Electric Vehicle Adoption: A Machine Learning Approach to Inform Policy Decisions and Combat Climate Change

Ameya Kiwalkar

Abstract

To combat climate change, this paper investigates numerous factors influencing Electric Vehicle (EV) adoption across U.S. states from 2014 to 2022 using various multivariate machine learning models. After testing multiple combinations and iterations of Gradient Boosting Machines, Decision Trees, Neural Networks, and Regressors; RandomForestRegressor, XGBoost, GradientBoostingRegressor, BayesianRidge, and LinearRegression were selected as the optimal ensemble model. These models analyzed the impact of ten socioeconomic, technological, operational, political, and policy variables on EV registrations per 10,000 people and were trained on a curated dataset utilizing multiple sources rather than a pre-existing dataset. Models were evaluated for quality of fit and robustness through control analysis and repeated iterations; along with sensitivity analysis using the linear regression model. Contrary to conventional thinking, findings through this work show that availability of charging infrastructure was the most significant factor driving EV uptake, outweighing in-kind and financial policy incentives. Notably, a 20% increase in charging infrastructure was linked to a 3.67% increase in EV ownership. Statistically significant coefficients were also found for gas prices and motor fuel taxes. These results provide novel insights for policymakers about the best practices to spur greater EV adoption, suggesting that a strategy prioritizing infrastructure development could more effectively promote EV uptake and accelerate the transition to a sustainable, emissions-free future.

Introduction

Climate change is one of humanity's greatest threats with the effects of continued warming being numerous [1, 2], making the next 5 years as the most critical for climate action [3]. While international action to combat this issue is desirable, mitigation at the national level in the United States is both possible and still needed, given the US's outsized role and impact on warming with one of the highest CO2 emissions per capita in the world [4].

Driving U.S. emissions is the transportation sector, which contributes to roughly 29% of all emissions [5]. Out of which, nearly half of transportation-related emissions come from light-duty passenger vehicles [6, 7], also known as ICEVs (Internal Combustion Engine Vehicles), which rely on gasoline for fuel [8]. To reduce these emissions, accelerating the adoption of electric vehicles is necessary. As a note, when Electric Vehicle (EV) is referenced, it solely refers to Battery Electric Vehicles (BEVs), or vehicles that run only on electricity from batteries built into the car as defined by [8].

Most studies have found a strong positive correlation between the number of public charging outlets and the sale of EVs [10, 11, 12]. [13] and [14] identify range anxiety as a major limitation. To address this issue, [15] isolates two main ways: increasing the availability of EV charging stations and increasing the range of each EV to assuage concerns about range anxiety [16, 17]; both factors are theorized to correlate to greater EV uptake. [18] find that changes in gas prices have four to six times the impact on EV adoption compared to electricity prices. Additionally, electricity prices do have a strong negative correlation to EV adoption [19]. Previous studies investigating the relationship between household income and EV adoption have found mixed results [20, 21].

Political ideology has been found to significantly affect EV adoption, with 50% of EV registrations in the top 10% most Democratic counties [23, 24]. This trend is explained by the alignment of EVs with pro-environmentalist Democrats [25]. Research shows a negative correlation between EV purchase cost and EV uptake, as well as the price of lithium-ion batteries, which power EVs [26, 27, 28, 29]. In terms of policy variables, we see mixed results with government tax credits [30, 31]; gas taxes have a negative impact [32, 33, 34] while offering HOV access for plug-in and hybrid EVs positively impacts EV purchases [35, 36, 37].

Methodology

Models

To determine which ML models were to be used, a review of existing research was conducted. [41] measured EV adoption in Italy, employing linear regression, bridge regression, decision tree regressor and extreme gradient boosting regressor. [42] explored a multitude of different models and combinations stemming from Gradient Boosting machines, extreme gradient boosting machines, and random forests. [43] employed Support Vector Machine, Decision Tree, and Random Forest. Finally, [44] and [45] use Gradient Boosting Decision Trees and linear regression. Thus, I employed a combination of previously tested ML techniques: (Multivariable) Linear Regression (LR), Bayesian Ridge Regression (BRR), Random Forest (RF), Extreme Gradient Boosting (XGB), and Gradient Boosting Regressor (GB).

Data

Based on the factors analyzed to be the most critical in the literature review, this paper took into account 10 socioeconomic, technological, operational, political, and policy variables to analyze EV adoption from 2014 to 2022. These variables were: presence of EV charging infrastructure, price of electricity, price of gasoline, median household income, political affiliation of state legislatures, difference in average cost of purchasing an EV versus an ICEV, average EV battery range, and average price of lithium-ion EV batteries. The policy factors were: EV tax credits, the state motor fuel tax rate, and HOV access for EVs. The target variable was EV adoption, measured in terms of total electric vehicles registered per 10,000 individuals in a given region. Note that while there are 50 states in the US, 4 states were omitted from the dataset due to data limitations[1].

EV charging infrastructure was calculated in terms of the number of public charging station outlets in each state and relied on data from the U.S. Department of Energy (DoE) [46]. Price of electricity entailed determining the residential cost of electricity per state in terms of cents per

[1] These states were: Alaska, Colorado, Hawaii, and New Hampshire. The District of Columbia (DC) was also omitted due to data limitations.

kilowatt of electric power and utilized data from the U.S. Energy Information Administration (EIA) [47]. Price of gasoline was measured using data from the EIA [48], and variable was calculated using the total wholesale/retail price of gasoline at gasoline refineries. Median income was calculated as the average household income in each state and was determined using data from the Federal Reserve Bank of St. Louis [49].

Political affiliation of each state used data from Ballotpedia, citing official electoral results [50]. Since this paper evaluated EV ownership trends at the state-level, political affiliation included solely the party affiliation of members of the state legislature and the state governor. To measure and scale political affiliation numerically based on each state's various numbers of seats in their upper and lower houses, an index from 0 to 1 was created, where 0 (100% Republican legislature) and 1 (100% Democrat legislature). This index gave 50% of weight to whether the governor is Democrat (1 if Democrat) and 50% equally between the lower and upper houses of the legislature. To ensure each body was given equal weight, the total number of seats and the number of Democrat-held seats were converted into the same relative units. The total state legislature seats value was measured by multiplying the number of seats in the lower house by the upper house seats and adding this to the product of the number of seats in the upper house and the lower house seats. The total Democrat seat value was calculated by multiplying the number of lower house seats held by Democrats by the total number of seats in the upper house and adding this to the product of the number of Democrat seats in the upper house and the total lower house seats.

The difference in cost of purchasing an EV versus purchasing an ICEV was calculated to be the annual, industry-wide average cost of purchasing an EV in the United States minus the yearly average cost of purchasing an ICEV. Data for the average price of an EV and of an ICEV came from Kelley Blue Book's annual September dataset on industry-wide prices [51]. Average range of an EV is the total distance in miles an EV can drive on a fully charged battery. Data for this cited the median EV range per year from the DoE. [52]. Average price of EV lithium-ion batteries also used data derived from the DoE. [53]. Data was standardized and converted into 2021 dollars to adjust for inflation. To shift to the policy-making variables: EV Tax Credit is designed to incentivize the purchase of EVs by reducing the cost of buying one. The total value of the credit was calculated to be the sum of the baseline $7,500 federal credit plus the value of the varying state credit. Due to the mixed literature consensus regarding efficacy of rebates versus tax credits, this variable solely includes the financial incentives offered by states and the federal government to subsidize the upfront cost of purchasing an EV. The Motor Fuel Tax, commonly known as "the gas tax," is a tax levied by states on the consumption of gasoline[54]. HOV Access refers to an exemption put into place by certain states that allows EVs to drive on (HOV) Lanes. Data for this variable came from the U.S. Department of Energy's Alternative Fuels Data Center [55].

Results and Discussion

We employed multiple machine learning models to conduct multivariate prediction of EV adoption, with the key motive of understanding which variables had the largest impact on EV uptake rates. Initial analysis revealed several key factors influencing EV adoption.

Error	LR	BRR	RF	XGB	GB
R^2	0.703	0.703	0.976	1.000	0.991
RMSE	12.46	12.47	3.57	0.03	2.22

Table 1. RMSE and R^2 values for all models: LR Regular, BRR Regular, RF, XGB, GB.

Table 1 compares different models used, with all models performing reasonably well with R^2 values above 0.70, meeting generally accepted criteria for model accuracy [56].

Feature	Type	LR	BRR	RF	XGB	GB	Final Rank	LR [N]	P-Values [LR]	BRR [N]
Infrastructure	Technology	1	1	1	2	1	1	11.85	9.50E-34	11.65
Motor Fuel Tax	Policy	5	4	2	1	2	2	3.30	1.84E-06	3.28
Gas Price	Operational	3	3	3	4	3	3	6.14	1.25E-11	6.07
Lithium Price	Socioeconomic	4	5	7	3	4	4	-3.32	4.19E-02	-3.27
HOV Access	Policy	2	2	10	5	8	5	8.42	1.95E-06	7.69
Political_Control	Political	6	6	5	6	6	6	2.96	1.38E-04	2.94
Median Income	Socioeconomic	9	9	4	8	5	7	0.79	3.18E-01	0.90
Electricity Price	Operational	7	7	6	9	7	8	-2.92	5.36E-04	-2.76
Tax Credit	Policy	10	10	8	7	9	9	0.64	4.19E-01	0.58
EV Range	Technology	8	8	9	11	10	10	1.68	3.18E-01	1.66
Car Price Difference	Socioeconomic	11	11	11	10	11	11	-0.39	6.70E-01	-0.30

Table 2. Relative Importance of Variables based on LR, BRR, RF, XGB and GB.
Standardized coefficient values for LR and BRR, along with LR P-values.

Table 2 presents the relative importance of each variable across five models based on coefficients or similar extracted values from each model, as well as the standardized coefficients based on the LR model. The final rank is the ensemble combined rank based on averaging the relative ranking across all models. Almost every model concluded that EV Charging Infrastructure was the most important factor affecting EV Adoption. Increased charging availability makes buying an EV more convenient and practical, easing "range anxiety" amongst consumers, which has been previously identified as a major hindrance to EV adoption [14, 15, 16]. The large impact of infrastructure on adoption can be seen in the examples of Vermont (VT) and Louisiana (LA): LA has the lowest number of charging outlets per 10,000, and VT has the highest (13x LA). As a result, VT has 7x EVs per capita compared to LA. The two next most impactful variables were Motor Fuel Tax and Gas Price, respectively – both consumption related factors. Higher gas prices and fuel taxes make ICEVs relatively more expensive to own and operate, increasing the cost-effectiveness appeal of EVs. Other factors that were found to positively correlate to EV adoption were: median income, political control, and EV Range. Political Control being positively correlated to EV adoption means that the greater degree to which seats in a state legislature are held by Democrats, the higher the levels of EV adoption. This is supported by evidence in the literature review [23, 24, 25]. Policy variables, EV tax credit, Motor Fuel Tax, and HOV Access, also were found to positively correlate to EV adoption, in the expected directions. However, these variables did not exhibit as much impact as the charging infrastructure did.

Conclusion and Analysis

Using various regression-based analyses based on data from 2014 to 2022, and modeling number of factors, it was concluded that EV charging infrastructure is the most influential factor for driving EV adoption across the US. These findings challenge conventional policy making approaches that prioritize financial and in-kind incentives.

Results show that state incentives are not nearly as effective at increasing EV uptake as is greater charging infrastructure availability. ML techniques revealed that EV infrastructure was by far the most impactful factor on EV adoption, with the outsized positive correlation between infrastructure and adoption. Additionally, conducting sensitivity analysis reveals that even a 20% increase in charging infrastructure availability could produce a 3.67% across-the-board increase in EV uptake, the most sizable impact out of any variable or policy[2]. Gas prices also emerged as a statistically significant factor, with a much stronger impact on adoption than electricity prices, which indicates that the comparative costs of refueling an ICEV outweigh those of charging an EV when influencing consumer purchasing decisions.

The importance of charging infrastructure over traditional incentives such as HOV Access, EV tax credits, and motor fuel taxes suggests a need to rebalance current EV efforts. Rather than solely continuing investment into tax credits to decrease the upfront vehicle purchase cost of EVs, federal and state governments need to invest more into expanding infrastructure access throughout the US. This data-driven approach, will lead to sound, cost-effective policy making. Administering tax credits will cost the US government over $180 billion over the next 10 years [57]. Conversely, federal calculations estimate that, the average public charging outlet costs $15,000 to construct, which means that increasing charging infrastructure by 20% would require

[2]A 20% increase in charging infrastructure was found to result in a 2.5 increase in delta EV adoption, which is an increase of 2.5 EVs per 10,000 people. Given that the average EVs per 10,000 people in each state is roughly 68, this represents an increase of around 3.67%.

less than $500 million[3]. That compared to the $18 billion per year being spent on tax credits, which are far less effective than increased charging infrastructure, strongly corroborates the findings of this paper.

In terms of limitations, each state has unique political, economic, and social factors influencing EV purchase decisions, including a litany of diverse types of incentives and policies, like varying rebates and credits for charging infrastructure and vehicle purchases. For model simplicity, these differences had to be generalized, potentially overlooking more nuanced, state-specific trends. Future research could conduct more focused regional or state -level analyses to uncover local trends in EV adoption. Additionally, the COVID-19 pandemic introduced unexpected variability in many factors. Moreover, the static, unchanging nature of certain variables throughout the entire 9-year dataset used may have contributed to uncertainty regarding their impacts on EV adoption. Future research could investigate these constant variables further, potentially using state-specific factors and build alternative models that can more accurately account for each factor.

References

[1] World Health Organization. (2023). Climate Change. WHO. https://www.who.int/ news-room/fact-sheets/detail/climate-change-and-health
[2] Chen, X., Sharma, A., Liu, H. (2023). The Impact of Climate Change on Environmental Sustainability and Human Mortality. https://www.mdpi.com/2076-3298/10/10/165.
[3] Gopal, K. (2024). UN Secretary-General Calls for Ban on Fossil Fuel Advertising, Says Next 18 Months Are Critical for Climate Action. https://insideclimatenews.org/news/ 06062024/united-nations-secretary-general-fossil-fuel-advertising-ban/.
[4] Stevens, P. (2019). US leads greenhouse gas emissions on a per capita basis, report finds. https://www.cnbc.com/2019/11/26/ us-leads-greenhouse-gas-emissions-on-a-per-capita-basis-report-finds. html.
[5] Environmental Protection Agency. (2023). Sources of Greenhouse Gas Emissions. https: //www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.
[6] Environmental Protection Agency. (2021). Fast Facts on Transportation Greenhouse Gas Emissions. https://www.epa.gov/greenvehicles/ fast-facts-transportation-greenhouse-gas-emissions.
[7] Energy Information Administration. (2017). Crossover utility vehicles blur distinction between passenger cars and light trucks. https://www.eia.gov/todayinenergy/detail. php?id=31352.
[8] Center for Sustainable Energy. (2023). The State of Electric Vehicle Adoption in the U.S. and the Role of Incentives in Market Transformation. https://energycenter.org/thought-leadership/blog/ state-electric-vehicle-adoption-us-and-role-incentives-market.
[9] Parekh S. (2023). Impact of Charging Infrastructure on Electric Vehicle Sales: An Impact of Charging Infrastructure on Electric Vehicle Sales: An Analysis from Counties in 13 US States. https://cupola.gettysburg.edu/cgi/viewcontent.cgi?article=1082& context=ger.

[3] The Biden Administration has allocated $7.5 billion for 500,000 public charging outlets, which equates to $15,000 per outlet [59]. Current number of public charging outlets is about: 144,000. A 20% increase is around 28,800 more charging outlets. Multiplied by $15,000 per outlet is approximately $432 million.

[10] Okoma, M. (2023). The Impact of Electric Vehicle Charging Stations on Light Duty Electric Vehicle Adoption and Rebates in California. https://doi.org/10.20944/preprints202310. 1841.v1.
[11] Zou, T., Khaloei M., MacKenzie, D., (2019). Effects of Charging Infrastructure Characteristics on Electric Vehicle Preferences of New and Used Car Buyers in the United States. https: //doi.org/10.1177/0361198120952792.
[12] Pevec, D., Babic, J., Carvalho, A., et al., (2019). Electric Vehicle Range Anxiety: An Obstacle for the Personal Transportation (R)evolution?. https://ieeexplore.ieee.org/document/ 8783178.
[13] Nazari, F., Mohammadian, A. (2023). Exploring the Role of Perceived Range Anxiety in Adoption Behavior of Plugin Electric Vehicles. https://scholarworks.utrgv.edu/cgi/ viewcontent.cgi?article=1069&context=ce_fac.
[14] Kim, S., Lee, J., Lee, C. (2017). Does Driving Range of Electric Vehicles Influence Electric Vehicle Adoption?. https://doi.org/10.3390/su9101783.
[15] Bushnell, J., Muehlegger, E., Rapson, D. (2022) Energy Prices and Electric Vehicle Adoption. https://haas.berkeley.edu/wp-content/uploads/WP326.pdf.
[16] Sobh, A., Bosworth, R., Heaslip, K. (2017) Analysis of the Electric Vehicles Adoption over the United States. https://doi.org/10.1016/j.trpro.2017.03.027.
[17] Best, R., Nazifi, F. (2023) Analyzing electric vehicle uptake based on actual household distributions: A contribution to empirical policy formulation. https://doi.org/10.1016/j. tranpol.2023.04.011.
[18] Liu, C., Li, X., Jia, J. (2019) Ownership and Usage Analysis of Alternative Fuel Vehicles in the United States with the 2017 National Household Travel Survey Data. https://doi.org/10. 3390/su11082262.
[19] Davis, L., Li, J., Springle, K. (2023) Political Ideology and U.S. Electric Vehicle Adoption. https://haas.berkeley.edu/wp-content/uploads/WP342.pdf.
[20] Beaumont, T., Seewer, J. (2024) Republicans make Biden's EV push an election-year issue as Democrats take a more nuanced approach. https://apnews.com/article/ trump-biden-china-electric-vehicles-tax-credit-31e0eca67c6a3ae9ca5a773a1ade9447.
[21] Sintonv, N., Abou-Ghalioum, V., White, L. (2020) The partisan politics of low-carbon transport: Why democrats are more likely to adopt electric vehicles than Republicans in the United States. https://doi.org/10.1016/j.erss.2020.101576.
[22] Machado P., Teixeira, A., dos Santos, E. (2023) Electric vehicles adoption: A systematic review (2016–2020). https://doi.org/10.1002/wene.477.
[23] Adepetu, A., Keshav, S. (2015) The relative importance of price and driving range on electric vehicle adoption: Los Angeles case study. https://link.springer.com/article/10. 1007/s11116-015-9641-y.
[24] Carey, N., Lienert, P. (2022) Insight: EV battery makers race to develop cheaper cell mate rials, skirting China. https://www.reuters.com/business/autos-transportation/ ev-battery-makers-race-develop-cheaper-cell-materials-skirting-china-2022-11-15/.
[25] Mekky M., Collins, A. (2024) The Impact of state policies on electric vehicle adoption -A panel data analysis. https://doi.org/10.1016/j.rser.2023.114014.
[26] Clinton, B., Steinberg, D. (2019) Providing the Spark: Impact of Financial Incentives on Battery Electric Vehicle Adoption. https://ceepr.mit.edu/wp-content/uploads/2021/ 09/2019-015.pdf.
[27] Shanjun, L., Muehlegger, E., Linn, J. (2012) Gasoline Taxes and Consumer Behavior. https: //dash.harvard.edu/bitstream/handle/1/8506866/RWP12-006-Muehlegger.pdf.
[28] West, S., Williams, R. (2004) Empirical Estimates for Environmental Policy Making in a Second-Best Setting. https://www.nber.org/papers/w10330.

[29] Baxandall, P. (2019) The Pros and Cons of Higher Gas Taxes, and How They Could be Offset for Lower-Income Families.https://www.massbudget.org/reports/pdf/Gas%20tax%20MassBudget%202019.pdf
[30] Narassimhan, E., Johnson, C. (2018) The role of demand-side incentives and charging infras tructure on plug-in electric vehicle adoption: analysis of US States.https://iopscience.iop.org/article/10.1088/1748-9326/aad0f8
[31] Sheldon, T., DeShazo, J.R. (2016) How does the presence of HOV lanes af fect plug-in electric vehicle adoption in California? A generalized propensity score approach.https://innovation.luskin.ucla.edu/wp-content/uploads/2019/03/How_Does_the_Presence_of_HOV_Lanes_Affect_PEV_Adoption_in_CA.pdf
[32] Chen, F. (2018) The Impact of High Occupancy Vehicle (HOV) Lane Access On Hybrid-Electric Vehicle Adoption: Evidence from U.S. States.https://repository.library.georgetown.edu/handle/10822/1050847
[33] Hoffer, A., Jarons, B. (2023) How Are Electric Vehicles Taxed in Your State?.https://taxfoundation.org/data/all/state/electric-vehicles-ev-taxes-state/
[34] Igleheart, A. (2023) State Policies Promoting Hybrid and Electric Vehicles.https://www.ncsl.org/energy/state-policies-promoting-hybrid-and-electric-vehicles6
[35] Miconi, F., Dimitri, G. (2023) A machine learning approach to analyse and predict the electric cars scenario: The Italian case.https://www.ncbi.nlm.nih.gov/pmc/articles/ PMC9858846/
[36] Bas, J., Zou, Z., Cirillo, C. (2021) An interpretable machine learning approach to understanding the impacts of attitudinal and ridesourcing factors on electric vehicle adoption.https://doi.org/10.1080/19427867.2021.2009098
[37] Che, F., Zhang, H., Shi, B., et al. (2020) Predicting the Regional Adoption of Electric Vehicle (EV) With Comprehensive Models.https://ieeexplore.ieee.org/stamp/stamp. jsp?arnumber=9162026
[38] Bi, J., Wang, Y., Zhang, J., et al. (2019) A Machine Learning Method for Predicting Driving Range of Battery Electric Vehicles.https://doi.org/10.1155/2019/4109148
[39] Abraham, P., Kamis, A. (2024) Predictive models of electric vehicle adoption in the United States: Charging ahead with renewable energy.https://doi.org/10.1016/j.trip.2024. 101041
[40] Ozili, P. (2023) The acceptable R-square in empirical modeling for social science re search.https://mpra.ub.uni-muenchen.de/115769/1/MPRA_paper_115769.pdf
[41] Muresianu, A. (2024) When Looking to Reform Inflation Reduction Act, Start with EV Credits.https://taxfoundation.org/blog/ ev-tax-credits-inflation-reduction-act/#:~:text=The%20IRA%27s%20credits%20for%20electric,billion%20over%20the%20next%20decade
[42] Bikales, J. (2023) Congress provided $7.5B for electric vehicle chargers. Built so far: Zero. https://www.politico.com/news/2023/12/05/ congress-ev-chargers-billions-00129996