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RESEARCH REPORT

Institute of Transportation Studies | UNIVERSITY OF CALIFORNIA

Heterogeneity of Plug-in Electric Vehicle Owners in Rural California

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16. Abstract

Little is known about plug-in electric vehicle (PEV) ownership, charging behavior, and vehicle characteristics in rural California. As the state works toward its goal of carbon neutrality by 2045, understanding the current state of PEV adoption in rural areas is essential for identifying where targeted support may be needed to meet electrification objectives. Existing definitions of "rural" may also obscure important variation within these regions. This study proposes a passenger-vehicle-based classification of rural areas in the state using k-means clustering, incorporating data on land use, travel behavior, vehicle characteristics, and housing attributes. Five distinct clusters were identified, three of which - Rural Remote, Farm Rural, and Small Town - were classified as rural. Survey data from PEV and conventional vehicle (CV) owners were analyzed to compare sociodemographic characteristics, vehicle attributes, and charging access and behavior. Across all clusters, PEVs were newer and generally smaller than CVs. The Rural Remote cluster exhibited the highest rural PEV adoption rates (1.4% BEVs, 1.0% PHEVs), along with higher household income, education, and Level 2 home charging prevalence. Farm Rural and Small Town clusters had lower adoption rates and relied more heavily on Level 1 charging, despite comparable at-home charging frequency. Public charging access per capita was lowest in Rural Remote areas and highest in Small Town clusters across rural areas. These findings indicate that rural California is heterogeneous with respect to PEV ownership and future adoption potential. Policies that account for demographic, infrastructural, and travel behavior differences between rural subtypes may be more effective than uniform approaches in supporting adoption.

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Institute of Transportation Studies | UNIVERSITY OF CALIFORNIA

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Executive Summary

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Little is known about plug-in electric vehicle (PEV) ownership, charging behavior, and vehicle characteristics in rural California. As the state works toward its goal of carbon neutrality by 2045, understanding the current state of PEV adoption in rural areas is essential for identifying where targeted support may be needed to meet electrification objectives. Existing definitions of "rural" may also obscure important variation within these regions.

This study proposes a passenger-vehicle-based classification of rural areas in the state using k-means clustering, incorporating data on land use, travel behavior, vehicle characteristics, and housing attributes. Five distinct clusters were identified, three of which - Rural Remote, Farm Rural, and Small Town - were classified as rural. Survey data from PEV and conventional vehicle (CV) owners were analyzed to compare sociodemographic characteristics, vehicle attributes, and charging access and behavior.

Across all clusters, PEVs were newer and generally smaller than CVs. The Rural Remote cluster exhibited the highest rural PEV adoption rates (1.4% BEVs, 1.0% PHEVs), along with higher household income, education, and Level 2 home charging prevalence. Farm Rural and Small Town clusters had lower adoption rates and relied more heavily on Level 1 charging, despite comparable at-home charging frequency. Public charging access per capita was lowest in Rural Remote areas and highest in Small Town clusters across rural areas.

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Contents

Introduction

This study seeks to explore and quantify plug-in electric vehicle (PEV) ownership and use in rural California. To reach the state's carbon neutrality goals by 2045 as directed under Executive Order B-55-18 (1), widespread electrification of passenger vehicles is required across all communities. With the goal of pinpointing specific challenges and opportunities unique to rural environments, we aim to generate the necessary data and information to guide policy and planning efforts aimed at mitigating barriers to PEV adoption in rural areas. Rural communities face unique physical and sociodemographic constraints to travel which may influence PEV adoption rates in these settings; Rural areas have greater distances between amenities, and lack access to public transit, causing residents to rely on personal passenger vehicles for mobility (2, 3). Research suggests that rural communities also tend to be lower income, thus making the financial burden of owning a car proportionally greater (2). As new and used PEVs, on average, cost more than conventional vehicles (CV) with internal combustion engines, the transition to new vehicle technologies may be additionally financially burdensome for rural residents. Additionally, some residents in rural communities may require specific vehicle features for hauling, or because of extreme terrain or weather. These requirements reduce the vehicle options available to rural residents. In this study, PEVs include both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs).

Much of the existing literature focuses on either travel behavior in rural areas or on PEV owners in urban areas, however, very little is known about PEV ownership and use across rural areas. Better understanding of the heterogeneity of rural areas as it relates to electrification could provide policy makers with the information required to develop regionally responsive policies. Therefore, this study aims to quantify the current state of PEV ownership in rural California and identify future PEV adoption potential by:

- Comparing vehicle and sociodemographic characteristics of rural PEV and CV owners.
- Understanding differences in charging access and behavior of PEV owners across California.
- Identify barriers to future PEV adoption in rural areas.

Additionally, existing literature on rural transport tends to either treat rural areas as homogenous or conduct analyses at broad spatial scales. To adequately capture the heterogeneity of vehicle ownership across rural areas, this study proposes a new vehicle-oriented definition of "rural". This study conducts analyses at the census tract level, combining data from a PEV-owner survey with vehicle and sociodemographic datasets to provide a granular understanding of vehicle ownership in rural California.

Defining Rural America

Different definitions of “rural” can capture anywhere from 7% to 49% of the American population (4, 5). Broadly, the rural-urban definitions can be categorized into three concepts: administrative, land-use, and economic. The administrative concept defines rural and urban areas along jurisdictional borders (e.g., U.S. Department of Agriculture (USDA) definition). The land-use concept defines areas based on population density (e.g., U.S. Census Bureau definition). Finally, the economic concept looks at variables such as trade, labor, and commuting areas (e.g., Office of Management and Budget (OMB) definition). The U.S. Department of Agriculture (USDA) categorizes land based on population density into metropolitan and nonmetropolitan areas (ref). These classifications can be broken down further into the rural-urban continuum codes (RUCC) *(6)*. They also use the rural-urban commuting area (RUCA) codes to delineate urban and rural *(7)*. Different definitions have varying spatial scales and differ in the number of classifications. For example, the OMB and USDA definitions are at a county level with three classifications (metropolitan, micropolitan or neither), the USDA definition is at a census tract level with ten primary classifications, and the U.S. Census Bureau definition is at census block level with a binary classification of rural-urban *(8)*. Varying spatial scales and the number of classifications are important elements as they determine the granularity of rural populations.

In the context of transport, some studies look beyond the government definitions of rural to find those that cater better to the study objectives. Barajas and Wang (2) looked at barriers and adaptations to carless households in rural areas and derived their rural-nonrural classification by merging ACS population data with Public Use Microdata Areas (PUMAs). Salon (3) looked at the role the built environment plays in vehicle miles traveled (VMT) in California and used a k-mean cluster approach to identify distinct groups. Quallen and others (9), conducted interviews to understand how opinions, beliefs and behaviors around travel differed in small cities, towns, and rural communities in Vermont. Participants were asked to self-report which of the three regions they lived in.

Vehicle Ownership Across the Rural-Urban Continuum

Most existing literature on rural passenger vehicle transport addresses vehicle travel behavior without distinguishing between vehicle fuel types (10, 11). Millward and Spinney (10) found that the vehicle trips decreased, and trip duration increased, with increasing rurality. Salon (3) had a similar finding, with one-way commute and nonwork weekday VMT increasing from urban to rural areas. Pucher and Renne (11) used 2001 National Household Travel Survey (NHST) data finding that on average, rural households made 5% fewer trips per day than urban households. These numbers varied across income categories with lower income rural households making almost the same number of trips and higher income households making 15% fewer trips per day than their urban counterparts. This difference in the number of trips by income categories may be explained by higher income rural residents being able to work from home more often than lower income residents.

Of the studies that have looked at passenger PEV adoption across the rural-urban continuum in western countries, all have demonstrated rural areas lag urban areas (12-14). In three European studies, regions were split into rural, intermediate, and urban areas using the Nomenclature of Territorial Units for Statistics third level (NUTS 3). Wappelhorst (13) looked at 13 European Union (EU) Member States finding that the average market share of new PEVs were 2.9%, 3.5%, and 4.0% for rural, intermediate, and urban regions, respectively. This study found that high PEV-adopting rural regions tend to have a mix of measures from multiple levels of government to encourage adoption (13). The study found no measure that was consistent across all high proportion rural regions.

Research Approach

Defining Rural Vehicle Ownership

Existing federal and state definitions of "rural" are largely inadequate in defining rural California in the context of passenger vehicle ownership as they are too broad. Therefore, we use a k-means clustering approach to propose a new definition of "rural" at the census tract level that aims to capture elements related to land use, travel behavior, vehicle characteristics, and housing characteristics (Table 1). K-means clustering is a non-parametric method for creating groups based on multiple continuous variables.

Table 1. Cluster data sources

Data source	Dataset	Variable(s)	Year	Spatial unit
US Geological Survey	NLCD	Land type: developed, farm, forest, herbaceous, shrubland	2021	30x30m pixels
US Census Bureau	LODES	Employment origin-destination	2020	Census tract (2020)
DMV	Vehicle registration	Vehicle size: compact, midsize, large	2020	Block group (2020)
US Census Bureau	ACS	House type: detached, attached	2020	Census tract (2020)

The National Land Cover Database (NLCD) provides land cover information for all the U.S. by assigning 30x30m pixels one of 16 land cover categories. The Longitudinal Employer-Household Dynamics Origin-Destination Employment Statistics (LODES) data provides employees residential and work addresses based on W-2 Wage and Tax Statement forms. This information is then aggregated at a census tract level to provide the number of employees commuting between and within census tracts across the U.S. The Department of Motor Vehicles (DMV) dataset provides vehicle information for all vehicles registered in California in 2020 at the block group level. Finally, the American Community Survey (ACS) provides information on the proportion of detached houses in each census tract. This variable is used to reflect the build environment of the area and as a proxy for at-home PEV charging potential. It is assumed that detached houses have a higher degree of access to at-home charging than attached houses such as townhouses and apartments. Note that current fuel type mix was excluded from the cluster analysis as the intention of the rural clusters is not to define current PEV ownership but vehicle ownership and use more broadly.

Data Processing

To determine predominant land use types for each census tract, the 16 land use categories were aggregated into five overarching categories: Developed, agriculture, forest, herbaceous, and shrubland. The area of each land use type divided by total land area within a census tract was calculated to determine the proportion of land use types per census tract. To calculate commute VMT across California, an origin-destination distance matrix was created with 2020 Census Bureau tract data to determine the network distance between the centroid of each census tract. LODES data was then used to determine the number of employees commuting between and within census tracts. The matrix distances were multiplied by the number of employees commuting to and from a given census tract to produce a commute VMT for employees traveling outside of a census tract. For employees whose place of residence and work were within the same census tract, a commute distance equivalent to the circumference of the census tract was applied. This approach likely overestimates commute distances within each census tract but does so uniformly across each tract. Eight vehicle body types from the DMV were categorized into three vehicle sizes: Hatchbacks and coupes were aggregated as compacts, sedans, convertibles, and wagons were aggregated as midsize vehicles, and pickup trucks, sports utility vehicles (SUVs), and minivans were aggregated as large vehicles. Each vehicle type was divided by the total number of vehicles registered in a tract to determine the proportion of compact, midsize, and large vehicles for each census tract. Finally, the proportion of detached houses in each census tract was calculated by dividing the number of detached houses by total houses. Table 2 provides a summary of descriptive statistics of all variables at a census tract level across California.

Table 2. Descriptive statistics of cluster variables

Data	Variable	Minimum	Mean	Median	Maximum
LODES	Commute VMT (miles)	0.1	79.5	98.0	100.0
NLCD	Developed (%)	0.0	4.8	0.0	94.4
	Agriculture (%)	0.0	3.0	0.0	91.2
	Forest (%)	0.0	4.2	0.1	86.0
	Herbaceous (%)	0.0	6.1	0.0	95.8
	Shrubland (%)	0.0	39.6	37.6	251.2
DMV	Compact vehicles (%)	0.0	10.7	10.2	24.7
	Midsize vehicles (%)	16.6	43.0	42.8	100.0
	Large vehicles (%)	0.0	43.8	44.3	70.7
ACS	Detached houses (%)	0.0	85.9	92.9	100.0

K-means Clustering

The ten variables described above were used to create transportation clusters of census tracts across California. A k-means approach was preferred over other clustering techniques as the variables used for the clusters were all continuous. To determine the optimal number of clusters *K*, a graphical method was used whereby the within-cluster-sum-of-squares (WSS) was graphed against *K*. The optimal *K* value was chosen at the 'elbow' of the graph; The point at which the WSS is minimized for the lowest *K* value. Once the optimal number of clusters was determined, each census tract was assigned to one of the clusters. The k-means approach groups census tracts based on the similarity of their variables to other tracts.

Rural Vehicle Owner Comparison

To understand how PEV owners differ across rural areas, vehicle and sociodemographic characteristics were compared along two dimensions: 1) The rural-urban continuum and 2) PEV versus CV owners. The clusters created in the previous section constitute the rural-urban dimension, while the datasets presented in Table 3 are used to compare PEV and CV owners. In this analysis, sociodemographic variables from the ACS, and CV registrations from the DMV were considered representative this CV group. As the ACS estimates sociodemographic variables for the whole state, the dataset invariably includes PEV owners. However, the proportion of PEV owners reflected in the dataset is sufficiently low that the authors feel this dataset is mostly representative of CV owners. The Electric Vehicle Miles Traveled (eVMT) survey and PEV registrations from the DMV dataset provide insight into vehicle and sociodemographic factors of PEV owners across California. The eVMT survey, which was administered by the Electric Vehicle Research Center at the University of California, Davis, is a subset of people who have previously applied for PEV incentives through the Clean Vehicle Rebate Program (CVRP). It should be noted that due to the sampling method of the eVMT survey, this dataset is not a random sample. Additionally, while the ACS provides information on the race of communities, the eVMT survey does not, and thus this variable was not captured for PEV owners.

The proportion of Disadvantaged Communities (DACs) was also calculated within each of the clusters to compare levels of disadvantage in rural and urban areas. The California Environmental Protection Agency (EPA) defines DACs based on sociodemographic, environmental hazard, geographic, and public health criteria. As defined under Senate Bill 535, census tracts designated as DACs are predominantly communities of color that are low income and disproportionately burdened by environmental hazards such as air pollution. Census tracts defined as disadvantaged were intersected with clusters to identify the proportion of DACs in each cluster. Table 3 provides an overview of the datasets used for comparison across clusters and PEV versus non-PEV owners.

Table 3. Cluster comparison data

Vehicle owner	Data source	Dataset	Variable	Year	Spatial unit
CV owners	DMV	CV registration	Vehicle size (proportion) Vehicle age (median)	2020	Census block (2020)
	U.S. Census Bureau	ACS	Income (median household) Age (median) Race: Asian, black, Hispanic, white (proportion) College (proportion)	2020	Census tract (2020)
	California EPA	SB 535 DACs	DAC	2022	Census tract (2010)
PEV owners	DMV	PEV vehicle registrations	Fuel type (proportion) Vehicle size (proportion) Vehicle age (median)	2020	Census block (2020)
	EV Research Center	eVMT	Income (median household) Age (median) College (proportion) Charging locations: at-home, away from home, both (proportion) At-home charging: Level 1, Level 2 (proportion)	2015-2020	Coordinate points (latitude, longitude)
	CEC	EV chargers	DCFC chargers: per capita, per area (count) Level 2 chargers: Per capita, per area (count)	2023	Coordinate points (latitude, longitude)

Data Processing

DMV registration data were first sorted into PEV and CV owners and then aggregated at the census tract level. The proportion of BEVs and PHEVs were calculated for each census tract, as were the proportions of compact, midsize, and large vehicles and the average age of vehicles in each tract for PEVs and CVs. To calculate CV sociodemographic information, median household income, and average population age was calculated for each census tract from the ACS data. The proportion of black, white, Hispanic, and Asian people within each census, and the proportion of the population with an undergraduate college degree was also calculated for each tract. California DAC data were only available for 2010 census tracts and therefore did not map directly to other datasets that used 2020 census tracts. To deal with this data mismatch, any 2020 census tract that intersected a 2010 DAC census tract was also designated as a DAC, regardless of the proportion of overlap. This conservative approach results in a higher proportion of California land being designated disadvantaged.

From the eVMT survey, coordinate points representing an individual PEV owner were sorted by cluster based on which census tract the point fell into. From the ACS dataset, median household income, average population, and proportion of the population with a college education was calculated for each cluster.

Charging Access and Behavior

Charging locations from the California Energy Commission (CEC) were also included in the analysis to understand public charging access/density across the clusters. The eVMT survey captures data on PEV owner charging locations and at-home charging infrastructure. In the survey, participants are asked where they charged in the last 30 days with “at home only”, “away from home”, and “both at home and away from home” and possible answers. Participants were also asked what at-home charging infrastructure they had available to them with “Level 1” or “Level 2” chargers as possible answers.

The proportion of PEV owners that charged at-home only, away from home only, and both at-home and away from home was also calculated. Given the smaller sample size and sparsity of PEV owner observations from the survey, aggregating data at the census tract level before conducting the calculations was not possible. Finally, public charging density was calculated by aggregating DCFC and Level 2 chargers at the census tract level and determining the number of chargers per capita (per 100,000 people) and per area (per 100mi^2).

Table 4 provides summary statistics of each variable. College education and charging location data from the eVMT, and DACs were not included in the table because they are binary. Note that the descriptive statistics present variables at the census tract level.

Table 4. Descriptive statistics of comparison variables

Data	Variable	Minimum	Mean	Median	Maximum
DMV	BEV (%)	0.0	1.3	0.7	12.1
	PHEV (%)	0.0	0.9	0.7	6.7
	CV age	4	10	10	41
ACS	Income (US$)	5,000	86,000	77,000	250,000
	Age (years)	17	38	37	79
	Asian (%)	0.0	14.1	8.4	94.5
	Black (%)	0.0	5.7	2.6	84.3
	Hispanic (%)	0.0	38.0	31.1	100.0
	White (%)	0.0	38.4	36.8	100.0
	College (%)	0.0	21.3	20.2	65.0
eVMT	Income (US$)	25,000	170,000	175,000	525,000
	Age (years)	17	50	45	85
CEC	DCFC chargers	0.0	0.2	0.0	28.0
	Level 2 chargers	0.0	1.5	0.0	294.0

The U.S. Census Bureau definition of rural and urban was used throughout this study as a point of comparison with the clusters. As the U.S. census definition of rural is at a census block level, data pre-processing was required to assign census tracts a rural or urban designation. Census tracts were assigned rural if 50% or more of the area within each tract was rural – all other tracts were designated urban. Using this technique 743 census tracts were designated rural.

Results

Redefining Rural California for Passenger Vehicle Transport

Results of the clustering identified five clusters: two rural, two urban, and a fifth combined urban/rural cluster. As the focus of this study is on rural California, the two urban clusters were amalgamated into one "Urban" cluster for simplicity. The fifth cluster appeared next to urban census tracts, and in small groups surrounded by large swathes of rural tracts. Given the dichotomous nature of this cluster, it was split into two separate clusters based on the surrounding context; Census tracts in this fifth combined cluster were reclassified as "Small Town" if they were surrounded by either of the two rural clusters and not adjacent to any urban tracts and reclassified as "Suburban" if they were adjacent to any urban tracts (Figure 1). Of the two rural clusters, one was characterized by a high mean commute VMT and high proportions of forest cover, while the other was characterized by a high proportion of agricultural land cover. These clusters were renamed "Rural Remote" and "Farm Rural", respectively.

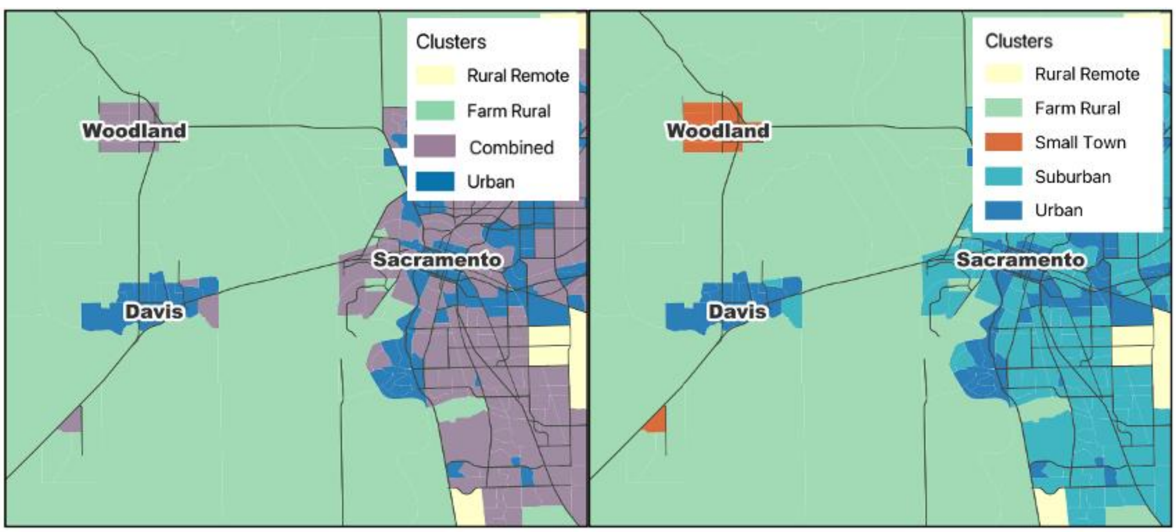

Figure 1. Original fifth cluster (labelled "Combined" in purple) on the left, separated into Small Town (in brown) and Suburban (in light blue) on the right.

Table 5 presents the mean value of each clustering variable across all census tracts, grouped by the five clusters. Mean commute VMT is highest in the rural remote cluster at 60 miles and decreases with decreasing rurality. The average proportion of developed land cover within Rural Remote and Farm Rural clusters is lowest at 19.8% and 25.9%, respectively. Agricultural cover is highest in the Farm Rural cluster with a mean land cover of 63.8%. Forest, herbaceous, and shrubland cover is, on average, highest in the Rural Remote cluster with an average of 20.2%, 19.6%, and 32.5%, respectively. The average proportion of large vehicles in both Rural Remote and Farm Rural clusters accounts for approximately half of all vehicles at 49.8% and 50.0%, respectively. The Small Town cluster also has a high proportion of large vehicles at 47.2%. The average proportion of detached houses is highest in the Farm Rural cluster at 96.2%, followed by Rural Remote at 95.2%, and Small Town at 92.4%. For the purposes of this analysis, we define rural California as the census tracts that fall within the Rural Remote, Farm Rural, and Small Town clusters. These three clusters include 2,149 census tracts and account for 93.9% of California's land mass.

Table 5 also shows the clustering variables grouped by the 2020 U.S. Census Bureau definition of Rural and Urban for comparison. The U.S. Census definition only counts 743 census tracts as rural, which accounts for 87.8% of California's land mass. According to the U.S. Census, shrubland is the highest proportion of land cover in Rural areas at 27.2%, commute distance is an average of 64 miles, 52.2% of vehicles are large, and 96.0% of houses are detached *(12-14)*.

Table 5. Average proportion of each cluster variable across all census tracts

	Clusters					**U.S. Census**	
	Rural Remote	Farm Rural	Small Town	Suburban	Urban	Rural	Urban
Census tract n	*1,139*	*490*	*520*	*3,796*	*3,049*	*743*	*7,112*
Land proportion (%)	77.2	16.1	0.6	4.0	2.1	87.8	12.2
Commute VMT (miles)	60	51	48	37	33	64	37
Developed (%)	19.8	25.9	87.2	91.8	93.8	8.6	86.2
Agriculture (%)	3.3	63.8	4.5	1.2	0.4	23.3	3.1
Forest (%)	20.8	0.2	0.6	0.4	0.6	19.8	1.4
Herbaceous (%)	19.6	5.6	3.1	2.1	1.0	16.5	3.0
Shrubland (%)	32.5	1.4	2.2	2.5	2.1	27.2	4.0
Compact vehicles (%)	9.4	8.1	8.7	9.8	13.2	8.6	10.9
Midsize vehicles (%)	36.8	38.9	41.4	43.4	48.1	35.0	44.7
Large vehicles (%)	49.8	50.0	47.2	44.2	36.9	52.2	42.1
Detached houses (%)	95.2	96.2	92.4	90.1	74.5	96.0	85.0

Figure 2 presents the spatial distribution of the five clusters. Most of the central valley is designated as Farm Rural, with much of the rest of the census tracts in the state being designated as Rural Remote. Pockets of Small Town clusters appear across the state but are mostly concentrated in the central valley and along the coast. Census tracts in the San Francisco Bay Area, Los Angeles, and Sacramento were designated as Urban and Suburban. Some census tracts in the central valley and along the coast were also identified as Urban and Suburban.

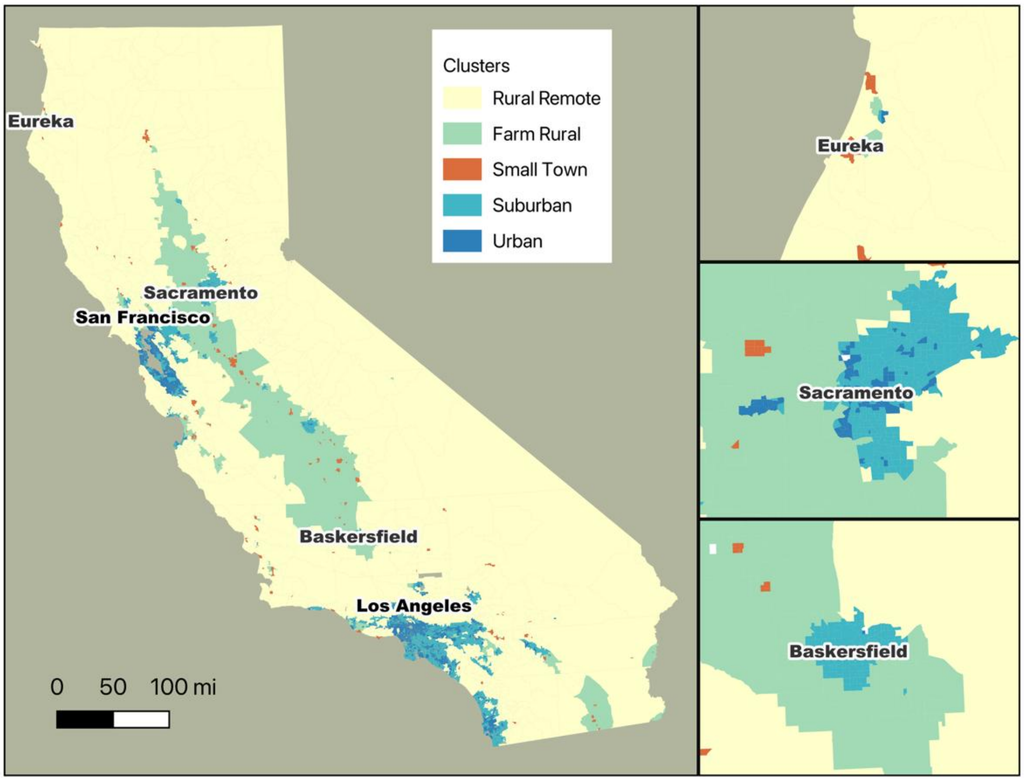

Figure 2. Spatial distribution of clusters across California

Rural PEV Ownership

Approximately 24.7% of California's total vehicle fleet or 5.9 million vehicles are registered in one of the three rural clusters with the remaining fleet registered in Suburban (10.9 million vehicles) or Urban (7.3 million vehicles) clusters (DMV, 2020). On average, PEVs account for 1.7% of total vehicle registrations across the three rural clusters, while Urban and Suburban PEVs account for 2.4% of all registered vehicles.

Table 6 separates PEVs percentages into the fleet wide average proportion of BEVs and PHEVs across the five clusters (DMV, 2020). The Urban cluster had the highest average proportion of BEVs with a fleet proportion of 2.0%. Surprisingly, the Rural Remote cluster had the second highest average proportion of BEVs at 1.4%. Suburban, Farm Rural, and Small Town had average BEV proportions of 1.1%, 0.5% and

0.4%, respectively. Average PHEV proportions were lower for all clusters, except for Small Town which had the same proportion of PHEVs and BEVs. Again, PHEV proportions were highest the Urban cluster, followed by the Rural Remote cluster. PHEV proportions in Rural Remote, Farm Rural and Small Town clusters were 1.0%, 0.5%, and 0.4%, respectively. For comparison, the U.S. Census Bureau definition of rural shows the average BEV proportion was 0.8% for Rural areas and 1.4% for Urban areas and an average PHEV proportion of 0.6% for Rural areas and 1.0% for Urban areas. Besides some negligible proportions of fuel cell electric vehicles (FCEVs), most vehicles across all clusters were CVs.

Table 6. Average PEV fleet percentage by cluster

	Clusters					**Census**	
	Rural Remote	Farm Rural	Small Town	Suburban	Urban	Rural	Urban
BEV (%)	1.4	0.5	0.4	1.1	2.0	0.8	1.4
PHEV (%)	1.0	0.4	0.4	0.8	1.3	0.6	1.0

Figure 3 visualizes PEV numbers as a percentage of total registrations in each census tract. PEV percentages appear to be highest in and around major cities, as well as along the coast of California. Lower proportions of PEVs occur inland along the Sierra Mountain range and in the most northern and southern parts of the state. A total of 44 census tracts did not have any registered PEVs. A total of 101 census tracts had over 10% PEVs, 22 of which were rural census tracts.

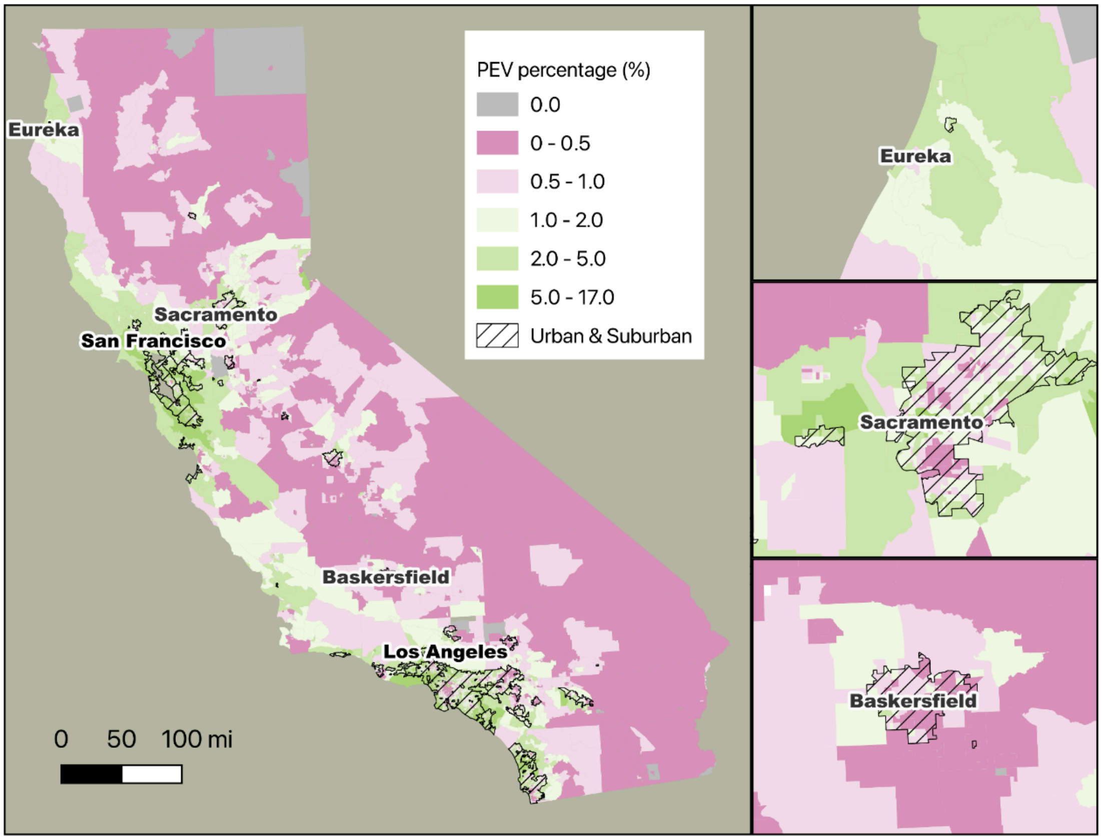

Figure 3. PEV percentage in each census tract

Rural PEV and CV Characteristics

Table 7 presents the proportion of CV and PEV sizes across the five clusters. In the CV fleet, average percentages of large vehicles were highest for all clusters except the Urban cluster where midsize vehicles were highest. In contrast, average percentages of compact vehicles were highest across all clusters for PEVs. The Small Town cluster had the highest average percentage of compact PEVs at 57.9%. Common compact PEVs included the Chevrolet Volt and Bolt, Nissan Leaf, and the Toyota Prius Plug-in Hybrid models. Midsize PEVs were the next highest proportion across all clusters. These midsize vehicles were dominated by the Tesla Model S and Model 3. Larger PEVs were in much smaller proportions but were highest in Rural Remote and Urban clusters at 7.6% and 7.1%, respectively, and included vehicle models such as the Tesla Model Y.

Table 7. Average percentage of PEV and CV sizes by cluster

		Clusters					U.S. Census	
		Rural remote	Farm rural	Small town	Suburban	Urban	Rural	Urban
CV (DMV)	Compact (%)	9.3	8.1	8.7	9.8	13.2	8.5	10.9
	Midsize (%)	36.8	38.9	41.4	43.4	48.1	34.8	44.7
	Large (%)	49.8	50.0	47.2	44.2	36.9	52.4	42.1
PEV (DMV)	Compact (%)	51.2	53.9	57.9	53.3	52.2	52.8	53.0
	Midsize (%)	41.3	40.0	37.1	40.8	40.6	39.9	40.6
	Large (%)	7.6	6.3	4.9	5.9	7.1	7.3	6.4

In addition to differences in vehicle size and fuel type across the five clusters, vehicle age also varied across the clusters. The average PEV age was 8.9 years, 7.1 years, and 8.0 years for Rural Remote, Farm Rural, and Small Town clusters, respectively. While the average CV age for the same clusters were 10.9 years, 11.04 years, and 11.05 years, respectively. Suburban and Urban clusters had slightly newer CVs at 10.2 years and 8.7 years, respectively. Figure 4 shows the normalized sum of PEVs and CVs in the California fleet from zero years (model year 2021) to 40 years (model year 1981). The Small Town cluster has the lowest proportion of newer vehicles and the highest proportion of older vehicles. The opposite trend is observed for Urban vehicles that had the highest proportion of newer vehicles and the lowest proportion of older ones. Interestingly, Rural Remote and Suburban vehicles follow a similar trend, sharing the second place below the Urban cluster for newness of vehicle ages. The dip in the normalized sum of vehicles at around 12 years is likely a response to the 2008 financial crisis.

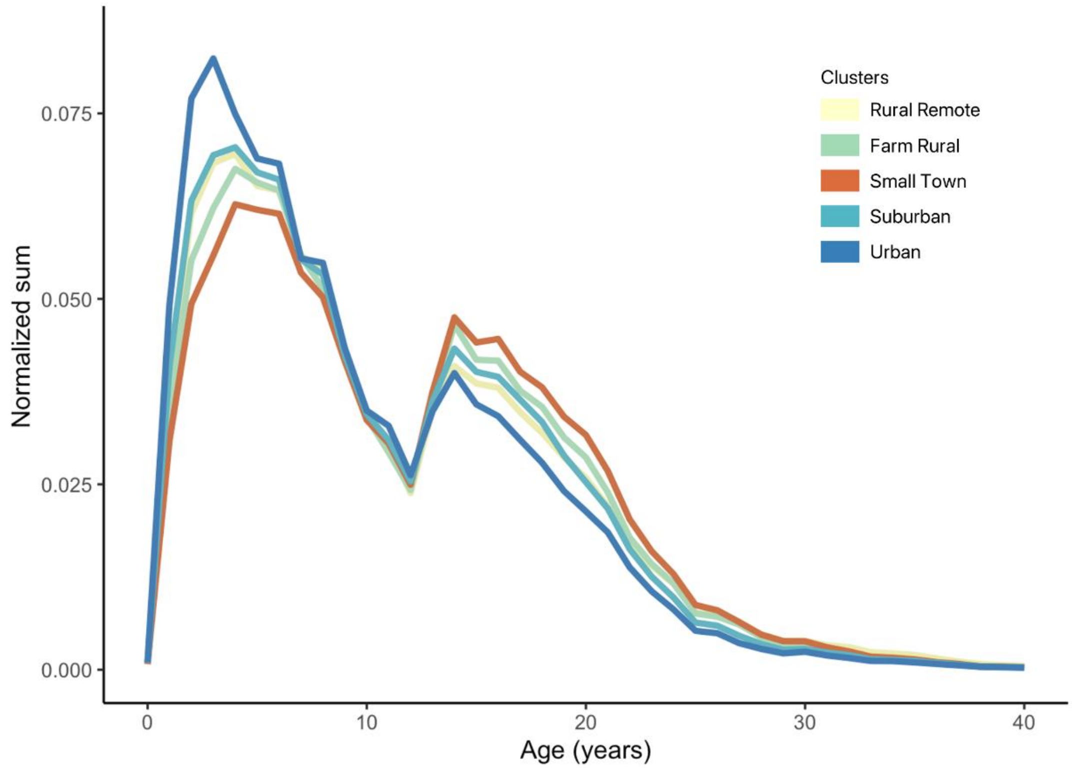

Figure 4. Normalized sum of vehicle ages from zero (model year 2021) to 40 years

Rural PEV and CV Owners

The three rural clusters comprise approximately 23.1% the California population or 9 million people, which is about proportional to the number of vehicle registrations in the same area. From the ACS data and the eVMT survey data, we can determine differences in CV and PEV owner median household income, average age, average population proportion by race, and average college education attainment levels (Table 8). For CV owners, median household income was highest in Rural Remote clusters ($92,000), followed by Urban ($91,000), Suburban ($85,000), Farm Rural ($70,000), and Small Town ($64,000) (ACS, 2020). Rural Remote clusters had the highest average age (44.6 years) and the highest proportion of white residents of all the clusters. About a fifth of people in this cluster also had a college degree (21.1%). The Farm Rural cluster had the lowest average age (34.8 years) and the highest proportion of Hispanic residents (53.1%). College education attainment was also lowest in this cluster (12.8%). The Small Town cluster had an average age of 35.2 years, with 51.5% Hispanic residents and a college attainment rate of 12.9%. Proportions of black and Asian residents were lower in rural areas compared to the Urban and Suburban clusters. College degree attainment was highest in the Urban cluster.

Compared to CV owners, PEV owners had a higher median household income, higher college degree attainment rates, and were older. For Rural Remote, Suburban, and Urban clusters, median household income was $175,000. Average median income for Farm Rural and Small Town PEV owners was $125,000. Average age of PEV owners was lowest in the Urban cluster (48 years), followed by Small Town (49.9 years). Conversely to CV owners, college degree attainment levels were highest among Small Town PEV owners (35.4%), followed by Suburban (34.7%), and Urban (34.6%). Proportion of female PEV ownership was low across all clusters but highest in the Farm Rural cluster (32.3%). Note that household income for PEV owners is expressed as the midpoint of a range due to survey question style. PEV and CV sociodemographic data was also calculated based on the 2020 U.S. Census Bureau for comparison.

Table 8. Average sociodemographic characteristics by cluster

		Clusters					U.S. Census	
		Rural Remote	Farm Rural	Small Town	Suburban	Urban	Rural	Urban
CV (ACS)	Income ($)	92,000	70,000	64,000	85,000	91,000	76,000	87,000
	Age (years)	44.6	34.9	35.2	37.4	38.2	43.4	37.8
	Black (%)	2.7	2.9	2.5	5.4	8.1	2.2	6.0
	White (%)	63.2	34.8	37.8	33.4	35.9	58.9	36.4
	Hispanic (%)	22.2	53.1	51.5	46.2	29.0	30.3	38.7
	Asian (%)	6.8	6.3	5.0	11.6	22.7	3.9	15.1
	College degree (%)	21.1	12.8	12.9	18.6	27.4	16.8	21.7
PEV (eVMT)	Income ($)	175,000	125,000	125,000	175,000	175,000	175,000	175,000
	Age (years)	53.6	49.9	53.0	50.0	48.0	55.0	49.5
	Female (%)	26.8	32.3	27.4	26.7	26.2	30.4	26.4
	College degree (%)	30.7	35.4	30.8	34.7	34.6	29.5	34.2

Given the sociodemographic disparities between the clusters, further investigation was conducted to compare DACs against the five clusters. The proportion of DACs was highest in the Farm Rural cluster with over half (60.6%) of the census tracts designated as disadvantaged (Table 9). Suburban, Small Town, and Urban clusters had the next highest proportion of DACs with 40.1%, 37.5%, and 28.9%, respectively. The Rural Remote cluster had the lowest proportion of DACs at 11.9%.

Table 9. Proportion of DAC census tracts within each cluster

	Rural Remote	Farm Rural	Small Town	Suburban	Urban
DAC count	136	297	195	3,796	3,049
DAC (%)	11.9	60.6	37.5	40.1	28.9

Charging Access and Behavior

Exploration of charging density in each cluster yielded highly different results based on the metric that was used. Table 10 compares per capita (100,000 people) and per area (100 mi^2) metrics for DCFC and Level 2 chargers in California. Using the per capita metric, density of DCFCs was highest in the Rural Remote (35.9 per 100,000) and Farm Rural (32.2 per 100,000) clusters. However, the per area metric shows Rural Remote and Farm Rural areas having just 0.7 and 2.7 DCFCs per 100mi^2, respectively. For both a per capita and per area metrics, Small Town clusters had a higher density of DCFCs than Suburban areas, and the opposite was true for Level 2 chargers. Level 2 charging density per capita was highest in Urban areas (138.8 per 100,000), followed by Rural Remote (64.1 per 100,000). Like DCFC density, using a per area metric shows that Level 2 chargers are much sparser in the Rural Remote and Small Town clusters. The U.S. Census Bureau definition shows higher DCFCs and Level 2 chargers per capita in Rural areas compared to all of the rural clusters, and lower DCFCs and Level 2 chargers per area compared to all rural clusters.

Table 10. Public charging infrastructure density

	Cluster					U.S. Census	
	Rural Remote	Farm Rural	Small Town	Suburban	Urban	Rural	Urban
DCFC chargers	1,625	697	562	3,095	3,678	1,307	8,350
DCFC per capita	35.9	32.2	24.0	17.9	29.0	46.8	23.0
DCFC per area	0.7	2.7	61.0	50.9	113.9	0.6	44.6
Level 2 chargers	2,903	817	957	8,209	17,608	2,075	28,419
Level 2 per capita	64.1	37.8	40.8	47.4	138.8	74.3	78.4
Level 2 per area	1.3	3.1	103.8	135.0	545.4	0.9	151.7

Charging locations were compared across the five clusters (Table 11). The proportion of PEV owners that exclusively charged at-home was highest in the Rural Remote cluster (46.2%), followed by Small Town (45.8%), Suburban (45.6%), and Farm Rural (45.2%) clusters. The Urban cluster had the lowest proportion of at-home only charging (40.0%). Away from home charging showed the opposite trend with the lowest proportion of PEV owners in the Rural Remote, Farm Rural and Small Town clusters charging exclusively away from home in the last 30 days. Access to Level 2 charging was highest in the Rural Remote cluster (56.6%), followed by Farm Rural (51.9%). All other clusters had slightly higher proportions of Level 1 chargers.

Table 11. Public and private charging locations

	Clusters					U.S. Census	
	Rural remote	Farm rural	Small town	Suburban	Urban	Rural	Urban
Charge at-home	46.2	45.2	45.8	45.6	40.0	47.2	43.3
Charge away	4.4	6.6	5.2	7.3	14.9	4.2	10.6
Charge both	49.0	47.2	48.4	46.6	44.1	48.6	46.1
Level 1	43.4	48.1	55.1	51.0	51.8	43.9	50.6
Level 2	56.6	51.9	44.9	49.0	48.2	56.1	49.4

Discussion

Existing definitions of “rural” in the U.S. are inadequate for capturing the heterogeneity in vehicle ownership and use across California. This study introduces a novel passenger-vehicle-based classification system, developed using k-means clustering, that incorporates land use, travel behavior, vehicle characteristics, and housing attributes. Five distinct clusters were identified, three of which - Rural Remote, Farm Rural, and Small Town - were categorized as rural.

Comparative analyses were conducted across clusters and between PEV and CV owners to assess differences in vehicle characteristics, sociodemographic profiles, and charging access and behavior. Across all clusters, CVs were generally older and larger than PEVs. The smaller size of PEVs likely reflects limited market availability of larger models, while their newer average age aligns with the recent emergence of PEV technology. Within the rural clusters, CVs were consistently older and larger than those in urban areas. Among PEVs, the Rural Remote cluster exhibited the highest proportion of larger vehicles, whereas the Small Town cluster had the highest proportion of compact PEVs. This divergence is likely driven by income differences rather than consumer preference: Rural Remote households had the highest median incomes, while Small Town households had the lowest.

Consistent with prior research, PEV owners in both rural and urban areas tended to be older, wealthier, more educated, and disproportionately male - traits that also characterize new vehicle buyers *(15)*. Within rural areas, PEV owners were older and had higher median incomes than rural CV owners, and had higher levels of educational attainment.

While urban areas recorded the highest percentage of BEVs (2.0%) and PHEVs (1.3%), the Rural Remote cluster ranked second, with 1.4% BEVs and 1.0% PHEVs. This pattern diverges from findings in European studies, that showed a monotonic decline in PEV adoption from urban to intermediate to rural areas *(10)*. Further to this finding, the Rural Remote cluster was socioeconomically distinct from Farm Rural and Small Town clusters, with a higher median income, higher average age, higher proportions of white residents, and higher educational attainment. The proportion of DACs in the Rural Remote cluster was also the lowest of the five clusters. This may be due to multiple factors, including income, but also may be because of a lower pollution burden, reflecting the distance of these census tracts from major agricultural operations and urban centers.

Charging access patterns further differentiate the clusters. The Rural Remote cluster had the lowest public chargers per area but the highest prevalence of Level 2 home charging infrastructure. This may reflect both necessity - due to sparse public charging and longer commute distances - and greater financial capacity to install Level 2 chargers. Income appears to play a significant role: Small Town PEV owners relied on home charging at similar rates to Rural Remote owners but were more dependent on Level 1 chargers, despite having the highest access to public Level 2 and DCFCs among the rural clusters.

Policy Recommendations

The heterogeneity observed in rural California underscores the need for targeted, context-specific policies to promote PEV adoption. Rural Remote residents often possess socioeconomic advantages that rival or exceed those in urban areas, whereas residents of Farm Rural and Small Town clusters face greater social and economic barriers. Given finite policy resources, incentive programs should prioritize Farm Rural and Small Town clusters, where uptake is most limited.

Metrics used to measure public charging access should be adapted to local context. For Rural Remote and Farm Rural areas, chargers per area or per road mile may better capture accessibility needs, given dispersed populations and long travel distances. In contrast, chargers per capita may be a more relevant metric for Small Town, Suburban, and Urban clusters. Incentives for public charging providers should be directed toward Rural Remote and Farm Rural areas, where charger density per area is lowest and VMT is highest, underscoring the need for reliable infrastructure.

Given that at-home charging potential is higher across all rural clusters compared with Suburban and Urban clusters, and survey data indicate that at-home charging is the predominant location for rural PEV owners, policymakers should expand subsidies for Level 2 home charger installation. Such programs would help overcome a critical infrastructure barrier and accelerate rural PEV adoption, especially in lower-income clusters where Level 1 charging remains prevalent.

Conclusions

This study applies a clustering approach to define passenger vehicle ownership and use across rural California. The results indicate that rural areas are heterogeneous, with distinct vehicle, sociodemographic, and infrastructural profiles. The Rural Remote cluster, characterized by higher income, educational attainment, and home charging capacity, exhibited the highest proportion of PEVs among rural clusters. In contrast, Farm Rural and Small Town clusters showed lower adoption rates despite comparable potential for at-home charging.

These differences suggest that uniform policy approaches may be less effective than strategies tailored to the specific characteristics of each cluster. Potential measures include using context-appropriate metrics for charging access, directing infrastructure investments to low-density areas with high VMT, and supporting Level 2 home charger installation and PEV purchases in lower-income rural areas. Such targeted approaches may improve the effectiveness and equity of programs designed to increase PEV adoption in rural areas.

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