Comparative Analysis of Municipal-Level Electric Vehicle Charging Station (EVCS) Development Patterns and Political Implications Using Statistical Methods: Philadelphia vs. Denver

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Introduction

In recent years, the United States has been actively promoting the adoption of electric vehicles (EVs) to reduce greenhouse gas emissions and combat climate change, along with which has been a line of federal policies and initiatives to support the EV market. The Bipartisan Infrastructure Law (BIL) passed in August 2021 to provide $7.5 billion funding for a national EV charger network in the United States.[1] The BIL also established the National Electric Vehicle Infrastructure Formula Program (NEVI) to fund EV charger installation at the state-level.[2] In August 2022, the Inflation Reduction Act was signed into law, providing substantial provisions to accelerate the transition to clean energy and transportation through providing incentives for EV purchases and funding to EV chargers countrywide[3]. This year, the Environmental Protection Agency (EPA) introduced new regulations to increase the production of EVs and phase out gas cars.[4] The new rules mandate that auto manufacturers significantly reduce emission of greenhouse gasses, and are estimated to prevent more than 7 billion tons of carbon dioxide emissions and generate $100 billion benefits annually.

The planning profession also observes emerging concerns on equitable EVCS planning. It is found that tenureship and home typology have prevented more than one-third of U.S. adults from owning private chargers and accessing EV-related energy and cost savings. This pattern is further exacerbated by persisting equity challenges surrounding minority communities and neighborhoods with denser multifamily housing[5].

These policies and discourses have demonstrated consistent effort from both the public and private end to promote a nationwide accessible network of EV chargers. However, the implementation and impact of policies vary across different municipalities due to different factors and priorities. Using comparative study, our project will explore Electric Vehicle Charging Station (EVCS) development patterns in Philadelphia and Denver to understand differences in development trends between the two cities, and how policy interventions factor respectively into shifting their respective EVCS landscape. Our research will provide insights in understanding nuances of EVCS associated factors across distinct municipalities, and identify locally-conscious policy recommendations for future EVCS deployment.

Literature Review

Existing scholar literature has revealed patterns of existing EVCS disparities US-wide. A census block group-level study using multivariate generalized additive model has suggested that lower-income and minority communities generally have less accessibility to public EVCS infrastructure across California.[6] On a municipal scale, by performing a variety of quantitative spatial machine learning on socioeconomic data in

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[1] The White House, "Fact Sheet: The Bipartisan Infrastructure Deal," The White House (The White House, November 6, 2021), https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/.
[2] U.S. Department of Transportation, "Bipartisan Infrastructure Law - National Electric Vehicle Infrastructure (NEVI) Formula Program Fact Sheet," Federal Highway Administration," www.fhwa.dot.gov, accessed May 11, 2024., https://www.fhwa.dot.gov/bipartisan-infrastructure-law/nevi_formula_program.cfm.
[3] Sarah Zimmerman, "Inflation Reduction Act Encourages EV Battery Sourcing, Production in North America," Supply Chain Dive, August 17, 2022, https://www.supplychaindive.com/news/biden-signs-inflation-reduction-act-in-boost-to-us-electric-vehicle-product/629854/.
[4] Camila Domonoske and Michael Copley, "In a Boost for EVs, EPA Finalizes Strict New Limits on Tailpipe Emissions," NPR, March 20, 2024, https://www.npr.org/2024/03/20/1239092833/biden-epa-auto-emissions-evs.
[5] Adam F Lubinsky, "How to Pave the Way for Equitable EV Adoption," American Planning Association (American Planning Association, August 24, 2023), https://www.planning.org/planning/2023/summer/how-to-pave-the-way-for-equitable-ev-adoption/.
[6] Chih-Wei Hsu and Kevin Fingerman, "Public Electric Vehicle Charger Access Disparities across Race and Income in California," Transport Policy 100 (January 2021): 59–67, https://doi.org/10.1016/j.tranpol.2020.10.003.

Orange county, CA, another study has used predictive modeling to show lower-middle income regions are less likely to receive future EVCS investments, among which most will be low-density installation.[7] Another New York City-based analysis further uses zip-code-level t-test and correlation-based conditional analysis to conclude that distribution of NYC's EVCS is heavily skewed against low-income and Black-identifying neighborhoods.[8] Finally, while focusing on residential EV chargers in Seattle, WA, a study also found that clustering of EV chargers is impacted by economic status, housing stability, and neighbor effects, resulting in uneven distributions.[9] The need for additional research focusing on equitable EVCS planning is further urged by the application end. Research focusing on charging station locations optimization and EV registration analysis is also channeling increasing consideration to social equity determinants, which recognizes a need to provide convenient EVCS access to encourage EV adoption.[10]

The ongoing discourse faces a few shortages. First, the pool of case studies is relatively constrained. Furthermore, areas with more progressive EVCS developments in the past like California tend to be overrepresented. Finally, while EVCS development is subjected to complex factors across regions, most literatures have not yet provided comparative studies accounting for municipal development requirements, potentially giving rise to generalized statements.

Our project therefore seeks to contribute in the following ways:

1. By offering critical studies of under-analyzed areas, we seek to continue and balance the trend of query through additional case studies.
2. Through comparative studies between areas of distinct history, culture, and features, our project critically challenges general EVCS distribution theories by revealing locally-conscious nuances.
3. Finally, by accounting for regional EVCS installation policy targets and comparing them with predicted development zones under existing trends, we interpret the relative effectiveness of policy in respective regions, and understand how policies will factor into city-based EVCS landscapes in the future.

Data

This report selects two U.S. cities, Philadelphia and Denver, for comparison. These two regions were chosen based on their similarities in geographical size and population age, while offering differences in population composition and historic backgrounds. Philadelphia has a population of approximately 1.6 million, while Denver, a younger and rapidly growing city, has a population of around 0.7 million. Denver also has a predominantly white population and a thriving technology ecosystem, contrasting with Philadelphia's diverse racial composition and deep historical roots. Furthermore, both Philadelphia and Denver are consolidated city-county entities, offering relatively fair comparative grounds at the administrative level.

Based on existing literature, we hypothesized a list of demographic, socioeconomic, and locational variables associated with EVCS installation outcomes in both cities, including property prices, household income,

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[7] Avipsa Roy and Mankin Law, "Examining Spatial Disparities in Electric Vehicle Charging Station Placements Using Machine Learning," Sustainable Cities and Society 83 (June 2022): 103978, https://doi.org/10.1016/j.scs.2022.103978.
[8] Hafiz Anwar Ullah Khan et al., "Inequitable Access to EV Charging Infrastructure," The Electricity Journal 35, no. 3 (April 2022): 107096, https://doi.org/10.1016/j.tej.2022.107096.
[9] Yohan Min and Hyun Woo Lee, "Social Equity of Clean Energy Policies in Electric-Vehicle Charging Infrastructure Systems," Construction Research Congress 2020, November 9, 2020, https://doi.org/10.1061/9780784482858.025.
[10] Abdolah Loni and Somayeh Asadi, "Data-Driven Equitable Placement for Electric Vehicle Charging Stations: Case Study San Francisco," Energy 282 (November 1, 2023): 128796, https://doi.org/10.1016/j.energy.2023.128796.

tenure, racial composition, education, building density and so on (Table.1). Our unit of analysis is census tract, to which data are processed to match.

Table 1. Description of Variables

Name	Description	Type	Source
EVCS_installed	whether a census tract has locally installed public EVCS or not	Categorical (Dependent Variable)	Alternative Fueling Station Locator, Department of Energy
MedAge	median Age	Continuous	2022 ACS 5-year Estimates
MedYearBuilt	median year structure built	Continuous	2022 ACS 5-year Estimates
pctWhite	share of white (non-hispanic) population in percentage	Continuous	2022 ACS 5-year Estimates
pctBlack	share of black (non-hispanic) population in percentage	Continuous	2022 ACS 5-year Estimates
pctOther	share of other race (non-hispanic) population in percentage	Continuous	2022 ACS 5-year Estimates
pctHis	percentage of Hispanic population	Continuous	2022 ACS 5-year Estimates
veh_ownership	vehicle ownership rate	Continuous	2022 ACS 5-year Estimates
pop_density	population per acre	Continuous	2022 ACS 5-year Estimates
PctParking	share of ground parking area in percentage	Continuous	OpenDataPhilly, Denver Open Data Catalog
pctSingleStruc	share of single family structure in percentage	Continuous	2022 ACS 5-year Estimates
pctBachelorAndAbove	share of individuals with education at or above bachelor's degree in percentage	Continuous	2022 ACS 5-year Estimates
renter_share	renter share	Continuous	2022 ACS 5-year Estimates
owner_share	owner share	Continuous	2022 ACS 5-year Estimates
building_density	ratio of building footprint to total land area	Continuous	OpenDataPhilly, Denver Open Data Catalog
pctFlooding	share of designated flooding risk area in percentage	Continuous	OpenDataPhilly
pctHistoric	share of ground designated historic area in percentage	Continuous	OpenDataPhilly
pctStruc_After20	share of structures built after 2020 in percentage	Continuous	2022 ACS 5-year Estimates
MedHHInc	average household income	Continuous	2022 ACS 5-year Estimates
AvgHHSize	average household size	Continuous	2022 ACS 5-year Estimates
MedRent	median gross rent	Continuous	2022 ACS 5-year Estimates
HomePrice	median value of owner-occupied housing unit	Continuous	2022 ACS 5-year Estimates
MedHHInc_cat	median household income divided into equally sized quartiles: Q1 (low), Q2(moderate), Q3(high), Q4(very high)	Categorical	2022 ACS 5-year Estimates
AvgHHSize_cat	average household size divided into equally sized quartiles: Q1 (small), Q2(moderate), Q3(large), Q4(very large)	Categorical	2022 ACS 5-year Estimates
MedRent_cat	median gross rent divided into equally sized quartiles: Q1(low), Q2 (moderate), Q3(high), Q4(very high)	Categorical	2022 ACS 5-year Estimates
HomePrice_cat	median value of owner-occupied housing unit divided into equally sized quartiles: Q1(low), Q2(moderate), Q3(high), Q4(very high)	Categorical	2022 ACS 5-year Estimates
Dom_race	whether a census tract is predominantly white	Categorical	2022 ACS 5-year Estimates
Dom_his	whether a census tract is predominantly Hispanic	Categorical	2022 ACS 5-year Estimates
station.buffer	whether a census tract's centroid is located in a half-mile transit station	Categorical	SEPTA GIS, RTD GIS
corridor.buffer	whether a census tract's centroid is located within a one-mile buffer to alternative fuel corridor	Categorical	Alternative Fuel Corridors, Department of Energy

Several variables created are reflective of each city's EVCS installation requirement. Both the state of Pennsylvania and Colorado have stressed the prioritization of siting EVCS in proximity to the federally-designated Alternative Fuel Corridors.[11] [12] Hence we created a unique category variable "corridor.buffer" indicating whether the census tract is located within a one-mile buffer to the Alternative Fuel Corridors. Likewise, both Philadelphia and Denver's city authorities have outlined spatial specifications on public EVCS installation.[13] [14] Therefore, the continuous variable "building_density"was created as a proxy measurement of open space conditions.

Additional city-specific features were gathered. For Philadelphia, these features including percent of historic designation ground area (pctHistoric) and percent of flooding area (pctFlooding) are gathered per its EVCS permit standard.[15] On the other hand, the percent of new structure after 2020 (pctStruc_After20) is aggregated for each Denver's tract, in light of the new building code requiring new constructions to provide EVCS since May 2023.[16] [17]

To identify EVCS-owning census tracts, we matched point-based EVCS locations from the Alternative Fueling Station Locator to corresponding Philadelphia and Denver census tracts, and classified tracts into two sample groups based on whether the census tract contains an existing EVCS or not.

Data sources utilized in this report include the Alternative Fueling Station Locator (public chargers)[18], 2022 American Community Survey 5-year estimates[19], the U.S. Department of Transportation's Alternative Fuel Corridors[20], and city-specific open data portals for Philadelphia (OpenDataPhilly, SEPTA GIS)[21] [22] and Denver (Denver Open Data Catalog, RTD GIS)[23] [24].

Table. 2 - 5 offer summaries by data type and city. Data cleaning involved removing observations with missing values and handling inconsistencies. To be further addressed in later steps, transformations were

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[11] Owen Racer, "Philly EV Drivers Are Itching for More Fast Chargers as New Federal Rules Seek to Boost EVs," WHYY, March 21, 2024, https://whyy.org/articles/electric-vehicles-charging-stations-philadelphia-pennsylvania-federal-rollout/.
[12] "Colorado National Electric Vehicle Infrastructure (NEVI) Plan" (Colorado Department of Transportation, June 2022), https://www.codot.gov/programs/innovativemobility/assets/co_neviplan_2022_final-1.pdf.
[13] "EZ Permit Standard: Electrical Vehicle Charger (EVC) Stations" (City of Philadelphia Department of Licenses & Inspections, accessed May 11, 2024), https://www.phila.gov/media/20220720130633/PB_020_F-EZ-Electrical-Vehicle-Charger-Permit-Standard-updated.pdf.
[14] City and County of Denver, "Electrical Vehicle (EV) Charging Spaces," denvergov.org, accessed May 11, 2024, https://denvergov.org/Government/Agencies-Departments-Offices/Agencies-Departments-Offices-Directory/Community-Planning-and-Development/Building-Codes-Policies-and-Guides/Electrical-Vehicle-Charging-Spaces.
[15] "EZ Permit Standard: Electrical Vehicle Charger (EVC) Stations."
[16] Kristen Bentley, "Denver Planning to Build Accessible EV Charging Stations," Electrify News Site, August 13, 2023, https://electrifynews.com/news/ev-chargers/denver-planning-to-build-accessible-ev-charging-stations/.
[17] City and County of Denver, "Electric Vehicle (EV) Supply Equipment," denvergov.org, May 16, 2023, https://www.denvergov.org/files/assets/public/v/1/climate-action/documents/hpbh/nze/2022-denver-energy-code-fact-sheets-c-ev-supply-equipment.pdf.
[18] National Renewable Energy Laboratory, Alternative Fueling Station Locator, U.S. Department of Energy, accessed April 29, 2024, https://afdc.energy.gov/stations#/find/nearest?fuel=ELEC.
[19] U.S. Census Bureau, American Community Survey, ACS 5-Year Estimates Data Profiles, 2022, accessed May 11, 2024. https://api.census.gov/data/2022/acs/acs5, retrieved using tidycensus R package.
[20] U.S. Department of Transportation, Alternative Fuel Corridors Rounds 1-7, Federal Highway Administration HEPGIS, November 07, 2023, https://hepgis-usdot.hub.arcgis.com/datasets/15593a84e7924814826faad39bd9ad12_0/explore?location=36.777588%2C-97.396605%2C4.97.
[21] City of Philadelphia, OpenDataPhilly, accessed May 11, 2024. https://opendataphilly.org.
[22] Southeastern Philadelphia Transit Authority, High speed Stations, SEPTA Web Mapping Portal, updated April 06, 2023. https://gis-septa.hub.arcgis.com/datasets/af52d74b872045d0abb4a6bbbb249453_0/explore?location=40.009034%2C-75.215731%2C11.68.
[23] City and County of Denver, Open Data Catalog, accessed May 11, 2024. https://www.denvergov.org/opendata.
[24] RTD, LightrailStations, RTD Open GIS Data, accessed April 29, 2024. https://gis-rtd-denver.opendata.arcgis.com/datasets/e14366d810644a3c95a4f3770799bd54_1/about.

applied to certain variables, such as log-transforming skewed distributions (e.g. percent historic area, percent parking area) and creating categorical variables (e.g. median rent quartiles). These processes ensure data integrity, normalized distributions, and created relevant variables for modeling EVCS installation patterns.

Table 2. Summary Table of Continuous Variables - Philadelphia

variable	mean	sd	min	max	se
MedAge	36.4	7.1	19.8	61.3	0.4
MedYearBuilt	1949.4	13.8	1938.0	1998.0	0.7
pctWhite	35.6	29.7	0.0	95.4	1.6
pctBlack	38.9	33.7	0.0	99.1	1.8
pctOther	25.5	20.1	0.0	96.3	1.0
pctHis	14.0	18.4	0.0	92.0	1.0
veh_ownership	71.6	15.9	21.5	98.4	0.8
pop_density	3253.9	1913.3	63.0	14436.3	99.7
PctParking	1.3	1.8	0.0	12.1	0.1
pctSingleStruc	66.1	25.0	1.5	98.7	1.3
pctBachelorAndAbove	35.1	24.7	0.5	95.6	1.3
renter_share	47.7	18.9	7.1	93.9	1.0
owner_share	52.3	18.9	6.2	92.9	1.0
building_density	28.5	11.4	2.2	70.0	0.6
pctFlooding	1.4	4.3	0.0	44.1	0.2
pctHistoric	4.4	10.8	0.0	71.0	0.6
MedHHInc	63898.4	31799.3	14983.0	181066.0	1657.7
AvgHHSize	2.4	0.5	1.3	4.0	0.0
MedRent	1103.6	367.8	474.0	2750.0	19.2
HomePrice	261982.1	171720.1	46700.0	1036700.0	8951.5

Table 3. Summary Table of Categorical Variables - Philadelphia

variable	category	share
EVCS_installed	N (no)	88.3%
EVCS_installed	Y (yes)	11.7%
Dom_race	Black	35.6%
Dom_race	Mixed	14.9%
Dom_race	Other	12.2%
Dom_race	White	37.2%
Dom_his	Hispanic	6.3%
Dom_his	non-Hispanic	93.8%
station.buffer	0 (no)	71.7%
station.buffer	1 (yes)	28.3%
corridor.buffer	0 (no)	56.8%
corridor.buffer	1 (yes)	43.2%

Table 4. Summary Table of Continuous Variables - Denver

variable	mean	sd	min	max	se
MedAge	36.2	6.4	25.3	73.9	0.5
MedYearBuilt	1969.3	22.2	1938.0	2015.0	1.7
pctWhite	58.6	23.6	3.7	93.5	1.8
pctBlack	7.1	8.5	0.0	41.9	0.7
pctOther	34.3	20.9	6.5	91.7	1.6
pctHis	26.1	21.8	3.1	89.7	1.7
veh_ownership	90.5	7.4	57.9	100.0	0.6
pop_density	1429.3	921.0	185.6	5039.9	71.9
PctParking	1.3	4.5	0.0	31.5	0.4
pctSingleStruc	54.2	30.4	0.0	100.0	2.4
pctBachelorAndAbove	55.8	22.3	6.8	91.1	1.7
renter_share	48.7	22.0	6.8	94.1	1.7
owner_share	51.3	22.0	5.9	93.2	1.7
building_density	20.8	6.7	3.4	50.5	0.5
pctStruc_After20	1.1	2.5	0.0	18.4	0.2
MedHHInc	95335.2	37542.6	36226.0	250001.0	2931.6
AvgHHSize	2.2	0.6	1.3	4.5	0.1
MedRent	1596.5	365.5	591.0	2696.0	28.5
HomePrice	586541.5	208001.2	237100.0	1645000.0	16242.2

Table 5. Summary Table of Categorical Variables - Denver

variable	category	share
EVCS_installed	N (no)	65.2%
EVCS_installed	Y (yes)	34.8%
Dom_race	Mixed	10.4%
Dom_race	Other	19.5%
Dom_race	White	70.1%
Dom_his	Hispanic	15.2%
Dom_his	non-Hispanic	84.8%
station.buffer	0 (no)	81.7%
station.buffer	1 (yes)	18.3%
corridor.buffer	0 (no)	36.6%
corridor.buffer	1 (yes)	63.4%

Methods

The project uses a multi-tiered approach. First, we conducted exploratory plots of data to visualize association patterns between the outcome variable (EVCS_installed) and selected features. To further investigate the statistical significance of preliminary patterns, we used t-tests to compare the means of selected interval features between EVCS-installed and non-EVCS-installed tracts respectively for Philadelphia and Denver. Then, two binomial Logistic models are developed to comprehensively investigate EVCS development trends and associative features with EVCS installation outcomes across Philadelphia and Denver. Finally, by using the model to identify tracts where development is likely but has yet to occur under existing trends (False Positives), we compare the predictive results with policy targets to see how policies would orient the development patterns in both cities.

Findings

i. Exploratory plots

We conducted preliminary data analysis using a series of exploratory plots to outline preliminary associations between EVCS installation outcomes with individual categorical and continuous features.

<u>Philadelphia</u>

Figure. 1 Feature associations with the likelihood of EVCS_installed - Philadelphia

Categorical features

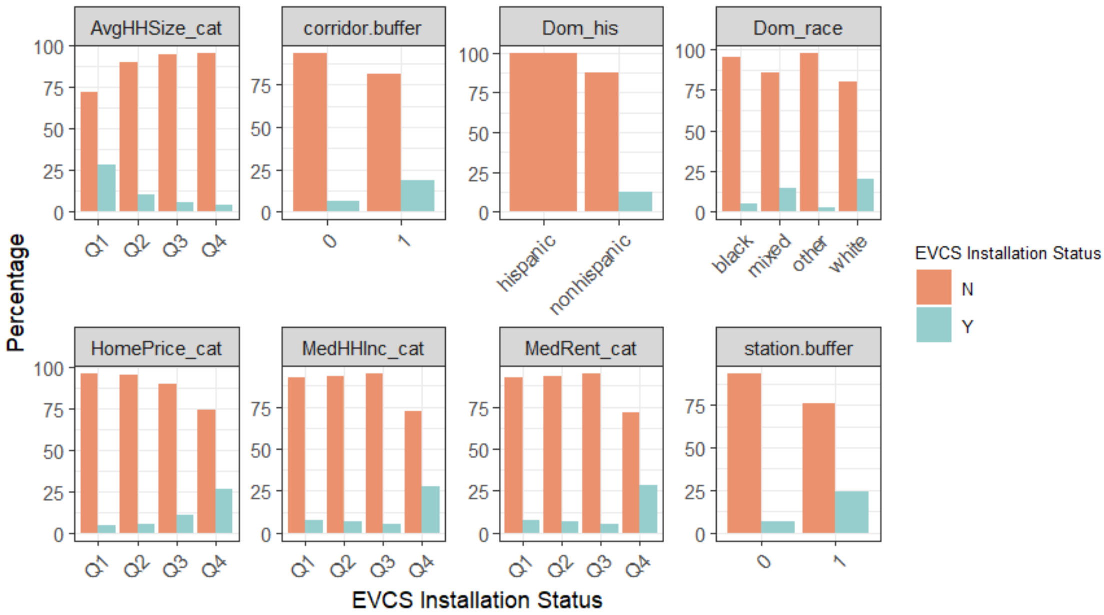
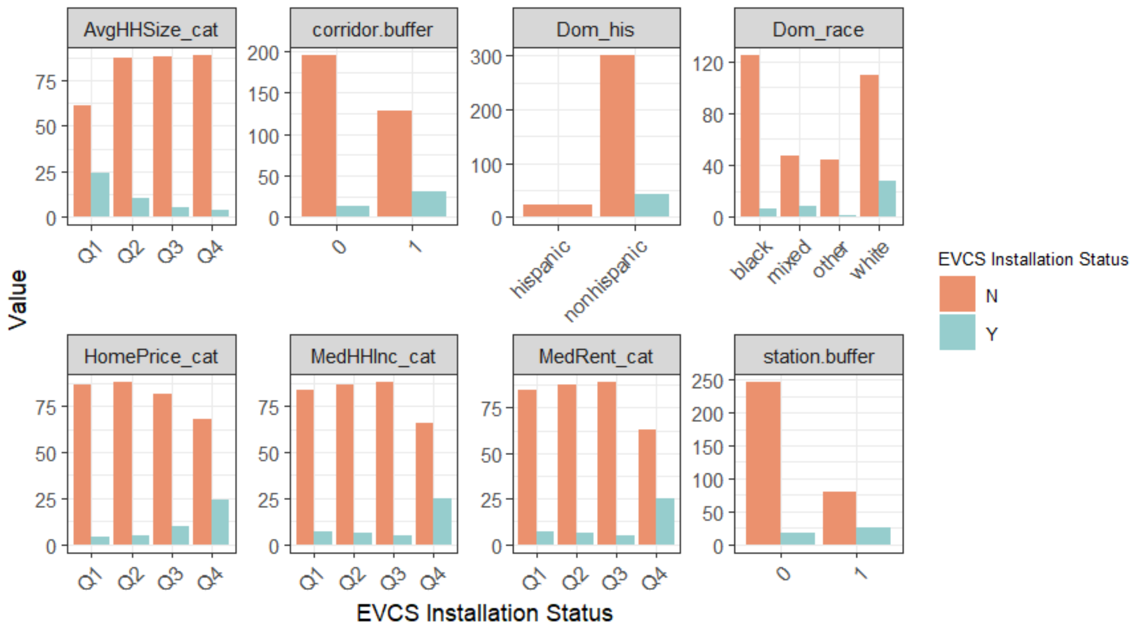


Figure. 2 Feature associations with the likelihood of EVCS_installed - Philadelphia

Categorical features



Comparing the share of the two sample groups (EVCS-installed or not) by feature categories in Philadelphia (fig. 1 and 2), we observe that census tracts with EVCS installation generally make up higher shares in areas that are non-Hispanic, predominantly white or mixed race, with higher home prices, median household incomes, and median rents, as compared to those falling under lower or alternative categories. The share of

EVCS-installed tracts is also higher among areas close to the Alternative Fuel Corridor and public transit stations.

Figure. 3 Feature associations with the likelihood of EVCS_installed - Philadelphia

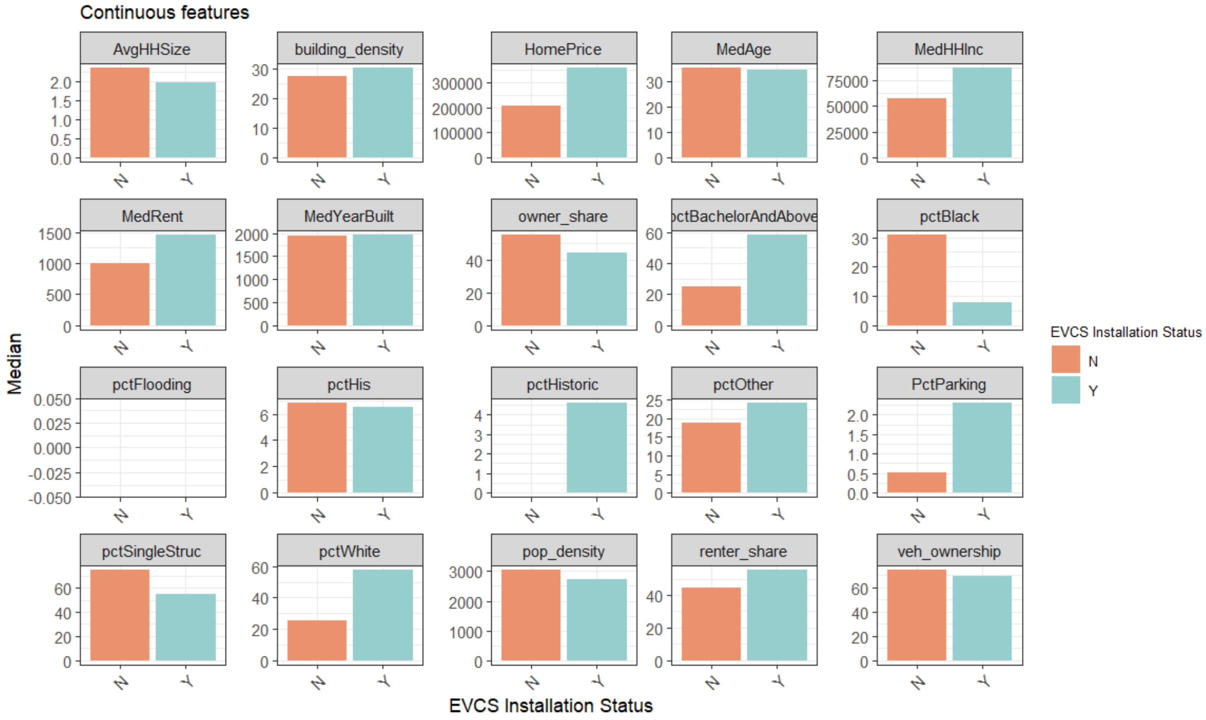


Figure. 4 Feature distributions of EVCS_installed vs. NO EVCS_installed - Philadelphia

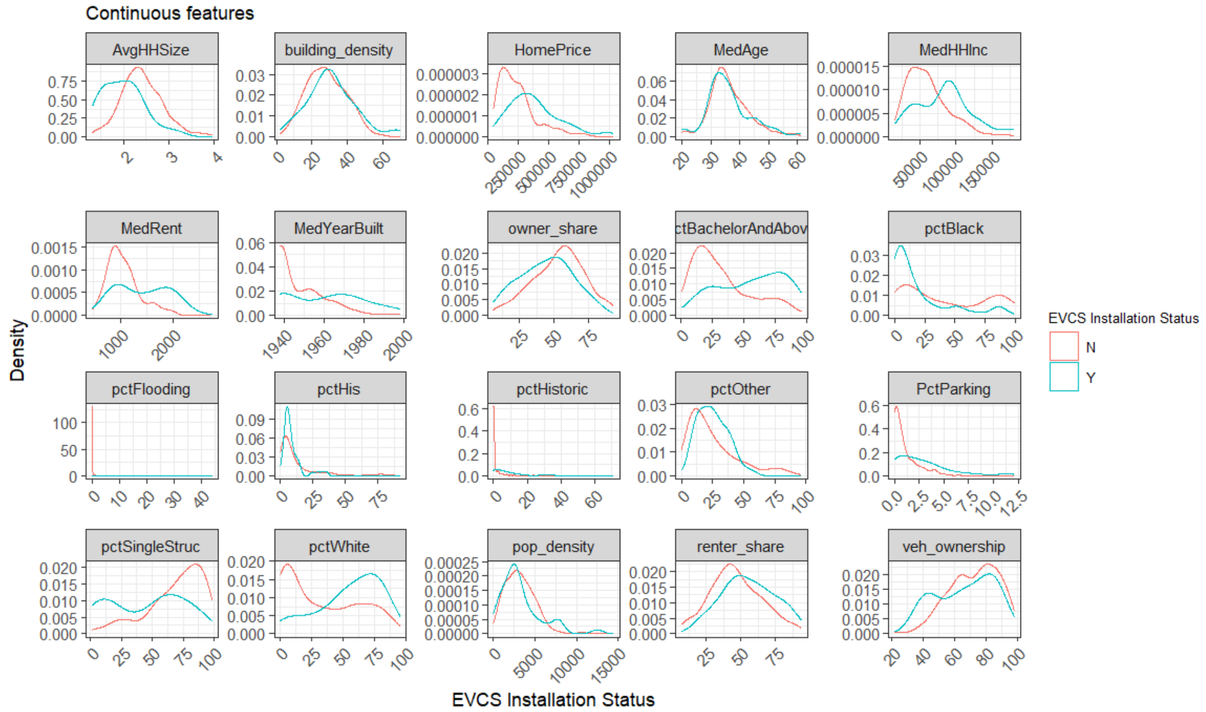


Figure. 3 and 4 illustrate the relationship between EVCS installation outcomes and continuous features. We notice that census tracts with EVCS installations are associated with higher educational attainment, higher percentage of White or other race/ethnicity populations, higher renter share, lower vehicle ownership, lower percentage of the Black population, and lower percentage of single-unit structures.

Denver

Figure. 5 Feature associations with the likelihood of EVCS_installed - Denver

Categorical features

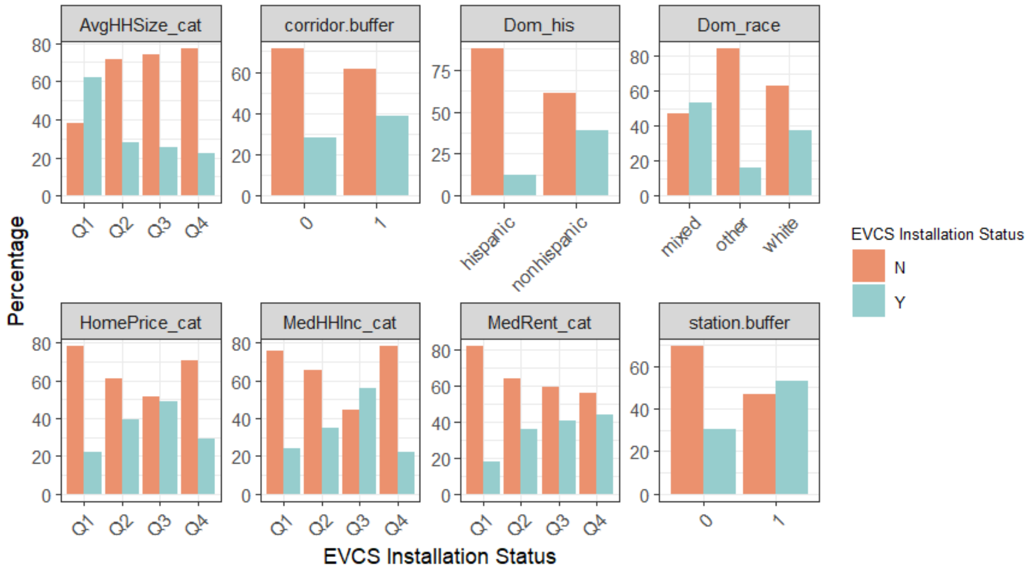
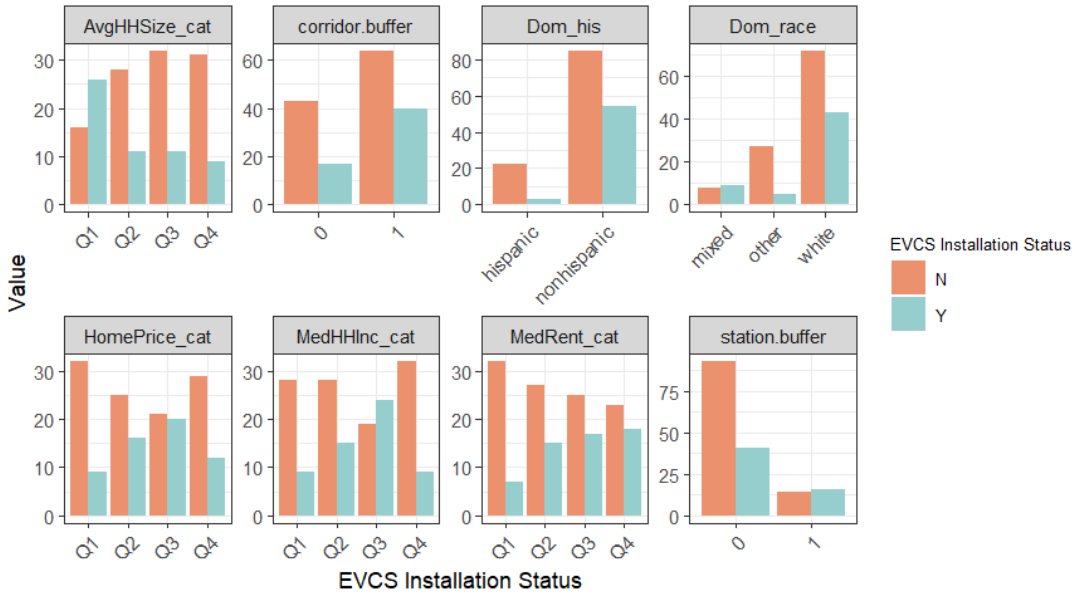


Figure. 6 Feature associations with the likelihood of EVCS_installed - Denver

Categorical features



With reference to categorical features in Denver (fig. 5 and 6), we found the share of EVCS-installed tracts is generally higher among those with higher home prices, rents, and median household income. The share of EVCS-installed tracts is likewise higher among tracts buffered by the corridor and transit stations.

Comparing the relative share of samples by different racial categories, however, our observations show that the highest share of EVCS-installed tracts is among racially-mixed communities as compared to predominantly white or other communities. This opposes the observations in Philadelphia and challenges existing common findings[25].

[25] See Literature Review.

Figure. 7 Feature associations with the likelihood of EVCS_installed - Denver

Continuous features

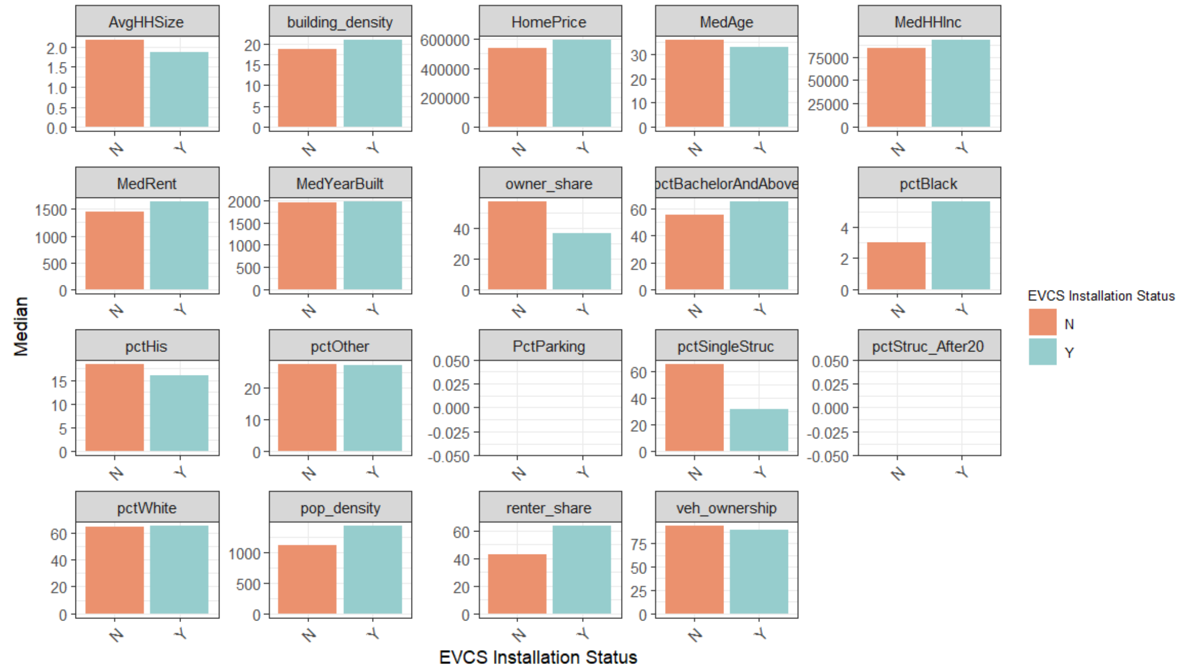


Figure. 8 Feature distributions of EVCS_installed vs. NO EVCS_installed - Denver

Continuous features

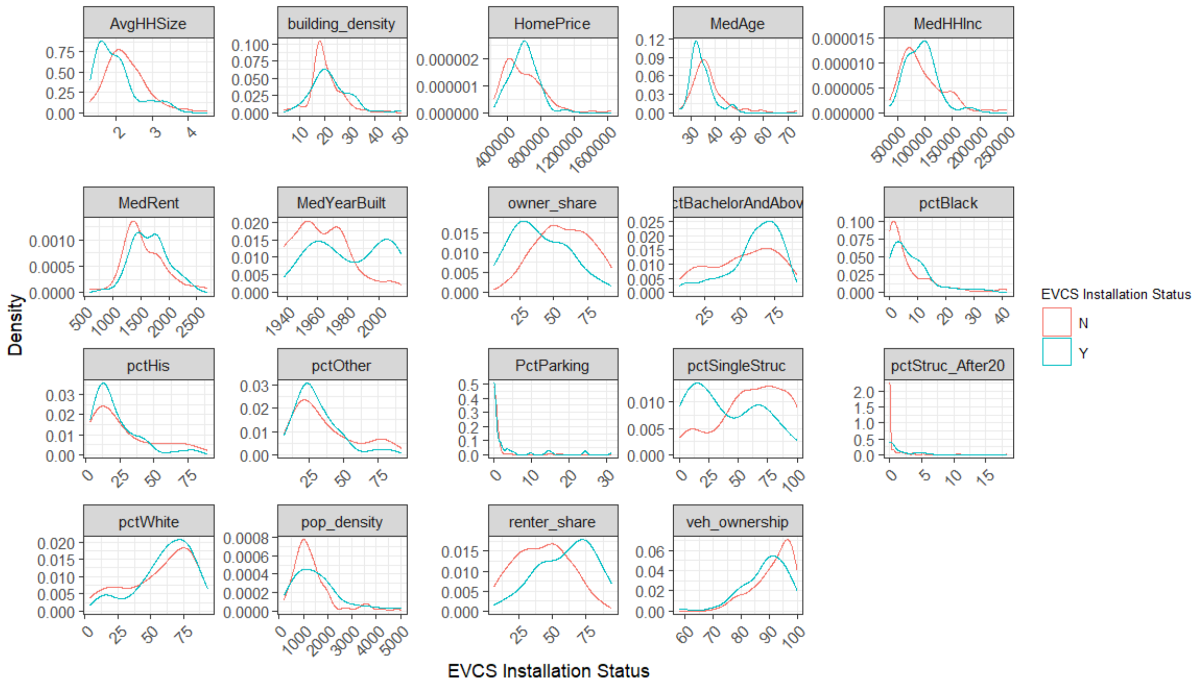


Figure 7 and 8 illustrate the association between EVCS installation outcome with continuous features, indicating correspondence between EVCS-installed tracts and lower average household size, lower median age, higher median household income, higher median rent and home value, higher education attainment, lower single structure share and lower owner share.

Findings relating to racial composition again contradicts Philadelphia, with Denver's EVCS-owning neighborhoods associating with higher shares of black residents. This discovery is likely an outcome of Denver's equity-driven EVCS planning principle[26].

ii. T-tests

To further identify statistically significant associations, we conducted t-tests to compare the means of selected interval features between EVCS-installed vs not-installed tracts of the two cities. Since t-test only performs on interval data, we selected the continuous form of several categorical features in this step.

Most of the selected features are normally distributed across both samples for both cities with a few outliers, we used logarithm transformation to process variables with highly skewed observations such as percent of parking lot (both cities), percent of flooding (Philadelphia), percent of historic designation (Philadelphia), and share of black population (Denver).[27]

For each two-tailed t-test, our null hypothesis is that the true difference in means between the variable of EVCS-installed census tract sample and non-EVCS-installed census tract sample is zero. We set the statistical significance threshold at the 95% confidence interval (p-value < 0.05).

<u>Philadelphia</u>

Table 6. T-test results between census tract group with and without EVCS - Philadelphia

Feature	Mean		t-stat	degree of freedom	p-value
	Without EVCS	With EVCS			
MedHHInc	61134.05	84791.70	-3.79	48.46	4.16E-04
MedRent	1061.31	1423.19	-4.63	46.83	2.94E-05
HomePrice	245138.80	389286.00	-4.24	48.15	1.01E-04
AvgHHSize	2.40	1.99	5.60	53.86	7.56E-07
MedAge	36.43	36.32	0.09	50.59	0.929
owner_share	53.32	44.38	2.93	53.50	0.00497
pctBachelorAndAbove	32.30	56.17	-5.76	51.29	4.87E-07
pctWhite	32.96	55.42	-5.42	58.36	1.18E-06
pctBlack	41.53	19.36	5.28	65.17	1.59E-06
PctParking	1.07	2.84	-3.94	44.79	2.80E-04
pctSingleStruc	68.92	45.16	4.95	48.48	9.42E-05
pop_density	3246.76	3307.84	-0.16	48.19	0.877
veh_ownership	72.29	66.69	1.94	50.50	0.0582
building_density	28.09	31.17	-1.40	49.18	0.169
pctFlooding	1.25	2.62	-1.69	49.67	0.0979
pctHistoric	3.73	9.73	-2.76	48.22	0.008048
log_pctFlooding	0.33	0.64	-1.92	48.05	0.0605
log_pctHistoric	0.66	1.67	-4.99	50.31	7.55E-06
log_PctParking	0.56	1.09	-4.55	48.22	3.65E-05
log_HomePrice	12.22	12.72	-5.24	55.43	2.61E-06

*Among log transformed variables, 1 was added to the original value where zero was observed.

Table. 6 shows that there are statistically significant differences in means of average household size (t-stat =5.60, p-value = 7.6E-07), median home price (t-stat = -4.24, p-value = 1.0E-04), and owner share (t-stat =

[26] "Denver Electric Vehicle (EV) Action Plan" (Denver Climate Action, Sustainability & Resiliency, April 2020), https://denvergov.org/files/assets/public/v/1/climate-action/documents/renewable-energy/denvervehicleelectrificationactionplan.pdf.

[27] See Appendix.

2.93, p-value = 0.005) between census tracts with and without EVCS in Philadelphia. We reject our null hypothesis and gain more confidence in the alternative hypothesis that there are true differences in means of those variables between the two census tract samples.

The t-test results also reveal statistically significant differences between the means of median household income (t-stat = -3.79, p-value = 4.2E-04), median rent (t-stat = -4.63, p-value = 2.9E-05), percent of single family home structure (t-stat = 4.95, p-value = 9.4E-05), percent of historic designation ground area (log transformed, t-stat = -4.99, p-value = 7.6E-06), and percent of parking area (log transformed, t-stat = -4.55, p-value = 3.7E-05) between census tracts with EVCS and those without, implying that true differences exist in the means of these variables. However, the validity of these t-test interpretations is potentially compromised due to the limitations in the data and transformation methods, as these variables exhibit observable skewness in their distributions, potentially violating the normal distribution assumption.

<u>Denver</u>

Table 7. T-test results between census tract group with and without EVCS - Denver

Feature	Mean		t-stat	degree of freedom	p-value
	Without EVCS	With EVCS			
MedHHInc	96437.19	93266.67	0.58	154.46	0.563
MedRent	1561.49	1662.16	-1.78	131.95	0.0777
HomePrice	583943.90	591417.50	-0.25	155.22	0.805
AvgHHSize	2.29	2.00	3.10	117.54	0.00246
MedAge	37.25	34.35	3.23	156.85	0.00151
owner_share	57.56	39.50	5.33	108.67	5.29E-07
pctBachelorAndAbove	53.03	60.99	-2.36	137.91	0.0197
pctWhite	56.98	61.75	-1.30	131.85	0.196
log_pctBlack	1.46	1.84	-2.40	131.72	0.0178
log_pctHis	3.06	2.89	1.39	131.97	0.166
log_pop_density	7.04	7.19	-1.50	102.87	0.136
building_density	20.05	22.07	-1.73	94.04	0.0869
veh_ownership	91.57	88.46	2.49	99.27	0.0145

*Among log transformed variables, 1 was added to the original value where zero was observed.

Table. 7 shows there are statistically significant differences in means of average household size (t-stat =3.10, p-value = 0.002), median age (t-stat = 3.2, p-value = 0.002), and owner share (t-stat = 5.33, p-value = 5.3E-07) between census tracts with EVCS and without. We therefore reject our null hypothesis and gain more confidence in the alternative hypothesis that the true difference in means of those variables between the two census tract samples in Denver is not equal to zero.

The t-test results also indicate there are statistically significant differences in means of percent of individuals with bachelor degree and above (t-stat = -2.36, p-value = 0.02), percent of black residents (log transformed, t-stat = -2.40, p-value = 0.018), and vehicle ownership rate (t-stat = 2.49, p-value = 0.014) between census tracts with EVCS and without, allowing us to gain more confidence that the two tracts samples are distinguished by true difference in means of those features. However, these variables also exhibit observable skewness in their distribution and potentially violate the normal distribution assumption and challenge the validity of t-test results.

To summarize, the most significant features distinguishing tract groups with and without EVCS, while there are some similarities across the two cities (eg. household size, owner share), there are also notable differences, such as the median age in Denver and median home price in Philadelphia.

iii. Binomial Logistic Model

In this section, we use binomial logistic regression to investigate prevailing associations between a census tract's demographic, socioeconomic, and environmental features with EVCS installation outcome ("EVCS_installed") in both cities.To comprehensively capture development patterns, our models prioritizes significance of variable-based coefficients and model-fit statistics. The iterative model building process involves evaluation and balancing of model results, AIC changes, and chi-squared tests.

Using the derived models and the share of existing EVCS tracts as a threshold, we further predict and visualize anticipated development tracts (represented by False Positive prediction results) under existing conditions and compare them with policy targeting zones to assess policy effectiveness.

Philadelphia

Table 8. Binomial Logit Model Results - Philadelphia

Variable	Estimate (S.E.)
(Intercept)	-82.263***(24.471)
MedYearBuilt	0.041***(0.012)
pctBlack	-0.017*(0.008)
owner_share	0.004(0.012)
building_density	-0.017(0.021)
station.buffer	1.059*(0.532)
log_pctHistoric	0.363*(0.157)
log_PctParking	0.721*0.365(0.365)
Log Likelihood	-98.753
AIC	213.51

Signif. Level: 0 '***' 0.001 '**' ,<0.01 '*' 0.05 '.', 0.1 ''

Table 8. summarizes statistics of the best binomial logistic model fitted to the Philadelphia dataset, which comprises 368 tracts upon removal of observations with missing analysis variables. Most independent variables align with previous t-test findings, including percent of black population, owner share, percent of historic designation area (log transformed), percent of parking (log transformed).

One notable pattern emerges concerning the age and historical character of the built environment in Philadelphia. The results indicate that census tracts with a later median year of structure built are more likely to have EVCS installations. Specifically, on average, a one-year increase in the median year built is associated with an 4.18% higher odds of having EVCS access, all else equal. However, census tracts with a higher historic designation are also more likely to have EVCS installations, with a 1 % increase in the share of historic area corresponding to a 0.36% higher odds of EVCS presence, all else equal. While these results seem contradictory, they may be explained by the fact that Philadelphia is a historic city where historic designations co-exist with highly urbanized areas like the Center City.

Another pattern is outstanding correlations between transportation assets and EVCS installation in Philadelphia. First, the model suggests that census tracts with a higher share of parking are more likely to have EVCS installations. Specifically, a 1% increase in the share of parking area is associated with 0.72% higher odds of EVCS installations in Philadelphia, all else equal. Likewise, census tracts located within a one-mile station buffer have a 188.58% higher odds of having local EVCS as compared to tracts outside of the station buffer, all else equal. Collectively, these observations imply that there have been patterns of co-locating EVCS with parking and transit stations, potentially for the benefit of park-and-charge and accessibility. However, these patterns highlight justice concerns, whereas investments facilitating mobility, in particular environmentally friendly modes, tend to cluster.

The model also suggests the census tract with higher percentage of black population are less likely to have EVCS installations. With a one unit (percent) decrease in the share of black population corresponding to a 1.69% lower odds of having EVCS installation, all else equal. This finding highlights equity concerns surrounding a lower likelihood of deploying EVCS in minority communities.

Denver

Table 9. Binomial Logit Model Results - Denver

Variable	**Estimate (S.E.)**
(Intercept)	4.134*(2.087)
MedRent_catQ2	1.113.(0.598)
MedRent_catQ3	1.295*(0.607)
MedRent_catQ4	2.340***(0.685)
AvgHHSize_catQ2	-1.443*(0.713)
AvgHHSize_catQ3	-1.345.(0.811)
AvgHHSize_catQ4	-1.538.(0.935)
owner_share	-0.039*(0.017)
log_pctBlack	0.478*(0.212)
MedAge	-0.085(0.052)
pop_density	-0.001*(0.0003)
Log Likelihood	-78.998
AIC	180

Signif. Level: 0 '***' 0.001 '**' ,<0.01 '*' 0.05 '.', 0.1 ''

Table 9. summarizes statistics of the best binomial logistic model fitted to the Denver dataset, which comprises 164 census tracts upon removal of observations with missing analysis variables. Most of the independent variables correspond with t-test findings, including average household size, owner share, percent of black residents (log transformed), median age, validating these variables as distinguishing features. The two remaining variables, median rent and population density, which yielded p-value close to the traditional threshold in previous t-tests, also factor as statistically significant predictors.

It is observed that renters are crucial to EVCS installation in Denver under existing conditions and development patterns. Overall, the odds associated with having EVCS installation is generally higher in census tracts classified into higher median rent quartiles as compared to tracts classified into bottom 25% median rent. The odds of EVCS installation is also higher in tracts with smaller average household size (bottom 25%) as compared to larger households, all else equal. Likewise, the results also indicate that with every unit (percent) increase in owner share, the odds associated with having EVCS access is lowered by 3.82%. These observations speak to aggregated association between renter economy and EVCS installation in Denver, implying that wealthier renters and renter-dominant neighborhoods in Denver tend to have better access to EVCS. However, these observations also imply an underlying concern that the EVCS development could be potentially associated with gentrification.

Other patterns are also discovered. Contrary to general scholar findings, a census tract is more likely to have local EVCS access with higher share of black residents, estimated as every 1% increase in the share of black population corresponds to 0.48% higher odds of owning EVCS installation. On the other hand, "younger" census tracts also have better EVCS access, with every one-year increase in median age would lower a tract's odds of having EVCS by 8.15%, all else equal. Moreover, a census tract's population density also has marginal but significant association with EVCS installation, whereby every unit (person/acre) increase in population would lower a tract's odds of having EVCS by 0.10%, all else equal.

Comparison between the two model findings indicate that existing EVCS development patterns in Philadelphia generally exhibit more equity challenges, particularly evidenced through clustered rather than diffusive transit asset developments (parking, station buffer, and EVCS) aggregating mobility conveniences and environmentally friendly assets. Likewise, Philadelphia distincts from Denver such that a census tract's likelihood drops with higher black population in Philadelphia, whereas it increases in Denver, which places a heavier emphasis on equitable EVCS development strategy. There are also similar patterns such as both cities exhibit favorable development approaches in "newer" neighborhoods. In Philadelphia, this is represented by higher odds in ECVS development in neighborhoods with a more recent median year of structure built. Whereas in Denver, this is evidenced through heavier association with a renter economy, characterized by smaller households and lower ownershare.

iv. Mapping Analysis

To simulate existing EVCS development patterns, we used the share of census tracts with EVCS installation among all census tracts the models trained upon to derive prediction results for Philadelphia and Denver. The model generates four prediction outcomes for each city (fig. 9 and 11):

- True Positive: where the model correctly predicts an EVCS-owning census tract to have EVCS).
- False Positive: where the model incorrectly predicts a non-EVCS-owning census tract to have EVCS.
- True Negative: where the model correctly predicts a non-EVCS-owning census tract to not have EVCS.
- False Negative: where the model incorrectly predicts a EVCS-owning census tract to not have EVCS.

As False Positives (FPs) may be the closest proximate census tracts where future EVCS is likely to occur without policy intervention, we used mapping analysis to compare these FPs with areas fitted under policy priority, to see how policy would re-orient current development trends.To visualize levels of policy-concerning indices, we created binarily colored maps to distinguish areas targeted under different policy criteria (fig. 10a - 10c, fig. 12a - 12c). The last map of each series (fig. 10d and fig. 12d), identifies policy targets accounting for all listed criteria in previous maps (fig. 10a - 10c, fig. 12a - 12c).

Philadelphia

Figure. 9 Prediction Results - Philadelphia

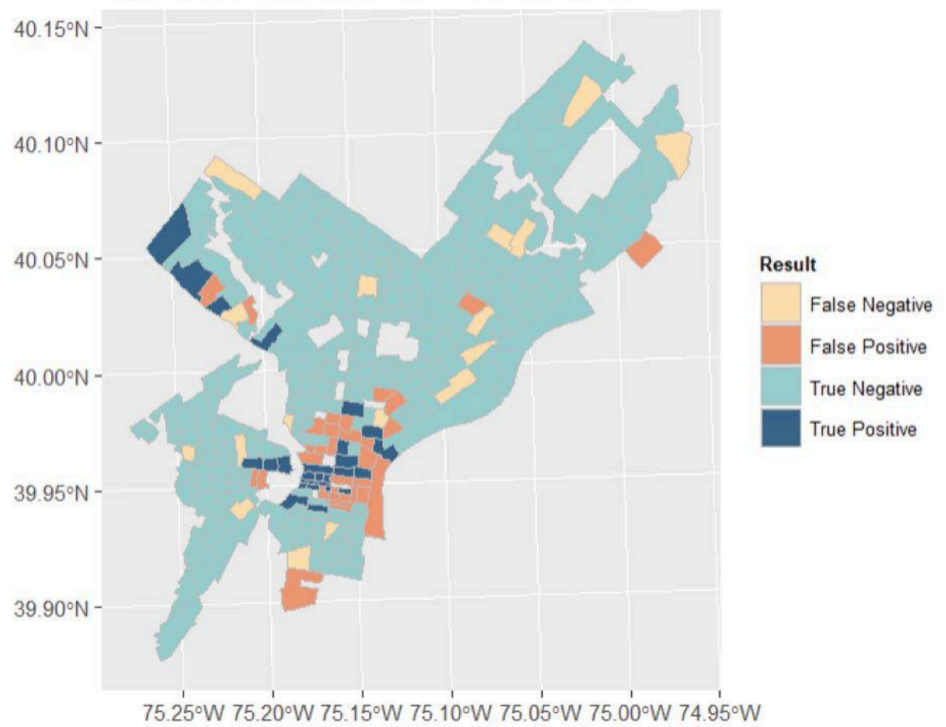


Figure. 10a Prediction Results vs. Corridor Buffer - Philadelphia

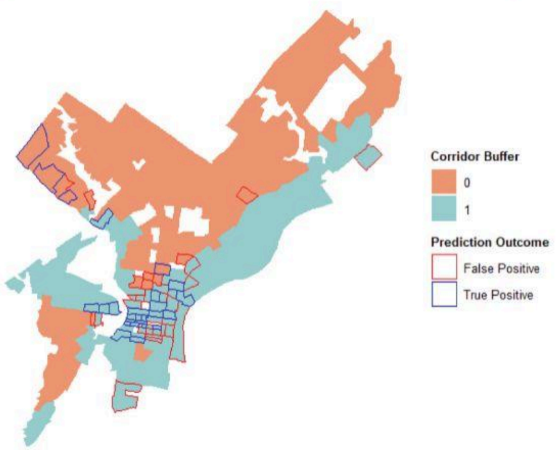


Figure. 10b Prediction Results vs. Flooding Risk - Philadelphia

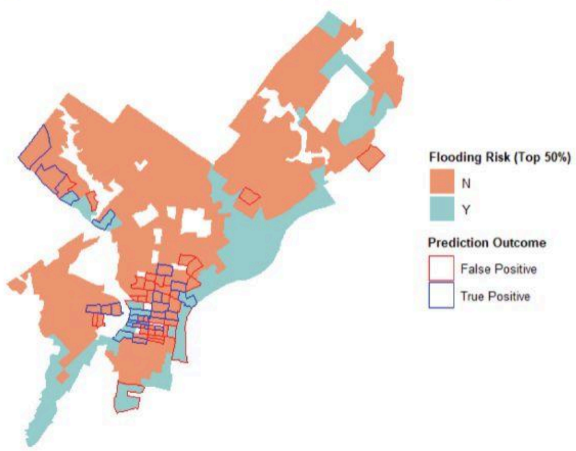


Figure. 10c Prediction Results vs. Historic Designation - Philadelphia

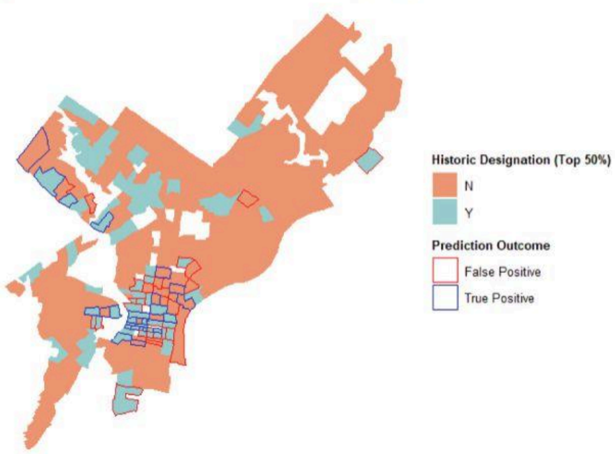
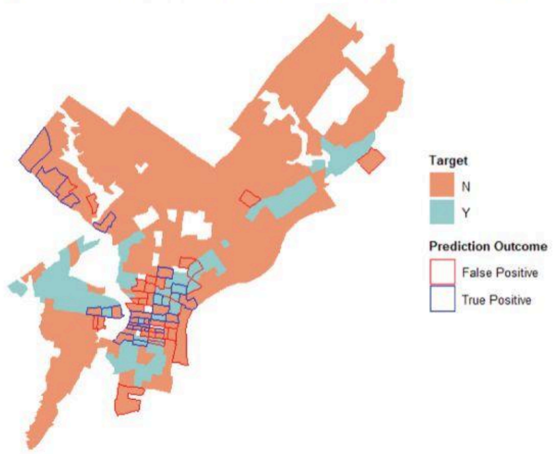


Figure. 10d Prediction Results vs. Policy Targets - Philadelphia



Philadelphia's Logistic model yields 33 False Positives at a false positive rate of 10.2%. These FP tracts are generally located in Central and Lower North regions, with a few scattered across Northeast, Northwest, and South Philadelphia (fig. 9).

We note an obvious mismatch between FPs and City target zones in Philadelphia (fig. 10a - 10d). Most FPs are located in tracts within a one-mile alternative fuel corridor buffer except for those in the Northeast and Northwest. With consideration of flooding risks, FPs on the eastern and southern end of Philadelphia are generally not considered suitable for future EVCS development. Furthermore, due to the prevalence of historically designated buildings particularly in the Central City and University City area, most FPs in those regions are undesirable for installation requirements.

As current predictions are made not upon site suitability but existing trends under racial and economic biases, there remains vast opportunities to intervene. With sole consideration of policy priorities, Philadelphia's EVCS landscape could be shifted to feature expansion in West, South, North, and North Delaware, which are deemed unlikely under current development trends (fig. 10d). As these regions generally feature higher minority population shares and lower investment, a planning-focused agenda would generate side-effects of more equitable outcomes.

Denver

Figure. 11 Prediction Results - Denver

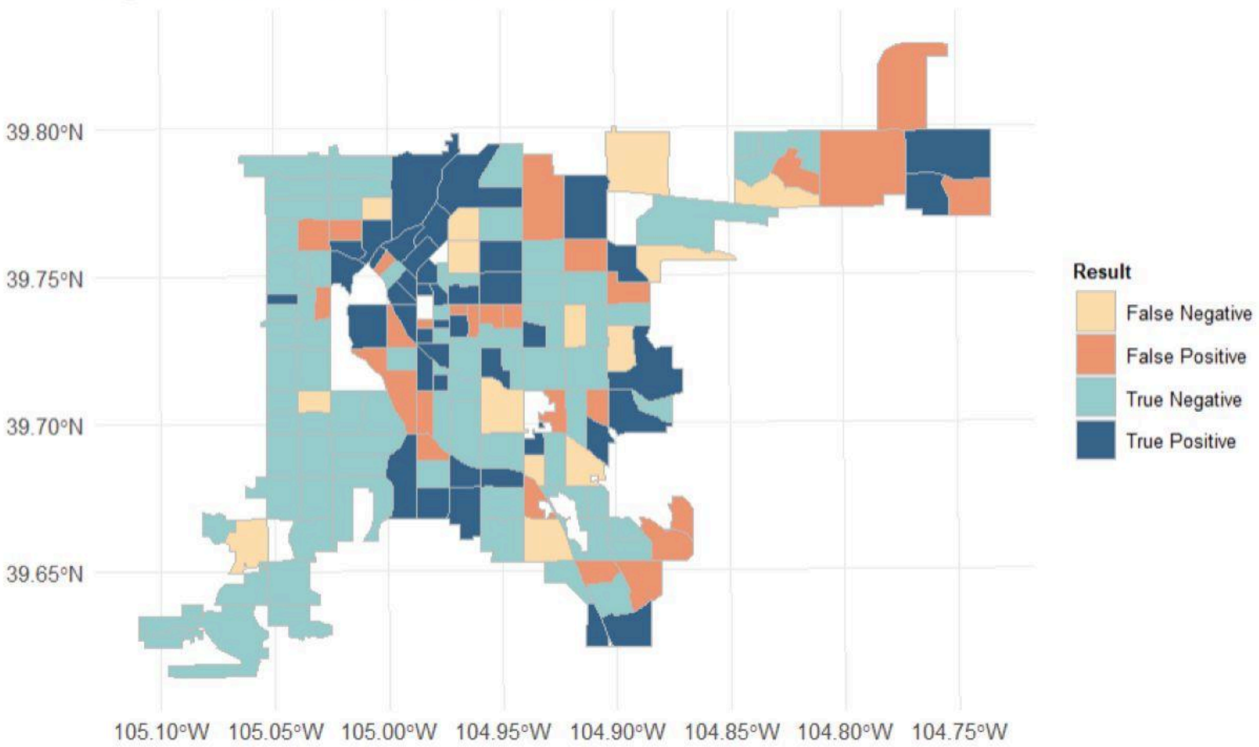


Figure. 12a Prediction Results vs. Corridor Buffer - Denver

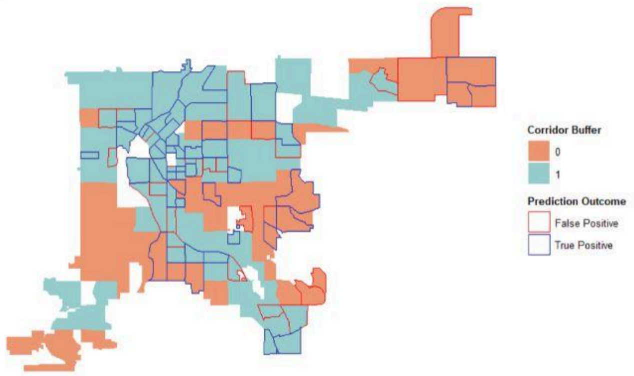


Figure. 12b Prediction Results vs. New Structure - Denver

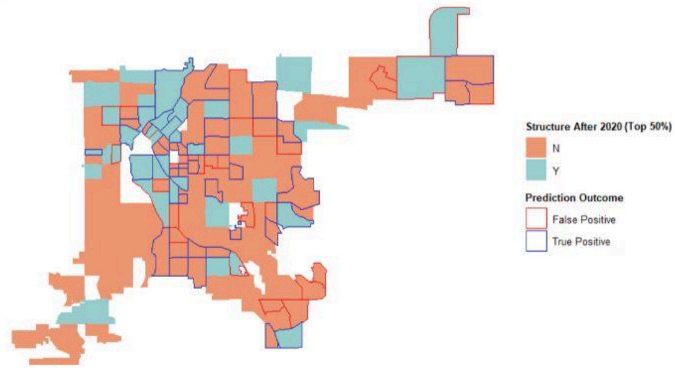


Figure. 12c Prediction Results vs. Equity Status - Denver

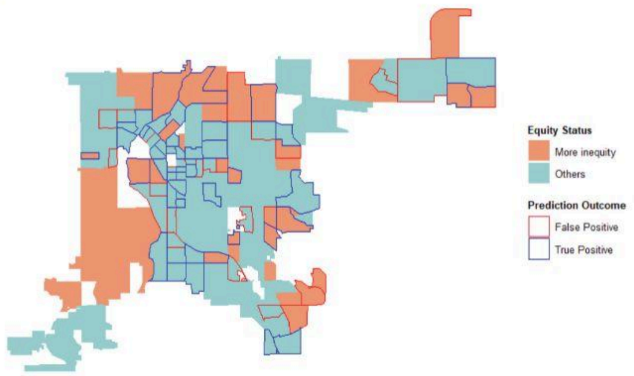
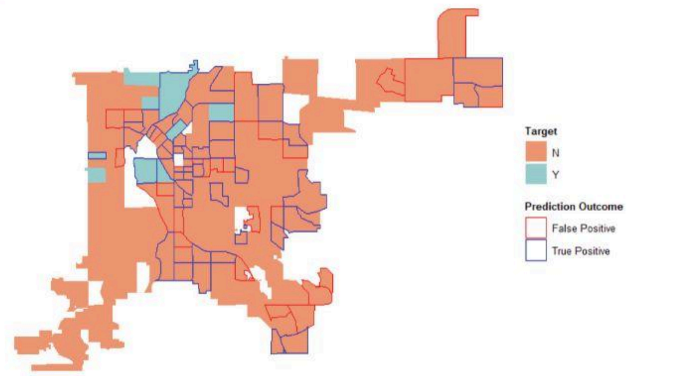


Figure. 12d Prediction Results vs. Policy Targets - Denver



Denver's Logistic model yields 27 False Positives at a false positive rate of 25.2%. Different from Philadelphia, FP tracts in Denver are scattered across the city without obvious patterns of clustering (fig. 11).

We found mismatch between FPs and potential City target zones in Denver, too (fig. 12a - 12d). First of all, the majority of FP tracts are located in corridor buffers, with a few exceptions on the southeast and northeast edge. Among areas with booming new developments, only four FP tracts are identified, which predominantly concentrate in northern Denver. Equity wise, by using income as a proxy since Denver's racial make-up is more homogenous, we find that while FPs and existing EVCS have covered most of the lower income regions, eastern Denver tracts remain the only unaddressed region. However, this region has not been identified as a policy target due to an absence of alternative fuel corridor buffers.

Our hypothesized thresholds lead to very few areas identified as policy targets, most of which already host EVCS (fig. 12d). While this potentially indicates restricted policy influences in Denver, it may also suggest that an equity-led vision is already embedded into Denver's ongoing EVCS siting rationale. However, our mapping has revealed notable disparities along east to southeast Denver, which features a cluster of low-income neighborhoods but cut off from policy attention due to absence of corridor access and new developments and unaddressed under existing development rationale.

Policy Implications

Summarizing previous observations, we identify different needs and concerns surrounding EVCS planning in Philadelphia and Denver, and propose the following recommendations respectively:

Philadelphia

1. Racially equitable EVCS development has yet to arrive in the racially diverse city, posing challenges to minority populations especially black communities. As the existing guidelines exhibit potential to bring EVCS access to previously under-serviced groups, site suitability over socio-economic characteristics or profitability should be prioritized during the permit review process.
2. The City should develop strategies to balance the distribution of transit resources, especially environmentally friendly assets. Instead of clustering EVCS in areas with high public transit access, the city should prioritize EVCS in highly auto-dependent neighborhoods.

Denver

1. With the notable association between EVCS installation and a renter economy in Denver, the City should expand research to inspect EVCS funding and usage in existing and emerging renter neighborhoods, in order to detect and mitigate incidents where EVCS becoming a side product of gentrification.
2. We recommend attention to EVCS development strategies in East Denver, an area unfavored by existing developing patterns and municipal priorities but populated with lower income communities. The City should provide guidance or alternative funding solutions, as well as partner with local community organizations and businesses to fill the existing charging gap.

Conclusion

Utilizing a comparative approach to investigate EVCS development trends in Philadelphia and Denver, our study has comprehensively considered demographic, socioeconomic, housing, transportation, as well as policy prioritization features, and concluded distinct findings between both cities. Greater equity concerns aligning with existing research revealing unfavorable EVCS development trends against minority populations is more evident in Philadelphia, which is further complexed by the factor that EVCS tend to cluster with other mobility-improving assets. Whereas in Denver, a younger city, public EVCS is found to be primarily correlated with a renter economy. However, due to potential risk of association between EVCS development and gentrification, Denver must channel additional resources into enhancing charging access in lower-income neighborhoods un-endowed with recent constructions or investments. Based on these, we were able to customize locally-conscious policy recommendations, including revising permit review priorities and de-clustering environmentally friendly transit infrastructure in Philadelphia, as well as expand surveys relating to gentrification and EVCS and develop public-private partnerships to empower under-serviced neighborhoods in Denver.

While our study has largely addressed our research goals, we recognize several limitations and opportunities for improvement. First, the independent variables' comprehensiveness is largely affected by available datasets. For instance, while the number of Alternative Fuel Corridor highways could add improved significance to the corridor feature by distinguishing buffered tracts into different priority ranks, the current source data is highly fragmented and results in inaccurate counts. Second, due to the limited time interval between passage of major EVCS acts and 2022 ACS results, we were unable to conduct longitudinal research at the moment. In the long run, additional research may analyze factors associated with change in

EVCS distribution to better contrast scenarios with and without policy interventions in different geographical regions. Finally, while the study has solely focused on supply-side EVCS development considerations with installation outcomes, demand-side features including fuel savings and charging rates may also highly correlate with the suitability of EVCS in a neighborhood, which can be incorporated into iterative model developments.

In conclusion, our study thus challenges generalizability of EVCS-related theories, and validates the strength of conducting region-based research to deliver better-suited recommendations. We propose the framework to be referenced and improved in later studies.

Bibliography

Bentley, Kristen. “Denver Planning to Build Accessible EV Charging Stations.” Electrify News Site, August 13, 2023. https://electrifynews.com/news/ev-chargers/denver-planning-to-build-accessible-ev-charging-stations/.

City and County of Denver. “Electric Vehicle (EV) Supply Equipment.” May 16, 2023. https://www.denvergov.org/files/assets/public/v/1/climate-action/documents/hpbh/nze/2022-denver-energy-code-fact-sheets-c-ev-supply-equipment.pdf.

City and County of Denver. “Electrical Vehicle (EV) Charging Spaces.” Accessed May 11, 2024. https://denvergov.org/Government/Agencies-Departments-Offices/Agencies-Departments-Offices-Directory/Community-Planning-and-Development/Building-Codes-Policies-and-Guides/Electrical-Vehicle-Charging-Spaces.

City and County of Denver. Open Data Catalog. Accessed May 11, 2024. https://www.denvergov.org/opendata.

“Colorado National Electric Vehicle Infrastructure (NEVI) Plan.” Colorado Department of Transportation, June 2022. https://www.codot.gov/programs/innovativemobility/assets/co_neviplan_2022_final-1.pdf.

City of Philadelphia. OpenDataPhilly. accessed May 11, 2024. https://opendataphilly.org.

“Denver Electric Vehicle (EV) Action Plan.” Denver Climate Action, Sustainability & Resiliency, April 2020. https://denvergov.org/files/assets/public/v/1/climate-action/documents/renewable-energy/denvervehicleelectrificationactionplan.pdf.

Domonoske, Camila, and Michael Copley. “In a Boost for EVs, EPA Finalizes Strict New Limits on Tailpipe Emissions.” NPR, March 20, 2024. https://www.npr.org/2024/03/20/1239092833/biden-epa-auto-emissions-evs.

“EZ Permit Standard: Electrical Vehicle Charger (EVC) Stations.” City of Philadelphia Department of Licenses & Inspections, accessed May 11, 2024. https://www.phila.gov/media/20220720130633/PB_020_F-EZ-Electrical-Vehicle-Charger-Permit-Standard-updated.pdf.

Hsu, Chih-Wei, and Kevin Fingerman. “Public Electric Vehicle Charger Access Disparities across Race and Income in California.” *Transport Policy* 100 (January 2021): 59–67. https://doi.org/10.1016/j.tranpol.2020.10.003.

Khan, Hafiz Anwar Ullah, Sara Price, Charalampos Avraam, and Yury Dvorkin. “Inequitable Access to EV Charging Infrastructure.” *The Electricity Journal* 35, no. 3 (April 2022): 107096. https://doi.org/10.1016/j.tej.2022.107096.

Loni, Abdolah, and Somayeh Asadi. “Data-Driven Equitable Placement for Electric Vehicle Charging Stations: Case Study San Francisco.” *Energy* 282 (November 1, 2023): 128796. https://doi.org/10.1016/j.energy.2023.128796.

Lubinsky, Adam F. “How to Pave the Way for Equitable EV Adoption.” American Planning Association. American Planning Association, August 24, 2023. https://www.planning.org/planning/2023/summer/how-to-pave-the-way-for-equitable-ev-adoption/.

Min, Yohan, and Hyun Woo Lee. “Social Equity of Clean Energy Policies in Electric-Vehicle Charging Infrastructure Systems.” *Construction Research Congress 2020*, November 9, 2020. https://doi.org/10.1061/9780784482858.025.

National Renewable Energy Laboratory. Alternative Fueling Station Locator. U.S. Department of Energy, accessed April 29, 2024. https://afdc.energy.gov/stations#/find/nearest?fuel=ELEC.

Racer, Owen. “Philly EV Drivers Are Itching for More Fast Chargers as New Federal Rules Seek to Boost EVs.” WHYY, March 21, 2024. https://whyy.org/articles/electric-vehicles-charging-stations-philadelphia-pennsylvania-federal-rollout/.

Roy, Avipsa, and Mankin Law. “Examining Spatial Disparities in Electric Vehicle Charging Station Placements Using Machine Learning.” *Sustainable Cities and Society* 83 (June 2022): 103978. https://doi.org/10.1016/j.scs.2022.103978.

RTD. LightrailStations. RTD Open GIS Data, accessed April 29, 2024. https://gis-rtd-denver.opendata.arcgis.com/datasets/e14366d810644a3c95a4f3770799bd54_1/about.

Southeastern Philadelphia Transit Authority. High speed Stations. SEPTA Web Mapping Portal, updated April 06, 2023. https://gis-septa.hub.arcgis.com/datasets/af52d74b872045d0abb4a6bbbb249453_0/explore?location=40.009034%2C-75.215731%2C11.68.

The White House. “Fact Sheet: The Bipartisan Infrastructure Deal.” The White House. The White House, November 6, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/.

U.S. Census Bureau. American Community Survey, ACS 5-Year Estimates Data Profiles, 2022, accessed May 11, 2024. https://api.census.gov/data/2022/acs/acs5, retrieved using tidycensus R package.

U.S. Department of Transportation. Alternative Fuel Corridors Rounds 1-7. Federal Highway Administration HEPGIS, November 07, 2023. https://hepgis-usdot.hub.arcgis.com/datasets/15593a84e7924814826faad39bd9ad12_0/explore?location=36.777588%2C-97.396605%2C4.97.

U.S. Department of Transportation. “Bipartisan Infrastructure Law - National Electric Vehicle Infrastructure (NEVI) Formula Program Fact Sheet,” Federal Highway Administration, accessed May 11, 2024. https://www.fhwa.dot.gov/bipartisan-infrastructure-law/nevi_formula_program.cfm.

Zimmerman, Sarah. “Inflation Reduction Act Encourages EV Battery Sourcing, Production in North America.” Supply Chain Dive, August 17, 2022. https://www.supplychaindive.com/news/biden-signs-inflation-reduction-act-in-boost-to-us-electric-vehicle-product/629854/.

Appendix

The following figures plot histogram of selected t-test interval variables in Philadelphia and Denver respectively.