Supplementary Materials

# Widespread Range Suitability and Cost Competitiveness of Electric Vehicles for Ride-hailing Drivers

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**https://doi.org/10.1016/j.apenergy.2022.119246**

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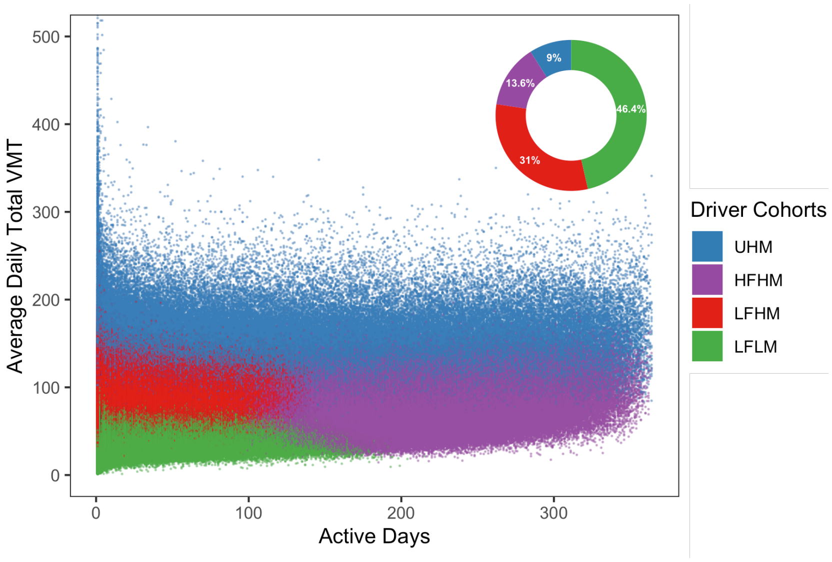

Fig. S-1. Near optimal and externally valid driver cohorts. *UHM*: Ultra High Mileage; *HFHM*: High Frequency High Mileage; *LFHM*: Low Frequency High Mileage; *LFLM*: Low Frequency Low Mileage.

Table S-1. Summary statistics of variables in the dataset for all drivers and by cohort.

| | *All* | UHM | HFHM | LFHM | LFLM |
|---|---|---|---|---|---|
| Number of Active Days in 2019 | **59** | 124 | 190 | 36 | 24 |
| Average Active-Day Number of Rides | **5.4** | 12.4 | 5.6 | 6.4 | 3.2 |
| Average Active-Day Observed VMT on Platform | **70** | 145 | 77 | 86 | 43 |
| Average Active-Day Occupied VMT | **25** | 58 | 26 | 30 | 14 |
| 90th-percentile VMT | **123** | 234 | 137 | 152 | 77 |
| 95th-percentile VMT | **139** | 261 | 160 | 173 | 88 |
| 99th-percentile VMT | **165** | 309 | 208 | 201 | 101 |
| Average Active-Day Shift Duration (hr) | **3.54** | 7.04 | 4.21 | 4.21 | 2.22 |
| Observed Annual VMT on Platform | **5,112** | 17,782 | 14,887 | 3,095 | 1,132 |
| Total Annual VMT* | **12,412** | 25,082 | 22,187 | 10,395 | 8,432 |

* Derived variable: annual observed VMT by Lyft plus 7,300 miles of personal miles.

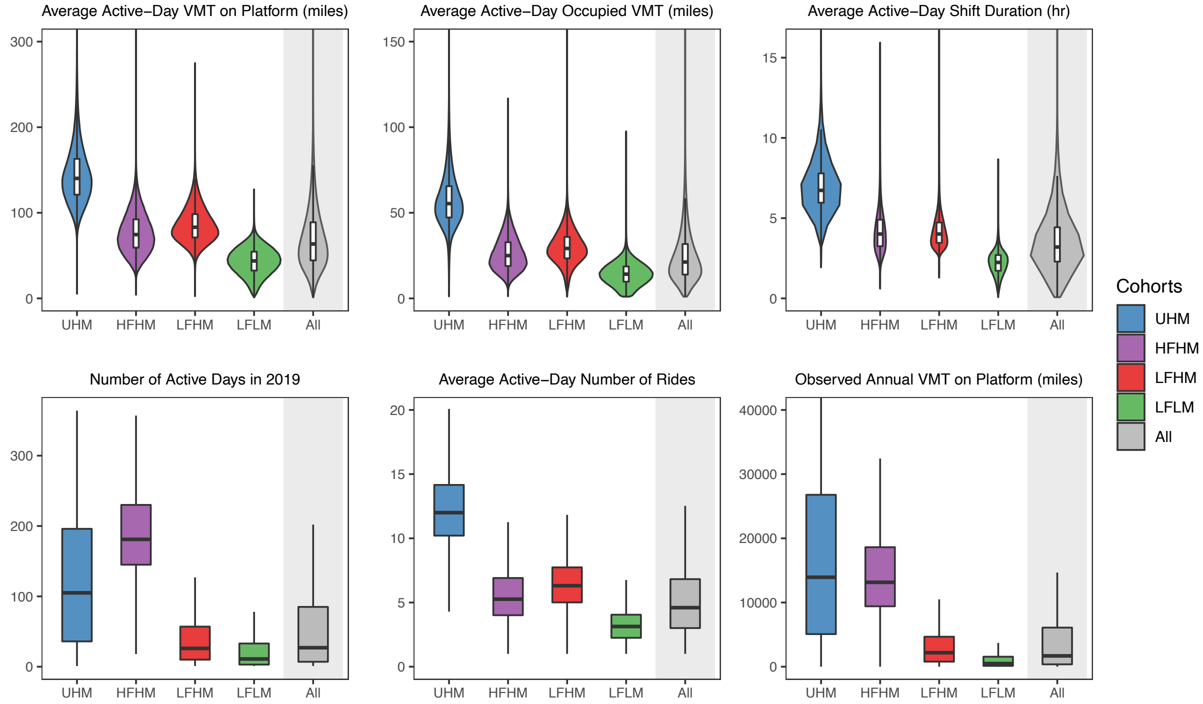

Fig. S-2. Distributions of selected variables in the dataset for all drivers and by cohort. The gray shade represents the distribution of variable for all drivers, regardless of cohort.

**Supplementary Note 1:** Driver clustering.

Based on computational efficiency and superior clustering power, we choose k-mean clustering, which minimizes within-cluster variances (squared Euclidean distances) of the aforementioned variables. Finally, we use several verification methods for checking the optimality of clusters (Fig. S-3). Both Elbow method and Silhouette width method suggest only two optimal clusters on selected variables and then marginal decrease in optimality with higher number of clusters (Fig. S-4). We use expert knowledge on average characteristics of resultant clusters to choose the near-optimal yet externally valid set of driver clusters. While the analysis is conducted at the individual driver level, some results are also reported on the cohort basis to provide a roadmap for identifying the ideal cohort of drivers for electrification efforts. Note that these cohorts based on the clustering method are not absolute, and drivers on the boundary of cohorts have travel patterns similar to those of either cohort.

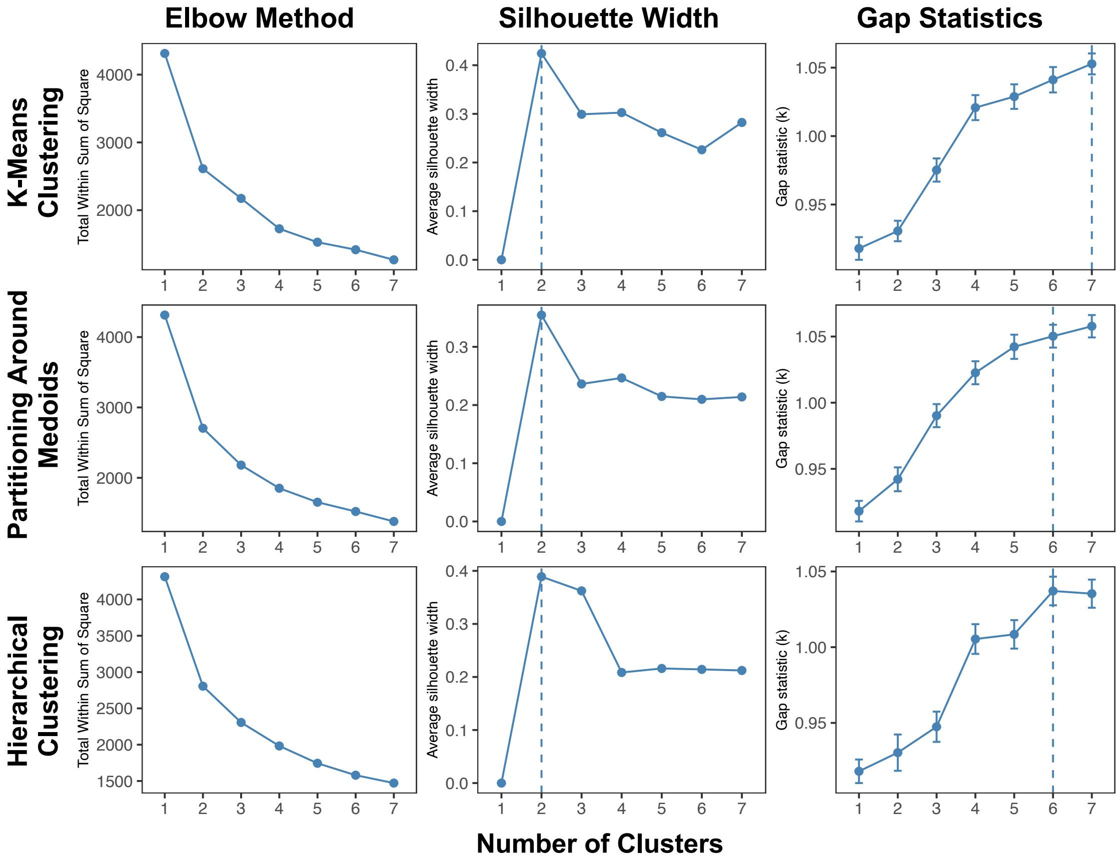

Fig. S-3. The performance of other unsupervised machine learning methods tested for defining the driver cohorts. Both Elbow method and Silhouette Width result in only two optimal clusters for all three algorithms. We use expert knowledge to choose four clusters as externally valid cohort without significantly losing the cluster optimality.

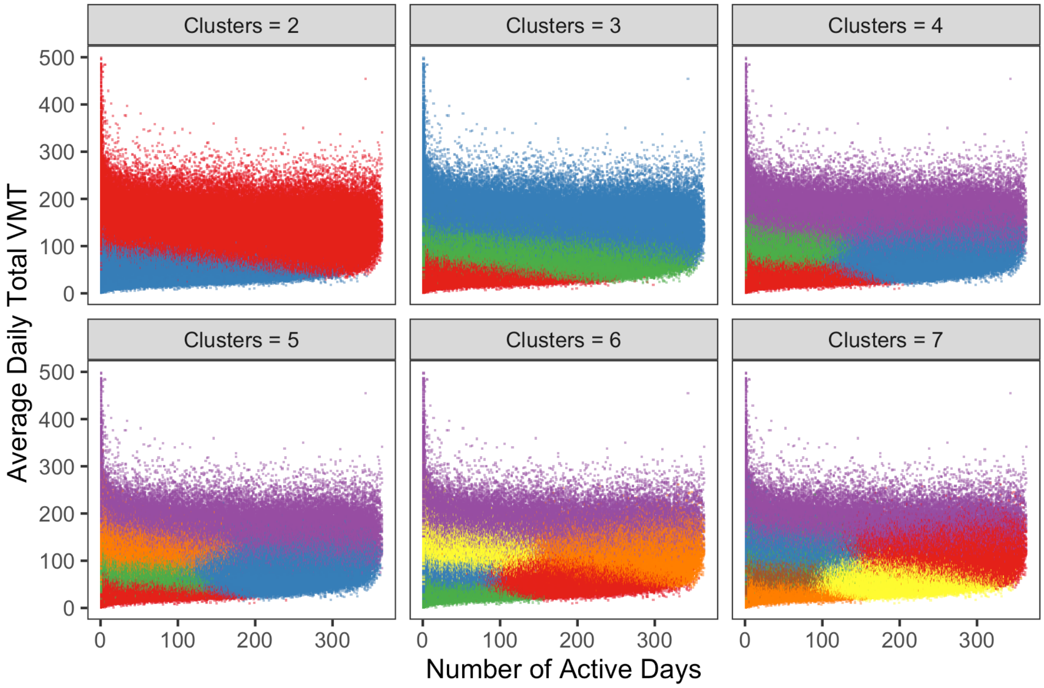

Fig. S-4. Results of different number of clusters on K-means clustering of cohorts on two variables. 4-cluster appears to have more external validity than others. The Greater number of clusters than 4 makes further cuts on low frequency low mileage drivers and does not improve the external validity.

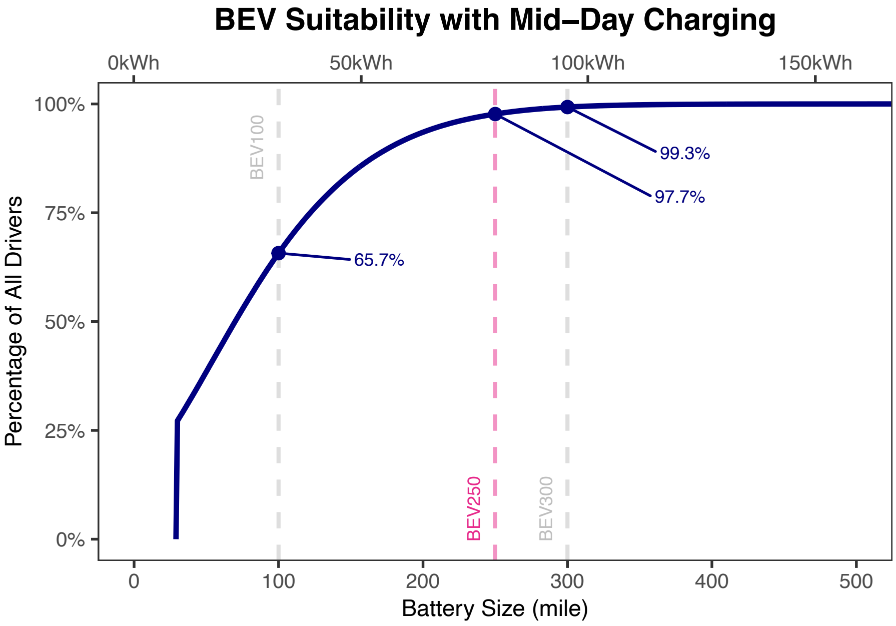

Fig. S-5. 95$^{th}$%-VMT BEV Suitability with midday 30-minute charging at 30 kW DCFC. We use the full sample of drivers on the Lyft platform. The procedure for producing this figure is identical to that of Fig. 1, except for the allowance of an additional 30-minute midday charge.

Table S-2. The residual value ($VRV$) of new vehicles at the end of ownership commitment period from alg.com. The residual value is expressed as the percentage of MSRP.

| *New Models* | ICEV | HEV | BEV250* |
|---|---|---|---|
| MSRP | \$24,365 | \$27,280 | \$36,620 |
| Mileage Per Year | 3-Year Commitment | | |
| 10K miles/year | 47% | 56% | 44% |
| 20K miles/year | 41% | 51% | 38% |
| 30K miles/year | 34% | 45% | 30% |
| 40K miles/year | 24% | 39% | 23% |
| | 5-Year Commitment | | |
| 10K miles/year | 32% | 39% | 34% |
| 20K miles/year | 23% | 27% | 23% |
| 30K miles/year | 10% | 16% | 13% |
| 40K miles/year | 1% | 8% | 8% |

*For simplicity, we assume EV tax credits and subsidies are directly deducted from MSRP. The depreciation cost over commitment period is the difference between MSRP and residual value.

Table S-3. The residual value ($VRV$) of pre-owned vehicles at the end of ownership commitment period from alg.com

| *Pre-owned Models** | ICEV | HEV | BEV250 | BEV100 |
|---|---|---|---|---|
| Pre-owned Certified Dealer Price | \$15,632 | \$18,362 | \$19,144 | \$11,083 |
| Mileage Per Year | 3-Year Commitment | | | |
| 10K miles/year | 38% | 49% | 51% | 61% |
| 20K miles/year | 29% | 42% | 40% | 45% |
| 30K miles/year | 19% | 33% | 26% | 26% |
| 40K miles/year | 9% | 24% | 13% | 8% |
| | 5-Year Commitment | | | |
| 10K miles/year | 32% | 42% | 33% | 52% |
| 20K miles/year | 17% | 29% | 14% | 25% |
| 30K miles/year | 2% | 15% | 2% | 3% |
| 40K miles/year | 2% | 2% | 2% | 3% |

*Kelly Blue Book estimate corresponding to “Certified Pre-Owned from Certified Dealer - Fair Purchase Price on Very Good Condition”, with typical mileage of 30K at the time of purchase.

Table S-4. Estimated annual insurance costs ($I$) for new and pre-owned vehicles. We assume the insurance rate is not a function of mileage, following the methodology of AAA.

| | ICEV | HEV | BEV |
|---|---|---|---|
| *New Models* | \$1,109 | \$1,200 | \$1,215 |
| *Pre-Owned Models* | \$964 | \$1,022 | \$1,001 |

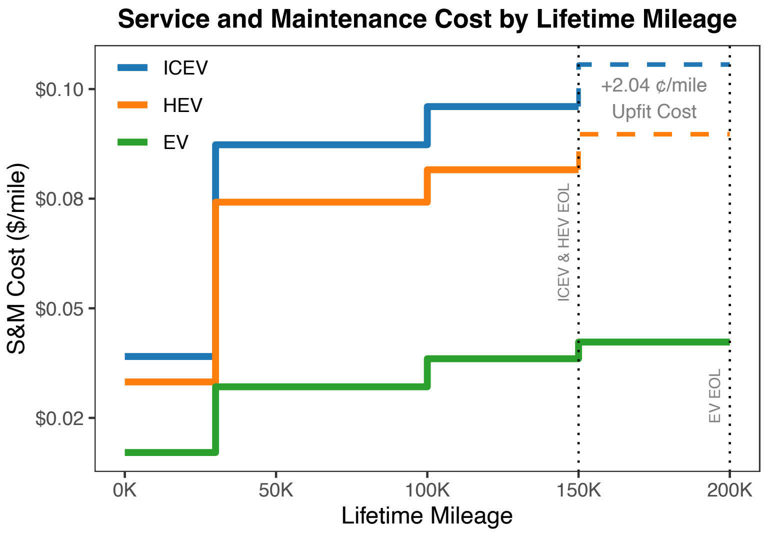

Fig. S-6. Service & Maintenance (S&M) costs per mile for different vehicle types. We assume that ICEV and HEV reach the end of their life (EOL) at 150,000 miles, while BEV reaches EOL at 200,000 miles. An upfit cost of $0.0204/mile is assumed for any mileage after 150,000 miles for ICEVs and HEVs. No vehicle in our analysis reaches over 200,000 miles under the assumption of a 3- or 5-year commitment period.

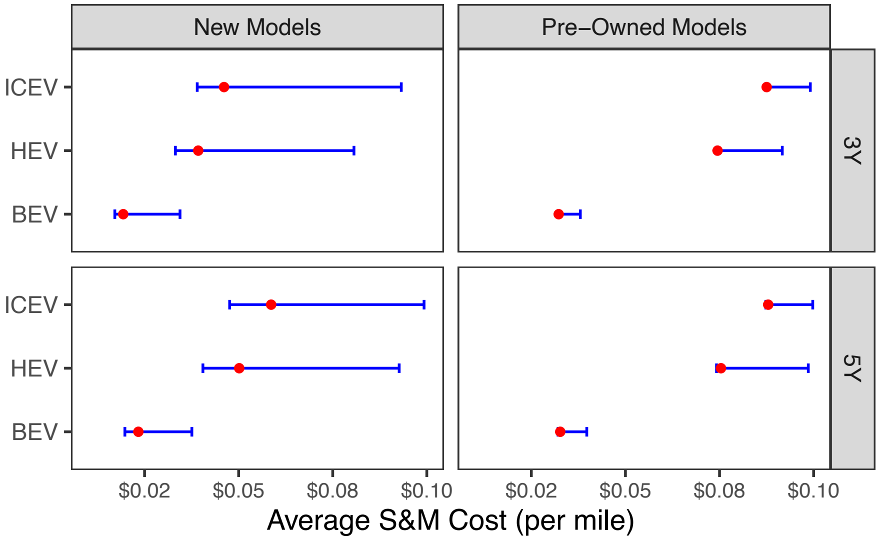

Fig. S-7. Range of mileage-weighted average S&M costs per mile for all drivers by model type, new vs. pre-owned, and commitment period length. The mileage-weighted average S&M cost additionally depends on annual mileage. Red points denote averages and whiskers show minimum and maximum.

Table S-5. 2019 average gas price and LCOC by state. Gas price includes taxes and is based on the weighted sales volume of three grades of gas, as calculated by the US Energy Information Administration.[1] The national average gas price in 2019 is $2.763/gal, and the median is $2.625/gal. LCOC is based on the central estimate of Borlaug et al. for each state.[2] The average LCOC is 0.15 $/kWh nationwide, with the highest costs in Hawaii and the lowest in the Oregon, Washington DC, Delaware, and Maine. For equivalent per mile cost, 0.28 kWh/mile and 27 mile/gal are used for energy efficiency of BEV and ICEV, respectively.

| *State* | *LCOC ($/kWh)* | *Gas Price ($\boldsymbol{G}_s$) ($/gal)* | *BEV per-mile LCOC ($/mile)* | *ICEV per-mile gas cost ($/mile)* |
|---|---|---|---|---|
| Alabama | 0.13 | 2.369 | 0.0364 | 0.0877 |
| Alaska | 0.25 | 3.516 | 0.0700 | 0.1302 |
| Arizona | 0.12 | 3.101 | 0.0336 | 0.1149 |
| Arkansas | 0.13 | 2.332 | 0.0364 | 0.0864 |
| California | 0.18 | 3.968 | 0.0504 | 0.1470 |
| Colorado | 0.13 | 2.503 | 0.0364 | 0.0927 |
| Connecticut | 0.15 | 3.040 | 0.0420 | 0.1126 |
| Delaware | 0.10 | 2.625 | 0.0280 | 0.0972 |
| District of Columbia | 0.10 | 3.089 | 0.0280 | 0.1144 |
| Florida | 0.15 | 2.698 | 0.0420 | 0.0999 |
| Georgia | 0.12 | 2.552 | 0.0336 | 0.0945 |
| Hawaii | 0.31 | 3.944 | 0.0868 | 0.1461 |
| Idaho | 0.13 | 2.930 | 0.0364 | 0.1085 |
| Illinois | 0.16 | 2.637 | 0.0448 | 0.0977 |
| Indiana | 0.15 | 2.491 | 0.0420 | 0.0923 |
| Iowa | 0.12 | 2.576 | 0.0336 | 0.0954 |
| Kansas | 0.16 | 2.393 | 0.0448 | 0.0886 |
| Kentucky | 0.13 | 2.576 | 0.0364 | 0.0954 |
| Louisiana | 0.13 | 2.381 | 0.0364 | 0.0882 |
| Maine | 0.10 | 2.723 | 0.0280 | 0.1009 |
| Maryland | 0.17 | 2.711 | 0.0476 | 0.1004 |
| Massachusetts | 0.23 | 2.955 | 0.0644 | 0.1094 |
| Michigan | 0.18 | 2.515 | 0.0504 | 0.0931 |
| Minnesota | 0.14 | 2.527 | 0.0392 | 0.0936 |
| Mississippi | 0.15 | 2.357 | 0.0420 | 0.0873 |
| Missouri | 0.15 | 2.332 | 0.0420 | 0.0864 |
| Montana | 0.15 | 2.784 | 0.0420 | 0.1031 |
| Nebraska | 0.15 | 2.613 | 0.0420 | 0.0968 |
| Nevada | 0.11 | 3.504 | 0.0308 | 0.1298 |
| New Hampshire | 0.12 | 2.808 | 0.0336 | 0.1040 |
| New Jersey | 0.15 | 2.845 | 0.0420 | 0.1054 |
| New Mexico | 0.14 | 2.479 | 0.0392 | 0.0918 |
| New York | 0.12 | 3.053 | 0.0336 | 0.1131 |
| North Carolina | 0.13 | 2.576 | 0.0364 | 0.0954 |
| North Dakota | 0.14 | 2.552 | 0.0392 | 0.0945 |
| Ohio | 0.15 | 2.393 | 0.0420 | 0.0886 |
| Oklahoma | 0.12 | 2.259 | 0.0336 | 0.0837 |
| Oregon | 0.10 | 3.480 | 0.0280 | 0.1289 |
| Pennsylvania | 0.16 | 3.004 | 0.0448 | 0.1113 |
| Rhode Island | 0.22 | 2.894 | 0.0616 | 0.1072 |
| South Carolina | 0.16 | 2.589 | 0.0448 | 0.0959 |
| South Dakota | 0.16 | 2.381 | 0.0448 | 0.0882 |
| Tennessee | 0.15 | 2.442 | 0.0420 | 0.0904 |
| Texas | 0.15 | 2.332 | 0.0420 | 0.0864 |
| Utah | 0.15 | 2.943 | 0.0420 | 0.1090 |
| Vermont | 0.15 | 2.943 | 0.0420 | 0.1090 |
| Virginia | 0.11 | 2.491 | 0.0308 | 0.0923 |
| Washington | 0.14 | 3.578 | 0.0392 | 0.1325 |
| West Virginia | 0.16 | 2.723 | 0.0448 | 0.1009 |
| Wisconsin | 0.12 | 2.503 | 0.0336 | 0.0927 |
| Wyoming | 0.15 | 2.906 | 0.0420 | 0.1076 |

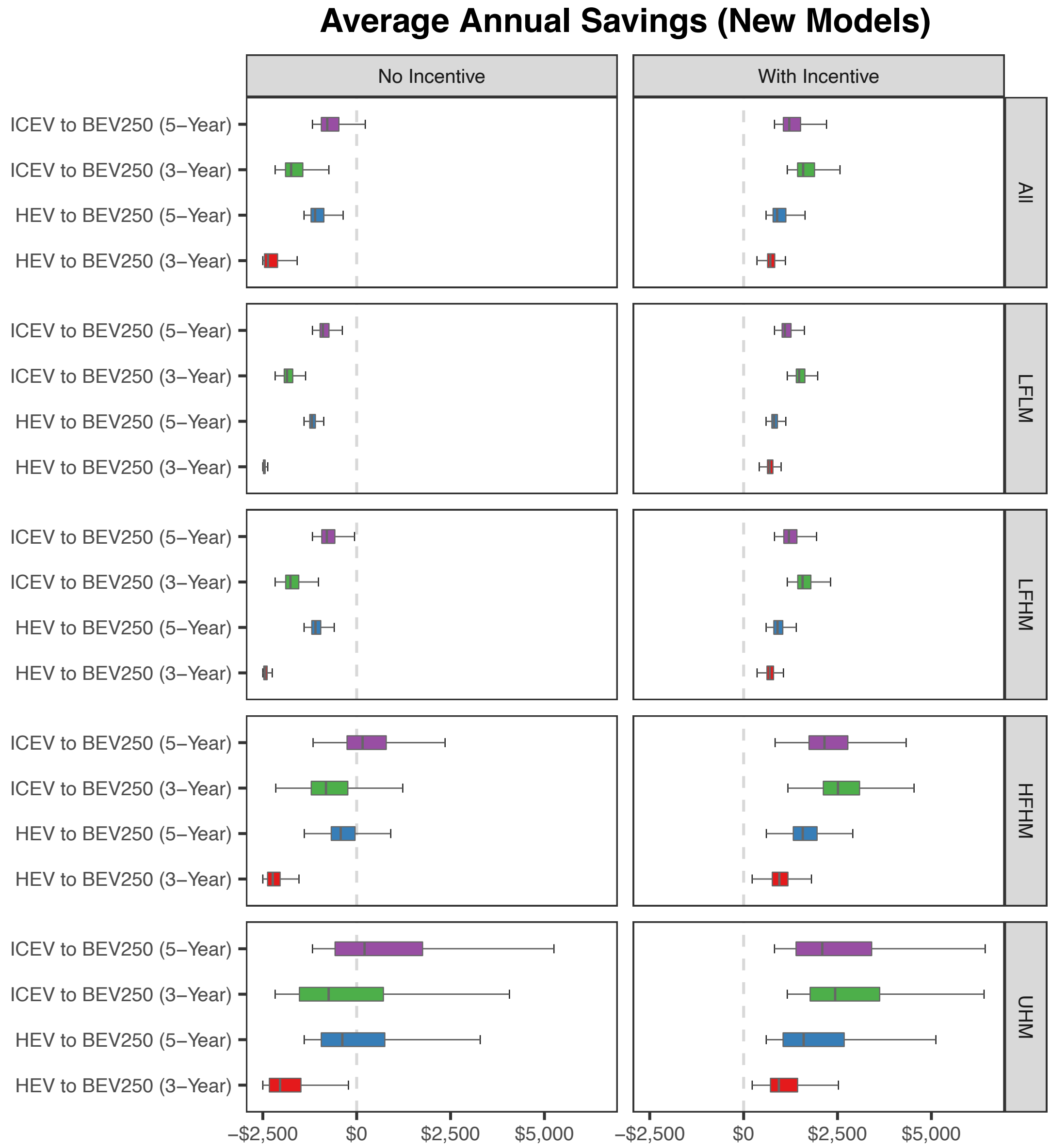

Fig. S-8. Distribution of average annual savings from switching to *new* BEVs under various scenarios. The range for all drivers is shown regardless of whether they are BEV suitable or not. Columns show with and without purchase subsidy and rows show the distribution for the cohorts. The boxes describe 25th percentiles (left hinge), medians, and 75th percentiles (right hinge) and whiskers describe 1.5 times the interquartile range.

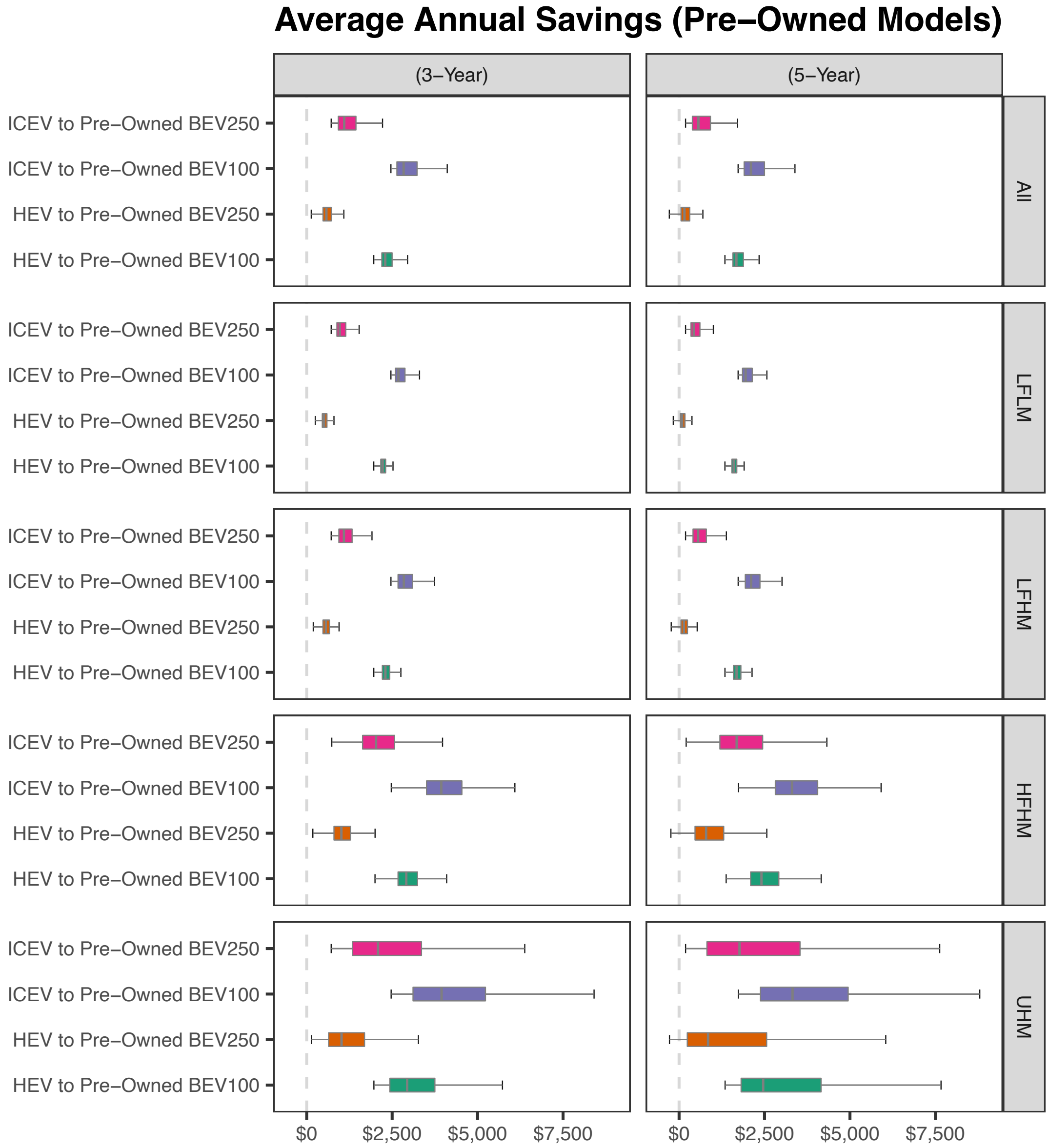

Fig. S-9. Distribution of average annual savings from switching to *pre-preowned* BEVs under various scenarios. The range for all drivers is shown regardless of whether they are BEV suitable or not. Columns show the average savings 3- and 5-year commitment period and rows show the distribution for the cohorts. The boxes describe 25th percentiles (left hinge), medians, and 75th percentiles (right hinge) and whiskers describe 1.5 times the interquartile range.

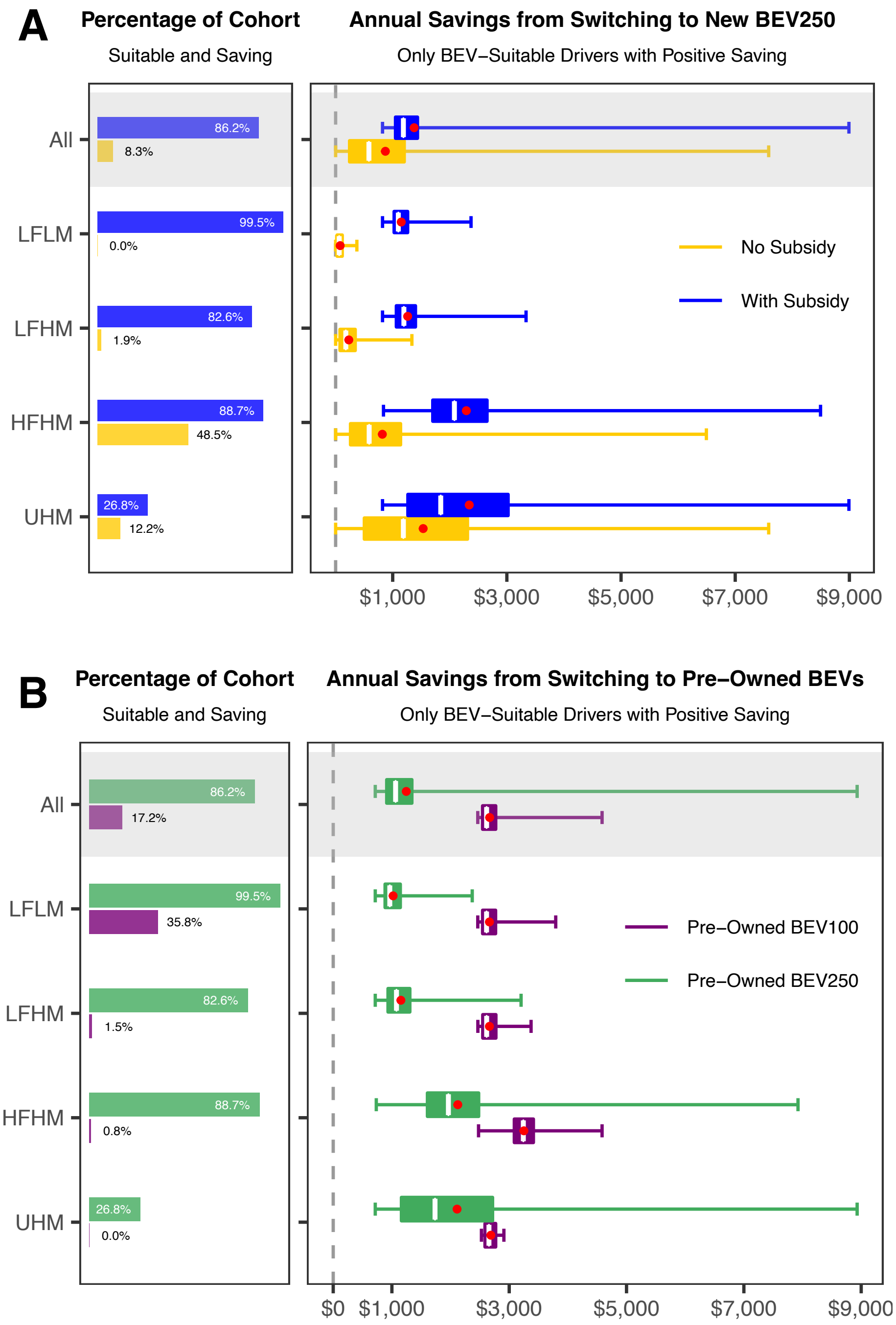

Fig. S-10. The range and distribution of annual saving from ICEV to BEV for BEV-suitable drivers with positive savings (Fig. 4 shows the full range). (A) From new ICEV to BEV250 with and without purchase subsidies under 5-year commitment period. (B) From pre-owned ICEV to pre-owned BEV250 and pre-owned BEV100 under 3-year commitment period. The red points show the average annual savings. The boxes describe 25th percentiles (left hinge), medians (white line), and 75th percentiles (right hinge) and whiskers describe absolute minimum and maximum.

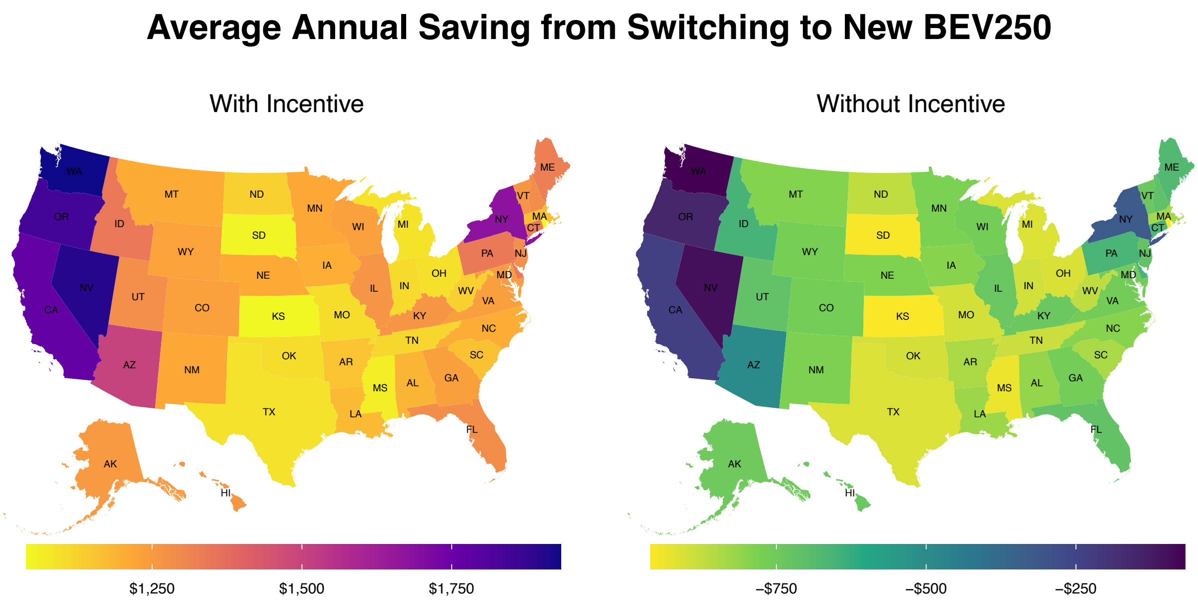

Fig. S-11. State-level average annual savings from new ICEV to new BEV250 with and without purchase subsidies under 5-year commitment period.

**Supplementary Note 2:** State-level average annual savings from new ICEV to new BEV250.

Fig. S-11 illustrates the state-level average annual savings from new ICEV to new BEV250 with and without purchase subsidies. With subsidies, states of WA, NE, OR, CA, and NY have the highest average annual savings. Without subsidies, Nevada's drivers return the highest savings, mostly due to the highest average mileage in the nation. States of KS, SD, MS, and RI have the lowest average annual savings in both cases. Note that, with subsidies, far more LFLM drivers in those states break even or save from switching to BEV, which changes the decomposition of the set of drivers in those states who are both BEV suitable and save from switching to BEVs.

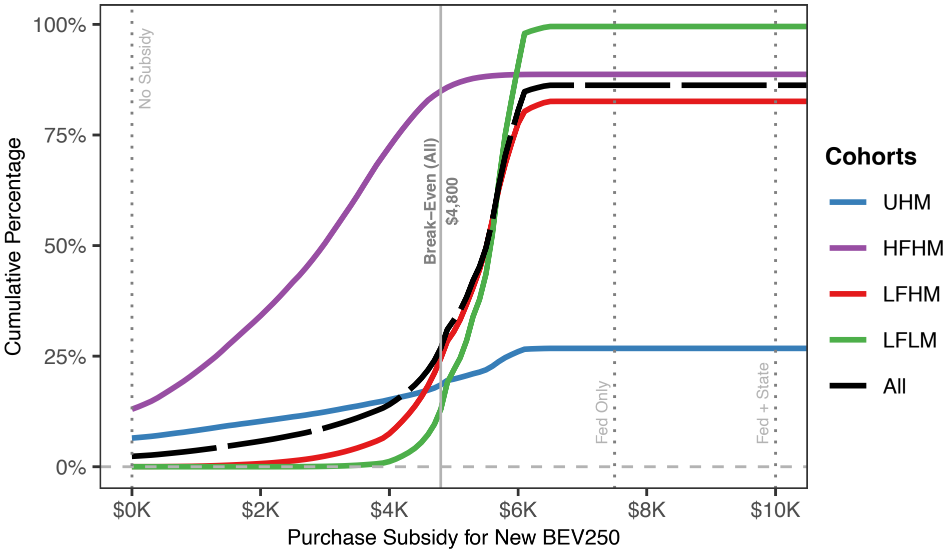

Fig. S-12. Percentage of drivers in each cohort that both find a BEV250 range-suitable and break even under a 3-year ownership commitment, as a function of subsidy level. Curves that plateau below 100% have drivers for whom a BEV250 does not have suitable range. An average driver breaks even with a minimum of $4,800 purchase subsidy. Vertical lines indicate certain specific levels of subsidy. *Fed + State*: current level ($10,000) for some states; *Fed Only*: $7500 federal tax credit; *Reduced*: a scenario where tax rebate is reduced to $5,000.

## **Supplementary Note 3:** Sustainability implications.

The emissions conversion from gasoline to $CO_2$ is based on EPA measurements of 8,887 gr$CO_{2\text{-}eq}$ per gallon of gas and the fuel economy of replaced ICEV (27 miles per gallon). For the life-cycle GHG emissions we use BEV energy efficiency, data from state-level average emission factor of electricity generation from NREL's Cambium dataset [3] and per-mile vehicle cradle-to-grave emissions (including vehicle manufacturing and battery production and end of life) for ICEV and BEV. The estimate of state-level marginal emission factor of electricity generation is for year 2020 based on short-run mid-case scenario of NREL's Regional Energy Deployment System [3]. The US average marginal emission factor of electricity generation is 365.16 gr$CO_{2\text{-}eq}$/kWh but varies greatly among the states. As a point of comparison, our estimate of California's marginal emission factor for electricity generation is 192 gr$CO_{2\text{-}eq}$/kWh which is slightly higher than the estimate of Jenn [4] (186 gr$CO_{2\text{-}eq}$/kWh). We use a central estimate of 43 gr$CO_{2\text{-}eq}$/mile for ICEV and a conversative estimate of 144 gr$CO_{2\text{-}eq}$/mile for BEV including battery production for cradle-to-grave emissions excluding the use phase. Note that Cox et al., Hoekstra et al. and Elgowainy et al. estimate a range of 85-162 gr$CO_{2\text{-}eq}$/mile for BEV as use-phase excluded cradle-to-grave emissions [5–7].

Table S-6. Implications of electrification of all drivers who are BEV250-suitable and save from switching. All figures are based on annual estimate

| | All | UHM | HFHM | LFHM | LFLM |
|---|---|---|---|---|---|
| **Annual Avoided Tailpipe GHG Emissions** (Million Metric Tons of $CO_{2\text{-eq}}$) | 5.72 | 0.85 | 1.52 | 1.55 | 2.34 |
| **Annual Avoided Life-Cycle GHG Emissions** (Million Metric Tons of $CO_{2\text{-eq}}$) | 4.30 | 0.22 | 1.18 | 1.16 | 1.74 |
| **Annual Electricity Consumption** (TWh) | 4.86 | 0.24 | 1.30 | 1.33 | 1.99 |

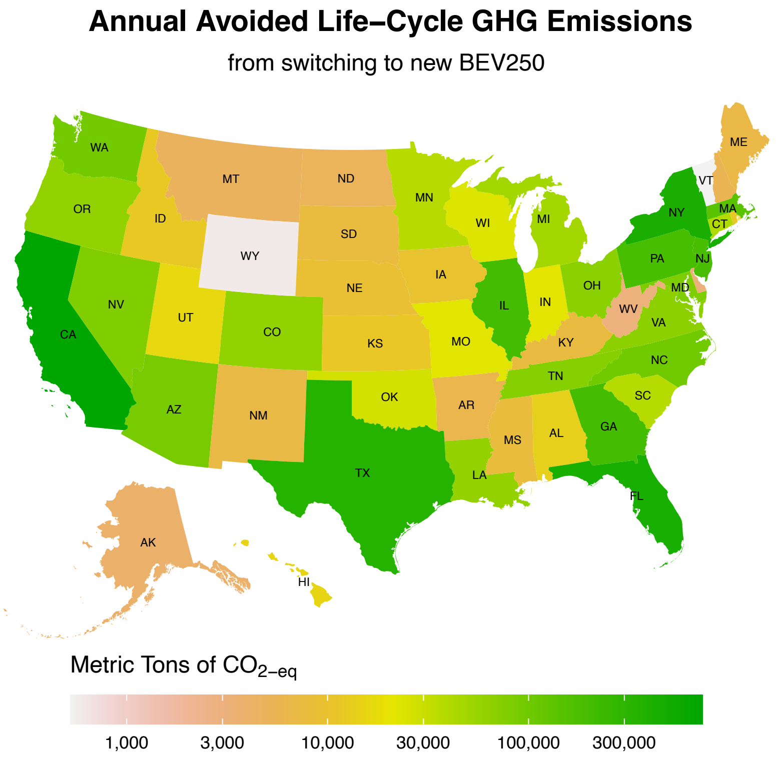

Fig. S-13. Annual avoided life-cycle GHG emissions from switching to new BEV250 across different states. We use average emission factor in each state and vehicle and battery life-cycle emissions.

## Supplementary References

[1] U.S. Energy Information Administration (EIA). The State Energy Data System (SEDS). 2019.

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