Charging into the future:

Using electric vehicle (EV) ownership patterns to identify suitable locations for deploying EV charging stations in Massachusetts.

A thesis submitted by

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Abstract

Different governments and policymakers have described promoting the use of electric vehicles (EVs) as an important policy option for reducing greenhouse gas (GHG) emissions resulting from traditional oil-powered vehicles. While EVs are expected to become more affordable in the future, previous studies have asserted that increasing the availability of public EV charging stations at convenient locations will be vital for promoting EV ownership and supporting EV owners.

This thesis examines EV ownership patterns in Massachusetts by analyzing where EV owners are located in the state and assessing the typical characteristics of neighborhoods with EV owners. Additionally, using existing EV ownership patterns, and other socioeconomic and spatial site suitability criteria, this thesis also identifies suitable locations for deploying public EV charging stations in areas within the Metropolitan Area Planning Commission (MAPC) region.

Logistic regression results suggest that EV ownership in Massachusetts is currently more likely to be in wealthier, educated, and suburban areas of the MAPC region. Multiple locations along major interstate highways and a variety of neighborhoods in the MAPC region are good candidates for the deployment of EV charging stations in the future, based on the results from the GIS based suitability analysis that was conducted for this thesis. The results suggest that investigating the change in EV ownership patterns as EVs become cheaper and conducting further assessments of the suitable locations identified here will be important for increasing the availability of charging facilities and supporting EV ownership in the region.

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Table of Contents

List of tables

List of figures

Chapter 1: Introduction

Private vehicles – powered by fossil fuels – have played an important role in various socioeconomic processes and the American economy throughout the 20th century. Cars continue to remain a vital commodity in numerous households in the country; about 85% of the American population rely on a private vehicle daily (The Economist, 2018). Private vehicles are likely to remain important considering the convenient and flexible mode of transport they offer and the different functions they perform in American livelihoods and the American economy. However, the scale of greenhouse gas (GHG) emissions that private vehicles have accounted for has brought the transportation sector at the forefront of climate change mitigation efforts and climate change policy discussions.

According the U.S. Energy Information Administration (EIA), the transportation sector in the country exceeded the electric power sector in terms of total GHG emissions for the first time in 2016 (EIA, 2016). Different studies assert that reducing GHG emissions from private vehicles is vital for mitigating climate change (Ross Morrow et al., 2010; Berggren and Magnusson, 2012; Room, 2006). However, considering the multiple socioeconomic benefits private vehicles offer and the different emotions associated with car ownership, it will be difficult for American societies to completely abandon car use (Sheller, 2004).

As cars are likely to remain important for American citizens and the U.S. economy, it is vital to "reconcile the need for travelling in private vehicles" with the goal of reducing carbon emissions from transportation (Heidrich et al., 2017). Hence, promoting the use of electric vehicles (EVs) has emerged as an attractive policy option as EVs offer the potential of reductions in GHG emissions – without curtailing the socioeconomic benefits cars offer. But there are different socioeconomic and infrastructural barriers that discourage common consumers from switching to EVs.

Historically, the cost of owning and operating an EV, limited driving range of EVs, and a lack of options in terms of EV models have been highlighted as the main factors that discourage EV ownership. But different studies point out that with improvements in EV battery technology and advancements in EV manufacturing processes, numerous EV models with better driving ranges are set to be available for purchase within the next decade (Nealer et al., 2015; Engle et al., 2018). Additionally, different financial incentives in the form of tax cuts, rebates, and subsidies have been implemented in various U.S. states – including Massachusetts – to offset monetary hurdles opposing EV ownership. While there are indications that EVs will become more affordable in the coming years, multiple sources point out that lack of accessible public EV charging stations will be the next serious barrier opposing widescale EV adoption.

To better understand how to develop convenient public EV charging infrastructures in suitable locations to support present and potential EV owners in the future, we must consider different key variables – socioeconomic, demographic, and spatial – that explain EV ownership – and the location and features of neighborhoods where EV owners are present. Previous studies have primarily examined inter-state or inter-country differences in EV adoption rates, EV adoption policies, and EV charging station availability. This thesis contributes to these fields by combining economic and spatial analytical methods to explain the characteristics and locations of neighborhoods within Massachusetts where battery powered EV and plug-in hybrid EV (combinedly referred to as EVs in the study) owners are likely to be present and examine if hypotheses proposed in previous studies accurately describe how EV ownership is developing in the state. Furthermore, by studying neighborhood-level EV ownership patterns, this study also highlights suitable neighborhoods in the Metropolitan Area Planning Commission (MAPC) region that policymakers can prioritize for deploying public EV charging stations in the future. The analysis in this thesis is guided by the following research questions:

1) What are the associations between socioeconomic characteristics (income, occupation types, and education levels), spatial variables (access to EV charging infrastructure and commute times), and EV ownership in MA?

2) Considering EV ownership patterns in the state and important site suitability criteria, where should policymakers deploy EV charging infrastructure in the future to support and promote EV ownership in state?

The results of this thesis indicate that EV owners are more likely to be present in wealthier and more educated neighborhoods within the MAPC region. These findings support the EV ownership patterns described in various previous studies and are understandable since the mass-market introduction of EVs in America only occurred in 2009 and since a majority of vehicle owners are yet to fully recognize all aspects of owning and driving an EV – and the different benefits EVs offer. Site suitability analysis results also reveal various suitable locations in the MAPC region that are available for the deployment of publicly accessible EV charging stations in the future. Increasing the availability of charging facilities at the suitable locations identified in this study can help promote and sustain widescale EV ownership – as EVs are set to become affordable to a greater majority of riders in the future.

The remainder of this thesis includes five chapters. Chapter 2 synthesizes key findings from the literature on the challenges the transportation sector offers for climate change mitigation, the case for EVs, EV adoption trends, and the main barriers for EV adoption. Additionally, Chapter 2 also discusses the environmental, socioeconomic, and spatial factors previous studies have used to identify suitable locations for EV charging stations.

Chapter 3 describes the data and methods employed in this thesis. In Chapter 4, key findings are described with maps and tables. Chapter 5 presents recommendations for expanding the availability of EV charging stations and explains the main limitations of this thesis. Chapter 6 provides concluding remarks about the importance of EVs and improving the availability of EV charging stations in the MAPC region.

Chapter 2: Literature Review

Since the beginning of the 20th century, private automobiles have acted as the primary mode of transportation in the U.S. – by playing a key role in various socioeconomic processes in the country. While private vehicles have played an important role in sustaining the daily livelihoods of numerous households and individuals in the country, strong preference for oil-powered private cars and continued dependence on this form of transportation have significantly contributed to climate change. Carbon emissions have been linked to global temperature rises and cars have played a major role in increasing the atmospheric concentrations of such GHGs (Graham-Rowe et al., 2012). The scale of GHG emissions that private vehicles account for, has brought the transportation sector at the forefront of climate change mitigation efforts. Although climate change is increasing the urgency to lower fossil fuel consumption, vehicle use, and GHG emissions, previous literature cautions that cars are likely to stay important because of the various socioeconomic benefits they offer.

Different sources have described promoting the use of EVs as an important policy option since EVs offer the potential of vehicular emission reductions without forcing people to limit car use (Graham-Rowe et al., 2012; Heidrich et al., 2017). However, different market and infrastructural barriers – such as higher upfront costs and a lack of widely available EV charging stations – have prevented higher rates of EV adoption (Slowik & Lutsey, 2019). In the next subsection, I highlight findings from empirical analyses that have examined EV adoption patterns, the impacts of EV policies, the importance of EV charging infrastructures, and identification of suitable locations of deploying EV charging stations.

2.1 A society dependent on cars

Several behavioral, policy, and socioeconomic factors have kept private vehicles at the center of American livelihoods. Sheller and Urry (2000) describe American societies as societies of "automobility" and highlight that after housing, automobiles emerged as the next major item of individual consumption – as they not only provided convenient mobility but also offered individuals the feeling of career success, status, and freedom throughout the 20th century. Additionally, they explain that due to benefits and convenience of automobiles, the "private mobility" offered by cars subordinates other forms of "public mobility" offered by walking, cycling, and public transit.

Other researchers also emphasize that apart from convenience and flexibility, values like comfort, safety, and individual freedom continue to make private cars the "most attractive mode of transport" (Beirão & Sarsfield Cabral, 2007). Furthermore, owning an automobile has allowed individuals to reap the benefits of working in cities and escaping the negative aspects of cities by living in suburban areas; along with zoning of land uses to maintain affordable residential tracts, government-guaranteed mortgages, and escalation in birth rates, automobile ownership has played a key role in intensifying suburbanization in the U.S. (Hall, 2014).

While motor cars became a technological reality around 1900, costs restricted private vehicle ownership to a tiny minority of households and individuals (Platt, 2014). However, as carmakers like Henry Ford started mass production of vehicles, declining ownership costs along with factors such as widely dispersed car infrastructures – like roads and fueling stations – and affordable fossil fuels have significantly contributed to an exponential rise in the number of cars and car travel in America since the early 1900s (Yergin, 1990). By the end of the 1920s, one out of five Americans owned a car (Hall, 2014); within Massachusetts, over 320,000 motor vehicles travelled about 1,800,000,000 miles in areas like the Boston metropolitan district in 1927 (City Planning Board Boston, 1930)

Such trends in private vehicle ownership and vehicle miles travelled (VMT) have continued to stay prevalent. Between 1960 and 2008, travel volume of private vehicles in the country, grew by a factor of nearly 3.5 (Schipper et al., 2011). Between 2011 and 2015, VMT in Massachusetts rose by 10% (U.S. Federal Highway Administration, 2015) while 2016 saw the largest annual increase in VMT in the U.S. since 1971 - as shown by Figure 1 (U.S. Federal Highway Administration, 2016).

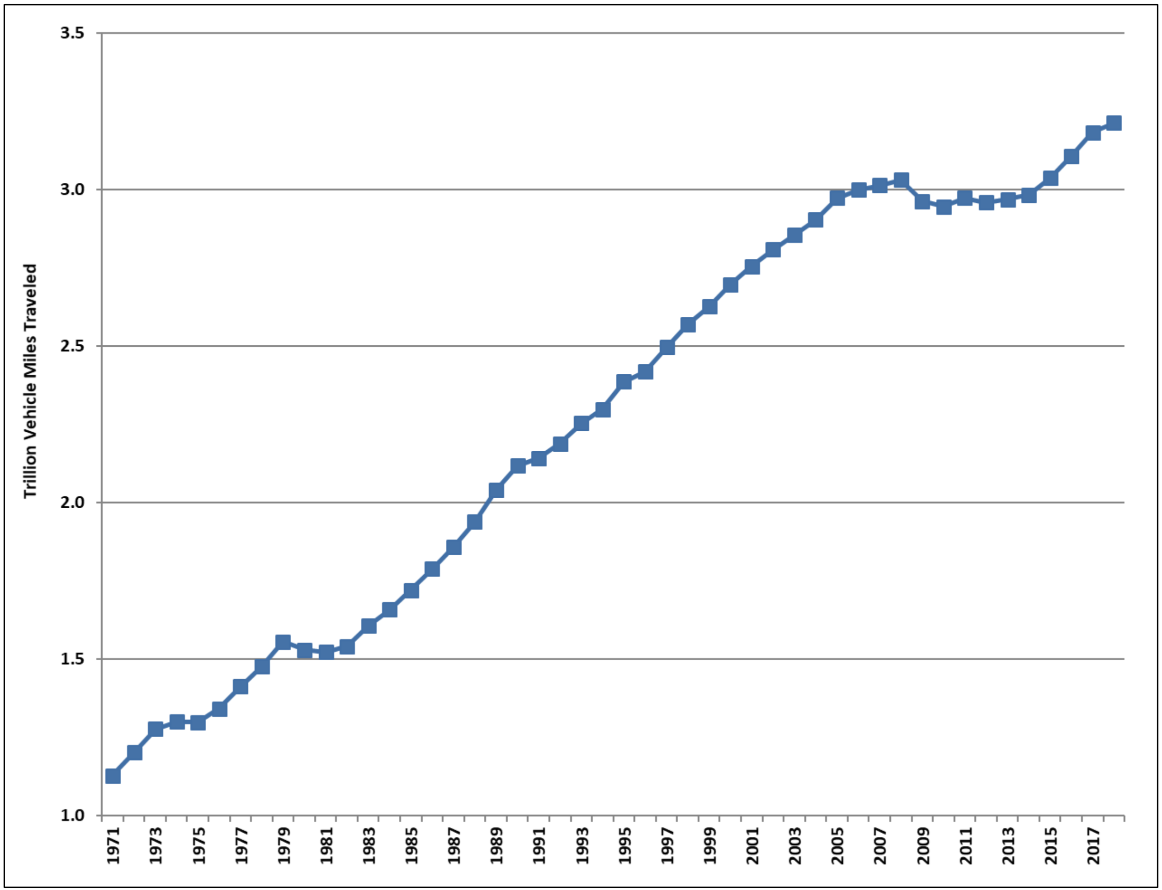


Figure 1: Annual vehicle miles travelled in the U.S. Source: U.S. Federal Highway Administration

2.2 Cars and climate change: causes and challenges

While private vehicles have continued to play an important role in the daily livelihoods of numerous American households and the country's economy, the use of cars has contributed to an escalation of carbon dioxide (CO_2) emissions and climate change. According to the EIA, combustion of a gallon of gasoline can release up to 19.60 pounds of CO_2 into the atmosphere (EIA, 2016). Knittel (2012) warns that continued reliance on fossil-fuel powered transportation raises the risk of destructive climate change.

Persistent dependence on private vehicles with internal combustion engines that burn gasoline and diesel, has made the transportation sector the leading and most-rapidly growing contributor to GHG emissions in the U.S. (Room, 2006). A comparative study by Newman and Kenworthy (1989) showed that in 42 cities across Asia, Australia, and Europe, average gasoline consumption from vehicle use in 10 U.S. cities was nearly twice as high than in Australian cities, four times higher than in European cities, and ten times higher than in Asian cities between 1960 and 1980. In the 1990s, the transportation sector saw the fastest growth in CO_2 emissions compared to other sectors of the U.S. economy (Room, 2006). Furthermore, GHG emissions from transportation in the country, increased by a factor of three between 1960 and 2011 (Schipper et al., 2011).

In 2016, the transportation sector exceeded the electric power sector in terms of total GHG emissions for the first time according to data compiled by the EIA (EIA, 2016). Likewise, the EIA also highlights that transportation-related CO_2 emissions have increased steadily in the country since 2012 – due to increasing economic activities and moderate fuel prices – with CO_2 emissions increasing by 8% in 2018 compared to emission levels in 2012; as shown in Figure 2, the same analysis also underscores that gasoline and diesel combustion from personal vehicles constituted the highest proportion of GHG emissions in the transportation sector (EIA, 2018).

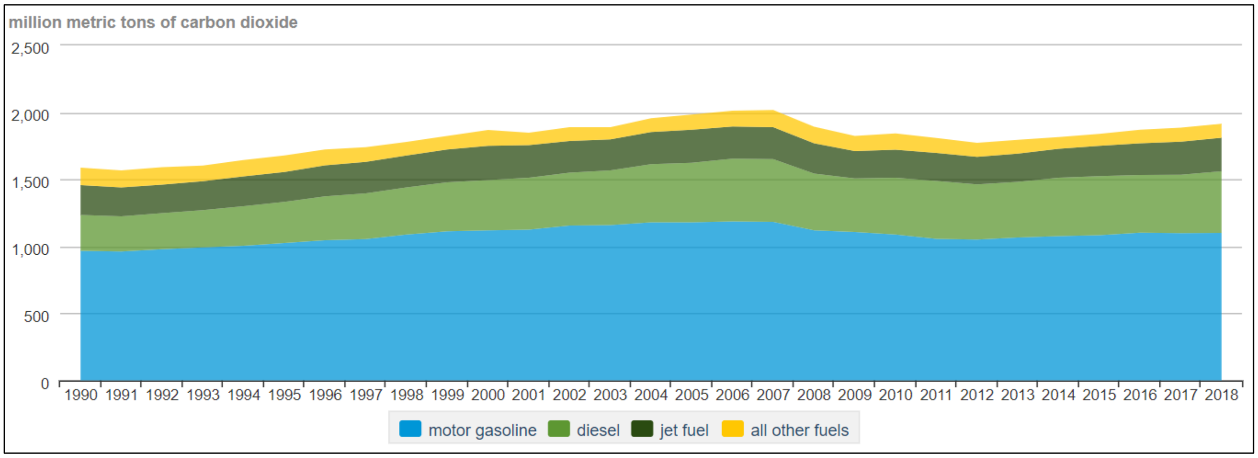


Figure 2: U.S. transportation fuel CO_2 *emissions by type, 1990-2018. Source: U.S. Energy Information Administration*

Other studies identify the continued reliance of vehicles on fossil fuels like gasoline and diesel – and the lack of other energy sources for vehicles, as the major reason for such trends (Schipper et al., 2011). Gasoline and diesel remain the dominant and most affordable source of energy for vehicles; affordable fuel prices continue to encourage people to drive (Chapman, 2007). Additionally, Schipper et al. (2011) assert that economic growth and higher incomes have increased - and will continue to increase - vehicle ownership and vehicular emissions.

Multiple sources emphasize that addressing GHG emissions from private vehicles is vital for mitigating climate change (Ross Morrow et al., 2010; Berggren and Magnusson, 2012; Room, 2006). Just to ensure that global CO_2 emissions do not rise, a more than 50% reduction in average emissions per vehicle is necessary by 2040 (Berggren and Magnusson, 2012). However, projections of further increase in transport emissions pose serious challenges to effective climate change mitigation (Egbue and Long, 2012). Failure to substantially decrease GHG emissions, create serious threats of disruptive and irreversible climate change effects (Covert et al., 2016).

2.3 Different policy options: impacts and debates

Transportation has featured heavily on political agendas and policy debates since the 1990s (Chapman, 2007). Developed nations like the U.S. have attempted to reduce fossil fuel consumption by implementing a mixture of taxes, fees, or regulation on emissions (Covert et al., 2016). While there is wide recognition of the importance of urgently reducing fossil fuel consumption and emissions from transportation, there have been a variety of debates on how to achieve this goal.

Metcalf (2009) notes that historically, the U.S. has turned to command and control regulations like the Corporate Average Fuel Efficiency (CAFE) standards (passed in 1978), which obligate car producers to meet minimum mileage standards for selling motor vehicles in the country. However, he highlights that such measures force carmakers to bear the disproportionate share of the high cost of reducing GHG emissions and create additional economic inefficiencies. Moreover, it also remains highly questionable if tightening CAFE standards effectively curb emissions, since U.S. GHG emissions rose by 15% between and 1990 and 2005 (Metcalf, 2009).

Schemes for increasing fuel taxes and indirect taxation have also been widely discussed (Chapman, 2007). But an evaluation of different policy models through the National Energy Modeling System (NEMS) show that options like carbon taxes (or higher carbon prices) have limited scope of achieving substantial reductions in GHG emissions (Ross Morrow et al., 2010); additionally, such economic models show that reduction in emissions can only be achieved if carbon taxes or fuel prices are raised to a level which is considerably higher than what the American public has historically tolerated. Knittel (2012) also warns that energy taxes in the U.S. are a “political hot button” and hence, implementing higher taxes on transport without properly recycling tax revenues may only end up creating tremendous public protests. Furthermore, tax schemes can not only be expensive to implement, but like CAFE standards, they do not guarantee reductions in fuel consumption and emissions. While many studies have explored the potential impacts of raising fuel prices through different mechanisms, Heidrich et al. (2017) warn that higher fuel prices may inflict substantial monetary losses to individuals, households, and the economy – due to the economic importance of efficient, convenient, and affordable transport.

Similarly, Chapman (2007) suggests taxation schemes such as parking fees and congestion pricing, and notes that such taxing schemes have low public acceptability and can disproportionately impact lower income consumers and younger families who rely heavily on private vehicles. The main debates surrounding different policy options that have been implemented or discussed in America to reduce GHG emissions from vehicles are summarized in Table 1.

Table 1: Main arguments against different policy instruments for reducing vehicular emissions

Policy option	**Challenges and drawbacks**
Improving fuel economy standards	- Can potentially create economic inefficiencies for car producers. - Does not guarantee reduction in emissions especially if vehicle ownership continues to increase.
Implementing taxes to increase fuel prices or Implementing a carbon tax	- Can generate political and public protests. - Can create adverse economic costs particularly for low income groups.
Promoting public transportation	- Not convenient for people who commute long distances. - Not favorable to people with inflexible work or commute schedules. - Overcrowding can create uncomfortable travel experiences.

2.4 The case for EVs

Despite the different policy instruments that have been discussed as potential solutions for lowering GHG emissions from private vehicles, Sheller (2004) warns that it is hard to completely abandon cars - and the way of life they offer. Additionally, while the scale of GHG emissions from vehicles has prioritized the transportation sector in climate change mitigation efforts, it is vital to “reconcile the need for travelling in private vehicles” with the goal of reducing carbon emissions from transportation considering the various socioeconomic functions private vehicles continue to perform in daily livelihoods (Heidrich et al., 2017). Hence, EVs have emerged as an attractive solution because they offer the potential of reducing vehicular GHG emissions without reducing the socioeconomic benefits cars offer. As Graham-Rowe et al. (2012) highlight, EVs can potentially emit substantially lower GHG emissions than traditional cars with internal combustion engines and have the potential of reducing transport emissions – without curtailing personal car use.

EVs are powered by electricity rather than traditional vehicle fuels such as gasoline or diesel. In 2010, studies showed that if already available models of EVs replaced the entire fleet of passenger cars, well-to-wheels carbon emissions would decrease by 60% in the U.S. (Graham-Rowe et al., 2012). Similarly, a report published by the Union of Concerned Scientists (UCS) in 2012, reveals that over its lifetime – from manufacturing to operation to disposal – an EV emits about 50% lower GHG emissions than a comparable oil-powered vehicle (Nealer et al., 2015).

Apart from cutting down tailpipe emissions Romm (2006), EVs can reduce the pollutants per unit of energy - and improve fuel economy by reducing the amount of energy required to travel a mile (Knittel, 2012). Furthermore, electric propulsion is more efficient than propulsion using internal combustion engines and supports the transition from oil to other energy sources (Plötz et al., 2014). The International Energy Agency (IEA) also asserts that along with reducing GHG emissions, EVs also offer a clean alternative to traditional oil-powered vehicles by limiting air pollution and noise – which can be vital for improving environmental quality in urban areas and along major travel routes (IEA, 2017). In addition to offering such environmental benefits and a pathway for reducing vehicular emissions, such studies also explain that increasing the use of EVs offers the chance for the U.S. to significantly reduce oil consumption, maintain energy security, and protect the American economy from the vulnerabilities of global oil market crises.

While multiple sources have advertised EVs as an attractive policy option, different studies have also questioned whether EVs offer a clean alternative to traditional vehicles that rely on fossil fuels. Covert et al. (2016) warn that transition to electrical mobility will not achieve reduction in GHG emissions, if electricity used to power EVs do not have lower carbon content compared to gasoline and diesel - and if electricity continues to be generated from sources such as coal-based power plants. Moreover, an econometric analysis of electricity emissions highlights that EVs can worsen environmental pollution and GHG emission levels particularly in areas where the supply of electricity continues to come from fuels with high carbon emission coefficients (Holland et al., 2016).

Studies that have raised questions over the environmental benefits of EVs and their potential for reducing vehicular emissions have primarily relied on the assumption that emissions coming from electricity production will not reduce emissions unless electricity is generated from cleaner sources. However, arguments made in different studies pacify such claims.

Knittel (2012) highlights that EVs present an ideal case scenario since it is possible to generate electricity for EVs through sources with lower carbon content - or even with carbon-free sources like solar or wind power. Similarly, the IEA asserts that electrification of transport will greatly contribute to reduction in GHG emissions if the electricity sector continues to transition towards sources with lower carbon content (IEA, 2017).

Graham-Rowe et al. (2012) also emphasize that EVs will substantially lower carbon emissions in markets where carbon intensity of electricity generation is low. Likewise, the UCS (2015) explains that EVs will become cleaner as more electricity is supplied by renewable sources of energy. As shown in Figure 3, by dividing the U.S. into 26 “grid regions” according to primary sources of electricity supply, Nealer et al. (2015) highlight that more than 66% of Americans are living in regions where charging EVs on the regional electricity grid produce lower GHG emissions than a 50 miles per gallon (MPG) gasoline car.

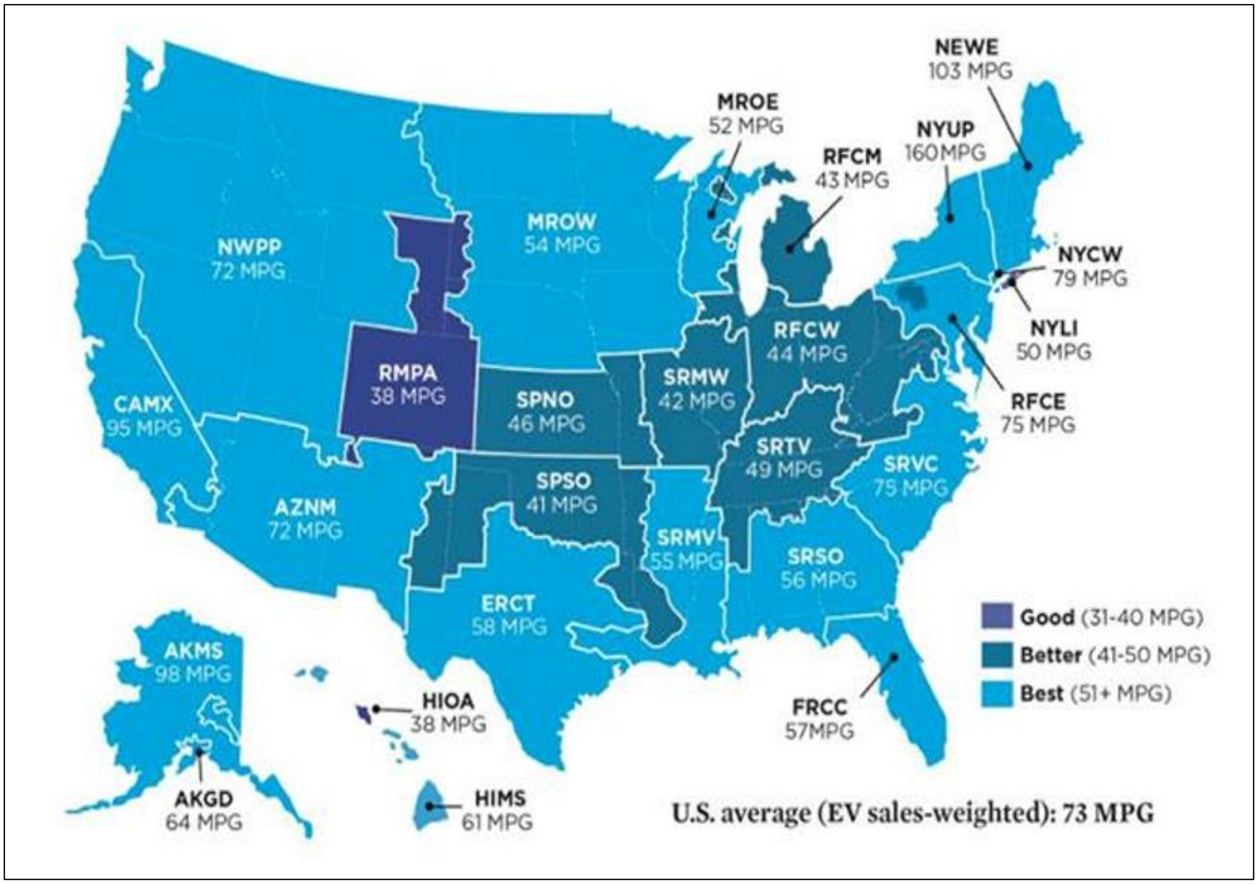


Figure 3: EV global warming pollution ratings and gasoline vehicle emissions equivalent by electricity grid regions. Source: Union of Concerned Scientists

2.5 EVs in America: a work in progress

The IEA notes that EVs still have a long way to go before reaching deployment scales capable of reducing GHG emissions (IEA, 2017). As of 2016, EVs accounted for only 1% of car sales in the U.S. (The Economist, 2018). EVs have failed to materialize as a common form of transport and have struggled to replace traditional oil-powered cars due to multiple reasons. Higher upfront costs compared to traditional vehicles, limited driving range, and limited charging infrastructure are some common problems associated with the use of EVs (Romm, 2006). In addition to such constraints, affordable oil prices continue to make such vehicles inferior to internal combustion engines (Chapman, 2007). Diamond (2009) also points out that affordable gas prices strongly dictate the kind of vehicles consumers prefer and purchase.

While cars that run on fossil fuels are still widely prevalent, there are indications that EVs are gaining more governmental support in America. States like California have shown commitment to promoting EVs since the early 1990s (Knittel, 2012). The American Recovery and Reinvestment Act (ARRA) formalized in 2009, provides over $2 billion for EV and battery technologies (Egbue and Long, 2012). 47 states and the District of Columbia have already formalized a total of 200 financial incentives for EVs (Jenn et al., 2018); along with financial incentives such as rebates and tax cuts, such states have also implemented additional incentives in the form of high occupancy vehicle (HOV) lane access and parking permits for EV owners.

In Massachusetts, the state has been providing rebates of up to $1,500 for EV buyers and leasers through the Massachusetts Offers Rebates for Electric Vehicles (MOR-EV) program since 2014 (Massachusetts Department of Energy Resources & Massachusetts Clean Cities Coalition, 2019). The state also offers multiple grants - funded by the Volkswagen Environmental Mitigation trust - for the deployment of public and private EV charging stations (Alternative Fuels Data Center, 2019). Furthermore, the Massachusetts Electric Vehicle Incentive Program (MassEVIP) provides grants for 50% of the cost of installing workplace EV charging stations, up to amounts of $25,000; likewise, funding ranging from $7,500 to $13,500 for installing EV charging stations is available to local governments, universities and colleges, public and private driving schools, and state agencies (Plug In America, 2016).

2.6 Key empirical findings: early EV adopters, the importance of charging infrastructure, and suitable locations for public EV charging stations

Empirical studies that have investigated how different policies and socioeconomic characteristics impact the sales of alternative fuel vehicles – such as hybrid-EVs and plugin-EVs, primarily rely on aggregate vehicle sales data to:

i) evaluate the effectiveness of various financial and non-monetary incentives implemented to increase EV adoption,

ii) examine the association between EV adoption rates and different socioeconomic characteristics of early EV adopters,

iii) and evaluate the importance of EV charging stations by assessing how availability of EV charging stations affects EV adoption.

Gallagher and Muehlegger (2011) examine quarterly state-level sales data for different hybrid EV models sold from 2000 to 2006 and incorporate time and state fixed-effects to measure the impact of different policy incentives on hybrid EV sales. Additionally, they control for different types of financial incentives (tax credits vs. sales tax waivers) and non-financial incentives (High Occupancy Vehicle (HOV) lane access and parking incentives) in their regression model. Their results suggest that conditional on value, sales tax waivers are associated with more than a ten-fold increase in hybrid vehicle sales compared to tax credits; additionally they also establish that increasing gasoline prices and state-level per-capita Sierra Club membership – their proxy for environmental awareness – are associated with greater hybrid vehicle sales.

Through a multiple linear regression model using 2012 data on the EV market shares in 30 different national EV markets, Sierzchula et al. (2014) find that financial incentives, charging stations, and local presence of production facilities are significantly and positively correlated with a country's EV market share. Their regression results suggest that holding all other factors constant, each additional EV charging station per 100,000 residents that a country added is associated with a 0.12% increase in the country's EV market share and availability of charging stations is the most strongly correlated variable with EV adoption.

Using a similar methodology on state level EV market share data for 2013 in America, Vergis and Chen (2015) examine the correlation between EV adoption rates and different social, economic, geographic, and policy factors across U.S. states – and compare the significant factors they identify with what previous studies have highlighted as possible significant drivers of EV adoption. According to their regression results, consumer attribute variables (education and awareness of electric vehicles), geographic variables (average winter temperature and population density), variables related to the cost of energy (gasoline and electricity costs), and ability to access charging stations away from home positively affect EV adoption rates across U.S. states.

Such studies also explain why the associations and correlations their models establish, may not portray causal impacts of different factors – including the availability of charging stations – on EV adoption rates. Gallagher and Muehlegger (2011) highlight that EV policy that a state may employ is endogenous as it may choose EV policies according to local environments and characteristics; for example, some states allow HOV lane access for EVs to reduce traffic congestion and consumers in such states may have a strong incentive to purchase an EV just to avoid traffic congestion. Likewise, Vergis and Chen (2015) underscore the issue of reverse causality by arguing that number of charging outlets available in different states may well be determined by EV ridership rather than EV ridership being determined by charging availability. Jenn et al. (2018) also point out endogeneity issues caused by the fact that states that have higher demand for EVs are motivated to provide more policy incentives for EVs and hence, higher EV market shares lead to more EV incentives rather than the other way around.

Additionally, researchers have also relied on vehicle choice and travel surveys to gain insights on the vehicle choice of individuals and characteristics of early EV adopters. For example, the 2000 San Francisco Bay Area travel survey revealed that the type of vehicle owned is spatially clustered at both the regional and household-level even after controlling for income and population density - and San Francisco Bay Area residents are more likely to choose a type of new car that is favored by their neighbors (Adjemian et al., 2010).

In analyzing the demographic attributes of EV buyers through a survey with 2,513 respondents, Curtin et al. (2009) discover that EV buyers in America tend to be wealthy and educated individuals who value the environmental benefits offered by EVs. Hidrue et al. (2011) also examine results from a survey with 3,029 American participants and find that EV adopters are young, middle-aged, and have a bachelor's degree or higher. Likewise, Plötz et al. (2014) discover that only consumers with specific socioeconomic and emotional characteristics identify as early EV adopters; based on analysis of different German driving behavior surveys, they find that private EV buyers in Germany are middle-aged men primarily working in the private sector and living in rural or suburban households.

Along with monetary incentives to offset the cost of EV ownership, increasing the availability of public EV charging stations will be vital for supporting widescale EV adoption (IEA, 2017). A comprehensive survey of more than 1,600 American adults aged 18 and older – who are considering buying or leasing a new vehicle in within the next two years – conducted by the UCS between 2018 and 2019 highlights the importance of the availability of EV charging stations and the charging preferences of potential EV adopters (UCS, 2019). According to the survey results, about a quarter of the survey respondents assert that seeing more public EV charging stations would encourage them to purchase an EV. Furthermore, a report compiled by McKinsey & Company explains that while historically poor driving ranges of EVs have acted as a huge barrier to widescale EV adoption, the severity of this hurdle is likely to decrease considering that by 2025, 350 new EV models – with driving ranges of up to 200 miles – are scheduled to be available for purchase (Engle et al., 2018). However, the same report outlines that if EV purchases continue to rise, a lack of widespread EV charging infrastructures will be the next serious barrier to EV adoption. According to McKinsey's analysis, while at-home chargers will be the priority for EV consumers living in single-family homes with access to parking and garages, the availability of public and long-distance charging stations will be vital as more middle- and lower-income consumers – who cannot acquire at-home charging options – start switching to EVs in the future.

Slowik and Lutsey (2019) explain that most public charging stations in the U.S. use Level 2 or DC fast charge electric vehicle supply equipment (EVSE). Level 2 chargers can provide 10 to 60 miles of range per hour of charging, while DC fast charge can deliver 60 to 100 miles of range in 20 minutes or less (U.S. Department of Energy (DOE), 2020). According to the DOE, public charging stations in America are typically available in areas where vehicles are highly concentrated, such as shopping centers, city parking lots and garages, airports, hotels, government offices, and other businesses. Level 2 chargers are suitable for commuters who can stop or park their vehicles at such locations for longer periods of time while DC fast chargers are more convenient for travelers who require quick charging for long distance interregional and intraregional travel (Jin, 2016).

Both the UCS (2019) and Engle et al. (2018) assert that availability of publicly accessible EV charging stations will be a vital factor for alleviating concerns associated with range anxiety and encouraging widescale EV adoption. As highlighted in the UCS's survey analysis, low-income prospective car buyers in particular, are more likely to find charging stations at grocery stores, restaurants, and shopping malls the most convenient locations to charge EVs. Jin (2016) also presents a similar argument, stating that identifying such commercial areas – where drivers tend to stop or park – and incorporating the likelihood of EV owners being present in a community or neighborhood are some key factors to consider for identifying optimal locations for EV charging infrastructures.

Some of the main findings of such survey reports, empirical studies, and spatial analyses that have examined EV adoption patterns, the importance of EV charging availability, EV charging preferences, and factors determining suitability of EV charging station locations are summarized in Table 2.

Table 2: Key findings from
EV consumer surveys, empirical studies, and spatial analyses

A) Factors significantly affecting vehicle choice and EV ownership		
Study:	Methodology:	Key Findings:
Adjemian et al. (2010)	Moran's I and spatial regressions on data from the 2000 San Francisco Bay Area Travel Survey.	- Type of vehicle ownership is spatially clustered. - The Bay area residents were more likely to choose a vehicle choice favored by their neighbors.
Gallagher and Muehlegger (2010)	Hedonic regression model using 2000-2006 data on state level EV market shares.	- Along with sales tax waivers, rising gasoline prices positively impact on EV market shares.
Hidrue et al. (2011)	Qualitative analysis of 2010 survey data on U.S. EV owners.	- EV adopters are middle-aged individuals who have a bachelor's degree or higher.
Sierzchula et al. (2014)	Hedonic regression model using 2012 data on the EV market shares	- Financial incentives, charging infrastructure, and local presence of EV production facilities were significantly and

	in 30 different national EV markets.	positively correlated with a country's EV market share.
Plötz et al. (2014)	Qualitative analysis of 2010 survey data on U.S. car drivers.	- Potential EV buyers are young and wealthy individuals who work in the private sector and have strong environmental awareness.
Vergis and Chen (2015)	Multivariate linear regression model using 2013 data on state level EV adoption rates.	- Consumer attribute variables (education, awareness of electric vehicles), geographic variables (average winter temperature, population density), variables related to the cost of energy (gasoline and electricity costs), and ability to access EV charging infrastructure away from home positively affected EV adoption rates across U.S. states.
B) Importance of EV charging infrastructure and EV charging preferences		
Study:	Methodology:	Key Findings:
Union of Concerned Scientists (2019)	Qualitative analysis of 2018-2019 survey data on American adults who are considering buying or leasing a new vehicle in within the next two years.	- Having access to an EV charging station would encourage 24% of respondents to purchase an EV. - Prospective car buyers who are people of color are more likely to find charging stations outside their homes more convenient. - More than 66% respondents express that grocery stores, restaurants, and shopping malls would be the most convenient locations to charge EVs.
Engle et al. (2018)	Analysis of EV ownership and EV charging demand projections based on McKinsey's 2016 EV consumer survey.	- A lack of EV charging infrastructure will be the next serious barrier to EV adoption. - The availability of public and long-distance charging stations will be vital as more middle- and lower-income consumers – who cannot acquire at-home charging options – start switching to EVs in the future.
C) Suitability factors and key considerations for identifying EV charging station locations		
Study:	Methodology:	Key Findings:
Efthymiou et al. (2012)	Demand-oriented multi-criteria suitability analysis to locate optimal locations for EV charging stations in Kalamaria, Greece.	- Demand for EV chargers will be high in high-income areas, highly populated areas, and areas with high points of interests (major attractions).
Jin (2016)	Site suitability analysis to locate optimal charging stations within Los Angeles County.	-Likelihood of EV ownership in a neighborhood or community significantly affect the usage of public EV charging stations. -Level 2 EV charging stations should be placed in commercial areas and public purpose areas such as libraries, and parks – accounting for factors such as typical characteristics associated with EV owners and availability of already installed charging stations. - DC fast charging stations are more appropriate for areas closer to major roadways.

Zhang and Iman (2018)	Weighted multi-criteria suitability analysis of ideal EV charging station locations in Wasatch Front, Utah.	-Apart from demographic, socioeconomic, and urban criteria, land use regulations are key for identifying suitable locations for EV charging stations.

Chapter 3: Methodology

Identifying neighborhoods with EV owners and understanding the characteristics of such neighborhoods, can provide important insights that can help planners and policymakers effectively develop public EV charging infrastructures and promote EV ownership. The analysis presented in this thesis asks the following research questions:

1) What is the association between EV ownership in the state and the key socioeconomic, demographic, and spatial variables – described by previous literature as vital factors promoting EV adoption?

2) Which locations in the state are suitable locations for deploying more EV charging stations – given current EV ownership patterns, key spatial and infrastructural factors, and the current availability of EV charging stations?

In this chapter, the data and methodology used to answer these questions are described in the following subsections.

3.1 Data description and justifications for variable selection

This study uses the Massachusetts Vehicle Summary Statistics dataset compiled by the MAPC – which provides Census Block Group level (referred to in this thesis as neighborhood) information for the total number of passenger EVs registered between 2009 and 2014. While this dataset provides quarterly information on EV registrations for each year of this time period, MAPC notes that data is missing for many neighborhoods for different quarters for 2009 to 2014. To address these missing data, a dummy variable was created to capture whether at least one EV owner was present in a neighborhood at any point in between 2009 and 2014. A brief description of the MAPC dataset is provided in panel A of Table 3.

Table 3: Datasets, sources, variable names, and description of variables

A) EV Ownership	
Dataset: Massachusetts Vehicle Census Source: Metropolitan Area Planning Council	Observational unit: Census Block Groups Time period: 2009-2014
Variable:	Description:
EV_Ownership	Dummy variable which =1 if a census block group has at least one EV owner = 0 if a census block group has no EV owners
B) Demographic, Socioeconomic, and Commute Characteristics	
Dataset: American Community Survey (5-year Estimates) Source: U.S. Census Bureau	Observational unit: Census Block Groups Time period: 2010-2014
Variable:	Description:
Pop_Density	Population per square mile
Rural	Dummy variable which =1 if a census block group's population density is less than 2,500 residents per square mile = 0 if a census block group's population density is greater than 2,500 residents per square mile
Household	Average household size
Income	Median income in $1,000s (2014 inflation adjusted dollars)
Rent	Median monthly gross rent (2014 inflation adjusted dollars)
Age	Median age
Bachelor	Percentage of adults with Bachelor's degree
Master	Percentage of adults with Master's degree
White	Percentage of white population
Unemployment	Unemployment rate
Private	Percentage of labor force employed in the private sector
Public	Percentage of labor force employed in the public sector
MPD	Average total miles travelled (Miles per Day)
Drive	Percentage of labor force driving to work
C) EV Charging Stations	
Dataset: Massachusetts EV Charging Station Locator Source: Alternative Fuels Data Center	Observational unit: Census Block Groups Time period: 2010-2014
Variable:	Description:
Charger	Dummy variable which = 1 if a census block group has at least one EV charging station = 0 if a census block group has no EV charging station
Charging_Stations	Number of public charging stations per 1,000 residents
D) GIS shapefiles for suitability analysis	
Dataset: Digital Elevation Model Source: Mass GIS	Observational unit: 5m x 5m raster cells Time period: 2005
Variable:	Description:
Elevation	Surface elevation in meters

Dataset: Land Use Source: Mass GIS	Observational unit: ¼ - 1acre area polygons Time period: 2005
Variable:	Description:
Land	Land use codes
Dataset: Massachusetts Department of Transportation (MassDOT) Roads Source: Mass GIS	Observational unit: roadway lines Time period: 2005
Variable:	Description:
Road	Major roadways

Data for key socioeconomic and demographic predictors of EV ownership that have been identified in previous studies, come from the 2010-2014 5-year estimates of the American Community Survey (ACS). Since the literature indicates that wealth, education, age, nature of employment, and commute distance are some key predictors of EV ownership, different variables capturing information for such factors are described in Panel B of Table 3.

Additionally, considering that availability of EV charging infrastructure is also described as a key factor promoting EV ownership (Engle et al., 2018; Slowik & Lutskey, 2019; UCS, 2019), data for already installed public EV charging stations in the state was retrieved from the Alternative Fuels Data Center (AFDC) Massachusetts EV Charging Station Locator. This data source provides physical addresses of available charging stations across MA. These addresses were geocoded and were converted to a point shapefile in ArcGIS; the shapefile shown in Figure 4 was then used to assess the availability of a charging station in each MA neighborhood.

Data for the variables described in Panel A, B, and C of the Table 2 were merged at the block group level to create the main dataset for analysis. Summary statistics for these variables are presented in Table 4. As reported by Table 4, only about 13% of neighborhoods in MA (657 out of 4979) had an EV owner between 2009 and 2014. Likewise, only about 9% of MA neighborhoods (422 out of 4979) had an already installed EV charging station available.

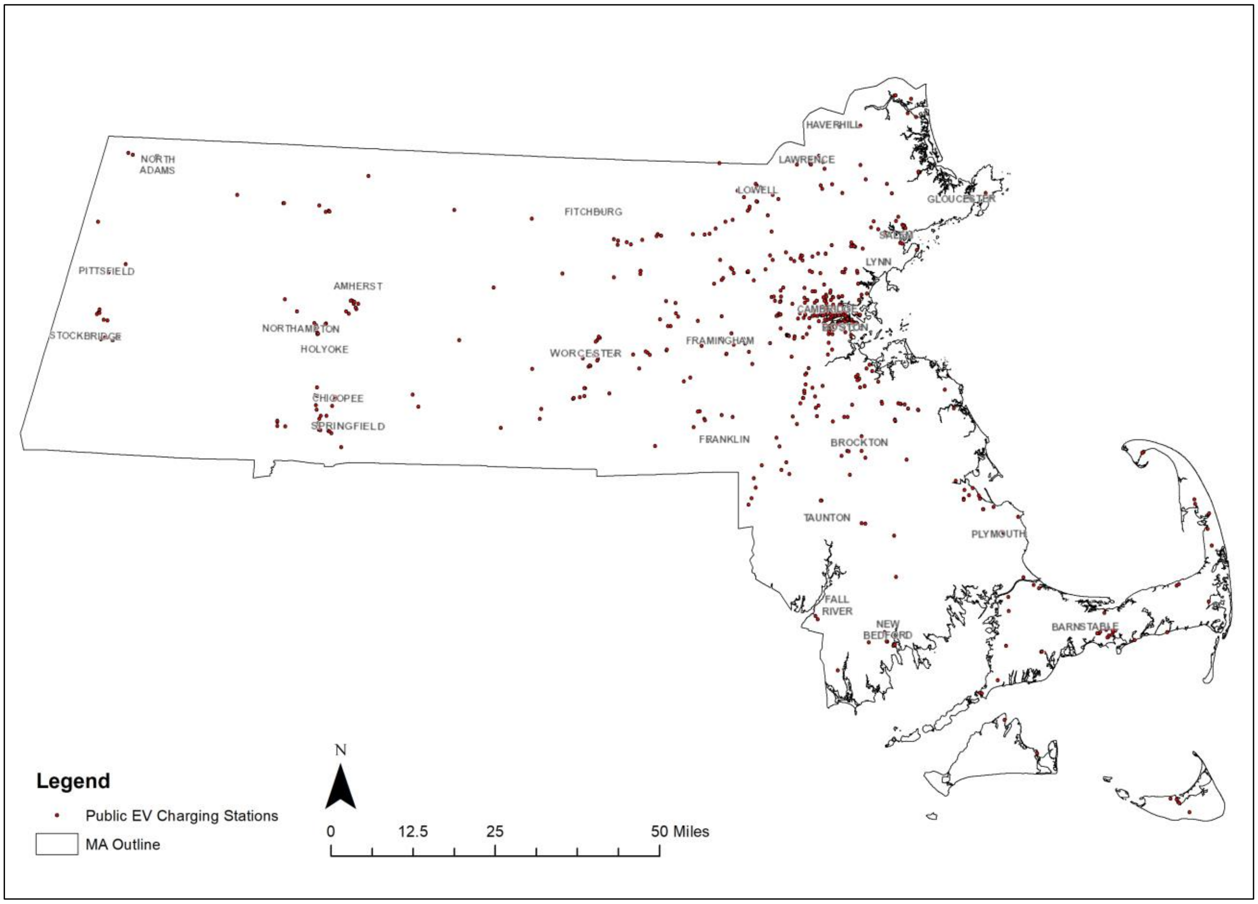


Figure 4: Public EV charging stations in Massachusetts between 2010 and 2014.

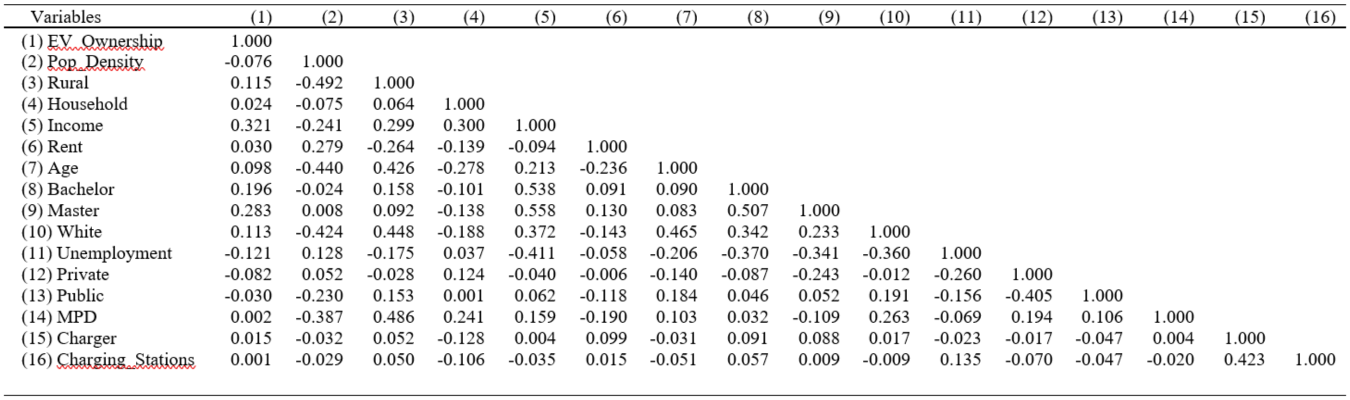
Table 4: Summary Statistics

	count	mean	median	sd	min	max
EV_Ownership	4,979	0.13	0.00	0.34	0.00	1.00
Pop_Density	4,979	8,254.02	3,666.60	12529.70	7.51	202,305.72
Rural	4,979	0.42	0.00	0.49	0.00	1.00
Household	4,979	2.55	2.53	0.50	0.00	5.25
Income	4,979	74.32	69.38	37.71	0.00	250.00
Rent	4,979	895.92	974.00	584.01	0.00	2,001.00
Age	4,979	40.49	40.90	8.83	0.00	86.20
Bachelor	4,979	22.23	21.61	11.42	0.00	100.00
Master	4,979	12.14	10.27	9.46	0.00	100.00
White	4,979	79.73	87.75	22.08	0.00	100.00
Unemployment	4,961	8.88	7.29	7.32	0.00	100.00
Private	4,961	59.11	59.72	11.76	0.00	100.00
Public	4,961	11.57	10.78	7.03	0.00	61.90
MPD	4,979	27.89	27.59	3.95	0.00	53.35
Drive	4,961	63.87	68.65	24.90	0.00	1,183.33
Charger	4,979	0.09	0.00	0.28	0.00	1.00
Charging_Stations	4,979	0.12	0.00	0.96	0.00	55.56

Table 4 also suggests that most of the population across different MA neighborhoods seem to be employed in the private sector. Average median income is reported at $74.05 (in 2014 inflation adjusted $1,000s) and on average, 22.16% of the population across different MA neighborhoods had a bachelor’s degree while this percentage is 12.10% for the population with a master’s degree. Additionally, driving to work seems to be the most common mode of commute for MA’s labor force as indicated by in Table 4 – with an average of about 64% of the population in different neighborhoods of the state driving to work on a daily basis. The correlations between the different variables in Table 4 is shown in Table 5.

As reported in column 1 of Table 5, all variables apart from Population Density, Unemployment, Private, and Public, show some level of positive association with the EV ownership dummy. Variables such as Income, Bachelor, and Master have a relatively higher level of positive correlation with the EV ownership dummy compared to factors such as average household size, monthly rent, the availability of EV charging stations, and whether a neighborhood is rural.

Table 5: Correlation Matrix



Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
(1) EV_Ownership	1.000															
(2) Pop_Density	-0.076	1.000														
(3) Rural	0.115	-0.492	1.000													
(4) Household	0.024	-0.075	0.064	1.000												
(5) Income	0.321	-0.241	0.299	0.300	1.000											
(6) Rent	0.030	0.279	-0.264	-0.139	-0.094	1.000										
(7) Age	0.098	-0.440	0.426	-0.278	0.213	-0.236	1.000									
(8) Bachelor	0.196	-0.024	0.158	-0.101	0.538	0.091	0.090	1.000								
(9) Master	0.283	0.008	0.092	-0.138	0.558	0.130	0.083	0.507	1.000							
(10) White	0.113	-0.424	0.448	-0.188	0.372	-0.143	0.465	0.342	0.233	1.000						
(11) Unemployment	-0.121	0.128	-0.175	0.037	-0.411	-0.058	-0.206	-0.370	-0.341	-0.360	1.000					
(12) Private	-0.082	0.052	-0.028	0.124	-0.040	-0.006	-0.140	-0.087	-0.243	-0.012	-0.260	1.000				
(13) Public	-0.030	-0.230	0.153	0.001	0.062	-0.118	0.184	0.046	0.052	0.191	-0.156	-0.405	1.000			
(14) MPD	0.002	-0.387	0.486	0.241	0.159	-0.190	0.103	0.032	-0.109	0.263	-0.069	0.194	0.106	1.000		
(15) Charger	0.015	-0.032	0.052	-0.128	0.004	0.099	-0.031	0.091	0.088	0.017	-0.023	-0.017	-0.047	0.004	1.000	
(16) Charging_Stations	0.001	-0.029	0.050	-0.106	-0.035	0.015	-0.051	0.057	0.009	-0.009	0.135	-0.070	-0.047	-0.020	0.423	1.000

In addition to the variables presented in Table 4, Panel D in Table 3 describes the GIS shapefiles this thesis used to identify optimal locations for deploying EV charging stations in the MAPC region. MassGIS shapefiles for Massachusetts’ land use codes, elevation raster, and major roadways were imported into a file geodatabase in ArcGIS. Likewise, data for variables reported in Table 4 were also imported as polygon feature classes into this geodatabase.

3.2 Research framework

Table 6 outlines the main research parts of this study and the goals each part tried to achieve in order to retrieve answers for the research questions of this thesis. Additionally, the table also describes the methodology employed during these different phases. The first three parts describe how neighborhoods with EV owners are spatially distributed across the state and typical demographic and socioeconomic characteristics of areas where EV owners are present. Building on the results from the first three parts, Part 4 and Part 5 identify and evaluate suitable locations for deploying EV charging stations in the state – considering existing EV ownership patterns, access to already available charging stations, and land use codes. The following subsection provides more details to the descriptions presented in Table 6.

Table 6: Main parts of the study, their aims, and employed methodologies

Research phase:	Aim(s):	Methodology
Part 1: Assessing EV ownership	- Investigating prevalence of EV owners - Description of the spatial distribution of neighborhoods with EV owners	- Generate maps to present spatial distribution of neighborhoods with EV owners - Generate descriptive statistics to explain where such neighborhoods are prevalent across MA
Part 2: Investigating associations between key predictors and EV ownership	- Identifying significant predictors that describe the presence of EV owners in neighborhoods across MA - Relating significant predictors with common hypotheses about characteristics of EV owners	- Conduct T-tests to describe typical characteristics of neighborhoods with EV owners - Conduct multivariate logistic regressions and assess significant predictors of EV ownership
Part 3: Synthesizing results from Phase 1 and Phase 2	- Finding neighborhoods with higher likelihoods of EV ownership	- Create probability maps to show and describe patterns and variations in the probability of a neighborhood having an EV owner by using results from Phase 2
Part 4:	- Identifying suitable locations for deploying EV charging stations considering EV	-Generate suitability maps to identify neighborhoods with

Suitability analysis of EV charging station locations	ownership patterns, the likelihood of a neighborhood having EV owners, and key spatial and infrastructural factors	higher suitability scores for an EV charging station
Part 5: Examination of suitable locations	- Describing and assessing key spatial and socioeconomic characteristics of suitable locations	-Description of neighborhoods with higher suitability scores.

3.3 Analytical methods: regression models and suitability analysis

As shown in Table 4, EV owners were present in only 13% of neighborhoods in MA from 2009 to 2014. The first part of this study describes where such neighborhoods are prevalent in the state. Neighborhoods in MA, fall within the boundaries of 13 different Regional Planning Agencies (RPAs) shown in Figure 4; each RPA in MA serves as forum for officials to address issues such as the development of plans and strategies in areas of population and employment, transportation, economic development, regional growth and the environment (MassGIS, 2016).

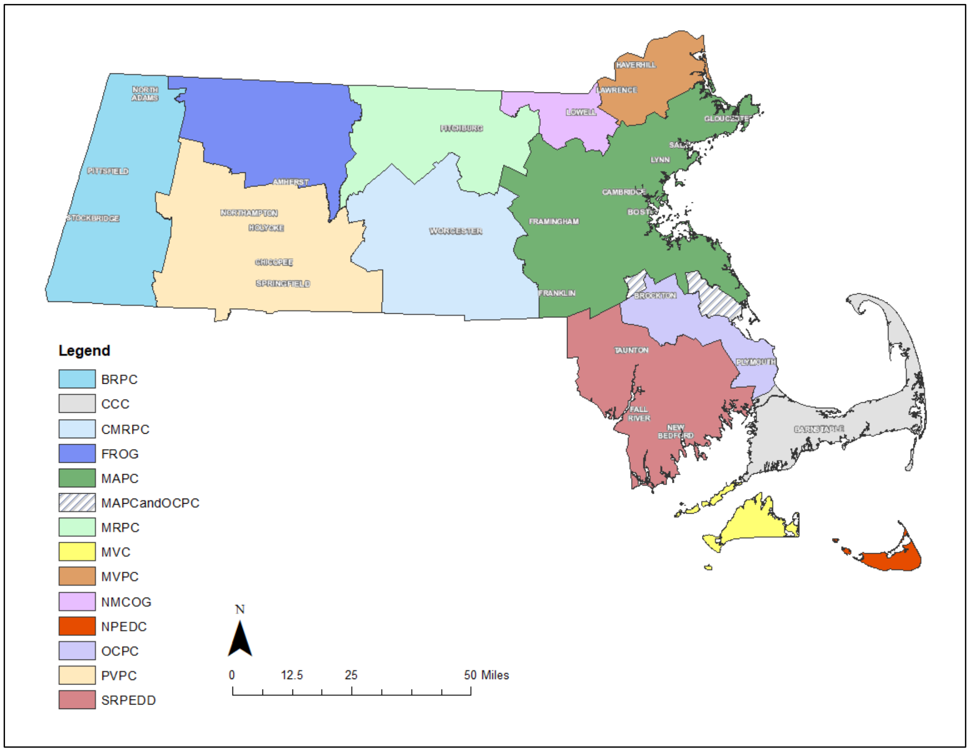


Figure 4: Regional Planning Agencies (RPAs) in Massachusetts.

The names of these RPAs and their abbreviations are shown in Appendix i. First, I show how neighborhoods with at least one EV owner are distributed across these RPAs by determining the percentage of neighborhoods in each RPA with an EV owner and the prevalence of MA EV neighborhoods – defined as the percentage of the 657 MA neighborhoods with at least one EV owner located in each RPA.

Using the data from the first part of this study, I use statistical analysis to understand the demographic and socioeconomic characteristics of MA neighborhoods with EV owners. In addition to t-tests for examining differences in means between neighborhoods with and without EV owners – for variables reported in Panel B and Panel C of Table 3, a multivariate logistic regression shown as Model A was conducted to assess associations between key EV ownership predictors highlighted by previous studies, and the likelihood of a MA neighborhood having an EV owner.

Model A:

$$Y_i = \beta_0 + \beta_1 Pop\_Density_i + \beta_2 Income_i + \beta_3 Rent_i + \beta_4 Age_i + \beta_5 Bachelor_i + \beta_6 Master_i + \beta_7 White_i + \beta_8 Unemployment_i + \beta_9 Private_i + \beta_{10} Public_i + \beta_{10} MPD_i + \beta_{11} Drive_i + \beta_{12} Charger_i + u_i$$

(where $Y = Log[\frac{p(EV\_Ownership= 1)}{1-p(EV\_Ownership=1)}]$ for Census Block Groups *i* and
u_i is the error term)

Additionally, Model B shows another multivariate logistic regression that was used to assess if EV owners in Massachusetts are present in urban or rural areas by incorporating the variable Rural. This variable is a dummy indicator which is 1 for neighborhoods with population density less than 2,500 residents per square mile which is a rural classification scheme set by the U.S. Census Bureau (U.S. Census Bureau, 2015). Model B also includes the variable Charging_Stations – the number of public charging stations per 1,000 residents in a neighborhood – to investigate how this measure of the availability of charging facilities impacts the likelihood of a neighborhood having at least one EV owner.

Model B:

$$Y_i = \beta_0 + \beta_1 Rural_i + \beta_2 Income_i + \beta_3 Rent_i + \beta_4 Age_i + \beta_5 Bachelor_i + \beta_6 Master_i + \beta_7 White_i + \beta_8 Unemployment_i + \beta_9 Private_i + \beta_{10} Public_i + \beta_{10} MPD_i + \beta_{11} Drive_i + \beta_{12} Charging\_Stations_i + u_i$$

$$\text{(where } Y = Log[\frac{p(EV\_Ownership=1)}{1-p(EV\_Ownership=1)}] \text{ for Census Block Groups } i \text{ and } u_i \text{ is the error term)}$$

Sierzchula et al. (2014) and Vergis and Chen (2015) employ a similar multivariate regression approach to assess how different socioeconomic and demographic predictors explain EV market shares and EV adoption rates. Based on their studies and the results reported by different surveys (Hidrue et al., 2011; Plötz et al., 2014), the coefficients of variables capturing wealth – β_2 and β_3 – were expected to be statistically and economically significant. Coefficients of variables incorporating educational factors – β_5 and β_6 – were also expected to be statistically and economically significant. Similarly, the estimated value of β_{12} shows if the hypothesis of charging station availability being a significant factor for promoting EV ridership (Sierzchula et al., 2014; Vergis & Chen, 2015; Engle et al., 2018) is accurate. Besides comparing results for Massachusetts to other parts of the world, this model also aimed to derive additional associations and factors that explain the presence of EV owners in different neighborhoods in Massachusetts.

In the next part of this study results from Model A and B were utilized to produce maps that show how the probability of a neighborhood having an EV owner varies across MA and its different RPAs. This identifies areas with high likelihoods of EV ownership, describes where such neighborhoods have emerged in the state, and hints at other possible factors contributing to the presence of EV owners in such areas.

To identify suitable locations for deploying EV charging stations, a multi-criteria evaluation (MCE) suitability analysis was conducted in ArcGIS. The layers used in the site suitability analysis included: the probability of a neighborhood having at least one EV owner and land use codes that are suitable for the deployment of EV charging stations. In addition to factors positively associated with EV ownership, Zhang and Iman (2018) explain the importance of selecting areas with appropriate land use codes while Efthymiou et al. (2012) point out that areas with higher population density, greater commute requirements, and major attractions – such as workplaces and recreational locations – will have greater demand for EV charging stations. Previous studies that have explored optimal locations for EV charging stations have also highlighted factors like proximity to road junctions and proximity to available EV charging stations as some key criteria to consider while planning for EV charging station deployment (Erbaş et al., 2018). Figure 5 presents a schematic diagram using Modelbuilder in ArcMap 10.7.1 that describes the site suitability framework this thesis employed to incorporate such factors and identify potential locations for EV charging station deployment.

As shown in Figure 5, the polygon feature class with the data for the probability of a neighborhood having at least one EV owner was converted to a raster layer using the feature to raster tool. This raster layer was then converted to a 1-10 scale by the reclassify tool with higher EV ownership probabilities receiving higher scores on the scale. Similarly, the polygon feature class with data for land use codes was converted to a raster dataset by the feature to raster tool and this raster shapefile was reclassified into values of 0 and 1 depending on whether a land use code is appropriate for the deployment of EV charging stations; land use codes such as multi-family residential, recreational, commercial, industrial, transitional, and urban/public institutional were assigned a score of 1 while all other land use codes were given a score of 0.

This binary land use raster was then used to select suitable neighborhoods that have appropriate land use codes for EV charging station deployment from the EV ownership probability raster. From this raster layer, the raster layer with reclassified values of the variable Charging_Stations was subtracted using the raster calculator to incorporate current availability of EV charging stations in the site suitability analysis.

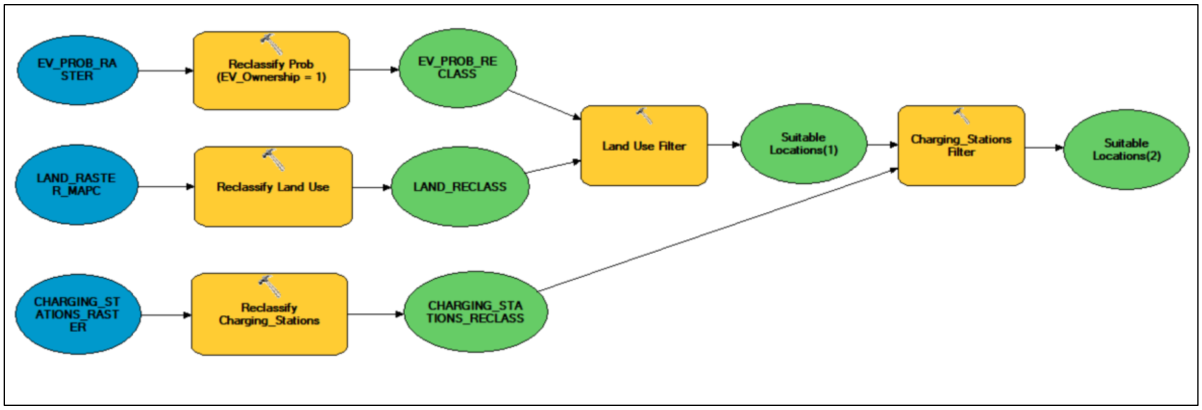


Figure 5: Site suitability analysis framework.

Tables showing reclassified values of all input layers used in the charging station site suitability analysis are presented in Appendix ii and Appendix iii. The process shown in Figure 5 produced a map that shows neighborhoods where there is limited availability of EV charging stations within areas with higher EV ownership probabilities and appropriate land use codes for EV charging station deployment. The results obtained from the MCE suitability analysis were used to assess the location and socioeconomic characteristics of neighborhoods that are suitable for installing EV charging stations. Additionally, I describe the type of EV charging stations that can be deployed in such areas and discuss key factors local policy and planning officials should consider for installing EV charging stations in the future.

Chapter 4: Results

In this chapter all the results from the statistical and spatial analysis are described. I describe the areas in Massachusetts where EV owners are present and explain the socioeconomic and demographic predictors of EV ownership in the state. Additionally, I also assess suitable neighborhoods for deploying more EV charging stations and recommend strategies for increasing the availability of EV charging infrastructure.

4.1 Where are EV owners in Massachusetts?

Figure 5 shows how the 657 neighborhoods with at least one EV owner are spatially distributed across Massachusetts. These neighborhoods are clustered around cities such as Boston, Cambridge, Framingham, and Franklin in the eastern part of the state. Likewise, neighborhoods around Amherst, Chicopee, Holyoke, Northampton, Pittsfield, and Springfield in the western part of MA also show some level of EV ownership.

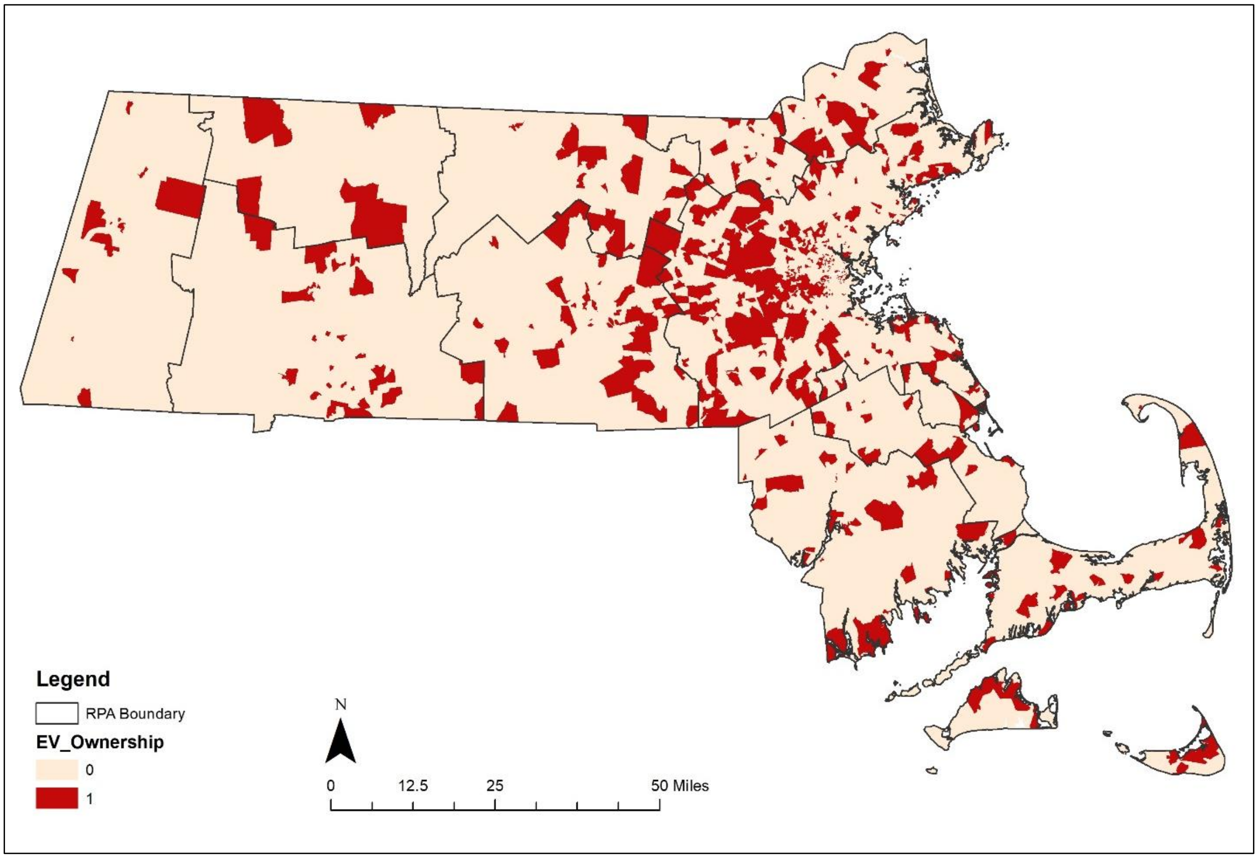


Figure 5: Neighborhoods with EV owners in MA between 2009 and 2014.

Table 7 and Figure 6 show the distribution of the 657 neighborhoods with at least one EV owner across Massachusetts' different RPAs. Column 4 shows the percentage of neighborhoods with EV owners across the different RPAs while the prevalence of MA EV neighborhoods in each RPA is reported in Column 5.

Table 7: Neighborhoods with EV owners across different RPAs

RPA	Number of neighborhoods (1)	Average Population Density (2)	Number of neighborhoods with EV Owners (3)	Percentage of neighborhoods with EV Owners (4)	Prevalence of MA EV neighborhoods (5)
BRPC	151	1,822.58	14	9.27	2.23
CCC	199	988.49	23	11.56	3.67
CMRPC	439	4,155.10	63	14.35	10.05
FRCOG	73	1,050.69	8	10.96	1.28
MAPC	2,463	12,286.33	410	16.65	65.39
MAPCand OCPC	45	2,031.20	4	8.89	0.64
MRPC	143	2,557.49	12	8.39	1.91
MVC	20	611.73	7	35.00	1.12
MVPC	226	6,941.04	26	11.50	4.15
NMCOG	163	7,098.82	14	8.59	2.23
NPEDC	11	927.70	5	45.45	0.80
OCPC	203	3,814.97	13	6.40	2.07
PVPC	422	4,604.51	32	7.58	5.10
SRPEDD	421	5,733.38	26	6.18	4.15

These two measures of EV ownership are mapped in Figure 6 (a) and (b). Out of the 657 neighborhoods with at least one EV owner, 410 – about 65.4% – are located within the MAPC boundary. In total, 414 of the 657 neighborhoods with some level of EV ownership in Massachusetts are in neighborhoods within MAPC's boundary.

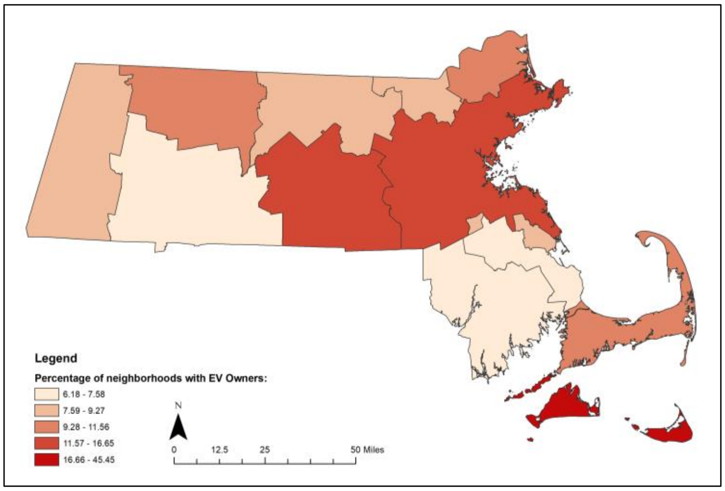


Figure 6 (a): EV owners across different RPAs (Percentage of neighborhoods with EV owners).

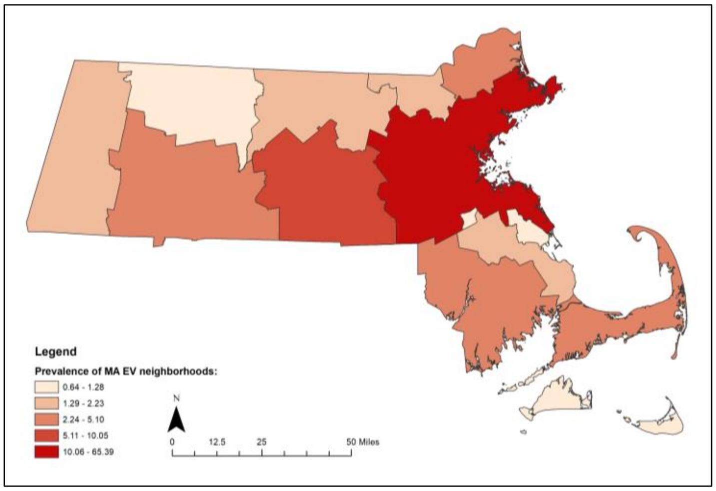


Figure 6 (b): EV owners across different RPAs (Prevalence of EV neighborhoods).

4.2 Typical characteristics of neighborhoods with EV owners

Average differences in the demographic and socioeconomic characteristics between neighborhoods with and without EV owners in the state and the statistical significance of these differences are reported in Table 8. For variables capturing wealth, both income and rent are higher in neighborhoods with EV owners compared to neighborhoods without any – although the difference in rent between the two groups of neighborhoods is not statistically significant. Similarly, neighborhoods with EV owners also seem to have higher levels of education with the percentage of adults with a Bachelor's and Master's degree being significantly higher in such neighborhoods compared to neighborhoods without any EV owners.

In contrast, factors such as unemployment and population density are greater in neighborhoods without any EV owners and these differences are statistically significant. While average MPD and the percentage of the labor force who drive to work daily is higher in neighborhoods with EV owners, these differences are not statistically significant. Likewise, the average of the variables capturing EV charging station availability in neighborhoods – Charger and Charging_Stations – are higher in areas with EV owners but this difference is not statistically significant.

Table 8: Results for difference in means
[mean(EV_Ownership = 0) – mean(EV_Ownership = 1)]

Variable	Difference in means
Pop_Density	$2,825.87^{***}$
	(6.05)
Rural	-0.17^{***}
	(-8.05)
Household	-0.04
	(-1.82)
Income	-35.73^{***}
	(-18.42)
Rent	-52.36
	(-1.82)
Age	-2.56^{***}
	(-7.36)

Bachelor	-6.59^{***}
	(-15.15)
Master	-7.90^{***}
	(-19.29)
White	-7.35^{***}
	(-11.15)
Unemployment	2.62^{***}
	(11.69)
Private	2.83^{***}
	(6.08)
Public	0.63^{*}
	(2.28)
MPD	-0.03
	(-0.15)
Drive	-1.08
	(-1.36)
Charger	-0.01
	(-1.02)
Charging_Stations	-0.00
	(-0.12)

t statistics in parentheses
$^{*} p < 0.05$, $^{**} p < 0.01$, $^{***} p < 0.001$

Logistic regression results of Model A and Model B are reported in Table 9. After accounting for missing observations, 4,961 neighborhoods were used in the regression analysis.

Variables capturing wealth-related factors such as income and rent are positively associated with the log odds of a neighborhood having an EV owner at the 99% significance level. Holding other factors constant, an increase of $1,000 in median income is associated with a 1.50% increase in the odds of a neighborhood having an EV owner while a one dollar increase in monthly gross rent is associated with a smaller increase in the odds of an EV owner being present in a neighborhood (by 0.03%). In terms of education, holding other factors fixed, a one percent increase in the percentage of adults with a Master's degree in a neighborhood is associated with a 3.81% increase in the odds of an EV owner being present in a neighborhood at the 99% significance level. The percentage of adults with a Bachelor's degree is positively associated with the odds of a neighborhood having an EV owner but this result is not statistically significant. Additionally, EV owners seem to be present in relatively older neighborhoods as a year's increase in the median age is linked with a 2.29% increase in the odds of a neighborhood having an EV owner (99% significance).

In contrast, results from Model A indicate that the percentage of labor force employed in the private and public sector are negatively associated with the odds of EV ownership in a neighborhood and these outcomes are statistically significant at the 99% significance level. Similarly, the availability of EV charging stations in a neighborhood is negatively correlated with the odds of a neighborhood having an EV owner. Likewise, average household size, unemployment rate, average miles travelled per day, and the percentage of labor force driving to work are negatively associated with the odds of a neighborhood having an EV owner, but all these results are not statistically significant. Population density of neighborhoods also seems to have a significantly negative impact on EV ownership.

Results from Model B also reveal that wealth-related variables such as Income and Rent are positively associated with the log odds of a neighborhood having an EV owner at the 99% significance level. In addition to factors such as the percentage of adults with a Master's degree, median age, the rural dummy is also positively associated with the odds of a neighborhood having an EV owner. Holding other variables constant, the odds of an EV owner being present in a rural neighborhood is higher by a factor of 1.59 compared to neighborhoods in urban areas (99% significance level). The estimated coefficient for Charging_Stations also suggest that the presence of charging stations in a neighborhood is not positively associated with EV ownership.

Table 9: Regression Results for EV_Ownership in Massachusetts

	Model A		Model B	
	log odds	odds ratio	log odds	odds ratio
Pop_Density	-0.0000 (2.44)*	1.0000 (2.44)*		
Rural			0.4666	1.5946

			(3.63)**	(3.63)**
Household	-0.0173	0.9829	0.0091	1.0091
	(0.12)	(0.12)	(0.07)	(0.07)
Income	0.0148	1.0150	0.0150	1.0151
	(8.50)**	(8.50)**	(8.71)**	(8.71)**
Rent	0.0003	1.0003	0.0003	1.0003
	(3.79)**	(3.79)**	(3.91)**	(3.91)**
Age	0.0226	1.0229	0.0214	1.0217
	(2.96)**	(2.96)**	(2.84)**	(2.84)**
Bachelor	0.0087	1.0087	0.0072	1.0073
	(1.65)	(1.65)	(1.38)	(1.38)
Master	0.0374	1.0381	0.0369	1.0376
	(6.33)**	(6.33)**	(6.24)**	(6.24)**
White	0.0039	1.0039	0.0028	1.0028
	(1.16)	(1.16)	(0.82)	(0.82)
Unemployment	-0.0093	0.9907	-0.0068	0.9933
	(1.05)	(1.05)	(0.76)	(0.76)
Private	-0.0127	0.9874	-0.0140	0.9861
	(2.58)**	(2.58)**	(2.84)**	(2.84)**
Public	-0.0259	0.9744	-0.0250	0.9753
	(3.16)**	(3.16)**	(3.01)**	(3.01)**
MPD	0.0083	1.0083	-0.0080	0.9921
	(0.56)	(0.56)	(0.50)	(0.50)
Drive	-0.0071	0.9929	-0.0032	0.9968
	(1.73)	(1.73)	(0.84)	(0.84)
Charger	-0.0945	0.9098		
	(0.60)	(0.60)		
Charging_Stations			-0.0432	0.9577
			(0.35)	(0.35)
_cons	-3.9292		-3.9606	
	(5.02)**		(5.25)**	
Pseudo R2	0.15	0.15	0.16	0.16
N	4,961		4,961	

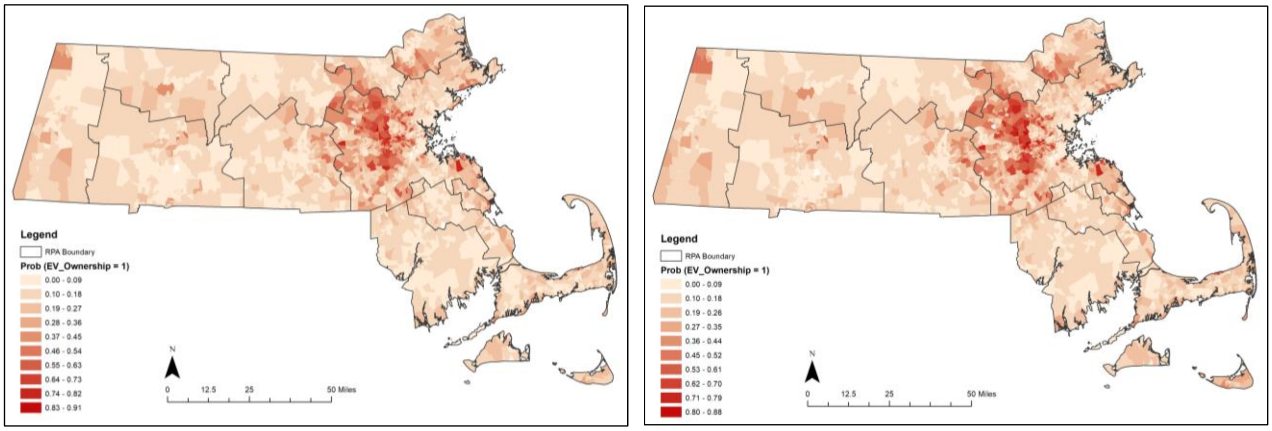
* p<0.05; ** p<0.01
Robust standard errors in parenthesis

Table 10 presents the summary statistics of the probability of EV owners being present in a neighborhood and how it varies for the different RPAs according to results from Model A and Model B. On average, both models show that neighborhoods in the NPEDC have the highest probability of having an EV owner; however, this result is based on just 11 neighborhoods falling within this RPA. After the NPEDC, neighborhoods falling within the boundary of the MAPC show higher probabilities of having an EV owner compared to neighborhoods in other RPAs.

Table 10: Probability of EV ownership in neighborhoods across different RPAs

		Model A		Model B	
RPA	count	Mean	Median	Mean	Median
BRPC	151	0.10	0.07	0.10	0.09
CCC	199	0.14	0.13	0.15	0.14
CMRPC	439	0.10	0.08	0.11	0.09
FRCOG	73	0.11	0.10	0.11	0.10
MAPC	2,450	0.17	0.12	0.17	0.12
MAPCandOCPC	45	0.15	0.13	0.16	0.15
MRPC	143	0.09	0.06	0.09	0.06
MVC	20	0.12	0.11	0.14	0.13
MVPC	226	0.12	0.10	0.12	0.08
NMCOG	162	0.09	0.06	0.09	0.06
NPEDC	11	0.19	0.18	0.24	0.24
OCPC	202	0.08	0.07	0.08	0.06
PVPC	420	0.07	0.05	0.07	0.05
SRPEDD	420	0.07	0.06	0.07	0.06
Total	4,961	0.13	0.09	0.13	0.09

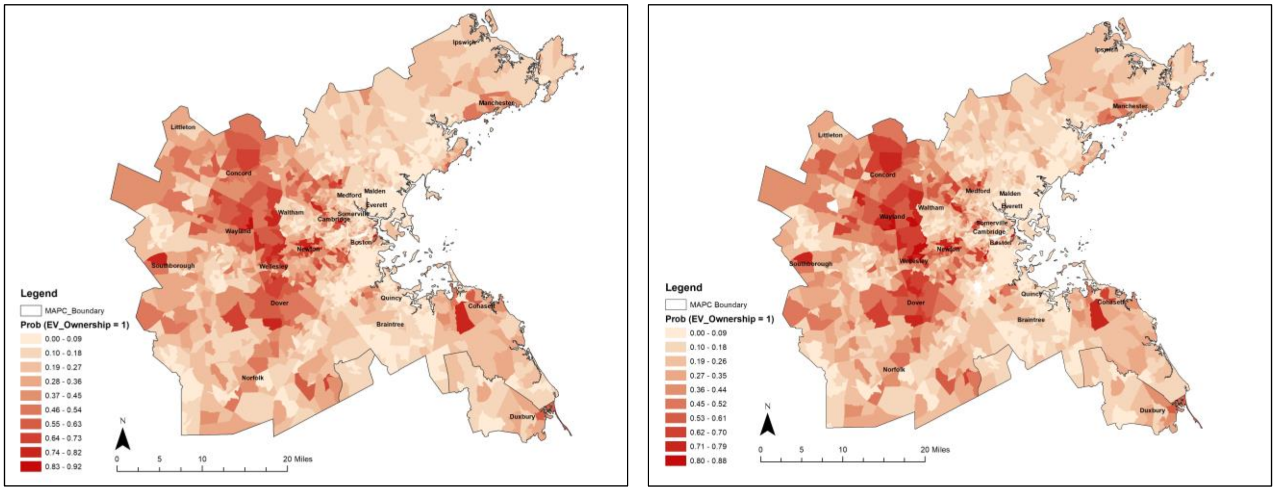
Such trends are corroborated in Figure 7 – which shows how the probability of EV ownership in a neighborhood varies across the state. Relatively high probabilities ranging from (0.46 to 0.91) of EV owners are predicted to be present in a neighborhood within the MAPC region. In contrast, neighborhoods in the western and southern parts of Massachusetts show relatively lower probabilities of EV ownership.


Model A

Model B

Figure 7: Probability of EV ownership in MA neighborhoods.

Figure 8 presents a closer view of how the probability of EV ownership in a neighborhood is distributed across the MAPC region. Probabilities of EV ownership ranging from 0.50 to 0.91 are seen in some neighborhoods around Boston, Cambridge, and Sommerville and such neighborhoods are also prevalent towards the western part of such cities – in areas around Concord, Dover, Newton, Norfolk, Wayland, and Wellesley. Some neighborhoods in the northern and western areas of Medford also share similar ranges of EV ownership probabilities. In contrast, the probability of an EV owner being present is low in neighborhoods towards the south of Boston and in the northwest of the city.



Model A

Model B

Figure 8: Probability of EV ownership in MAPC neighborhoods.

These results support the associations revealed by some previous studies that have investigated the socioeconomic characteristics of EV owners. Vergis and Chen (2015) note that early EV adopters tend to be individuals with higher levels of education and studies that have surveyed the characteristics of EV owners (Hidrue et al., 2011; Plötz et al., 2014) suggest that EV owners are wealthier and have at least a Bachelor's degree. Coefficients presented in Table 9 reveal that neighborhoods in Massachusetts where EV owners are present are wealthier and more educated compared to neighborhoods without any level of

EV ownership. Figure 7 and Figure 8 also suggest that neighborhoods with EV owners in the state are in wealthier suburban areas.

In contrast, the coefficients for variables like Charger and Charging_Stations differ from the results shown in previous studies. Multivariate regression results presented in Sierzchula et al. (2014) and Vergis and Chen (2015) indicate that the availability of EV charging stations is associated with higher EV adoption rates. Likewise, Slowik and Lutsey (2019) also highlight that EV use is higher in American cities with greater availability of charging stations. However, the fact that results from Model A and Model B do not rule out β_{12} being zero suggests that EV owners in Massachusetts may have access to some form of private charging stations in their residences or charging facilities at work or other nearby neighborhoods.

Additionally, a dummy variable or the number of charging stations available in a neighborhood may not fully capture the availability of charging stations to residents of a neighborhood. For example, even if a charging station is not available in a particular neighborhood, residents may have access to charging stations in nearby areas or areas where they commute to on a daily basis. Along with such factors, other limitations of Model A and Model B are further explained in Chapter 5.

4.3 Input factors for site suitability analysis

Regression results from Model A and Model B reveal that EV owners in Massachusetts tend to be in neighborhoods with higher median incomes and higher monthly gross rents. Likewise, factors such as the median age of a neighborhood's population and the percentage of adults with a Master's degree in a neighborhood are also positively associated with the presence of EV owners in a neighborhood in the state. In addition to such socioeconomic differences, results from section 4.1 and 4.2 also reveal that areas with

EV owners in Massachusetts are spatially clustered in some towns and cities across the MAPC region. In addition to the probability of a neighborhood having at least one EV owner, land use codes, and the presence of already available charging stations were used to identify suitable locations for deploying EV charging stations in the MAPC region.

The probability of a neighborhood having at least one EV owner was reclassified into a 1-10 scale with higher probability values receiving higher scores on the scale. The reclassified EV ownership probabilities are shown in Figure 9 (a).

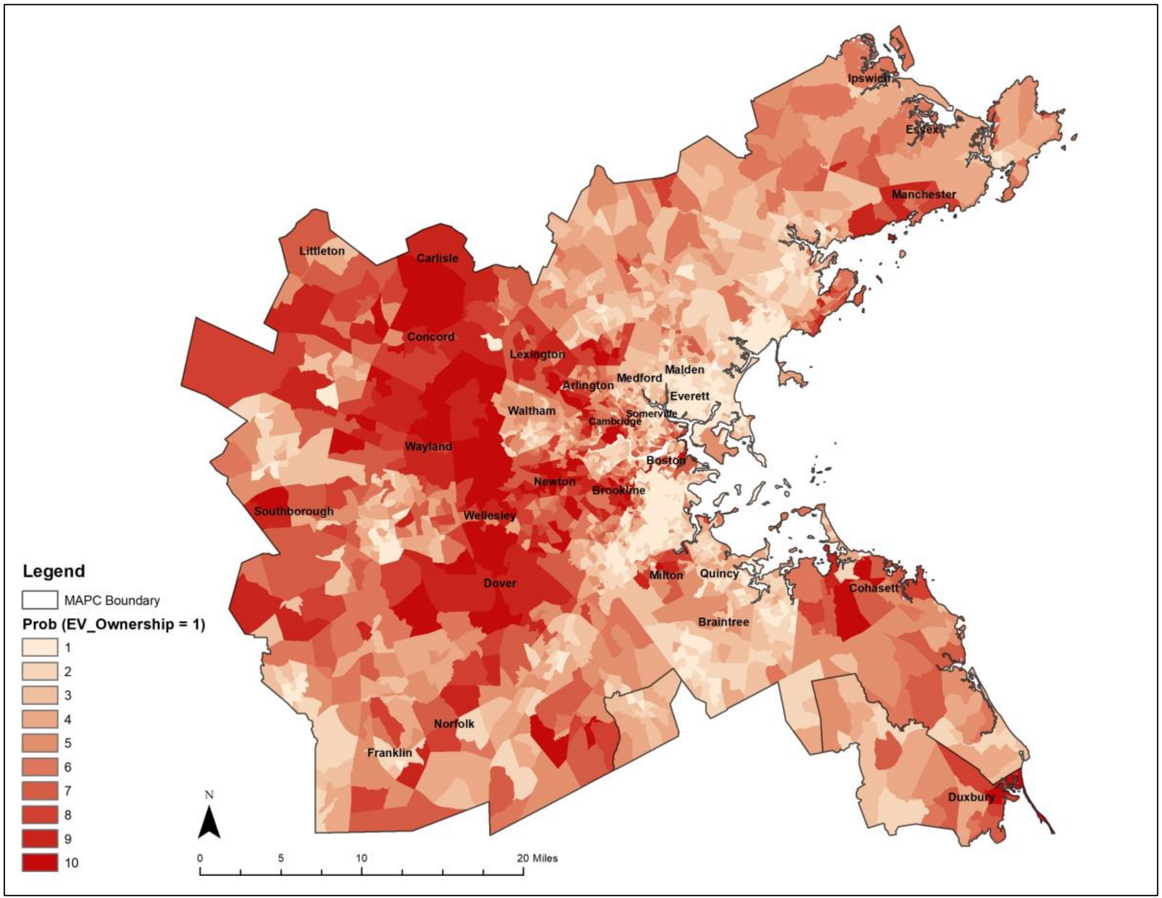


Figure 9 (a): Reclassified Prob (EV_Ownership = 1).

As indicated by regression results, higher probabilities of EV ownership exist in areas around cities such as Boston, Cambridge, and Somerville and a similar trend is apparent in suburban cities and towns such as Newton, Dover, and Wellesley in central areas of the

MAPC region. Areas such as Concord, Wayland, and Southborough in western parts of Waltham also have higher reclassified values of EV ownership probabilities while towns such as Cohasett and Duxbury show higher EV ownership probabilities in the eastern parts of the MAPC region.

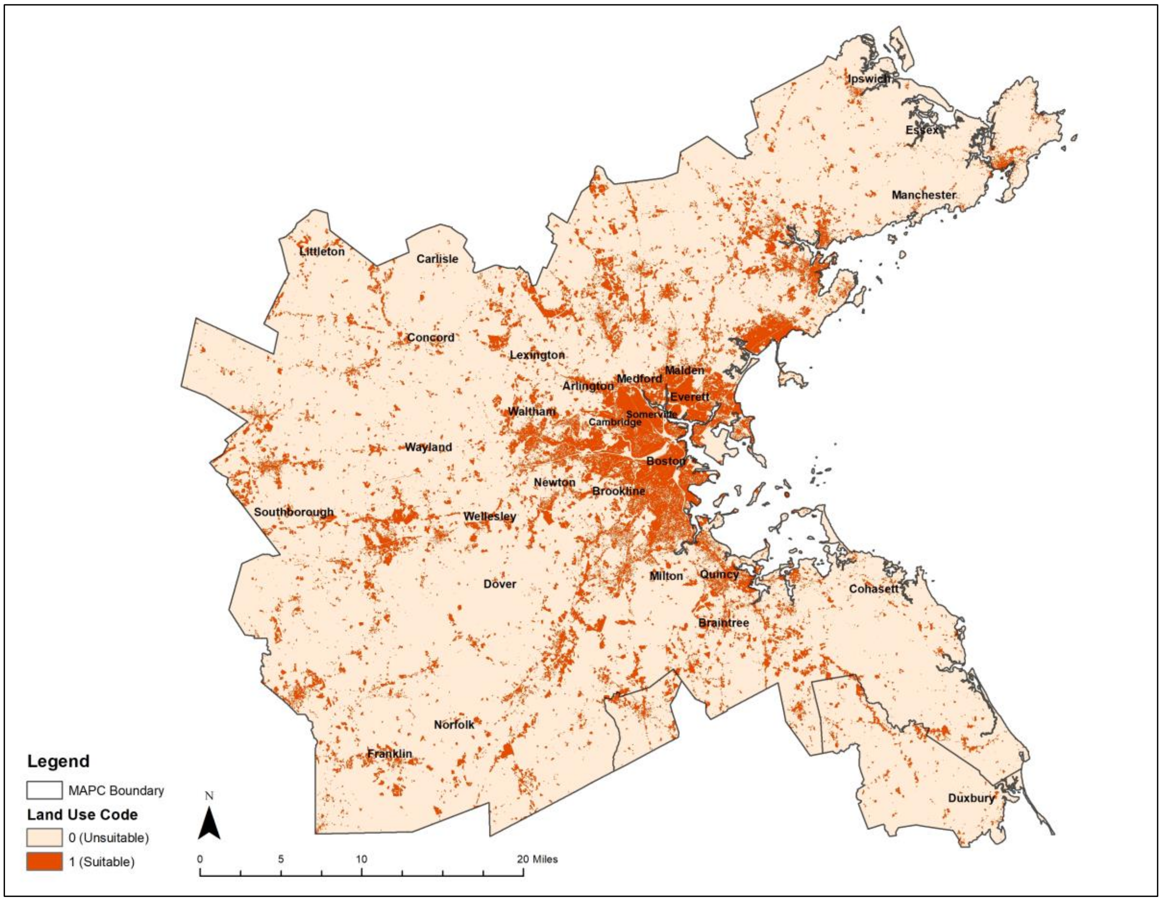


Figure 9 (b): Reclassified land use codes.

Figure 9 (b) shows how reclassified values for land use codes vary across the MAPC region. Areas with suitable land use codes for deploying EV charging stations are primarily prevalent in Boston and cities such as Cambridge, Everett, Malden, and Somerville. Suitable land use codes in Figure 9 (b) show areas that allow the development of multi-family residential properties as well as recreational, commercial, and industrial buildings. Additionally, areas with suitable land use codes also show land parcels comprising schools, churches, colleges, hospitals, museums, town halls or court houses, police and fire stations, dormitories, university housing, and parking lots associated with such urban public/institutional spaces.

The reclassified values of the variable Charging_Stations were used to select neighborhoods with limited availability of charging stations among areas that have higher likelihoods of EV ownership and suitable land use codes for installing EV charging stations. As shown by Figure 9 (c), the number of EV charging stations per 1,000 residents are higher in Boston and its surrounding cities compared to areas in the outskirts of the MAPC region. Beyond the inner core of the MAPC region, Waltham, Concord, Wellesley, and Norwood are some other neighborhoods with a relatively higher number of charging stations per 1,000 residents.

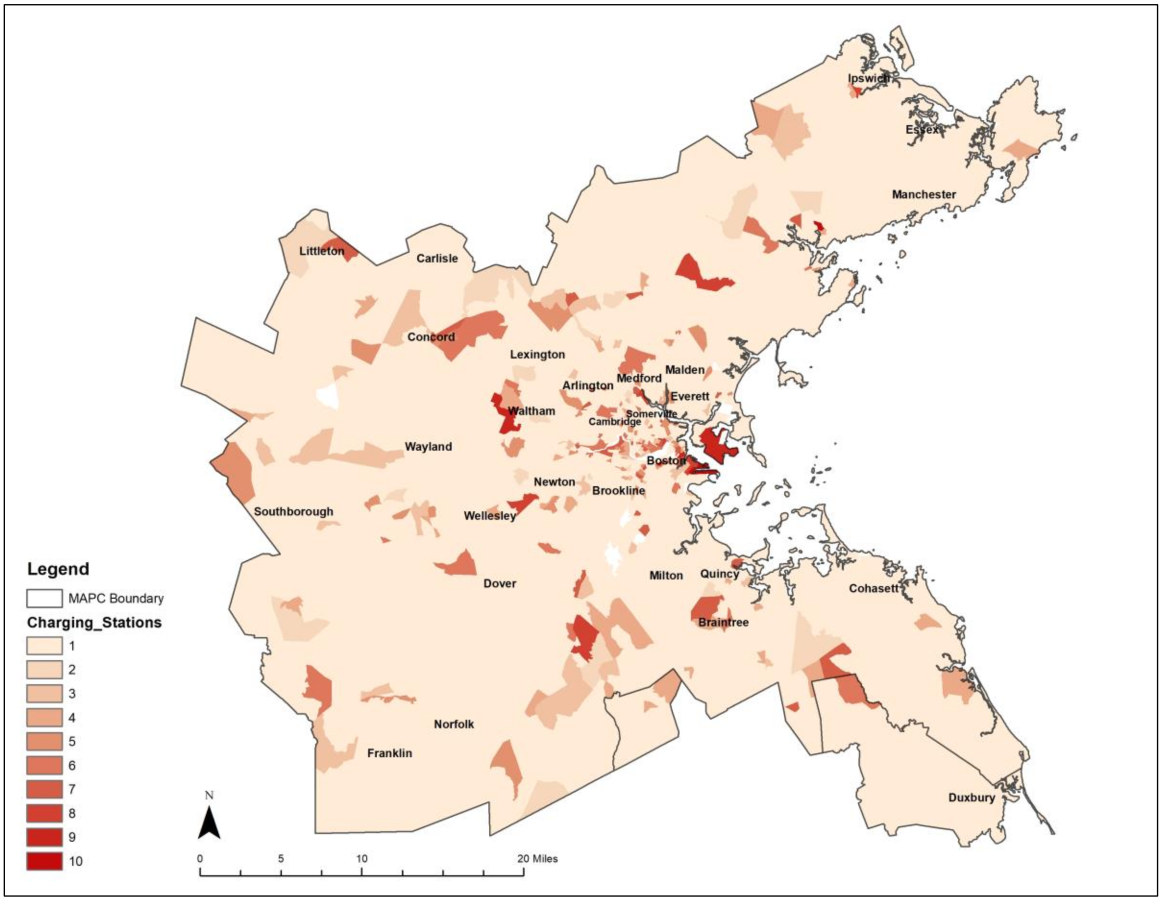


Figure 9 (c): Reclassified Charging_Stations.

4.4 Suitable locations for deploying EV charging stations

Figure 10 shows EV charging station site suitability scores according to the probability of a neighborhood having at least one EV owner, appropriate land use codes for EV charging station deployment, and the current availability of EV charging stations in the MAPC region.

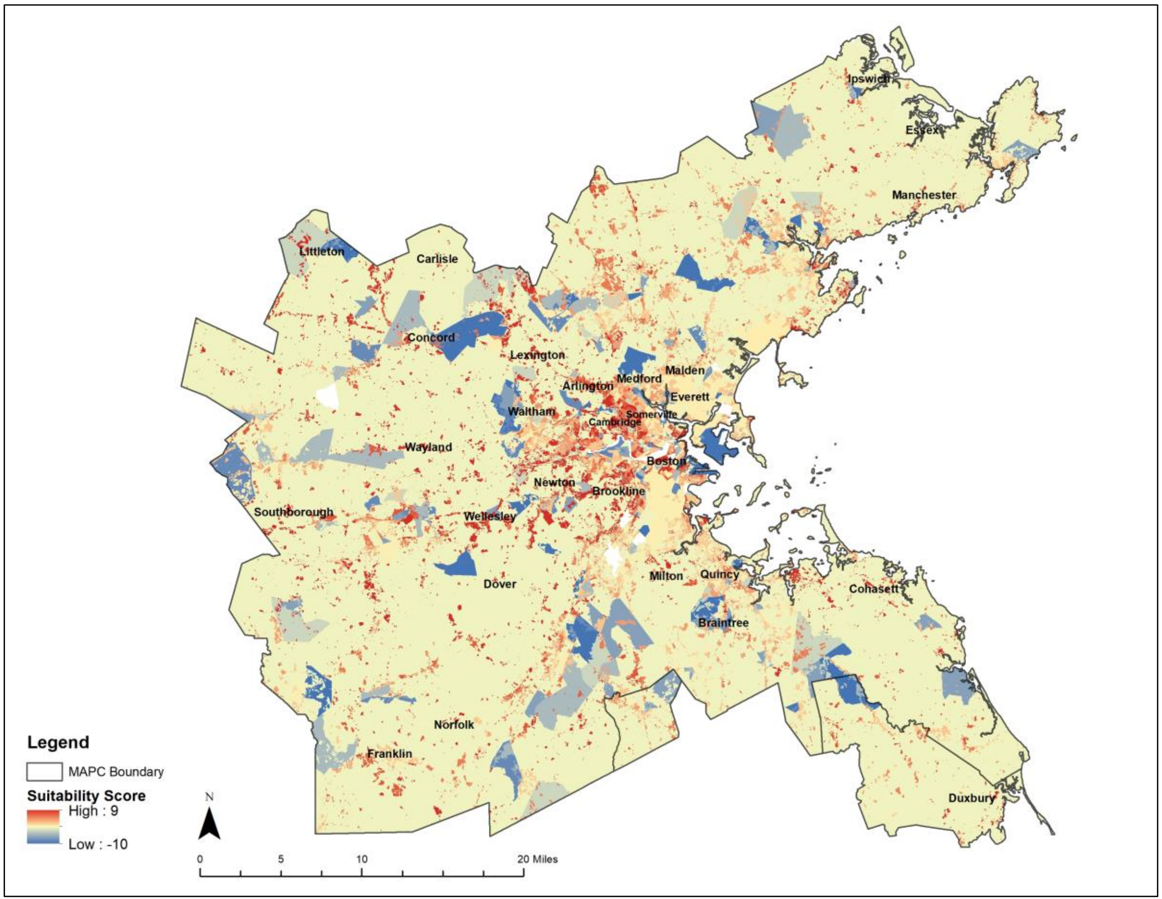


Figure 10: Suitability scores for EV charging station deployment.

Areas receiving with negative suitability scores show sections of the MAPC region that have relatively lower likelihoods of EV ownership and relatively higher number of already available charging stations per 1,000 residents. Such neighborhoods are located towards the eastern parts of cities like Everett, Malden, and Lynn and in coastal towns like Winthrop. Similarly, neighborhoods towards the south of Boston, Brookline, Braintree, and Quincy also show a similar pattern of low suitability scores. Low suitability scores also prevalent in areas north of Medford and in neighborhoods north of Southborough.

In contrast, areas receiving high suitability scores ranging from 5 to 9, show neighborhoods with higher probabilities of EV ownership, limited availability of charging stations, and appropriate land use codes for EV charging station deployment. Within the inner core of the MAPC region, these neighborhoods are concentrated in Arlington, Boston, Brookline, Cambridge, Newton, and Milton. Additionally, multiple neighborhoods around Concord, Wayland, Wellesley, Dover, and Norfolk – towards the west of Interstate 95 (I-95) – show suitability scores greater than 5. Likewise, towns like Cohasett, Duxbury, and Manchester also show scores of 5 or more in the east of the MAPC region.

DC fast chargers are more suitable for long distance interregional or intraregional travel and drivers who require quick charging times (Jin, 2016). Hence, from the suitable areas shown in Figure 10, areas falling within a half mile buffer of interstate highways are selected as potential locations for the deployment of more DC chargers in the MAPC region.

As shown in Figure 11, multiple locations favoring DC charger deployment are available along I-495 – the region's outer circumferential highway. Similarly, such suitable sites are also located along portions of I-95 passing through areas like Burlington, Waltham, Wellesley, and Westwood – and in urban areas within MAPC's inner core, along I-90 and I-93. The availability of such locations presents a promising setting for establishing an extensive charging station network and alleviating range anxiety concerns associated with interregional or intercity travel.

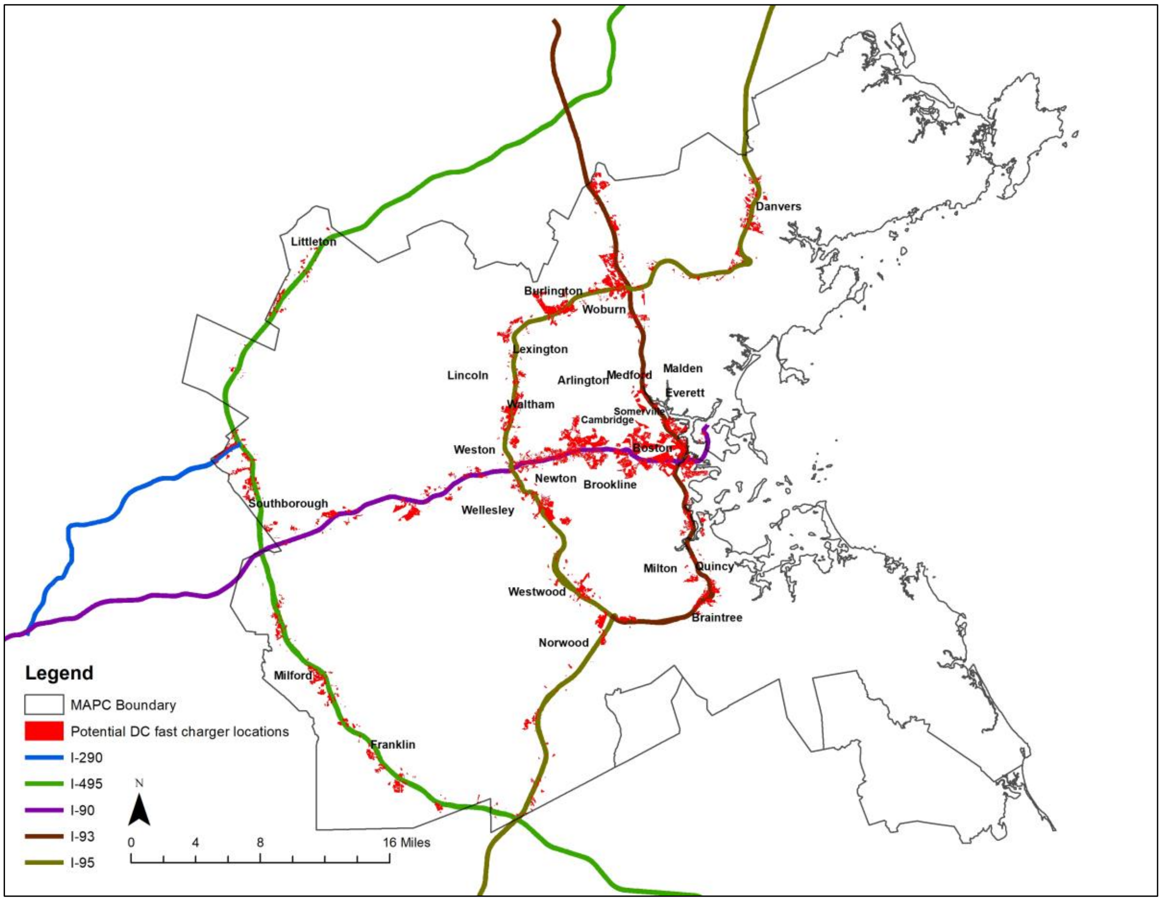


Figure 11: Potential DC fast charger locations along interstate highways in the MAPC region.

In addition to potential DC fast charger sites shown in Figure 11, suitability analysis results also identify suitable areas for the deployment of more Level 2 charging stations. Areas favoring Level 2 charging station development in the MAPC region are shown in Figure 12. These areas have suitability scores of 5 or more, have appropriate land use codes, and lie outside a half mile radius of interstate highways.

In and around the Metro Boston region, suitable areas for Level 2 chargers are seen around Boston Common, Charlestown, Faneuil Hall Marketplace, Dorchester Center, and Jamaica Plain. Likewise, areas around Daheny Park, Fresh Pond, Harvard University, and Massachusetts Institute of Technology are some other locations that can enable the installation of more Level 2 chargers. Neighborhoods around Lincoln Park, Nathan Tufts Park, Davis Square, and Porter Square in Somerville also present suitable locations for

Level 2 charging stations within the inner core of the MAPC region. Considering EV charging preferences expressed by prospective car buyers (UCS, 2019) and the recommendations highlighted by previous charging station site suitability studies (Jin, 2016; Zhang and Iman, 2018), the presence of various local retailers, office buildings, parks, recreational locations, and shopping centers in such urban areas presents a promising setting for increasing the number of Level 2 charging stations within the Greater Boston region. Installing more Level 2 chargers in available parking areas close to these locations can enable drivers to charge their EVs while they are working, shopping, or engaging in other socioeconomic activities that may require them to park their vehicles for a long duration.

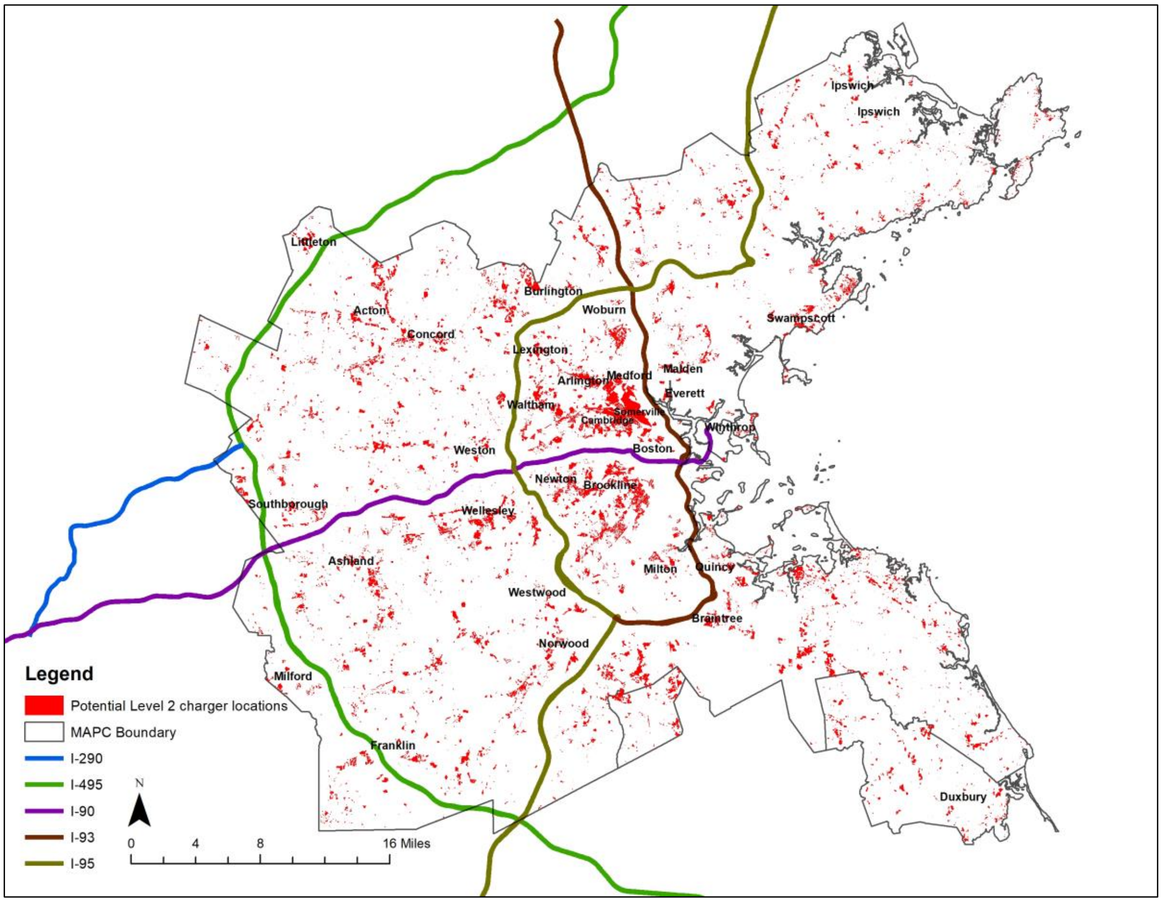


Figure 12: Potential Level 2 charger locations along interstate highways in the MAPC region.

Beyond the urban areas within Greater Boston, Level 2 chargers can also be installed in multiple locations in towns and cities like Acton, Concord, Newton, Wellesley, and Southborough in the western parts of the MAPC region. Likewise, suitable locations shown by weighted overlay results around seaside towns like Duxbury, Winthrop, and Swampscott are also favorable for more Level 2 chargers since drivers travel to such locations for sight-seeing or visiting beaches.

Chapter 5: Discussion

Results reveal that EV ownership in Massachusetts is confined to wealthier suburban areas within the MAPC region. In addition to wealth-related factors such as median income and monthly gross rent, regression results reveal that the presence of residents with a Master's degree is another factor significantly associated with the likelihood of a neighborhood in Massachusetts having an EV owner. In contrast, the availability of public EV charging stations is a neighborhood is not positively associated with EV ownership – which suggests that present EV owners in the state either have access to private charging facilities in their parking lots or garages or charging stations available at workplaces or other public spaces.

Although regression results indicate that wealthier suburban areas like Brookline, Concord, and Newton have higher likelihoods of EV ownership, other factors can potentially increase the number of EV owners in other areas of the MAPC region in the future. According to the Boston Region Metropolitan Planning Organization (MPO), median income in towns like Lynnfield, Weston, North Reading, Norfolk, and Middleton increased by 24% to 35% between 2010 and 2015 (MPO, 2017). Transit development projects such as the Green Line Extension (GLX) are also projected to increase median incomes, property values, and rents in areas along the GLX corridor in cities like Medford and Somerville. Previously in the area, the opening of the T station at Davis Square ended up increasing median income in the neighborhood by 60% between 1990 and 2000 (MAPC, 2014). Such trends and expected changes in median income within the MAPC region are likely to impact where consumers who can afford currently available EVs will be prevalent in the future.

Furthermore, the decreasing up-front cost of EVs and the availability of more EV models is also likely to make EVs attractive and affordable to a broader range of consumers in the coming years (Engle et al., 2018). The Electrification Coalition (EC) notes that Massachusetts lacks widely deployed public EV charging infrastructure compared to other regions in the U.S. (EC, 2018). Multi-unit Dwellings (MuDs) make up about 33% of urban residential markets in the Northeast – which leaves a lot of existing and potential EV drivers without access to EV charging stations where they live (Plug In America, 2016). Hence, developing EV charging infrastructure in the suitable areas identified in this thesis, can play an important role in promoting and supporting EV ownership. Possible ways to utilize these suitable areas are discussed below.

5.1 Recommendations for deploying EV charging stations

For DC charging stations, following the model of the West Coast Electric highway is one possible way to utilize the suitable DC charger locations shown in this thesis. As shown in Figure 13, DC fast chargers are located every 25 to 50 miles along I-5, US-101, and US-99 (Washington State Department of Transportation (WSDOT), 2014), to provide drivers on major roadways in British Columbia, Washington, Oregon, and California convenient charging options. DC fast chargers are available at shopping centers, fueling stations, and restaurants within a half mile of such highways and highway interchanges. WSDOT underscores that the availability of charging stations at different locations along such highway corridors gives EV drivers assurances when they travel between cities, make long-distance road trips, and commute to work – and encourages other residents and businesses to consider driving EVs (WSDOT, 2020).

Figure 13: West Coast Electric Highway. Source: Washington State Department of Transportation

In Massachusetts, the availability of DC chargers on highways such as I-90 are limited to areas within the Greater Boston region. The Massachusetts Department of Transportation (MassDOT), announced plans to increase the number of DC chargers along I-90 in 2016 (PlugInSites, 2016). The suitable areas along I-90 and north-south interstates like I-93, I-95, and I-495 identified in this thesis present different possible locations at retail outlets, fueling stations, and plazas that future EV charging infrastructure plans can consider.

Gurcan (2018) notes that in cities like Boston, the availability of EV charging stations is restricted to hotel garages or malls. Multiple locations in urban areas around cities like Boston, Cambridge, and Somerville shown in Figure 12, offer the possibility of installing Level 2 chargers within clusters of workplaces, retailers, and shopping areas – and making EV charging facilities more accessible to broader sections of local communities.

In regions like Northern Colorado, local businesses and local technology firms have heavily engaged in programs such as the Workplace Charging Challenge (WCC) – by signing commitments to make workplace charging stations available to employees and incorporate EVs into their environmental or sustainability goals (EC, 2018). Boston was the second largest startup funding hub in America in 2018 (Glasner, 2018). The presence of a growing tech-based startup environment presents an opportunity for Boston and its surrounding cities to encourage technology businesses and startups in the region to utilize state funding resources such as the MassEVIP and make more Level 2 chargers available to the region's workforce.

As more workplaces start installing EV charging stations, this will allow employers to offer EV charging spaces as an additional benefit to employees and create a platform for employees and staff to learn more about EVs. Furthermore, making EV charging stations and EVs more visible at local businesses and workplaces can also play an important role in making local residents more aware about EVs.

5.2 Limitations of regression and suitability analysis results

While the analysis presented in this thesis offers some insights into existing EV ownership patterns in Massachusetts and potential locations for the deployment of EV charging stations in the MAPC region, there are multiple limitations that future studies can address in order to retrieve better insights about EV ownership patterns and EV charging infrastructure planning.

Logistic regression models employed in this analysis leave out variables that are likely to impact if residents of an area decide to adopt an EV or not. For example, Diamond (2009) demonstrates that gasoline prices strongly dictate whether individuals purchase alternate fuel vehicles. Similarly, the purchase price of EVs and financial incentives offered for consumers to purchase an EV are key factors that determine the sales of EVs (Slowik & Lutsey, 2019). Environmental awareness and regional climate change or clean energy policies also affect the availability of incentives that promote cleaner fuel vehicles and whether individuals or households decide to purchase cleaner vehicles such as EVs (Gallagher & Muehlegger, 2011). Important variables such as the price of EVs, availability and utilization of financial incentives for EVs, gasoline prices, the level of environmental awareness in a neighborhood, and whether other clean energy policies are implemented in a neighborhood are some key factors that are omitted in this analysis due to data restrictions.

While regression results indicate that the likelihood of EV ownership in a neighborhood is positively associated with factors such as median income, median age, and the percentage of adults with a Master's degree, the variables that are omitted in this analysis may bias the regression estimates presented in Table 9. The direction of bias for the estimated coefficients of variables such as income, age, and Master's is dependent on how these variables are correlated with omitted variables. For example, residents who have higher incomes and higher education levels, maybe better informed about the availability of EV purchase incentives. Hence, the estimated values of β_2 and β_6 might be greater than the true value of the impact of income or education on EV ownership.

Furthermore, endogeneity issues present in the cross-sectional dataset used for analysis also prevent the associations established by this thesis from being causal relationships. Panel or time-series datasets offer the use of frameworks like difference-in-differences. Such frameworks that can compare changes in EV ownership rates – before and after a particular time period – will be important in future studies that aim to investigate how the deployment of additional EV chargers impacts EV ownership.

The methods used in the site suitability analysis presented in thesis also have some additional restrictions. Critical factors like electricity prices, charging costs, and the impact of additional charging stations in the local electricity grid are omitted in this thesis. For example, He et al. (2011) use an equilibrium-modeling framework to assess interactions between the destination and route choices of EV drivers, public EV charging stations, and prices of electricity; this analysis highlights that charging load from EVs can significantly impact local power networks and electricity prices. Such factors need to be verified to further assess the appropriateness of potential EV charging station locations presented in Chapter 4.

Additionally, the dataset this thesis used to measure the current availability of charging stations in the state does not consider the type of EVs available stations support. For example, Tesla charging stations can only be used by Tesla owners and such stations do not serve the owners of other types of EVs. Hence, it will be important for future studies to account for such discrepancies in order to accurately measure the availability of charging facilities in and around different neighborhoods. Likewise, accounting for other important factors – like traffic volume on different routes and development costs – and comparing the results of different reclassifying and weighting schemes will also be important for future research in this field.

Chapter 6: Conclusions

Private vehicles continue to play important roles in various socioeconomic activities. However, the magnitude of GHG emissions private vehicles produce has made the transportation sector a priority in climate change mitigation and policy efforts. Despite the negative impacts of private vehicles on the environment and the role cars are playing in accelerating climate change, Sheller and Urry (2000) underscore that it will be difficult for people to completely abandon cars. EVs are expected to become cleaner, cheaper, and more convenient in the future – and different states including Massachusetts have started implementing various policies and programs to promote EV ownership. As EVs start becoming affordable to a broader range of consumers in the coming years, it will be important for Massachusetts to increase the availability of public EV charging stations in the state since not all EV riders can install charging stations in their garages or parking lots.

The main goals of this thesis were to assess existing EV ownership patterns in Massachusetts and identify suitable locations for public EV charging stations – considering where EV owners are located, the typical characteristics of neighborhoods with EV owners, and other important socioeconomic and spatial criteria.

The analysis presented here reveals that EV ownership in the state, is restricted to wealthier and more educated suburban areas of the MAPC region. EV registration data from 2009 to 2014 reveal that EV owners are present only in 13% of neighborhoods in the state. The likelihood of EV owners being present in a neighborhood is significantly associated with factors such as income and the percentage of adults with a Master's degree. Additionally, higher likelihoods of EV ownership are only seen in some suburban towns and cities in the MAPC region. Such results indicate that higher upfront cost of EVs and other factors such as range anxiety maybe discouraging a vast majority of drivers in the state from using EVs.

Massachusetts has outlined the goal of increasing the number of EV registrations in the state to at least 300,000 by 2025 (MassCEC, 2019). Since the availability of charging facilities has been highlighted as the next barrier for widescale EV adoption, this thesis also identifies different locations that can be considered for EV charging station deployment in the future.

Suitable EV charging station locations shown in Figure 12 and Figure 13 can be utilized to increase the availability of DC chargers and Level 2 chargers. Placing more charging facilities at such locations can not only support existing EV owners, but also make EVs in the MAPC region more visible to local residents and encourage them to consider buying EVs. Conducting further assessments of the locations identified here and choosing the locations that are ideal for EV charging stations will be important for addressing problems associated with range anxiety and limited availability of charging facilities.

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Appendix i: Regional Planning Agencies in Massachusetts

RPA Name	RPA Abbreviation
Berkshire Regional Planning Commission	BRPC
Cape Cod Commission	CCC
Central Massachusetts Regional Planning Commission	CMRPC
Franklin Regional Council of Governments	FRCOG
Metropolitan Area Planning Commission	MAPC
Montachusett Regional Planning Commission	MRPC
Martha's Vineyard Commission	MVC
Merrimack Valley Planning Commission	MVPC
Northern Middlesex Council of Governments	NMCOG
Nantucket Planning & Economic Development Commission	NPEDC
Old Colony Planning Council	OCPC
Pioneer Valley Planning Commission	PVPC
Southeast Regional Planning & Economic Development District	SRPEDD

Appendix ii: Reclassified values of factors used in site suitability analysis

Variable:	**Actual value:**	**Reclassified value:**
Prob (EV_Ownership = 1)	0.00 – 0.05	1
	0.05 – 0.09	2
	0.09 – 0.13	3
	0.13 – 0.17	4
	0.17 – 0.22	5
	0.22 – 0.27	6
	0.27 – 0.35	7
	0.35 – 0.45	8
	0.45 – 0.58	9
	0.58 – 0.91	10
Charging_Stations	0.00	1
	0.00 – 0. 45	2
	0.45 – 0.64	3
	0.64 – 0.86	4
	0.86 – 1.17	5
	1.17 – 1.78	6
	1.78 – 2.91	7
	2.91 – 3.98	8
	3.98 – 6.83	9
	6.83 – 55.55	10

Appendix iii: Reclassified Land use codes used in site suitability analysis

Variable:	**Actual value:**	**Reclassified value:**
Land use code	1 – Cropland	0
	2 – Pasture	0
	3 – Forest	0
	4 – Non-forested wetland	0
	5 – Mining	0
	6 – Open land	0
	7 – Participation recreation	1
	8 – Spectator recreation	1
	9 – Water-based recreation	1
	10 – Multi-family residential	1
	11 – High density residential	0
	12 – Medium density residential	0
	13 – Low density residential	0
	14 – Saltwater wetland	0
	15 – Commercial	1
	16 – Industrial	1
	17 – Transitional	1
	18 – Transportation	1
	19 – Waste disposal	0
	20 – Water	0
	23 – Cranberry log	0
	24 – Powerline/utility	0
	25 – Saltwater sandy beach	0
	26 – Golf course	0
	29 – Marina	0
	31 – Urban public/institutional	1
	34 – Cemetery	0
	35 – Orchard	0
	36 – Nursery	0
	37 – Forested wetland	0
	38 – Very low density residential	0
	39 – Junkyard	0
	40 – Brushland/successional	0