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Total cost of ownership of electric and gasoline used vehicles

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Supplementary material for this article is available online

Abstract

We assess the total cost of ownership (TCO) of internal combustion engine (ICEV), hybrid (HEV), plug-in hybrid (PHEV), and battery electric vehicles (BEVs) in the United States. As previous studies have shown, we find that current new BEVs, with some exceptions for smaller or shorter-range vehicles, have a higher TCO than conventional alternatives. However, we also present the first comparative analysis of the TCO of *used* vehicles, which make up 70% of all vehicle purchases in the U.S. We find that for used vehicles, BEVs have the lowest TCO among all powertrains. As vehicle TCO varies spatially and with use patterns, we test 5 different vehicle classes, 17 different U.S. cities, and 5 different charging strategies. The finding that BEVs have the lowest total cost for used vehicles is robust across these variables and is largely driven by vehicle depreciation patterns. We conduct a regression analysis based on 260 000 publicly available used vehicle listings, collected from January to December of 2024. We find that BEVs depreciate more rapidly than other powertrains in the first several years of vehicle life but follow similar depreciation patterns afterwards. With a 7 year ownership period, buying a used (3 year-old) midsize SUV vs a new midsize SUV has a TCO savings of approximately $3000 for an ICEV, $1000 for an HEV or PHEV, and $13 000 for a BEV. These results highlight an opportunity for savings via BEV adoption among used vehicle purchasers.

1. Introduction

Transportation is responsible for 28% of U.S. greenhouse gas (GHG) emissions [1], and 16% of U.S. household expenditures [2], making it the largest emitting sector of the U.S. economy and the second largest contributor to U.S. household costs (after housing). Because electric vehicles have lower life cycle GHG emissions than conventional vehicles [3], vehicle electrification is one of the main strategies being pursued to decarbonize this sector [4]. Yet high purchase prices are a large barrier to battery electric vehicle (BEV) adoption [5], and transportation costs are a significant burden for many households.

Vehicle total cost of ownership (TCO) measures all the costs required to own and operate a vehicle. Common components of TCO include the purchase of the vehicle, fuel (gasoline or electricity), insurance, maintenance, repairs, taxes, and fees. Vehicle TCO has been compared across countries [6], cities [7], and neighborhoods [8]. Others have noted the importance of vehicle class [9, 10] and charging patterns [8, 11, 12]. Internal combustion engine vehicles (ICEVs) currently have lower upfront (purchase) costs, but BEVs generally have lower recurring costs due to lower refueling and maintenance costs. This allows BEVs to break even and become cheaper after a number of years, but currently in the U.S. this advantage only exists for smaller and low range BEVs [13]. Previous studies have focused on the TCO to the first purchaser of a vehicle. No TCO studies have examined TCO from the perspective of a used vehicle consumer even though used vehicles make up 70% of vehicle purchases in the U.S [14].

One major source of uncertainty in the cost of used vehicles is depreciation. Previous studies have collected used vehicle prices from sources including Edmunds, Kelly Blue Book, and Marketcheck. Schoettle and Sivak found that BEVs depreciated more quickly than ICEVs when incentives were not included, but found similar retention rates (RR) (i.e., how much value a vehicle retains over time) when incentives were included [15]. Guo and Zhou similarly found lower RRs for BEVs in general, with Tesla vehicles as a notable exception having the highest RR among all vehicles (including ICEVs) [16]. Schlotter found a 10.4% annual depreciation rate for ICEVs and a 13.9% annual depreciation rate for BEVs [17]. In contrast, Burnham *et al* found that BEVs and plug-in hybrid electric vehicles (PHEVs) had higher 3 year value retention than ICEVs and hybrid electric vehicles (HEVs) [18]. Rush *et al* also found higher 3 year RRs for BEVs, while noting that over longer periods the RR was lower [19]. Most recently, Roberson *et al* found that although BEVs and PHEVs depreciated more rapidly than ICEVs and HEVs, the difference was decreasing for more recent model years and for models with greater ranges [20]. Despite some disagreement, the general consensus from these studies is that the gap between ICEV and BEV depreciation was quite large through 2016 but has been shrinking since then. Notably, each of these studies consider vehicle model years prior to 2020, in part due to disruptions to the used vehicle market from the Covid-19 pandemic. However, given the trend in depreciation rates prior to 2020, updated depreciation data are critical to understanding the total cost of vehicle ownership and have important implications for BEV adoption.

Here we conduct the first comprehensive TCO analysis focused on *used vehicles*. We collect data on used vehicle sales from craigslist.org and use this data to calculate depreciation rates for each powertrain. We then integrate these data into a TCO model to compare ownership costs over different ownership periods, and for different vehicle classes, powertrains, and locations. These results will help inform consumers and policy makers as the transportation sector transitions to a zero-carbon future.

2. Methods

2.1. Goal and scope

We compare the TCO of vehicles across 4 powertrains (ICEVs, HEV, PHEVs, and BEVs) and 5 vehicle classes (figure 1(a)) in 17 different U.S. cities (figure 1(b)). In addition to these cities, our base case uses U.S. average values. We obtain key vehicle parameters from Argonne National Laboratory's Autonomie model [21]. These vehicles are not real models from specific vehicle manufacturers; rather, they are representative synthetic vehicles that meet certain performance thresholds enabling comparison across powertrains (see supplemental note 1).

2.2. Vehicle depreciation model

2.2.1. Vehicle cost data collection

To estimate the purchase and sale price of used vehicles within our TCO model, we developed vehicle depreciation curves (figure 1(c)). We collected 4000 000 vehicle postings on craigslist for one year (January through December of 2024). Each posting was taken from with a 50 mile radius of the cities investigated in this study. Craigslist, which has not been used as a data source in any previous vehicle depreciation studies, offered several distinct challenges, as well as opportunities. As craigslist data is self-reported by each individual seller, the data required significant cleaning and filtering (supplemental note 2). Analysis was performed on a final data set of 260 000 vehicles.

2.2.2. Vehicle cost regression

Following the work of Roberson *et al* [20], we calculate the RR as the listed vehicle price divided by the vehicle's manufacturer's suggested retail price (MSRP) (equation (1)). We find the MSRP by matching the VIN to data on carsheet.io [22]. For vehicles without an exact match (for example, the make and model match but there are multiple trims) we use the mean value of reported MSRPs for that make and model.

$$\text{Retention Rate} = \frac{\text{Listed Price}}{\text{MSRP}} \tag{1}$$

To calculate depreciation we use an exponential decay model (equation (2)). Like Roberson *et al*, we conduct a linear regression in which we regress the natural log of the retention rate on age interacted with powertrain type. We also include age interacted with the vehicle class, age interacted with the natural log of the MSRP (as in Schloter) [17], and the vehicle's mileage divided by its age (to avoid multicollinearity of age and mileage). Finally, we include the seller type—dealership or private owner—a unique variable enabled by using craigslist as the data source.

$$\begin{aligned}\log(\text{RR}) \sim\ & \text{Miles per year} + (\text{Age} * \text{Powertrain}) \\ & + (\text{Age} * \text{Class}) + (\text{Age} * \text{Seller Type}) \\ & + (\text{Age} * \log(\text{MSRP}))\end{aligned} \tag{2}$$

Previous studies have noted large differences in Tesla and Non-Tesla BEV depreciation [20]. Our goal is to compare powertrains generally, not specific manufacturers, so we do not include the vehicle manufacturer as an independent variable. Additionally, our

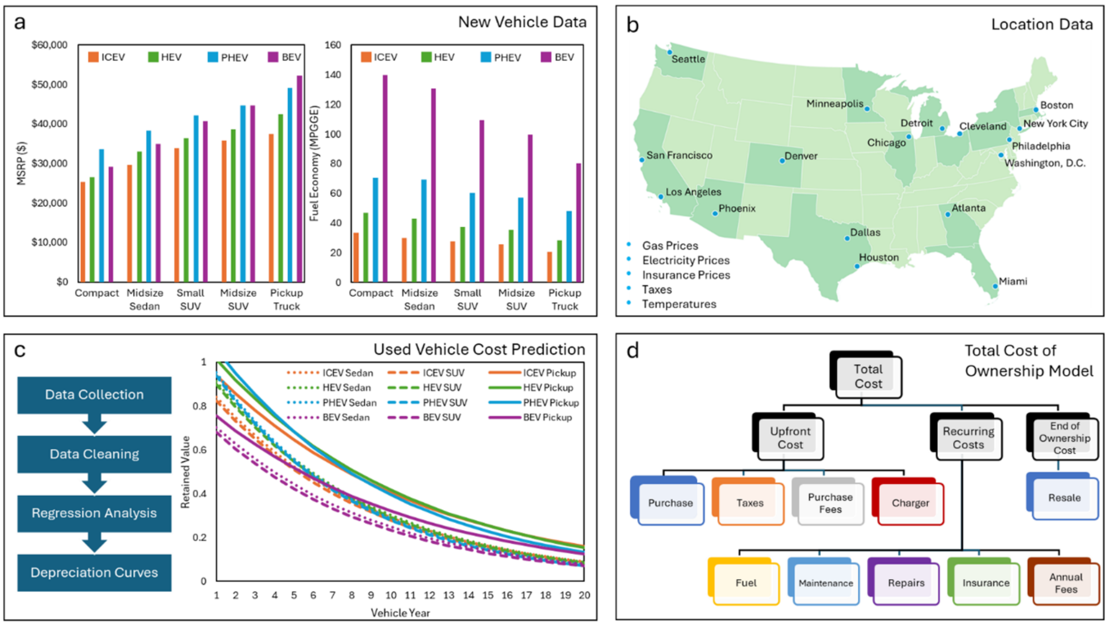

Figure 1. (a) The manufacturer's suggested retail price (MSRP) and fuel economy for the combinations of vehicle class and vehicle powertrain used in this study. (b) The 17 U.S. cities investigated in this study, and the location specific data that was used in modeling. (c) Vehicle depreciation curves resulting from regression analysis of used vehicle listings collected from craigslist.org. (d) The components of total cost of ownership.

data set shows a much smaller difference in Tesla and Non-Tesla RRs compared to previous studies (supplemental note 3). Studies have demonstrated a correlation between BEV range and retained value [20]; however, these data are not available in our dataset.

2.3. TCO model

As shown in figure 1(d), vehicle TCO is the sum of upfront costs, paid at the time of purchase; recurring costs, paid over the lifetime of the vehicle; and end of ownership costs, paid (or gained) when the vehicle ownership period ends through sale or scrappage (equation (3)).

$$\text{TCO} = \text{Upfront Costs} + \text{Recurring Costs} + \text{End of Ownership Costs} \quad (3)$$

We only include costs to the consumer; there are also social costs attributable to vehicles, including GHG emissions, local air pollutants, traffic congestion, road safety, and noise [23].

2.3.1. Upfront costs

The largest upfront cost is the purchase price of the vehicle. Vehicle MSRP's are adjusted from 2023 dollars to 2025 dollars. We note that PHEV pickup trucks do not currently have a real-world equivalent on the market in the U.S.; therefore, there is greater uncertainty associated with the results for that combination of vehicle class and powertrain.

The purchase price for new vehicles is the adjusted MSRP, while the purchase price for used vehicles is determined by the depreciation model described in section 2.2. We assume the vehicle is initially purchased from a dealership (i.e. the seller type in the regression is set as dealer) and at the end of the ownership period the vehicle is resold by an individual (i.e. the seller type in the regression is set as owner). While 80% of new vehicle purchases are financed, only 37% of used vehicle purchases are financed in the U.S [24]. Therefore, we assume the entire cost of the vehicle is paid at the time of purchase (no financing). Other upfront costs include sales tax and fees. Sales taxes vary by city, and in some cities also vary by fuel economy and vehicle weight. Fees include registration, title, and license fees, as well as other state or local fees. Many studies related to BEV adoption have focused on the impact of subsidies [7, 25, 26], but we do not include any government incentives (e.g., for PHEVs, BEVs, or chargers) in our analysis.

For BEVs only, we include the cost of installing a level 2 home charger (including equipment, permitting, and labor) as part of the upfront cost. Labor costs vary by city, resulting in charger costs of $2000–$3000. We include this because currently most U.S.

BEV purchases are from first-time BEV purchasers (85% in 2023) [27]. This cost would not apply to consumers that already have home charging access.

$$\text{Upfront Costs} = \text{Purchase} + \text{Taxes} + \text{Fees} + \text{Home Charger} \quad (4)$$

2.3.2. Recurring costs

Recurring costs paid over the ownership period of the vehicle include refueling (gas or electricity), insurance, maintenance, repairs, and annual fees (equation (5)). Each of the recurring costs are discounted, using a discount rate, d, of 5% to account for the time value of money.

$$\text{Recurring Cost} = \sum_{y=1}^{Y} \frac{\text{Fuel}_y + \text{Insurance}_y + \text{Maintenance}_y + \text{Repairs}_y + \text{Fees}_y}{(1+d)^y} \quad (5)$$

Fuel costs are determined by the miles traveled in each month, the vehicle's fuel economy (which we adjust based on monthly temperatures in each city [28]), the percentage of city and highway driving [29], the percentage of electric driving (for PHEVs), and the cost of either gasoline or electricity in each city in each month. For gas prices we use the monthly price averaged over the last five full years (2019–2023) in each city [30]. For electricity prices we use rate plans from a local electric utility in each city, and location specific public charging prices, rather than average electricity prices. Due to time-of-use pricing and consumer's ability to adjust their charging timing in response to these prices, average electricity prices may not reflect the cost that a BEV owner would actually pay to charge their vehicle [13].

Insurance costs are based on the formula used by Liu *et al* [31], in which costs are dependent on MSRP and powertrain; the mileage adjustment used by Parker *et al* [8], in which cost depends on annual miles, and state level adjustments as used in Woody *et al* [13], in which the cost is modified based on the average insurance cost in each state.

For maintenance (i.e. planned replacement of parts) we use the component replacement schedule and corresponding component costs for each powertrain from Argonne National Laboratory's BEAN model [18]. Replacement of the high voltage li-ion battery is not included in our base case maintenance schedule. For repairs (unplanned care and upkeep) we use the formula from the BEAN model, in which annual repair costs are dependent on the vehicle's age, class, powertrain, and MSRP.

We collect data on recurring fees from city and state government websites and apply these to each vehicle. Most states require annual or bi-annual renewal of the vehicle's registration. Of the 17 cities in this study, 12 have additional annual fees for BEVs, ranging from \$50 to \$250. For details on each TCO component see supplemental notes 4–11. Other recurring costs that are excluded from this study include parking, tolls, and the owner's time value of charging, maintenance, and repairs [32].

2.3.3. End of ownership costs

End of ownership costs are applied as a credit to the vehicle owner. We use the resale value of the vehicle, as determined by the depreciation model, for a private sale using a 5% discount rate.

$$\text{End of Ownership Costs} = -1 * \frac{(\text{Resale Price})}{(1+d)^y} \quad (6)$$

2.3.4. Parameters

Although average annual mileage varies by vehicle class and powertrain and generally decreases as vehicles age, we use a constant annual mileage (15 000 miles per year) throughout this study in order to compare fairly across classes, powertrains, and ownership periods. In general, BEVs have a greater cost savings for consumers with higher annual vehicle miles traveled (VMT), as they have lower operating costs (fuel, maintenance, and repairs) than other powertrains [13].

In our base case charging scenario, we assume the vehicle owner charges 80% at home at 20% at public chargers [33]. Of the home charging, we use 50% off-peak prices, 25% part-peak prices, and 25% peak prices, where applicable. For public charging we use 50% level 2 charging and 50% DC fast charging. We explore 4 additional charging scenarios, with different amounts of on- vs off-peak pricing and home vs public charging, in section 3.4.

For our base case we present used vehicles purchased after 3 years of vehicle life (e.g., after a 36 month lease) and sold after 10 years of vehicle life (i.e., a 7 year ownership period). We explore different purchase years and ownership periods in section 3.5. We assume all vehicles have sufficient lifetime to last through each ownership period.

Table 1. Regression coefficients used to estimate retention rate.

Variable	Coefficient	*t* value	*p* value
Intercept	2.456 89	59.687 15	0.000 00***
Miles per year	−0.000 02	−225.436 83	0.000 00***
Age	0.114 09	23.500 32	0.000 00***
ln(MSRP)	−0.207 01	−52.281 85	0.000 00***
Fuel = diesel	0.430 86	29.487 50	0.000 00***
Fuel = HEV	0.107 33	16.118 27	0.000 00***
Fuel = PHEV	0.191 38	8.595 88	0.000 00***
Fuel = BEV	−0.147 58	−17.931 76	0.000 00***
Class = SUV	0.021 43	6.686 42	0.000 00***
Class = pickup	0.134 26	26.094 16	0.000 00***
Seller = owner	−0.039 83	−8.780 54	0.000 00***
Age:ln(MSRP)	−0.021 55	−45.852 73	0.000 00***
Age:fuel = diesel	−0.034 65	−20.536 63	0.000 00***
Age:fuel = HEV	−0.002 64	−3.265 54	0.001 09 **
Age:fuel = PHEV	−0.010 00	−3.044 31	0.002 33 **
Age:fuel = BEV	0.005 89	4.107 74	0.000 04***
Age:class = SUV	0.001 72	4.588 42	0.000 00***
Age:class = pickup	0.029 41	46.901 22	0.000 00***
Age:seller = owner	−0.010 09	−20.770 56	0.000 00***
Observations		259 685	
Adjusted R-squared		0.61660	
Signif. codes:		'***' = 0.001, '**' = 0.01, '*' = 0.05	

3. Results and discussion

3.1. Vehicle depreciation

Table 1 shows the results of the linear regression (equation (2)) used to estimate vehicle depreciation. The categorical variables are relative to a gasoline vehicle (for fuel type), a sedan (for vehicle class), and a dealership (for seller type). Compared to ICEVs, HEVs and PHEVs retain more value for the first several years, though this difference eventually disappears. BEVs have much lower initial value retention than other powertrains, though they follow similar depreciation patterns after several years. Diesel vehicles have the highest retained value among all the powertrains. Across vehicle classes, pickup trucks retain greater value initially and over time than sedans or SUVs. Vehicles sold by a dealer retain more value than vehicles sold by an individual, and vehicles with a higher MSRP generally lose value more quickly than vehicles with a lower MSRP.

The resulting regression is applied to the synthetic vehicles of each powertrain and class using the MSRP from Autonomie (adjusted to 2025 dollars) and with 15 000 annual VMT. The resulting depreciation curves are shown in figure 2. For a consumer buying a 3 year old used vehicle from a dealership (figures 2(a)–(c)), our model estimates that they would pay 70%–84% of the vehicle's MSRP for ICEVs, 75%–89% for HEVs, 77%–91% for PHEVs and 58%–67% for BEVs, with the lower bound representing sedans and SUVs and the upper bound representing pickup trucks. These findings are somewhat higher than what is reported in the literature, but they correspond with Roberson *et al*'s finding that vehicles generally retained more value post-2020 following the Covid-19 pandemic than in prior years (potentially due to increases in the average range of BEVs). We also find higher initial retained value 'off the lot' than previous studies. Though not the focus of our study, this may be related to the significant price increases, for new and especially for used vehicles, that occurred between 2021 and 2023 (see supplemental note 12). For HEV and PHEV pickup trucks, our regression results in a value greater than one at year one (figures 2(c) and (f)). It is improbable that this reflects real year one depreciation (since this would mean consumers could make a profit selling their one-year-old used vehicles); however, we note that this does not impact our TCO results, which rely on the MSRP for new vehicles (i.e. retained value equals one at year zero). For a consumer selling their 10 year-old vehicle as a private owner (figures 2(d)–(f)), our model estimates that they would recoup 28%–41% of the vehicle's MSRP for ICEVs, 29%–42% for HEVs, 28%–40% for PHEVs, and 23%–32% for BEVs with the lower bound representing sedans and SUVs and the upper bound representing pickup trucks. A lower retained value does not necessarily result in a lower purchase price, as MSRP generally increases with increased amounts of electrification.

3.2. Gasoline vs electric TCO

For our base case we present used vehicles purchased (from a dealership) after 3 years of vehicle life (e.g. after a 36 month lease) and sold (by the owner) after 10 years of vehicle life (i.e. a 7 year ownership period). These results are compared to a new vehicle and a

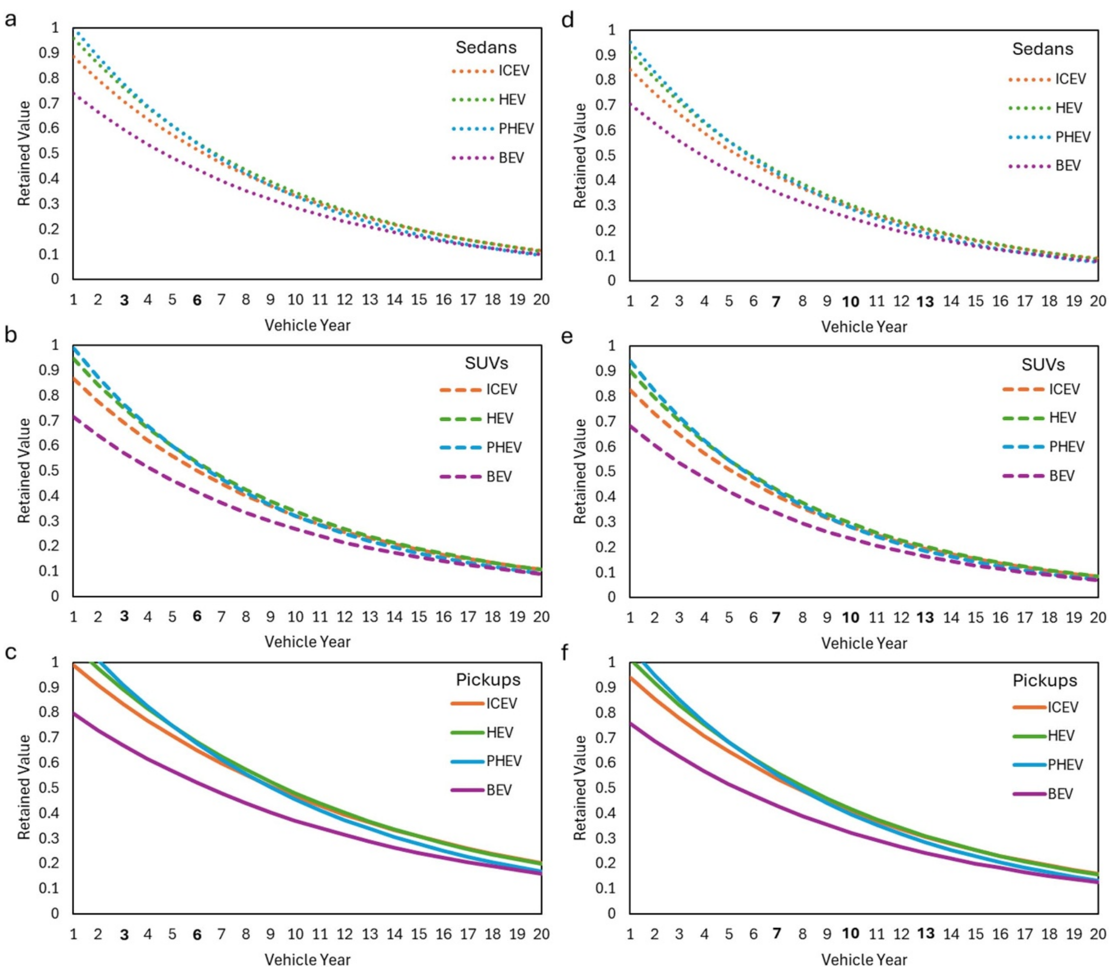

Figure 2. Vehicle depreciation regression applied to the synthetic vehicles used in this study, with 15 000 annual miles, for (a) sedans, (b) SUVs, and (c) pickup trucks with seller type set to 'dealer' (used for purchase of the vehicle), and (d) sedans, (e) SUVs, and (f) pickup trucks with seller type set to 'owner' (used for the resale of the vehicle) When applied to the total cost of ownership model, the initial purchase price uses the MSRP for a new vehicle (year 0), or the MSRP multiplied by the dealership regression value (a)–(c) at years 3 or 6. The resale of the vehicle uses the MSRP multiplied by the owner regression values (d)–(f) at years 7, 10, or 13.

6 year-old vehicle over a 7 year ownership period (figure 3).

For new vehicles, BEVs are more expensive to purchase, more expensive to insure, typically have additional annual fees, and have an additional cost for home charger installation. BEVs have lower costs for maintenance, repairs, and refueling. Across all vehicle classes, HEVs have the lowest TCO for new vehicles. The difference between the BEV and alternatives increases with vehicle size. For new compact vehicles the ICEV and the BEV have a similar TCO. Over a longer ownership period, new compact and midsize sedan BEVs may have a lower TCO than ICEVs [13]. However, for new midsize SUVs and pickup trucks BEVs have a much larger TCO than ICEVs.

For used vehicles, BEVs have the lowest TCO across all vehicle classes. Between the new and used vehicle scenarios, the total mileage is kept constant. Therefore, many costs (charger, fuel, insurance, purchase fees, and annual fees) are the same in figures 3(a)–(c). The BEV switching from often the most expensive (for new vehicles) to always the least expensive (for used vehicles) is attributable to changes in 2 major cost components. First is the purchase and sale prices. Due to BEVs exhibiting greater initial depreciation than other powertrains, followed by slightly slower depreciation than other powertrains, the net purchase cost (purchase-resale) for BEVs is much lower for the used vehicles than the new vehicles. Using the midsize SUV as an example, the net purchase cost for the new BEV is \$34 100 vs a 3 year-old used BEV net purchase cost of \$18 300 (\$15 800 difference). While this trend exists for other powertrains, the magnitude is lower. For the ICEV midsize SUV the net purchase cost (purchase-resale) for the new vehicle is \$25 600 vs \$17 800 (\$7 800 difference) for the 3 year-old used ICEV.

The second major factor is maintenance and repair costs. Across all powertrains, maintenance and repair costs are higher for used vehicles than

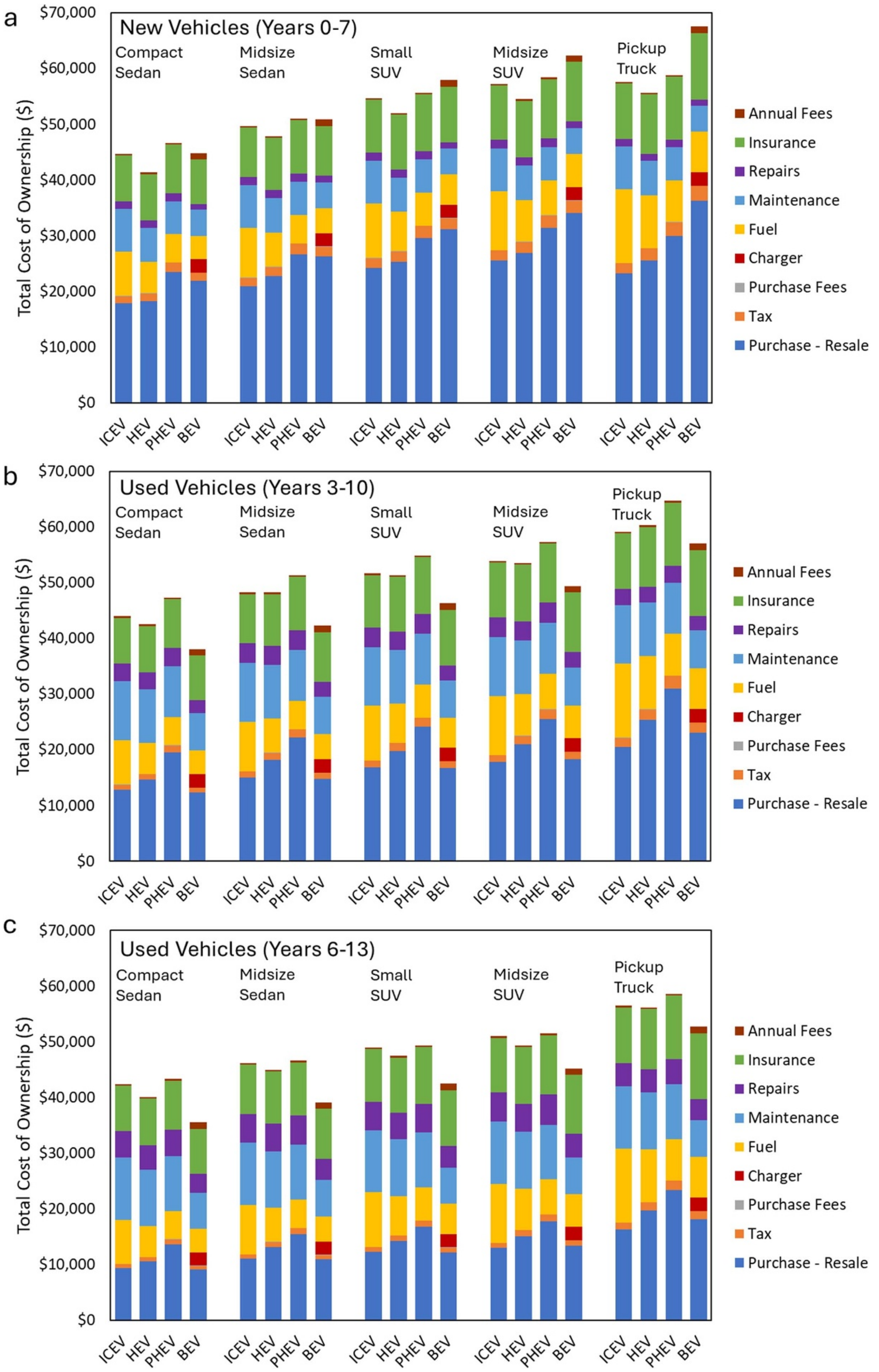

Figure 3. Seven-year total cost of ownership of internal combustion engine vehicles (ICEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and battery electric vehicles (BEV), across vehicle classes, (a) for a new vehicle purchased at year 0 of vehicle life and sold after 7 years of vehicle life, (b) for a used vehicle purchased after 3 years of vehicle life and sold after 10 years of vehicle life, and (c) for a used vehicle purchased after 6 years of vehicle life and sold after 13 years of vehicle life, using U.S. average values and 15 000 annual miles.

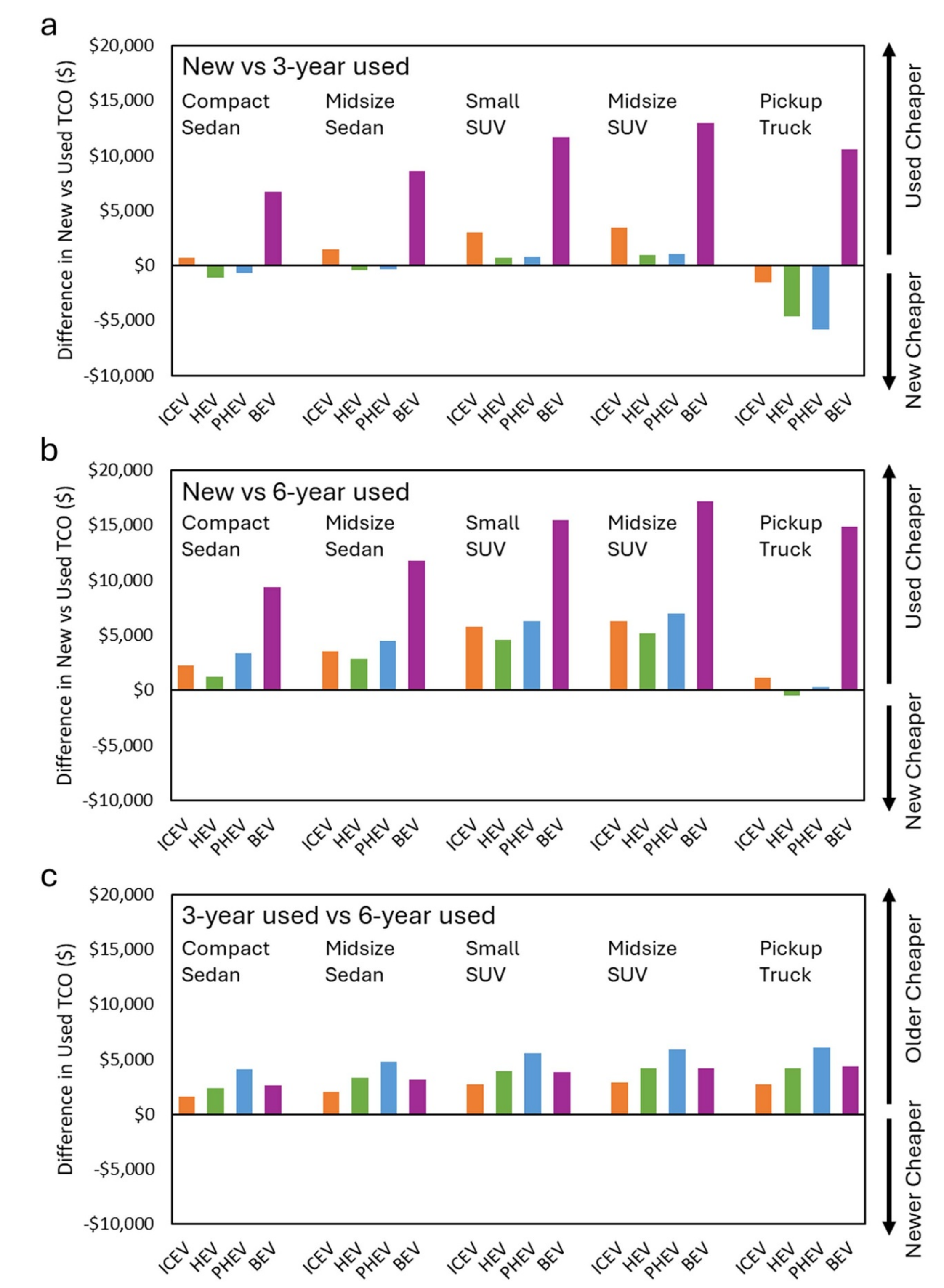

Figure 4. Difference in the seven-year total cost of ownership of internal combustion engine vehicles (ICEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and battery electric vehicles (BEV), across vehicle classes, for (a) the new vehicle compared to the 3 year used vehicle, (b) the new vehicle compared to the 6 year used vehicle, and (c) the 3 year used vehicle vs the 6 year used vehicle, using U.S. average values and 15 000 annual miles.

new vehicles. However, since BEVs have lower maintenance and repair costs than other powertrains, the magnitude of the difference is lower for new and used BEVs than for new and used ICEVs, HEVs, and PHEVs. For example, the new BEV midsize SUV has a combined maintenance and repair cost of $5900 while the 3 year-old used BEV has a combined cost of $9600 ($3700 difference). The new ICEV midsize SUV has a combined maintenance and repair cost of $9200 while the 3 year-old used ICEV has a combined cost of $14 200 ($5000 difference). Because our maintenance costs are based on manufacturers' recommended

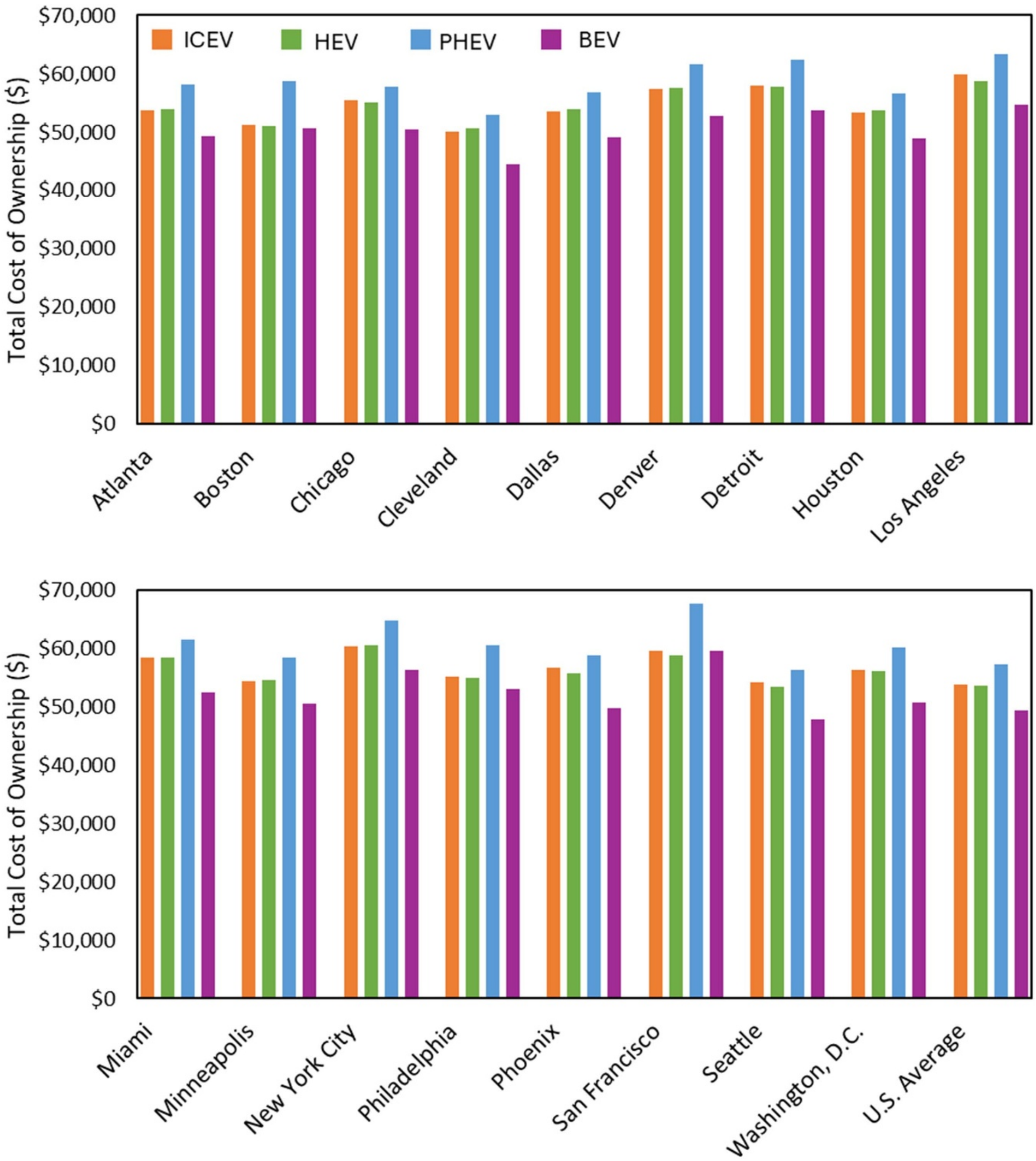

Figure 5. Total cost of ownership for a used midsize SUV purchased after 3 years of vehicle life and sold after 10 years of vehicle life in different U.S. cities. Other vehicle classes are shown in supplemental note 18.

replacement schedules, the values may reflect a high estimate (as consumers may replace parts less frequently than manufacturers recommend).

Combining these effects shows that used BEVs have a significantly lower TCO than new BEVs ($6700–$13 000 savings for the 3 year-old used vehicle compared to the new vehicle). For ICEVs, the difference in TCO by buying a 3 year-old used sedan or SUV is compared to a new sedan or SUV is $700–$3400, while for HEVs and PHEVs the difference is approximately $1000 or less (figure 4(a)). There is a larger TCO savings offered by buying a 6 year-old used sedans or SUVs ($1300–$6900) (figure 4(b)). Pickup trucks follow a different trend than other vehicle classes; new pickup trucks have a lower TCO than the 3 year-old used vehicles across all powertrains. This is largely due to the higher retained value for pickup trucks (see figure 2) and may reflect the specific vehicle market in 2024 (when data were collected) in which some used vehicles could be sold at or above their original MSRP. Across all powertrains and vehicle classes, the 6 year-old used vehicles have a lower TCO than the 3 year-old used vehicles (figure 4(c)).

Sensitivity to battery size, battery replacement, hybrid powertrain configuration, electricity prices, and gasoline prices are shown in supplemental notes 13–17. Our base case uses a 50 mile range PHEV and a 300 mile range BEV. With a smaller range BEV, the savings offered by a used BEV increases compared to the base case. However, for 400 mile range BEVs, the used BEV used only provides savings compared

Table 2. Charging scenarios.

	Home charging			Public charging	
No public charging	100%			0%	
	Off-peak	Part-peak	On-peak	Level 2	DC fast charging
	80%	10%	10%	—	—
Rare public charging	Home charging			Public charging	
	90%			10%	
	Off-peak	Part-peak	On-peak	Level 2	DC fast charging
	80%	10%	10%	50%	50%
Occasional public charging (base case)	Home charging			Public charging	
	80%			20%	
	Off-peak	Part-peak	On-peak	Level 2	DC fast charging
	50%	25%	25%	50%	50%
Frequent public charging	Home charging			Public charging	
	60%			40%	
	Off-peak	Part-peak	On-peak	Level 2	DC fast charging
	50%	25%	25%	75%	25%
All public charging	Home charging			Public charging	
	0%			100%	
	Off-peak	Part-peak	On-peak	Level 2	DC fast charging
	—	—	—	75%	25%

to alternative powertrains for small vehicle classes (compact, midsize sedan) and does not offer savings for larger vehicles. In the U.S., BEV batteries have a minimum 8 year or 100 000 mile warranty, though some manufacturers have warranties up to 10 years or 175 000 miles [13]. If a battery requires replacement within the warranty period, there would be no cost to the consumer. In a worst-case scenario (the battery requires replacement just after the warranty period ends), the additional cost would shift the used BEV from the lowest TCO to the highest TCO option across all vehicle classes. The specific powertrain configuration (parallel or power split) impacts the fuel economy and MSRP for HEVs and PHEVs, though this does not significantly change our results. We tested a 20% increase in electricity prices, finding that in the used vehicle market the BEV remains the cheapest powertrain across all vehicle classes. With a 20% increase in gasoline prices, the ordering of powertrains is unchanged for used vehicles. For new vehicles, the BEV becomes cheaper than the ICEV for compact and midsize sedans, though the HEV remains the cheapest powertrain across all classes.

3.3. Regional cost variability

TCO varies significantly from city to city. For a midsize SUV purchased after year 3 and sold after year 10 of the vehicle's lifetime, ICEV TCO ranges from $50 000 to $60 400; HEV TCO ranges from $50 600 to $60 600; PHEV TCO ranges from $52 900 to $67 700; and BEV TCO ranges from $44 400 to $59 500. Of the cities investigated, Cleveland is the least expensive city across all powertrains, whereas New York City is the most expensive city for ICEVs and HEVs and San Francisco is the most expensive city for PHEVs and BEVs. Different components drive these different costs in each city. For example, San Francisco has the highest electricity cost, Los Angeles has the highest gasoline cost, New York City has the highest insurance cost, and Chicago has the highest additional annual fee for BEVs. Houston, Dallas, and Cleveland all have low electricity and gasoline prices. Notably, the BEV has a lower TCO than the ICEV, HEV, and PHEV alternatives in almost every city investigated (figure 5). The only exceptions are San Francisco and Boston, where the TCO of the BEV is approximately equal to the HEV.

3.4. Charging patterns

The cost a BEV owner pays for charging depends on their personal charging habits. We explore 5 different charging scenarios for different consumer archetypes (table 2). The '*no public charging*' and '*rare public charging*' scenarios are cost-conscious consumers who do most of their charging at home during off-peak hours. The '*occasional public charging*' scenario is the base case, in which a consumer generally charges at home and off-peak, but does not as consistently as the cost-conscious consumers. The '*frequent public*

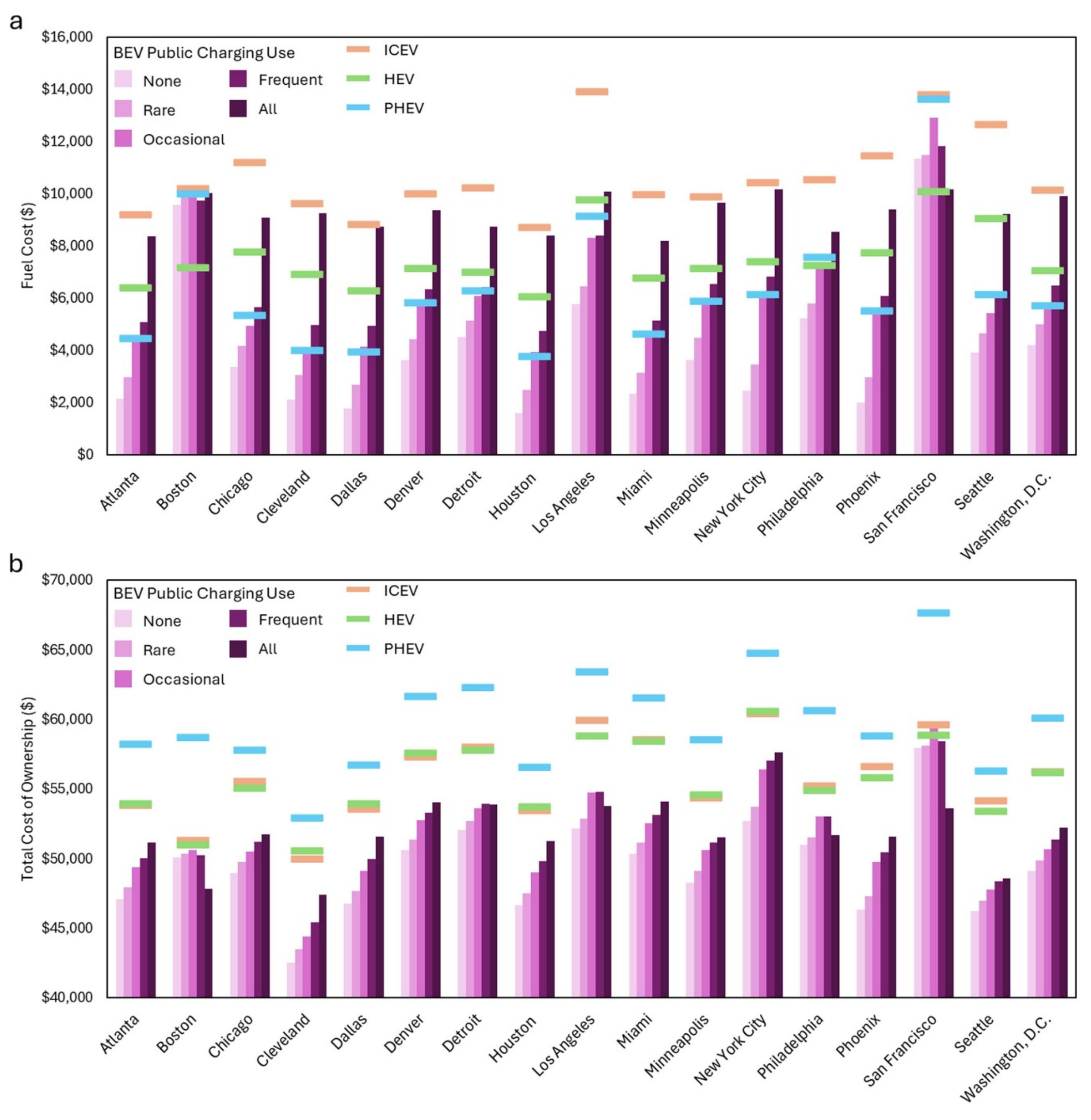

Figure 6. (a) Fuel cost, and (b) total cost of ownership for a used midsize SUV purchased after 3 years of vehicle life and sold after 10 years of vehicle life under 5 different charging scenarios in 17 cities. The legend for BEVs refers to the charging scenario, as explained in table 2. Note the y-axis in figure (b) does not start at zero.

charging' and '*all public charging*' scenarios are consumers that rely on public charging because their travel patterns require frequent charging en-route, or they do not have access to home charging (the cost of a home charger is excluded from the '*all public charging*' scenario). As public charging is a greater part of their charging routine, these consumers rely more on level 2 chargers, and less on DC fast chargers, (as a percentage of public charging) than the other scenarios. For PHEVs we use the base case percentages for peak pricing and assume 100% of charging is done at home.

In most cities, a BEV owner that relies only on public charging can expect to spend 2–4 times as much on charging as a consumer charging only at home (figure 6(a)). Using only public charging, a BEV owner may spend more on fuel than an HEV owner (though still less than an ICEV owner). This is an important consideration for potential BEV owners without dedicated access to a home charger. Woody *et al* found that without home charging access, *new* BEVs typically would not break even with conventional alternatives [13]. However, for *used* BEVs we find that even in the most expensive charging scenario—zero home charging access—the BEV has lower TCO than the alternatives in most locations (figure 6(b)).

The impact of different charging patterns is much greater in cities with large differences in their time-of-use electricity rates. The two cities in which there is the least variation based on charging patterns are the same two cities in which the BEVs and HEVs have similar costs: Boston, which does not include time-of-use pricing, and San Francisco, which has peak home electricity prices that can exceed DC fast charging prices.

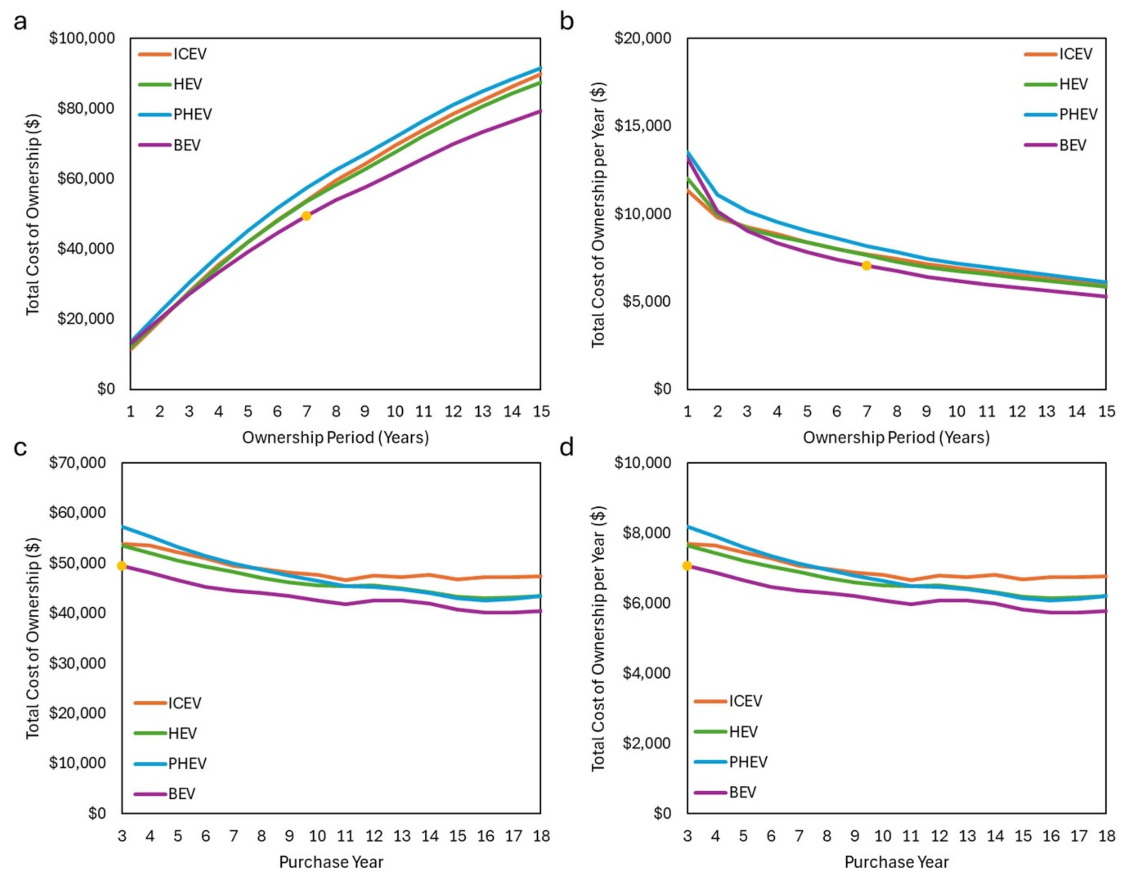

Figure 7. Total cost of ownership (a) and (c) and total cost of ownership per year (b) and (d) for used midsize SUVs of each powertrain that are purchased at vehicle age 3, and owned for a variable number of years (a) and (b) and vehicles that are owned for 7 years, and are purchased at different vehicle ages (c) and (d). For example, yellow points on each figure all represent a vehicle purchased at vehicle age 3 and owned for 7 years before resale. Other vehicle classes are shown in supplemental note 18.

3.5. Vehicle ownership periods

Our base case compares used vehicles purchased after 3 years of vehicle life and resold after 10 years, for a 7 year ownership period. Here we investigate both the purchase year and the ownership period. Figure 7(a) compares midsize SUVs of each powertrain purchased after 3 years of vehicle life, but with ownership periods ranging from 1 to 15 years. Resale is included in the total ownership cost, so the value for an ownership period of 1 represents a vehicle that is purchased at vehicle year 3, driven for 1 year, and then resold at vehicle year 4. Figure 7(b) shows the total ownership cost divided by the years of ownership. Note that this is not the ownership cost *each* year, as the purchase and resale components of TCO are distributed over the ownership period. The declining cost per year with longer ownership periods reflects both the longer period of time over which the vehicle's purchase is distributed and the discount rate that is applied to future costs. Figure 7(b) also shows that over very short ownership periods (2 years or less) the BEV is more expensive, but it becomes the least expensive powertrain over 3 years or more of ownership.

Figure 7(c) compares used midsize SUVs of each powertrain with a 7 year ownership period, but with different initial purchase years. Therefore, purchase year 3 represents a vehicle purchased at year 3 and sold at year 10 of the vehicle's lifetime, while purchase year 18 represents a vehicle purchased at year 18 and sold at year 25 of the vehicle's lifetime. Because we use a constant annual VMT (15 000 miles), each of these scenarios contain the same number of miles over the ownership period (105 000 miles). Figure 7(d) shows this cost per year. Up until year 10 of a vehicle's lifetime, TCO decreases with vehicle purchase age. However, following year 10 of a vehicle's lifetime, TCO plateaus. This suggests that for a consumer focusing on used vehicles, there is little to no savings from buying a vehicle over 10 years old. After that point any decreases in purchase cost may be offset by increased maintenance and repair costs.

4. Conclusion

We show that used BEVs have a lower TCO than ICEVs, HEVs, and PHEVs. This is true across different vehicle classes, different purchase years, different ownership periods, and across most charging strategies and locations.

There are several limitations to this analysis. Because the vehicle depreciation curves were estimated from one year of data, the results represent a certain point of time and may not reflect how vehicles will depreciate in the future, particularly with the removal of federal BEV incentives. While the overall sample size is large, it is limited for some of the more rare combinations of vehicle class and type (e.g., BEV pickups, PHEV sedans). Faster depreciation rates for BEVs may in part be driven by (a) the rapid increase in the availability of new BEVs, suppressing demand for used BEVs, (b) the declining cost of new BEVs, which compete with used BEVs among BEV focused vehicle purchasers, and (c) lack of consumer confidence in used BEV reliability, particularly for batteries. Since BEVs are expected to both increase in availability and decrease in cost in the future, it is unclear whether this trend in depreciation will continue, or if BEVs will depreciate more like conventional vehicles as the market matures and consumer perceptions change. The depreciation results are also limited by the data that were available. Our regression does not include the vehicle's range or manufacturer, both of which have been shown to influence depreciation rates. Additionally, we use listed prices, which may differ from transaction prices.

Despite these limitations, our results have important implications for vehicle manufacturers, vehicle owners, and policy makers. For manufacturers, these results suggest that consumers may not yet be comfortable with used BEVs, especially since the TCO advantage held by used BEVs is reversed if the battery needs to be replaced. Extended warranties on BEV batteries, or battery health certificates for used vehicles may increase consumer confidence in used BEVs [34]. This in turn could reduce 'resale anxiety' [35] and increase sales of new BEVs.

For consumers, these results suggest that there is a large opportunity to minimize their total vehicle spending by purchasing a used BEV. Consumers can also minimize their cost by purchasing smaller vehicles, older vehicles (up until year 10 of vehicle lifetime), owning their vehicles longer, and for BEV owners, by charging at home during off-peak electricity price periods, where possible. However, TCO is only one of many factors consumers consider when purchasing a vehicle; other factors include household needs, aesthetic preferences, and risk tolerance (particularly for used vehicles).

For policy makers, these results have several important implications. For climate impact, the total number of ICEVs replaced by new BEVs drives reductions in GHG emissions, so climate policies should focus on new vehicle adoption. However, ensuring there is a market for used BEVs may contribute to new BEV sales. Additionally, for reducing local air pollution and supporting environmental justice, the location of BEVs, and who can afford to drive them are important factors [36]. Focusing on the used BEV market can support these goals.

Different policy strategies are needed in different locations. Using time-of-use electricity rates to schedule charging can significantly lower the TCO of BEVs. Municipalities without time-of-use pricing could work with local electric utilities to support the creation of affordable vehicle charging options. Ensuring the availability of home charging is another important way to lower costs. Consumers who rent their homes, who or live in multi-unit dwellings, or who do not have access to off-street parking may be unable to access home charging [37] and face greater charging costs, as shown in figure 6. Programs to install chargers in multi-unit dwellings, to incentivize landlords to install chargers, or to create more affordable public charging options near residences could all help alleviate these concerns. State level subsidies can lower costs and are available in many of the cities in this study (though not included in our analysis). Ensuring incentives are available at the point of sale—rather than as a tax credit—provides an important source of liquidity to consumers [38]. These incentives are generally only available for new BEVs, though several states have incentives for used BEVs as part of vehicle scrappage programs or programs targeted to low-income residents [39]. Targeted programs may improve cost effectiveness, as historically many BEV purchasers would have purchased a BEV even without the subsidy [40].

Providing TCO information may help increase consumer's intent to purchase a BEV [41, 42]. Outreach programs and publicization of vehicle TCO, particularly for used vehicles, may support BEV adoption. These could be targeted in locations with low BEV TCO. However, for many consumers the down payment is more important than the total cost, so reducing BEV prices remains an important policy goal to spur adoption.

Our results demonstrate that BEVs have achieved cost parity with conventional vehicles in the U.S. used vehicle market. Supporting adoption of used BEVs can help reduce household travel costs and reduce personal GHG emissions. Future modeling that combines TCO and lifecycle GHG emissions may help reveal optimal pathways for reducing vehicle emissions [43]. Meeting emissions reduction goals for the transportation sector will require far more than vehicle electrification [44, 45], but used BEVs having a lower TCO than other powertrains is a noteworthy step towards transportation decarbonization.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors. The dataset is too large for public archiving.

Supplemental Information available at https://doi.org/10.1088/1748-9326/ae38f8/data1.

Figure Source Data available at https://doi.org/10.1088/1748-9326/ae38f8/data2.

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