); $PME_{ICEV,t}$ = ICEV per-mile emissions (g CO_2e/mi.) given *t* miles travelled, calculated using Eq. (1.0); and $PME_{EV,t}$ = EV per-mile emissions (g CO_2e/mi.) given *t* miles travelled, calculated using Eq. (1.0).

To account for battery replacements, we leverage previous work (De Gennaro et al., 2020) to estimate battery longevity as a function of annual utilization (see Supplementary Information, Section I). Based on our model of battery longevity, we adjust Eq. (1.0) to account for lifecycle emissions from necessary EV battery replacements:

$$E_{PM} = \frac{((e_{vm} * 1,000,000) + \ e_{vd} + e_{mr})}{au} + \left(\frac{1}{FE} * \left(\frac{e_{fp}}{MJ_E} + \ \frac{e_{fu}}{MJ_E}\right) * EC_G\right) + \left(\frac{au}{BatLife\left(\frac{AnnVMT}{12}\right)} - 1 * BatSize * Bat_e * 1,000\right) \tag{1.1}$$

where E_{PM} = emissions per mile (g CO_2e/mi.); e_{vm} = vehicle manufacturing emissions (metric tons CO_2-equivalent (CO_2e)); e_{vd} = emissions from end-of-life vehicle disposal; e_{mr} = emissions from vehicle maintenance and repair; au = aggregate utilization (miles); FE = vehicle fuel efficiency (miles per gallon-equivalent (MPGe)); $\frac{e_{fp}}{MJ_E}$ = fuel production emissions (g CO_2e per megajoule of energy); $\frac{e_{fu}}{MJ_E}$ = fuel usage emissions (g CO_2e per megajoule of energy); EC_G = energy content of gasoline (lower heating value); $BatLife(\frac{AnnVMT}{12})$ = battery lifespan (miles) as a function of annual utilization; BatSize = EV battery size (kWh); and Bat_e = emissions from battery replacement (kg CO_2e/kWh).

Using Eqs. (1.1) and (3.0), we re-estimate EVs' requisite aggregate utilization threshold to achieve per-mile emissions parity with an ICEV travelling 180,000 over its lifetime, accounting for necessary battery replacements. We subsequently reassess the requisite utilization threshold assuming aggregate utilization parity between EVs and ICEVs using Eqs. (1.1), (2.0), and (3.1) to achieve per-mile and total emissions parity.

Finally, to estimate the sensitivity of our emissions results in response to independent changes to each parameter, we show the effect of a 1%, 5%, and 10% change using the following equation:

$$\Delta ED_t = \frac{ED_t(p_1) \ - \ ED_t(p_0)}{ED_t(p_0)} \tag{4.0}$$

where ΔED_t =% change in emissions difference with *t* miles travelled; $ED_t(p_0)$ = total emissions difference given the initial value of parameter *p*, calculated using Eqs. (1.1), (2.0), and (3.1); and $ED_t(p_1)$ = total emissions difference given the adjusted value of parameter *p*, calculated using Eqs. (1.1), (2.0), and (3.1).

2.2. Financial estimation

Expenditures considered when estimating TCO include vehicle purchase price (MSRP), sales tax, title fees, annual taxes and fees, maintenance, repair, and insurance costs, average fuel price, fuel efficiency, discount rates, and resale value (MIT Energy Initiative, 2019; Propfe et al., 2012; Breetz & Salon, 2018). For EVs specifically, we also take account of potential battery replacement costs. ICEV and EV financial profiles also consider an array of aggregate and annual utilization rates and ownership durations. Given existing uncertainties over whether EVs achieve similar mileage to equivalent ICEVs (Davis, 2019; Burlig et al., 2021), aggregate and annual utilization warrant attention. Similarly, ownership duration accounts for the period over which a vehicle is used—an important consideration given that resale value and, for EVs, battery longevity are both partial functions of time (Breetz & Salon, 2018; Stroe & Schaltz, 2018; Kleiner & Friedrich, 2017).

To begin, we present TCO differences between EVs and ICEVs given equivalent annual utilization, assuming utilization patterns representative of average ICEVs (Mitropoulos et al., 2017) for an array of ownership periods, with and without requisite battery replacements. Then, we assess how potential changes to financial parameters may impact EVs' ability to achieve TCO parity with ICEVs assuming average, equivalent annual utilization rates. We subsequently describe how increased annual utilization rates can facilitate potential reductions in EVs' TCO differential. Given that high aggregate utilization may result in a loss of resale value (Feng & Figliozzi, 2012), we present estimates of requisite annual utilization rates with and without resale value consideration.

2.2.1. Financial estimation equations

Specifically, we employ models derived in previous works (MIT Energy Initiative, 2019; Breetz & Salon, 2018) combined with our battery longevity estimates (Supplementary Information, Section I). We account for vehicle purchase price (MSRP), resale value, fuel efficiency, fuel price, maintenance costs, repair costs, insurance costs, annual taxes and fees, sales tax, title fees, and EV battery replacements in our analysis (see Eqs. (5.0) and 5.1).

$$TCO_{EV} = MSRP_{EV} + \left(MSRP_{EV} * \frac{Tax}{100}\right) + TitleFee + \left(\sum_{k=1}^{n} \frac{\left(\left(Elec\$ * \frac{AnnVMT}{MPK}\right) + AnnFees + AnnInsur_{EV} + (MR_{EV} * AnnVMT)\right)}{(1 + DiscRate)^k}\right) - \frac{((MSRP_{EV}) * DepRate^n)}{(1 + DiscRate)^n} + \left(\frac{AnnVMT * n}{BatLife\left(\frac{AnnVMT}{12}\right)} - 1 * BatSize * BatCost\right) \tag{5.0}$$

where $MSRP_{EV}$ = EV purchase price ($); Tax = sales tax (%); TitleFee = vehicle title fee ($); Elec$ = average cost of electricity ($/kWh); AnnVMT = annual vehicle utilization (mi./year); MPK = miles per kilowatt hour; AnnFees = annual taxes and fees including registration, license plate, and inspection fees ($/year); $AnnInsur_{EV}$ = annual EV insurance costs ($/year); MR_{EV} = EV maintenance and repair costs ($/mi.); DiscRate = annual discount rate; DepRate = remaining resale value (relative to the previous year); BatLife($\frac{AnnVMT}{12}$) = battery lifespan (miles) as a function of annual utilization; BatSize = EV battery size (kWh); BatCost = EV battery cost ($/kWh); and n = ownership duration (years).

$$TCO_{ICEV} = MSRP_{ICEV} + \left(MSRP_{ICEV} * \frac{Tax}{100}\right) + TitleFee + \left(\sum_{k=1}^{n} \frac{\left(\left(Gas\$ * \frac{AnnVMT}{MPG}\right) + AnnFees + AnnInsur_{ICEV} + (MR_{ICEV} * AnnVMT)\right)}{(1 + DiscRate)^k}\right) - \frac{((MSRP_{ICEV}) * DepRate^n)}{(1 + DiscRate)^n} \tag{5.1}$$

where $MSRP_{ICEV}$ = ICEV purchase price ($); Tax = sales tax (%); TitleFee = vehicle title fee ($); Gas$ = average cost of gasoline ($/gal.); AnnVMT = annual vehicle utilization (mi./year); MPG = miles per gallon; AnnFees = annual taxes and fees including registration, license plate, and inspection fees ($/year); $AnnInsur_{ICEV}$ = annual ICEV insurance costs ($/year); MR_{ICEV} = ICEV maintenance and repair costs ($/mi.); DiscRate = annual discount rate; DepRate = remaining resale value (relative to the previous year); and n = ownership duration (years).

After separately estimating EV and ICEV TCOs, we subsequently analyze the cost differential using Eq. (6.0).

$$TCOD = TCO_{EV,t,n} - TCO_{ICEV,t,n} \tag{6.0}$$

where TCOD = EV-versus-ICEV TCO difference; $TCO_{EV,t,n}$ = EV TCO given t annual utilization and n years of ownership, calculated using Eq. (5.0); and $TCO_{ICEV,t,n}$ = ICEV TCO given t annual utilization and n years of ownership, calculated using Eq. (5.1).

To address the potential impact of slight variations in our TCO estimates, we also conduct sensitivity analysis for all key financial parameters (see Section 3.1 and 3.2). To do so, we use the following equation:

$$\Delta TCOD = \frac{TCOD(m_1) - TCOD(m_0)}{TCOD(m_0)} \tag{7.0}$$

where $\Delta TCOD$ =% change in EV-ICEV TCO difference; $TCOD(p_0)$ = TCO difference given the initial value of parameter m, calculated using Eqs. (5.0), (5.1), and (6.0); and $ED_t(p_1)$ = TCO difference given the new value of parameter m, calculated using Eqs. (5.0), (5.1), and (6.0).

2.3.1. Abatement cost estimation equations

To calculate abatement cost in US dollars per ton of CO_2 emissions reduced – relative to the counterfactual wherein an equivalent ICEV is purchased and utilized in place of an EV – we first modify Eq. (3.1) to estimate the total emissions benefit EVs offer relative to ICEVs and subsequently use Eq. (8.0) to estimate abatement cost:

$$ED = PME_{ICEV,t} - PME_{EV,t} \tag{3.1}$$

$$ED_{Total} = (PME_{ICEV,t} - PME_{EV,t}) * \frac{au}{1,000,000} \tag{3.2}$$

where ED = per-mile emissions difference (g CO_2e/mi.); $PME_{ICEV,t}$ = ICEV per-mile emissions (g CO_2e/mi.) given t miles travelled, calculated using Eq. (1.0); $PME_{EV,t}$ = EV per-mile emissions (g CO_2e/mi.) given t miles travelled, calculated using Eq. (1.0); au = aggregate utilization (miles); and ED_{Total} = total lifecycle emissions difference (tons CO_2e);

$$AbateCost = \frac{TCOD}{ED_{Total}} \tag{8.0}$$

where $AbateCost$ = abatement cost ($/ton CO_2e reduced); TCOD = TCO difference (EV TCO – ICEV TCO) ($), estimated using Eqs. (5.0), (5.1), and (6.0); and ED_{Total} = total lifecycle emissions difference (ICEV emissions – EV emissions) (ton CO_2e), estimated using Eqs. (1.0) and (1.1).

We then calculate the requisite aggregate utilization thresholds to satisfy given abatement cost targets by setting $AbateCost$ equal to our target abatement cost, c, and solving for aggregate utilization, holding constant all other parameters – except for, implicitly, annual utilization. For example, increasing aggregate utilization from 100,000 to 200,000 miles - holding ownership duration constant at 5 years - implicitly raises annual utilization from 20,000 to 40,000 miles/year. We then repeat this process for TCO differences, estimating the requisite aggregate utilization to achieve select total abatement costs.

To estimate the efficiency of current policy, we first assess the implied abatement cost of EV procurement under two key assumptions: (United States Environmental Protection Agency, 2018) existing federal incentives (i.e., a $7500 tax credit) are equivalent to the TCO difference between EVs and ICEVs – in short, this assumes the current magnitude of available incentives is set to an efficient level; and (Axsen et al., 2020) current incentives induce EV adoption among households representative of average utilization and ownership behaviors. We thus adjust Eq. (8.0) accordingly:

$$AbateCost = \frac{TCOD}{ED_{Total}} \tag{8.0}$$

$$AbateCost = \frac{7,500}{ED_{Total}(au = c)} \tag{8.1}$$

where $AbateCost$ = abatement cost ($/ton CO_2e reduced) and ED_{Total} = total lifecycle emissions difference (ICEV emissions – EV emissions) (ton CO_2e), estimated using Eqs. (1.0) and (1.1), assuming an aggregate utilization of c miles, where c is between 41,000 and 75,000 miles (Mitropoulos et al., 2017; Davis, 2019; Burlig et al., 2021; Vehicles Getting Older, 2016).

Then, we relax our first assumption and instead estimate the associated abatement cost using our TCO model given average utilization and vehicle ownership trends (Eq. (8.2)). This enables a more accurate abatement cost estimate, as we now consider all costs realized owing to EV procurement.

$$AbateCost = \frac{TCOD(au = c)}{ED_{Total}(au = c)} \tag{8.2}$$

where $AbateCost$ = abatement cost ($/ton CO_2e reduced); TCOD(au=c) = TCO difference ($), estimated using Eqs. (5.0), (5.1), and (6.0), assuming an aggregate utilization of c miles; and ED_{Total}(au=c) = total lifecycle emissions difference (ICEV emissions – EV emissions) (ton CO_2e), estimated using Eqs. (1.0) and (1.1), assuming an aggregate utilization of c miles. We again assume c to be between 41,000 and 75,000 miles based on existing public data (Mitropoulos et al., 2017; Davis, 2019; Burlig et al., 2021; Vehicles Getting Older, 2016).

Next, we estimate requisite emissions and TCO differences to achieve – given current policy and behavioral trends – abatement costs which are efficient compared to alternative policies, defined as an abatement cost of approximately $50/ton CO_2e reduced (Jia & Chen, 2022). To do so, we leverage two approaches. First, we estimate the requisite aggregate utilization threshold to achieve a TCO difference of $7500 and subsequently use the following equation to calculate the requisite emissions benefit to achieve our abatement cost target:

$$ED_{Req} = \frac{TCO(au = c)}{AbateCostTarg} \tag{8.3}$$

where ED_{Req} = requisite EV emissions advantage (ton CO_2e); TCO (au=c) = TCO difference ($), estimated using Eqs. (5.0), (5.1), and (6.0), given an aggregate utilization of c miles, where c is chosen such that the resultant TCO difference equals $7500; and $AbateCostTarg$ = abatement cost target ($/ton CO_2e reduced).

Using our abatement cost target of $50/ton CO_2e reduced, the requisite EV emissions advantage exceeds the total emissions produced by the ICEV travelling c miles (estimated using Eqs. (1.0) and (2.0), see Section 2.1.1). We subsequently estimate the maximum emissions benefit possible, assuming an EV without any lifecycle emissions, and use Eq. (8.2) where ED_{Total}(au=c) is set to zero to estimate the most efficient possible abatement cost under this scenario (Section 3.3).

Additionally, we estimate the total EV emissions advantage given current vehicle utilization trends using Eq. (3.2), where aggregate utilization is assumed to be 75,000 miles. We then use Eq. (8.4) to calculate the requisite TCO differential for EV procurement policies to become economically efficient given the current estimated emissions EV advantage:

$$TCO_{Req} = ED_{Total}(au = 75,000) * AbateCostTarg \tag{8.4}$$

where TCO_{Req} = requisite TCO differential ($); ED_{Total}(au=75,000) = total lifecycle emissions difference (ton CO_2e), estimated using Eqs. (1.0) and (1.1), assuming an aggregate utilization of 75,000 miles; and $AbateCostTarg$ = abatement cost target ($/ton CO_2e reduced).

To assess the feasibility of realizing our requisite TCO difference, we explore reductions in EVs' most elastic financial parameters (Supplementary Information, Section 2.1); namely, MSRP and annual insurance. Using Eqs. (5.0), (5.1), and (6.0), we calculate TCO differentials while manipulating annual insurance costs; however, even if EVs realized equivalent insurance costs as ICEVs, the associated TCO difference still exceeds the requisite threshold. Conversely, sufficient reductions in EV MSRP facilitate the necessary TCO difference (Section 3.3).

Finally, we quantify the impacts of potential changes to key aspects of our model on estimated abatement costs and requisite aggregate utilization thresholds. Specifically, we quantify the impacts of zero and one additional battery replacement, cleaner electricity grids, and greater ICEV fuel efficiency on our results. Our sensitivity analysis is presented in Tables 4 and 6.

Table 2
Per-mile emissions estimates and EV annual utilization thresholds.

Aggregate Utilization (mi.)	EV Emissions (g CO_2e/mi.)	ICEV Emissions (g CO_2e/mi.)	Requisite EV Annual Utilization w/ Battery Replacements (mi./year)
10,000	1488.77	1128.28	–
20,000	808.77	728.28	–
28,069	613.29	613.29	1246
30,000	582.10	594.94	1762
40,000	468.77	528.28	4112
50,000	400.77	488.28	6102
55,749	372.72	471.78	7136
60,000	355.44	461.61	7860
70,000	323.06	442.56	9452
80,000	298.77	428.28	10,917
90,000	279.88	417.17	12,282
100,000	264.77	408.28	13,565
110,000	252.41	401.00	14,779
120,000	242.10	394.94	15,934
130,000	233.38	389.82	17,038
140,000	225.91	385.42	18,097
150,000	219.44	381.61	19,116
160,000	213.77	378.28	20,100
170,000	208.77	375.34	21,051
180,000	204.33	372.72	21,974
190,000	200.35	370.38	22,869
200,000	196.77	368.28	23,741
450,000	158.99	346.06	40,799

Note: For each level of aggregate utilization, "EV Emissions" and "ICEV" Emissions" denote the estimated lifecycle emissions realized by utilizing an EV (expressed on a per-mile basis) and ICEV (expressed on a per-mile basis), respectively. The rightmost column denotes the annual utilization rate needed for EVs to achieve the estimated EV per-mile emissions rate, accounting for battery replacements. – denotes EV annual utilization thresholds for which – owing to a lack of precise data availability – our battery replacement model cannot estimate exact thresholds.

2.4. Uncertainty considerations

Given challenges in predicting future technological improvements, uncertainty surrounding future improvements to EVs and ICEVs financial profiles warrants acknowledgement. Our model's assumptions and the resultant predictions are admittedly based on imperfect information. For example, there is little publicly available data on future long-run electricity costs or resale values of alternative powertrains. Additionally, estimates of emissions benefits consider existing vehicles' emissions profiles and, for EVs, electricity grid carbon intensity and battery longevity. Our estimates may therefore over or underestimate the true long-run emissions advantage of EVs.

To address these concerns, we perform elasticity testing and sensitivity analyses on our input parameters for both emissions and TCO differences (see Tables 2, 4, 5, and 6 and Supplementary Information for more details). We also quantify the requisite aggregate utilization thresholds for EV-incentive policy to achieve an array of abatement cost targets assuming zero and one additional battery replacement, as well as if envisioned improvements to electricity grids and ICEV fuel efficiency are realized. In doing so, we estimate requisite aggregate utilization thresholds for an array of future scenarios, acknowledging that variations in our projections would demand a less or more stringent EV aggregate utilization profile (detailed in the supplementary information section).

Additionally, given homogeneity in federal EV procurement incentives (though separate state-level incentives also exist), we focus our analysis on national-level data, while acknowledging that in states with relatively cleaner electric grids and cheaper electricity prices, EVs may offer a more favorable abatement cost than in states with dirtier electric grids and costlier electricity. We subsequently account for this possibility in our analysis.

3. Results and discussion

Our results and discussion are structured as follows. First, we present and discuss the lifecycle emissions estimates of EVs compared to ICEVs. Next, we assess TCO differences between EVs and ICEVs given heterogeneity in aggregate utilization patterns. Based on our results, we subsequently characterize the aggregate utilization required for EV-incentive policies to achieve comparable abatements costs to alternative policies. Finally, we discuss the policy implications of our results and propose alternative programs that would facilitate greater economic efficiency and distributional equity.

3.1. Emissions evaluation

Across all scenarios, EVs per-mile emissions decrease as a function of aggregate mileage compared to ICEVs, suggesting that greater aggregate utilization produces more favorable emissions outcomes for EVs (Nunes et al., 2022). To illustrate this tradeoff, we first estimate the aggregate utilization required for an EV to achieve equivalent per-mile emissions as ICEVs absent consideration of battery replacements (see Table 1 for key input parameters). Under this scenario, assuming an ICEV travels 180,000 miles over its lifetime (MIT Energy Initiative, 2019), EVs must travel 55,749 miles to realize an equivalent per-mile emission footprint. That is, both the ICEV and EV will realize an emissions rate of 372.7 g CO_2e/mile. However, the relative contributions of vehicle manufacturing and operation differ; namely, vehicle manufacturing only accounts for 11.9% of the ICEV's per-mile emissions, while emissions associated with fuel production and use account for the remaining 88.1%. Comparatively, the EV's vehicle manufacturing emissions constitute 65.5% of its per-mile emissions, while fuel production is only responsible for 34.5%.

As aggregate utilization exceeds this threshold, EVs begin to produce per-mile emissions benefits. Conversely, should this threshold not be met, driving an EV would – our model predicts – generate greater emissions than an ICEV. Moreover, assuming ICEVs travel the same aggregate distance as EVs, the relationship between aggregate utilization and emissions becomes more pronounced. Absent battery replacements, EVs must now only travel 28,069 miles to realize emissions parity – measured on both per-mile and total bases – with ICEVs.

We subsequently allow for battery replacement, as the requisite utilization for an EV to have an emissions advantage over an ICEV is sensitive to whether a battery replacement is required. Existing literature suggests battery manufacturing accounts for a significant proportion of EV lifecycle emissions (MIT Energy Initiative, 2019). Consequently, failing to consider battery degradation and consequent replacements can produce inaccurate emissions assessments (Yang et al., 2018). Given that EV battery longevity depends, in part, on annual utilization, accounting for battery replacements also produces heterogeneity in requisite aggregate utilization thresholds as a function of annual miles travelled.

For example, if an EVs annual utilization exceeds 7135 miles, it must travel 55,749 miles to achieve per-mile emissions parity with an ICEV (assuming the ICEVs aggregate utilization is 180,000 miles) (Table 2). This yields effects nearly identical to our original finding, as our model predicts a battery longevity of 55,751 miles and thus, no battery replacements are required. That is, given an average annual utilization rate of 11,300 miles/year (Mitropoulos et al., 2017), EV batteries will remain at approximately 87% capacity after five years of ownership.

Table 3
EV battery lifecycle literature.

Author (year)	Assumptions	Results
Schoch et al. (2018)[a]	Simulated degradation model (no primary data collection) Assumes average of 5500 miles/year annual utilization Assumes typical current charging behaviors Assumes temperatures between 10 and 20 °C End of life defined when battery reaches 80% capacity	Batteries last between 32,450–54,615 miles
Micari et al. (2021)[b]	Primary data collected Assumes average of 7560 miles/year annual utilization End of life defined when battery reaches 70% capacity	Batteries last an average of 85,600 miles
Patil et al. (2023)[c]	Simulated degradation model (no primary data collection) Assumes average of 8700 miles/year annual utilization End of life defined when battery reaches 80% capacity	Batteries last an average of 80,350 miles

Note: Existing literature on EV battery longevity and degradation. We review the following sources: [a] (Schoch et al., 2018); [b] (Micari et al., 2022); and [c] (Patil et al., 2023).

Table 4
Sensitivity analysis - lifecycle emissions difference.

	Difference in Lifecycle Emissions (ICEV – EV) 1% Change	5% Change	10% Change	Parameter Increase/ Decrease
Annual Utilization (mi.)	0.14 1.71	0.68 8.53	1.35 17.06	*Increase*
Aggregate Utilization (mi.)	0.14 1.71	0.68 8.53	1.35 17.06	*Increase*
ICEV Fuel Efficiency (mi./gal.)	−0.22 −2.78	−1.06 −13.37	−2.02 −25.53	*Increase*
EV Fuel Efficiency (mi./gallon-equivalent)	0.09 1.09	0.42 5.24	0.79 10.01	*Increase*
EV Vehicle Manufacturing Emissions (tons CO_2e)	0.14 1.72	0.68 8.58	1.36 17.16	*Decrease*
ICEV Vehicle Manufacturing Emissions (tons CO_2e)	−0.08 −1.01	−0.40 −5.05	−0.80 −10.09	*Decrease*
EV Fuel Production Emissions (g CO_2e/MJ)	0.09 1.10	0.44 5.51	0.87 11.01	*Decrease*
ICEV Fuel Production Emissions (g CO_2e/MJ)	−0.05 −0.58	−0.23 −2.90	−0.46 −5.80	*Decrease*
ICEV Fuel Usage Emissions (g CO_2e/MJ)	−0.18 −2.23	−0.88 −11.14	−1.77 −22.28	*Decrease*
Replacement Battery Manufacturing Emissions (g CO_2e/mi.)	0.00 0.00	0.00 0.00	0.00 0.00	*Decrease*
Battery Lifespan (mi.)	0.00 0.00	0.00 0.00	0.00 0.00	*Increase*

Note: For each scenario, the absolute change in total lifecycle emissions difference (ICEV emissions – EV emissions) resulting from a 1%, 5%, or 10% change in each input parameter (t CO2e) is shown on the top line. Relative changes (%) are displayed on the lower line. The rightmost column denotes whether each parameter was increased or decreased. Initial emissions differences presume average utilization and vehicle ownership behaviors (Mitropoulos et al., 2017; Vehicles Getting Older, 2016). Changes to EV Fuel Production Emissions refer to the average emissions factor associated with electricity generation.

Conversely, if an EV's annual utilization is between 3359 and 7135 miles, an additional battery will be required as the EV must remain in service for longer to achieve an equivalent aggregate utilization threshold, thereby resulting in greater battery degradation (De Gennaro et al., 2020; Krupp et al., 2021). This generates additional emissions that raise the requisite aggregate utilization threshold to 73,171 miles.

Subsequent reductions in annual utilization continue to increase requisite aggregate utilization thresholds. However, meeting these thresholds is unlikely as doing so would require an ownership period inconsistent with existing patterns (Vehicles Getting Older, 2016). We find similar trends when allowing ICEVs and EVs to travel equivalent total miles and accounting for battery replacements. For example, the requisite aggregate utilization threshold remains at 28,069 miles if EVs annual utilization exceeds 1245 miles. Conversely, if an EV's annual utilization is between 275 and 1245 miles, the requisite aggregate utilization threshold increases to 49,371 miles. This suggests that for households with average annual utilization rates (i.e., 11,300 miles/-year (Mitropoulos et al., 2017)), EVs only require 2.49 years of ownership to realize an emissions advantage over ICEVs.

Collectively, our estimates of requisite aggregate utilization thresholds exceed those of past studies (The Greenhouse Gases, 2020) and highlight the importance of annual utilization and, by consequence, battery longevity in realizing emissions benefits (see Table 3). Put simply, higher annual utilization rates correspond to lower requisite aggregate utilization thresholds, and vice versa when accounting for battery replacements. Moreover, we find that an EV's emissions benefit is highly contingent upon aggregate utilization, which is sensitive to the counterfactual vehicle that the EV presumably supplants in the market (see Table 4). As abatement costs of public policy focused on emissions reduction depend on the volume of avoided emissions, the efficiency of EV subsidy is thus affected by aggregate EV utilization. Furthermore, it is plausible that EVs with low levels of aggregate utilization would result in no emissions abatement at all.

3.2. Financial evaluation

We subsequently assess the TCO differences between EVs and ICEVs given specified aggregate and annual utilization patterns.

Here, we find that – assuming average ICEV annual utilization rates (i.e., 11,300 miles/year (Mitropoulos et al., 2017)) and equivalent EV annual utilization – EVs are unable to realize a lower TCO than ICEVs, regardless of ownership duration or whether battery replacements are considered. Specifically, we find that the difference in TCOs between EVs and ICEVs increases with ownership duration. Assuming equivalent, average annual utilization patterns, 6-year TCOs for EVs and ICEVs are $40,111 and $33,206 respectively, a difference of $6906. Yet, raising the ownership duration to 12 years and holding constant all other factors produce EV and ICEV TCOs of $61,688 and $51,997, respectively. By raising the ownership duration from 6 to 12 years, TCO differences between EVs and ICEVs have increased from $6906 to $9691. Accounting for potential battery replacements further worsens the EV's financial profile, as each additional battery replacement levies an approximate $11,645 expenditure, though future advancements to manufacturing processes may reduce this cost (see Section 4.0).

This finding – which contradicts findings from previous literature (Mitropoulos et al., 2017) – is explained by the fact that although EVs benefit from lower operating costs (i.e., maintenance, repair, and fuel costs), they are disadvantaged by greater loss of resale value, higher upfront costs, and higher annual insurance costs, which challenge their

Table 5
TCO differences.

Annual Utilization (mi./year)	Vehicle Length of Ownership (years) 6	8	10	12
5300	9169 9169	10,913 10,913	23,966 12,321	25,106 13,461
7000	8528 8528	21,754 10,109	23,022 11,377	24,038 12,393
10,000	7396 7396	20,337 8692	21,354 9709	22,153 10,508
11,300	6906 6906	19,723 8078	20,632 8987	21,336 9691
15,000	5510 5510	17,975 6330	18,576 6931	19,010 7365
20,000	3625 3625	15,612 3967	15,797 4152	15,868 4223
45,000	−5804 −5804	−7844 −7844	−9741 −9741	157 −11,488
90,000	−22,776 −22,776	−29,106 −29,106	−34,749 −34,749	−39,769 −39,769

Note: The top line in each cell denotes the estimated TCO difference (EV – ICEV) assuming necessary battery replacements. The bottom line denotes estimated TCO differences without accounting for battery replacements. All TCO differences are expressed in US dollars and account for resale value as a function of ownership duration. Positive TCO differences imply EVs realize greater total costs than ICEVs; negative TCO differences suggest that EVs achieve a cost advantage over ICEVs.

Table 6
Sensitivity analysis - TCO difference.

	Difference in TCO (EV – ICEV) 1% Change	5% Change	10% Change	Parameter Increase/ Decrease
Annual Utilization (mi.)	−42.56 −0.62	−213.09 −3.09	−426.17 −6.17	*Increase*
Aggregate Utilization (mi.)	−42.56 −0.62	−213.09 −3.09	−426.17 −6.17	*Increase*
EV Remaining Resale Value (%)	−1103.51 −15.98	−6100.40 −88.34	−6464.14 −93.60	*Increase*
ICEV Remaining Resale Value (%)	712.52 10.32	3938.94 57.04	4173.80 60.44	*Increase*
ICEV Fuel Efficiency (mi./gal.)	50.03 0.72	240.64 3.48	459.41 6.65	*Increase*
EV Fuel Efficiency (mi./kWh)	−23.84 −0.35	−114.65 −1.66	−218.88 −3.17	*Increase*
Average Electricity Cost ($/kWh)	−24.08 −0.35	−120.38 −1.74	−240.76 −3.49	*Decrease*
Average Gasoline Cost ($/gal.)	50.54 0.73	252.68 3.66	505.35 7.32	*Decrease*
EV MSRP ($)	−214.29 −3.10	−1071.46 −15.52	−2142.92 −31.03	*Decrease*
ICEV MSRP ($)	138.27 2.00	691.83 10.02	1383.65 20.04	*Decrease*
Sales Tax (%)	−9.73 −0.14	−48.66 −0.70	−97.31 −1.41	*Decrease*
EV Maintenance & Repair Costs ($/mi.)	−16.16 −0.23	−80.79 −1.17	−161.59 −2.34	*Decrease*
ICEV Maintenance & Repair Costs ($/mi.)	32.32 0.47	161.59 2.34	323.17 4.68	*Decrease*
EV Annual Insurance ($/year)	−114.40 −1.66	−571.98 −8.28	−1143.97 −16.57	*Decrease*
ICEV Annual Insurance ($/year)	78.65 1.14	393.24 5.69	786.48 11.39	*Decrease*
Annual Discount Rate	26.37 0.38	130.68 1.89	258.45 3.74	*Increase*

Note: For each scenario, we show absolute changes in TCO difference (EV – ICEV) associated with 1%, 5%, and 10% changes in each key input parameter on the top line, expressed in US dollars. The lower line shows relative changes (%). The rightmost column denotes whether each parameter was increased or decreased. Adjustments to Remaining Resale Value for both EVs and ICEVs are capped at 100% of the previous year's value (i.e., no depreciation year over year). Initial TCO differences presume average utilization and vehicle ownership behaviors (Mitropoulos et al., 2017; Vehicles Getting Older, 2016).

ability to realize a TCO advantage over ICEVs. For example, based on existing data, our model presently assumes an MSRP difference between EVs and ICEVs of $12,975, which is equivalent to 32.3% of EVs' 6-year TCO and 39.1% of ICEVs' 6-year TCO (MIT Energy Initiative, 2019). As we assume equivalent annual depreciation rates for EVs and ICEVs, higher upfront costs raise EV's TCO differential through both initial purchase price and greater loss of resale value – in absolute dollar amounts – year over year. Additionally, based on current data, average annual insurance costs are approximately $800/year greater for EVs than ICEVs (MIT Energy Initiative, 2019; Brennan, 2022), further challenging an EV's ability to achieve TCO parity.

However, were the EV's upfront cost differential lowered to $1173 more than ICEV's, our model suggests – ceteris paribus – TCO parity could be realized over a 6-year ownership period within existing utilization trends. Similarly, whereas our sensitivity analysis suggests that increases in ICEVs' fuel costs or declining electricity prices (Clifford, Catherine, 2022) will result in relatively inelastic declines in TCO differentials, reductions in costs associated with resale value and insurance offer elastic returns (see Tables 5 and 6).

Additionally, EVs can achieve less onerous financial prospects through increased annual utilization rates. For example, although raising annual utilization from 11,300 to 20,000 miles increases TCOs for both EVs and ICEVs, EVs' TCO *differential* decreases from $6906 to $3625 after 6 years of ownership. Yet after 12 years, EVs' TCO is – owing to required battery replacements – $15,868 greater than ICEVs'. To achieve TCO parity over 12 years given current financial parameters (Table 1) and accounting for battery replacements, EVs' requisite annual utilization is approximately 46,686 miles/year (45,249 miles/year accounting for resale value). Absent consideration of requisite battery replacements, EVs' requisite annual utilization to achieve TCO parity in 12 years is – our model suggests – 31,673 miles/year (26,720 miles/year accounting for resale value).

3.3. Achieving abatement cost parity

Collectively, our results suggest that – under average annual utilization patterns (Mitropoulos et al., 2017) – as aggregate utilization increases, EVs realize greater emissions advantages, yet their total costs relative to ICEVs also rise. The reasons for this are twofold. First, because EVs – compared to ICEVs – generate greater manufacturing emissions but fewer combined emissions from fuel production and use (MIT Energy Initiative, 2019), each mile travelled partially offsets the difference in manufacturing emissions, eventually generating an EV emissions advantage. Second, holding constant annual utilization, achieving greater aggregate utilization requires longer ownership durations. Consequently, both EVs and ICEVs are associated with greater TCOs, owing to the accumulation of annual costs such as insurance and depreciation of resale value. Because these costs are greater for EVs compared to ICEVs (Table 1), extending ownership durations to achieve higher aggregate utilization raises EV costs more rapidly.

Given these findings, the potential cost-effectiveness of EV-incentive policies largely depends on the rate at which emissions benefits rise relative to TCO. Our model shows that EV emissions benefits increase more rapidly – as a function of aggregate utilization – than TCO. This subsequently leads to an inverse relationship between abatement cost and aggregate utilization (described in Section 1.1) and allows us to estimate requisite aggregate utilization thresholds for several abatement cost targets (see Tables 8 and 9, Fig. 1).

For example, our model estimates that, after accounting for battery replacements, EVs must travel approximately 150,000 miles in 6 years to achieve an abatement cost of $350/ton CO_2e reduced, with a requisite subsidy of $8293. Realizing an abatement cost of $50/ton CO_2e reduced requires traveling almost 250,000 miles over the same period yet only a $2158 subsidy. If spread over a 12-year ownership period, achieving an abatement cost of $350/ton CO_2e reduced requires travelling over 23,000 miles annually and subsidies totaling $16,551.

How cost effectively does current EV procurement incentive policy – specifically the Qualified Plug-In Electric Drive Motor Vehicle Credit (IRC 30d New Qualified, 2022) – facilitate emissions reductions? Based on emergent trends in overall vehicle ownership and annual utilization, the $7500 procurement incentive program produces EVs that travel between 41,000 and 75,000 miles over 6.61 years (Davis, 2019; Burlig et al., 2021; Vehicles Getting Older, 2016; Qualified Plug-in Electric, 2023). This translates to – considering only government expenditure – an abatement cost of $801/ton CO_2e reduced, which significantly exceeds that of alternative policies (Gillingham & Stock, 2018). Moreover, accounting for the total cost differential between EVs and ICEVs raises the effective abatement cost to at least $1368/ton CO_2e reduced.

Furthermore, the Qualified Plug-In Electric Drive Motor Vehicle Credit produces a TCO differential of – our model estimates – $12,809 ($6453 accounting for EV and ICEV resale values). This policy is thus,

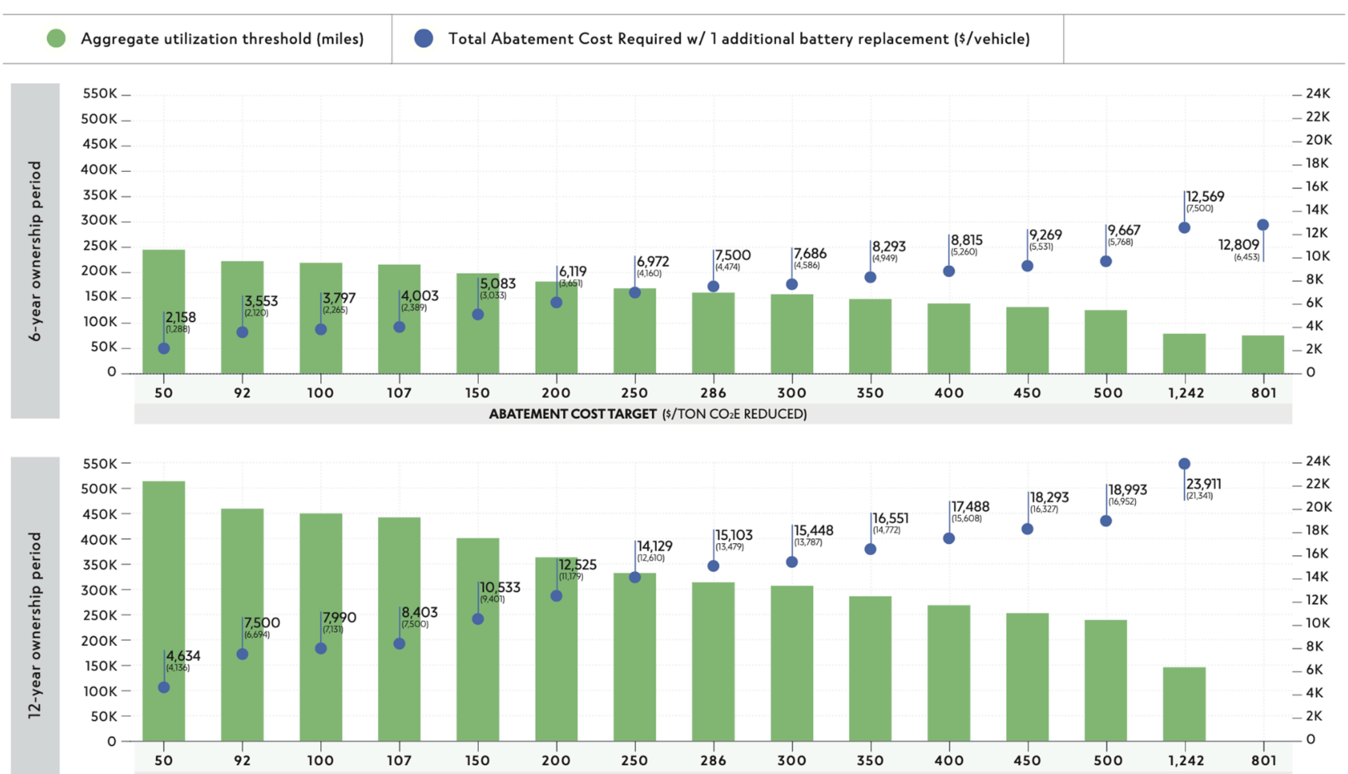

Fig. 1. Aggregate utilization thresholds and associated abatement cost targets (no resale value).

regardless of vehicle resale value, inefficient from a fiscal perspective. To realize a $7500 TCO difference, EVs must travel approximately 159,456 miles (58,347 miles accounting for resale value) over 6 years. Moreover, because our estimates represent the requisite distance an EV must travel to achieve a given cost differential, driving fewer than 159,456 miles (58,347 miles) may result in greater costs incurred by EV owners.

Additionally, realizing a TCO difference of equivalent magnitude using existing federal subsidies produces an associated abatement cost of $286/ton CO_2e reduced ($1242/ton CO_2e reduced). To realize an economically efficient abatement cost (i.e., $50/ton CO_2e reduced (Gillingham & Stock, 2018)) under this scenario, EVs' requisite emissions advantage is 150.0 tons CO_2e. Producing such an emissions advantage is unviable given that ICEVs – assuming 159,456 miles (58, 347 miles) travelled – currently only generate 60.3 tons CO_2e (27.2 tons CO_2e), accounting for emissions from vehicle manufacturing and utilization. This suggests an upper-bound abatement cost of $124/ton CO_2e reduced ($276/ton CO_2e reduced) were EVs to produce zero total emissions (see Supplementary Information, Section III). This suggests that – regardless of potential improvements to EV manufacturing or utilization emissions profile – current incentives are unlikely to facilitate economically efficient emissions reductions.

Conversely, EVs current emissions advantage given existing utilization behaviors is – our model estimates – 7.93 tons CO_2e, suggesting a requisite TCO differential of $397 to realize an abatement cost of $50/ton CO_2e reduced (see Supplementary Information, Section III). Given existing utilization trends, parity in annual insurance costs is insufficient to realize the requisite TCO differential; however, an EV MSRP of $25,889 would produce a $397 TCO difference. This result is analogous to previous estimates (Breetz & Salon, 2018). Yet, such a prospect – owing to additional costs from battery manufacturing (MIT Energy Initiative, 2019) – may be challenging to achieve.

Likewise, future decarbonization of the electrical grid – and by consequence, reductions in EV-related emissions from fuel production – appear, ceteris paribus, insufficient to realize efficient abatement costs. For example, the requisite aggregate utilization threshold for EVs to realize an abatement cost of $50/ton CO_2e reduced given current electric grids is 244,437 miles (157,176 miles accounting for resale value) over a 6-year ownership period, or 513,943 miles (464,012 miles accounting for resale value) over a 12-year ownership period (see Tables 8 and 9). Yet, even if the emissions footprint associated with EV fuel production were reduced to zero (a condition representative of complete grid decarbonization), EVs' requisite utilization thresholds are 224,583 miles (144,410 miles accounting for resale value) over a 6-year period and 465,838 miles (420,580 miles accounting for resale value) over a 12-year period. These figures – which are equivalent to approximately a 10 percent reduction in aggregate utilization relative to the baseline scenario – would still exceed vehicle utilization trends observed today (Lu, 2006; Average, 2022; Maps & Data, 2020).[3] Moreover, to the extent that successful EV adoption requires additional investments in public charging infrastructure (Mutarraf, Muhammad Umair, 2022), our results potentially underestimate the stringency of EVs' utilization thresholds and TCO differentials required to realize a given abatement cost target.

3.4. Pathways to reform and equity implications

However, EVs may achieve abatement cost parity with other policy options were existing procurement incentive policy restructured to incentivize electrifying high-utilization vehicles. For example, incentivizing EVs as replacement vehicles for taxis, which drive an estimated 450,000 miles over a 5-year period (Nunes & Hernandez, 2020), would allow EVs to realize both a TCO and emissions advantage over ICEVs – making it economically efficient compared to alternative policies. Specifically, previous literature (Gillingham & Stock, 2018) calculates policies such as reforestation, wind energy subsidies, gasoline taxes, CAFE standards, renewable fuel subsidies, and weatherization assistance programs to have abatement costs of $1 – $10/ton CO_2e reduced, $2 – $260/ton CO_2e reduced, $18 – $47/ton CO_2e reduced, $48 – $310/ton CO_2e reduced, $100/ton CO_2e reduced, and $350/ton CO_2e reduced, respectively.

Our results highlight the importance of high utilization rates if existing EV procurement incentive policies are to achieve efficient emissions reductions. We emphasize targeting high-utilization vehicles for the following reasons. First, holding constant ownership duration, lower costs and fewer emissions associated with driving EVs persist relative to ICEVs. Conversely, longer ownership durations – ceteris paribus – increase TCO differences between EVs and ICEVs. This is due to higher annual costs and reduced battery longevity, the latter of which is a consequence of calendar aging (i.e., capacity fade due to the passage of time) (De Gennaro et al., 2020).

Additionally, vehicles with high annual utilization are better positioned to realize greater aggregate utilization thresholds during a single ownership period. This, a) allows incentives to be more directly targeted towards individuals who help facilitate emissions benefits and, b) reduces the requisite magnitude of financial support owing to lower TCO differences (Tables 8 and 9). Put simply, high-utilization vehicles may reduce the requisite magnitude of current subsidies while facilitating more efficient emissions reductions (Table 7).

Finally, adjusting policy in this way would help address existing

Table 7
EV-ICEV TCO differential literature.

Author (year)	Assumptions	Results
Prud'homme and Koning (2012)[a]	Examines 2010 EV and ICEV models in France Assumes 15-year lifespan Assumes average of 10,000 km/year	EVs' TCO exceeds ICEVs' by €15,000 Fuel cost changes are insufficient in producing EV cost advantages
Wu et al. (2015)[b]	Uses Monte Carlo simulations to estimate EV and ICEV TCOs in Germany Models up to 10-year lifespan	EVs traveling 7483–15,184 km/year are unlikely to realize a TCO advantage through 2025 EVs traveling 28,434 km/year can achieve a TCO advantage over ICEVs Fuel cost changes are insufficient in producing EV cost advantages
Elgowainy et al. (2018)[c]	Examines vehicle models through 2030 in US Assumes 15-year lifespan Assumes 178,000 aggregate utilization Ignores maintenance and insurance costs	EVs' TCO exceeds ICEVs' by at least $0.32/mi.
Danielis et al. (2018)[d]	Examines 2017 models through 2025 in Italy Assumes 5000–15,000 km/year annual utilization Assumes 6-year first ownership period	EVs' TCO exceeds ICEVs' by 0.13 €/km – 0.55 €/km, depending on annual utilization

Note: Existing literature on EV versus ICEV TCO differentials. We review the following sources: [a] (Prud'homme & Koning, 2012); [b] (Wu et al., 2015); [c] (Elgowainy et al., 2018); and [d] (Danielis et al., 2018).

[3] Were emissions associated with ICEV and EV vehicle and battery manufacturing reduced to 0 – a potential consequence of a decarbonized electric grid and manufacturing process, – requisite aggregate utilization thresholds remain beyond current trends. Specifically, to achieve a $50/ton CO2e abatement cost, EVs must travel 221,050 miles (140,878 miles accounting for resale value) over a 6-year period, or 458,678 miles (413,420 miles accounting for resale value) over a 12-year period.

Table 8
Aggregate utilization thresholds.

	6-year ownership period								
Abatement cost target ($/ton CO_2e reduced)	Aggregate utilization threshold (miles)	Total Abatement Cost ($/vehicle)	Total Emissions Advantage (tons CO_2e reduced/ vehicle)	Aggregate utilization threshold – clean electricity (miles)	Total Abatement Cost – clean electricity ($/vehicle)	Total Emissions Advantage – clean electricity (tons CO_2e reduced/ vehicle)	Abatement cost w/ extra battery ($/ton CO_2e reduced)	Total Abatement Cost w/ extra battery ($/vehicle)	Total Emissions Advantage w/ extra battery (tons CO_2e reduced/ vehicle)
50	244,437 (157,176)	2158 (1288)	43.16 (25.76)	224,583 (144,410)	3406 (2090)	68.13 (41.81)	355 (601)	13,803 (12,933)	38.88 (21.52)
92	222,246 (143,934)	3553 (2120)	38.62 (23.04)	193,836 (125,542)	5339 (3276)	58.03 (35.61)	441 (730)	15,198 (13,765)	34.46 (18.86)
100	218,372 (141,623)	3797 (2265)	37.97 (22.65)	188,984 (122,564)	5644 (3463)	56.44 (34.64)	458 (756)	15,442 (13,910)	33.72 (18.40)
107	215,092 (139,666)	4003 (2389)	37.41 (22.33)	184,952 (120,090)	5897 (3619)	55.12 (33.82)	473 (779)	15,648 (14,034)	33.08 (18.02)
150	197,912 (129,415)	5083 (3033)	33.89 (20.22)	163,810 (107,116)	7226 (4435)	48.18 (29.56)	564 (919)	16,728 (14,678)	29.66 (15.97)
200	181,424 (119,576)	6119 (3651)	30.60 (18.26)	145,067 (95,613)	8404 (5158)	42.02 (25.79)	674 (1092)	17,764 (15,296)	26.36 (14.01)
250	167,855 (111,479)	6972 (4160)	27.89 (16.64)	130,569 (86,717)	9316 (5717)	37.26 (22.87)	788 (1276)	18,617 (15,805)	23.63 (12.39)
286	159,456 (106,484)	7500 (4474)	26.22 (15.64)	122,011 (81,465)	9854 (6047)	34.45 (21.14)	872 (1415)	19,145 (16,119)	21.96 (11.39)
300	156,491 (104,699)	7686 (4586)	25.62 (15.29)	119,021 (79,630)	10,042 (6162)	33.47 (20.54)	905 (1470)	19,331 (16,231)	21.36 (11.04)
350	146,836 (98,938)	8293 (4949)	23.69 (14.14)	109,606 (73,852)	10,633 (6525)	30.38 (18.64)	1025 (1678)	19,938 (16,594)	19.45 (9.89)
400	138,532 (93,982)	8815 (5260)	22.04 (13.15)	101,783 (69,051)	11,125 (6827)	27.81 (17.07)	1150 (1899)	20,460 (16,905)	17.79 (8.90)
450	131,312 (89,674)	9269 (5531)	20.60 (12.29)	95,179 (64,999)	11,540 (7082)	25.65 (15.74)	1279 (2136)	20,914 (17,176)	16.35 (8.04)
500	124,979 (85,895)	9667 (5768)	19.33 (11.54)	89,530 (61,532)	11,895 (7300)	23.79 (14.60)	1413 (2390)	21,312 (17,413)	15.08 (7.29)
1242	78,811 (58,347)	12,569 (7500)	10.12 (6.04)	52,017 (38,512)	14,253 (8747)	11.48 (7.04)	4123 (10,691)	24,214 (19,145)	5.87 (1.79)
801	75,000	12,809 (6453)	15.99 (8.06)	–	–	–	4783 (3540)	24,454 (18,098)	5.11 (5.11)

Note: - = not applicable. The top line of each cell denotes an estimate assuming the EV and ICEV have no resale value at the end of the initial ownership period, a potential consequence of both vehicles' high aggregate utilization. The bottom line relaxes this assumption and includes resale value as a function of ownership duration. We present results for 6-year ownership durations, which represent the duration of vehicles' average first ownership period (Vehicles Getting Older, 2016). The bottom row presents abatement costs realized under current policy given a $7500 tax incentive and 75,000-mile aggregate utilization.

inequities in subsidy distribution. Current EV subsidies are disproportionately claimed by higher-income households, many of whom use these vehicles as secondary (or tertiary) compliments rather than primary substitutes (Nunes et al., 2022; The Plug-in Electric, 2019; Pucher & Renne, 2005). This procurement pattern demands even higher aggregate mileage to realize efficient abatement costs, mileage – existing utilization data suggests – that is unlikely to be realized (Nunes et al., 2022; Lu, 2006; Average, 2022; Maps & Data, 2020). Shifting the distribution of incentives towards high-utilization vehicles offers the possibility of a more equitable realization of EV subsidies, particularly among low-income households whose vehicle utilization patterns are more consistent with those required to achieve efficient abatement costs (Nunes & Hernandez, 2020; Mishel, 2018; Campbell, 2021; Shoja Rani, 2018; Rogers, 2015; Kooti et al., 2017).

We acknowledge that the realization of this outcome necessitates partial (or full) restructuring of EV subsidies away from credits alone. Overrepresentation of higher-income households in EV subsidy programs reflects – in part – distribution of program benefits as credits, rather than refunds. The former is less advantageous to low-income households, as these households lack sufficient tax liability to claim tax credits (which constitute most EV procurement incentive programs). Consequently, achieving equity in EV subsidy distribution and efficient abatement costs is unlikely absent first moving away from credit-only incentive programs, and second, prioritizing the distribution of subsidies to high utilization vehicles.

How might policymakers target subsidies towards vehicle utilization? In addition to providing procurement incentives to taxis and rideshare vehicles, programs can prioritize single-vehicle households, as multi-vehicle households often utilize EVs as a secondary or tertiary vehicle with less total mileage (Nunes & Woodley, 2023). Programs may also reward utilization via mechanisms such as road tax exemptions, toll exemptions, subsidized vehicle maintenance fees, or eligibility restrictions (e.g., only households whose historic annual utilization exceeds a specified threshold may claim procurement subsidies).

The racial and ethnic implications of directing EV subsidies towards high-utilization vehicles also warrant further discussion. Workers identifying as non-White are consistently overrepresented in industries characterized by high vehicle utilization (Labor Force Characteristics by Race & Ethnicity, 2018). This is particularly true of the ridesharing and taxi industries, which disproportionally serve as an employment source for Asian Non-Hispanic, Black Non-Hispanic, and Hispanic Americans (Hall & Krueger, 2018). While the reasons for overrepresentation of these groups in the ridesharing and taxi industry are varied, their presence reflects – in part – low barriers to occupational entry and historical and systemic disparities in educational access, which consequently impact long-term earnings potential vis-à-vis occupational choice (Quintana & Mahgoub, 2016).

Furthermore, existing literature suggests that lower-income households – which are disproportionately non-White (LaVeist, 2005) – often live farther away from urban centers, thereby requiring greater travel time, travel distances, and vehicle access than their wealthier counterparts (Mattioli, 2017; Mattioli, 2014; Mattioli & Colleoni, 2016; Guzman

Table 9
Aggregate utilization thresholds.

	12-year ownership period								
Abatement cost target ($/ton CO_2e reduced)	Aggregate utilization threshold (miles)	Total Abatement Cost ($/vehicle)	Total Emissions Advantage (tons CO_2e reduced/ vehicle)	Aggregate utilization threshold – clean electricity (miles)	Total Abatement Cost – clean electricity ($/vehicle)	Total Emissions Advantage – clean electricity (tons CO_2e reduced/ vehicle)	Abatement cost w/ extra battery ($/ton CO_2e reduced)	Total Abatement Cost w/ extra battery ($/vehicle)	Total Emissions Advantage w/ extra battery (tons CO_2e reduced/ vehicle)
50	513,943 (464,012)	4634 (4136)	92.68 (82.72)	465,838 (420,580)	7154 (6411)	143.07 (128.22)	184 (201)	16,279 (15,781)	88.47 (78.51)
92	459,225 (415,117)	7500 (6694)	81.52 (72.76)	393,064 (355,363)	10,965 (9826)	119.18 (106.81)	247 (267)	19,145 (18,339)	77.51 (68.69)
100	449,865 (406,821)	7990 (7131)	79.90 (71.31)	381,873 (345,334)	11,551 (10,352)	115.51 (103.52)	260 (280)	19,635 (18,776)	75.52 (67.06)
107	441,981 (399,783)	8403 (7500)	78.53 (70.09)	372,632 (337,053)	12,035 (10,785)	112.48 (100.80)	271 (292)	20,048 (19,145)	73.98 (65.57)
150	401,321 (363,494)	10,533 (9401)	70.22 (62.67)	325,034 (294,398)	14,528 (13,019)	96.85 (86.79)	336 (360)	22,178 (21,046)	66.01 (58.46)
200	363,272 (329,535)	12,525 (11,179)	62.63 (55.90)	284,004 (257,628)	16,677 (14,945)	83.38 (74.72)	414 (442)	24,170 (22,824)	58.38 (51.64)
250	332,648 (302,202)	14,129 (12,610)	56.52 (50.44)	252,994 (229,838)	18,301 (16,400)	73.20 (65.60)	493 (525)	25,774 (24,255)	52.28 (46.20)
286	314,056 (285,608)	15,103 (13,479)	52.81 (47.13)	234,976 (213,691)	19,244 (17,246)	67.29 (60.30)	551 (586)	26,748 (25,124)	48.54 (42.87)
300	307,468 (279,728)	15,448 (13,787)	51.49 (45.96)	228,731 (208,095)	19,571 (17,539)	65.24 (58.46)	573 (610)	27,093 (25,432)	47.28 (41.69)
350	286,399 (260,923)	16,551 (14,772)	47.29 (42.21)	209,231 (190,619)	20,593 (18,454)	58.84 (52.73)	655 (696)	28,196 (26,417)	43.05 (37.96)
400	268,510 (244,957)	17,488 (15,608)	43.72 (39.02)	193,215 (176,267)	21,431 (19,206)	53.58 (48.01)	738 (784)	29,133 (27,253)	39.48 (34.76)
450	253,132 (231,232)	18,293 (16,327)	40.65 (36.28)	179,827 (164,269)	22,132 (19,834)	49.18 (44.08)	822 (873)	29,938 (27,972)	36.42 (32.04)
500	239,771 (219,307)	18,993 (16,952)	37.87 (33.90)	168,469 (154,090)	22,727 (20,367)	45.45 (40.73)	908 (964)	30,638 (28,597)	33.74 (29.66)
1242	145,868 (135,497)	23,911 (21,341)	19.25 (17.18)	95,163 (88,397)	26,566 (23,808)	21.39 (19.17)	2370 (2551)	35,556 (32,986)	15.00 (12.93)
801	–	–	–	–	–	–	–	–	–

Note: - = not applicable. The top line of each cell denotes an estimate assuming the EV and ICEV have no resale value at the end of the initial ownership period, a potential consequence of both vehicles' high aggregate utilization. The bottom line relaxes this assumption and includes resale value as a function of ownership duration. We present results for 12-year ownership durations, which approximate the average age of vehicles in the United States vehicle fleet (Average, 2022; Vehicles Getting Older, 2016). The bottom row presents abatement costs realized under current policy given a $7500 tax incentive and 75,000-mile aggregate utilization.

& Bocarejo, 2017). Existing EV procurement incentive policies perpetuate these disparities by implicitly rewarding racial and ethnic groups whose vehicle utilization patterns are both less likely to produce large emissions reductions and less likely to deliver efficient abatement costs. Our analysis suggests that revisiting this approach may be warranted.

In addition to low earnings within ridesharing and taxi industries – which see a higher concentration of racial and ethnic minorities, we emphasize the importance of EV procurement incentives' proportional benefits. Given the reality that – owing to lower average income levels – transportation represents a greater proportion of minorities' total expenses (Passenger Vehicle Drivers, 2022; Cooper & Mundy, 2016; Bauer et al., 2021; Consumer Expenditure Surveys, 2022), financial incentives that reduce transportation costs may have a larger impact on these groups' vehicle procurement decisions while maximizing the efficiency of potential emissions reductions.[4] Furthermore, structuring such incentives as tax refunds rather than credits affords greater accessibility to minority households via reduced income requirements to obtain the full benefit.

We acknowledge that existing EV procurement policies do not explicitly seek to exclude specific racial and ethnic groups. However, by virtue of their design, these programs have historically benefited middle and high-income households who typically identify as White Non-Hispanic (The Plug-in Electric, 2019). Given that race and ethnicity in terms of stratification often determine socioeconomic status (SES), the relationships between SES, race, and ethnicity are invariably related (Ethnic & Racial, 2017; Williams et al., 2010). Redirecting government capital towards incentivizing purchases of high-utilization EVs offers a pathway towards rectifying this inequity while addressing an important public policy objective; namely, efficient emissions reductions.

4. Limitations

Limitations of our work warrant discussion.

First, uncertainties regarding future EV production emissions and cost – potentially owing to improvements in battery manufacturing processes – can affect our requisite aggregate utilization thresholds. Though it remains unclear whether further reductions in battery manufacturing costs may be realized due to rising material costs (Gearino, 2021), we apply sensitivity testing to our emissions and financial input parameters to assess to relative contribution of different factors. Given the relatively high abatement costs associated with incentivizing EVs with average annual utilization (i.e., 5000–11,000 miles/year), our results suggest the structure of current policy is unlikely to achieve economically efficient emissions reductions absent significant improvements to multiple parameters, such as EVs' MSRP, battery longevity, and insurance costs.

Second, given the nascent nature of EV adoption, there is currently little data on real-world battery longevity, particularly when subjected

[4] Such is the case in the ride hailing industry where drivers directly incur vehicle procurement costs. These costs are borne indirectly in the taxi industry via a gate fee (99).

to high annual utilization rates. Our model extrapolates from existing studies of battery degradation, which largely focus on outcomes under more modest driving behaviors. As such, it is possible that high annual utilization – owing to disproportionately increased cycle aging (i.e., capacity fade owing to repeated charge/discharge cycles) – could cause EV batteries to degrade more rapidly than our model predicts. However, emerging work suggests that calendar aging remains the dominant source of capacity loss and battery degradation even in higher utilization scenarios (De Gennaro et al., 2020; Leng et al., 2015).

Third, our model does not account for regional differences in climate and carbon intensity of electricity grids. The efficiency and range of EVs depends, in part, on ambient temperatures; namely, warmer climates can quicken battery degradation, while cooler temperatures can limit a battery's total capacity and thus EV range (Archsmith et al., 2015; De Gennaro et al., 2020; Leng et al., 2015; Lohse-Busch et al., 2013). Similarly, EV emissions depend on the relative cleanliness of the electricity grid, as less carbon-intense grids reduce emissions associated with EV fuel production, and vice versa (Rasbash et al., 2023; Woody et al., 2022; Vega-Perkins et al., 2023). Thus, geographic areas with moderate climates and cleaner electricity grids will realize – owing to improved battery longevity and efficiency of fuel production - lower aggregate utilization thresholds. Conversely, regions with especially warm or cool climates and more carbon-intense electricity grids will require greater aggregate utilization to meet abatement cost thresholds. We emphasize however that carbon-free electrical grids alone are insufficient to deliver economically efficient abatement costs.

Nevertheless, existing literature on regional and international differences in electric grid carbon intensities, fuel prices, climates, and vehicle utilization patterns can offer useful insights in translating our findings (Rasbash et al., 2023; Woody et al., 2022; Vega-Perkins et al., 2023). Namely, in states such as California, Nevada, Washington, New York (Woody et al., 2022; Vega-Perkins et al., 2023), New Mexico, and Oregon (Woody et al., 2022), as well as countries including Canada (Rasbash et al., 2023), Sweden, Norway, and France (Shafique & Luo, 2022), EVs' likely require less stringent utilization thresholds and TCO differentials to realize a given abatement cost target. Conversely, EVs utilized in regions such as Michigan, Ohio, Montana, Wyoming (Woody et al., 2022; Vega-Perkins et al., 2023), Iowa (Rasbash et al., 2023) and Utah (Woody et al., 2022) or countries such as Mexico (Rasbash et al., 2023), Korea, and China (Shafique & Luo, 2022) likely require more stringent thresholds. Moreover, even in racially or ethnically homogenous countries (e.g., Norway), our findings and subsequent emphasis on vehicle utilization-based policies may improve socioeconomic inequities in existing policies' distributions (Sovacool et al., 2019).

Fourth, our analysis focuses on standardized vehicles that are likely to represent the typical vehicle a household might purchase. However, emerging literature suggests that EVs may frequently replace relatively fuel-efficient ICEVs (Xing et al., 2021). To the extent such a substitution pattern is pervasive among prospective EV owners, our results may slightly overestimate the emissions benefit EVs offer, thereby raising the actual implied abatement cost. Similarly, we recognize that to the extent potential rebound effects may encourage EV drivers to travel additional miles relative to their ICEV counterparts, our results may slightly overestimate EVs' emissions benefit, raising implied abatement costs.

Fifth, to facilitate an apples-to-apples comparison between EVs and ICEVs, we standardize vehicle type. This entails comparing an EV sedan to an ICEV sedan as e-sedans represent the largest share of the EV market (Archsmith et al., 2022). We further note that sedans have historically represented the largest share of the conventional vehicle market and the greatest number of available EV types (Highlights of the Automotive, 2022; Alternative, 2022). While other vehicle profiles could be used (e.g., SUVs/crossovers), the lack of sufficient EV models in this market precludes meaningful comparison with conventional SUVs (Almeida et al., 2019). Nevertheless, future studies examining multiple vehicle segments and estimating aggregate emissions benefits via sales-weighted averages would offer valuable insights to policymakers.

Sixth and finally, our work does not address future economies of scale and technological advancements that may develop owing to increased EV procurement, which may improve EVs' potential emissions benefits and – consequently – lower their implied abatement cost. This decision is intentional, as existing literature suggests that supply-side incentives have a greater impact on prices and may more effectively reduce emissions than demand-side policies (García-Álvarez, 2020; Asheim et al., 2019), while additional work demonstrates that supply-side policies are frequently prerequisites for effective demand-side incentives (Crespi & Castillo, 2022; Reyes-Mercado et al., 2020). Therefore, if policymakers' primary goal is to promote future innovation rather than achieve present emissions reductions, policy should nevertheless be focused – at least initially – towards supply-side policies.

5. Conclusion

Despite the limitations discussed thus far, our results show consistent evidence of EV-incentives' potential to generate significant emissions reductions, even with battery replacements. However, the magnitude of these reductions is dependent in large measure on EV utilization. Aggregate utilization below 55,749 miles may – in the United States at least, - fail to generate any emissions benefit over ICEVs. Consequently, public policies aimed at reducing transportation emissions through EV adoption are more likely to garner benefits if focused on utilization, rather than simply market volume.

The potential for emission reductions should be caveated with an appreciation of economic efficiency. Because we estimate the typical lifecycle emissions of an ICEV to be 60.3 tons of CO_2e, the current federally provided $7500 subsidy per vehicle can at best have an emission abatement potential (with typical vehicle utilization) of $124/ton, which exceeds that of alternative policy options (Gillingham & Stock, 2018) as well as estimated $50/ton emissions benefit (Wagner et al., 2021). For the EV subsidy to be economically efficient and to have equal cost and benefit, the EV lifecycle emissions would have to be zero and the requisite subsidy $3015 per vehicle.

The challenge in garnering emission abatement through EV subsidy is further exacerbated when considering TCO. Even though EVs have lower operating costs, higher insurance costs and greater value depreciation (due to their higher sticker price) mean that the more EVs are used, the more expensive they become relative to ICEVs. To achieve a TCO of $7500, an EV would have to travel 159,456 miles within six years (or 58,347 miles if including resale value). If an EV remains in operation for 12 years, it may require a battery replacement—a cost of $11,645—which means that, perversely, the older the EV, the higher the subsidy required to overcome TCO differences relative to an ICEV. Our research suggests that an EV with comparable utilization rates to a typical ICEV always has a higher TCO, and battery replacements significantly widen TCO gaps.

The TCO difference between EVs and ICEVs may be counteracted, though, when considering the potential for extremely high vehicle utilization, such as taxis or rideshare. For example, EVs that are utilized at more than 450,000 miles over 5 years have advantages over ICEVs for both emissions and TCO. This suggests that subsidies targeted at high utilization vehicles (e.g., taxis and single-vehicle households) are far more likely to reduce both emissions and produce net financial benefits to the EV consumer. Similarly, programs that incentivize vehicle utilization over simple vehicle procurement (e.g., toll exemptions, subsidized vehicle maintenance fees) can offer an improved cost-to-benefit ratio in abating CO_2 emissions. Conversely, EV subsidies that are mostly dispersed to homes with low vehicle utilization are far less likely to have either environmental or financial benefits.

Our findings are timely given government interest in widespread EV adoption. EV procurement incentives feature prominently in current U.S. government efforts to reduce carbon emissions, as do grid decarbonization efforts. However, passage of legislation instantiating these efforts remains challenging owing – in part – to financial concerns. Our work can help inform these efforts. We demonstrate that maximizing emissions reductions per dollar spent may entail shifting emphasis away from the universal application of EV subsidies to the adoption of a more targeted approach; one that considers behavioral heterogeneity in EV utilization. We further note that this approach would disproportionally benefit racial and ethnic minorities who have historically been excluded from such programs.

We emphasize that our study does not cast judgment on the economic wisdom of EV subsidies. The potential for accelerating spill-over benefits or economies of scale for the EV industry is outside the scope of this analysis, as is any assessment of the fiscal and economic impacts from additional federal subsidy. We note however, that while it is possible for these subsidies to produce environmental benefits, the magnitude of benefit is dependent on vehicle utilization. Consequently, consideration of this parameter in subsidy policies warrants scrutiny by policymakers.

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Declaration of Competing Interest

The authors declare no competing interests.

Data availability

Data will be made available on request.

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Supplementary materials

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