Challenges with fast-charging infrastructure expansion: A case study in Alaska

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Abstract

The transport sector has transitioned into the highest global emitter of greenhouse gases, surpassing the emissions of energy generation. Electrification of this sector is currently a priority with regards to meeting climate goals and improving air quality in cities. A heavily-cited method to promote transport electrification is through the expansion of fast-charging infrastructure, which allows charging periods for electric vehicles (EVs) to be similar in duration to fuelling times for traditional vehicles. However, there are numerous technical and economic barriers to its implementation, whose magnitude and influence depend heavily on the particular case study being considered. Although fast-charging is likely a global solution to improve the prospect of electric vehicles, a lack of diverse use cases of EVs and limited modelling of EV systems with consideration for local travel behaviour and preferences, especially for communities which are not highly-populated and urban, has produced inequalities within the transition to electrified transport.

As such, this study considers a systemic approach in the analysis of a unique EV system: the Municipality of Anchorage (MoA), Alaska. Stakeholder interviews (n=5) were conducted to acknowledge the barriers to EV adoption and expansion of fast-charging infrastructure from a multitude of perspectives. Moreover, a survey of drivers (n=215) was distributed to understand travel behaviour, consumer preferences for charging infrastructure, and motivations regarding electric mobility. Finally, this analysis is supported by an agent-based model of EV drivers within the community, which used insights from the survey and interviews, as well as real-world demographic and travel data, to examine the EV load on the grid system and utilisation of the public charging network. This was done for weekday and weekend schedules during the summer and winter, in an attempt to characterise the breadth of local travel behaviours and environmental conditions.

The results of the model indicate that weekday travel needs in the MoA are met primarily without the aid of public charging infrastructure , with 86% of charging occurring at home during the weekday in 2021. On the other hand, the existing public infrastructure is limited in its capacity to handle weekend recreational travel, with clear limitations on the charging options available to drivers. In the baseline scenarios, the limited infrastructure located south of the Anchorage bowl produced long queues for charging, which left some agents unable to make it home by the end of the simulation. Improvements in this area of the network were proposed through an additional fast-charging station and a supplementary charging port at the most congested station (Alyeska Resort), which significantly reduced queuing and improved the feasibility of recreational EV use within the boundaries of the MoA. These improvements even had success with higher penetration of EVs, seeing less queuing with the 2025 EV fleet than what was observed with the unimproved 2021 baseline infrastructure. The model also indicated that the addition of workplace charging infrastructure has the potential to reduce negative grid impacts of increased EV penetration in 2025, however its impacts are much reduced in the winter. With a 25% penetration, summertime peak demand and peak energy consumption were reduced by 35% and 29% compared to the baseline, respectively. On the other hand, increasing workplace charging past 5% did not produce consistent improvements in the winter, with reductions to peak demand and total peak energy consumption stagnating at approximately 12% and 16% from the baseline, respectively.

The methodology proposed in this study can be applied broadly to case studies concerning EV impacts and utilisation of public charging infrastructure. Through the three-phase approach, the analysis produced can serve as a baseline to make specific, impactful policy and regulatory change through an understanding of local stakeholder needs and a foundation of end user requirements and preferences.

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List of Abbreviations

ABM	Agent-Based Model
AEA	Alaska Energy Authority
ANWR	Arctic National Wildlife Refuge
BTMS	Battery thermal management system
CAFE	Corporate Average Fuel Economy
DCFC	Direct current fast charging
DMV	Department of Motor Vehicles
DNO	Distribution Network Operator
EMSP	Electro-mobility service provider
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EV	Electric vehicle
EVSE	Electric vehicle service equipment
FCLM	Flow-Capturing Location Model
FERC	Federal Energy Regulatory Commission
FRLM	Flow-Refueling Location Model
GWP	Global Warming Potential
HOV	High-occupancy vehicle
ICE	Internal combustion engine
LCGHG	Life-cycle greenhouse gas
LCOC	Levelised cost of charging
MCLM	Maximum Covering Location Model
MoA	Municipality of Anchorage
NOx	Nitrogen oxides
PM	Particulate matter
PV	Photovoltaic
RCA	Regulatory Commission of Alaska
RCN	Rapid Charge Network
RMI	Rocky Mountain Institute
SCLM	Set Covering Location Model

SOx	Sulfur oxide
TOU	Time-of-use
V2G	Vehicle-to-grid
VAT	Value-added tax
ZEV	Zero emissions vehicle

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1 Introduction

1.1 Context

With the push to decarbonise energy generation, transport has become the highest-emitting sector globally, now accounting for almost a quarter of carbon dioxide emissions and contributing significantly to air pollution [1]. As a result, more focus is now being placed on the decarbonisation of the transport sector, and as a result the electric vehicle (EV) market has grown substantially in the last decade [2]. Electric vehicles eliminate tailpipe emissions and have a positive impact on air quality and provide health benefits [3]. However, there are still many barriers to widespread electric vehicle adoption, of which range anxiety and a lack of public charging infrastructure play significant roles [4]. Even in the presence of available charging infrastructure, it has been shown that EV uptake was lower than expected as a result of charging inconveniences [5] and that consumers tend to lack a willingness to accept disruptions in their daily routines for charging purposes [6].

A proposed solution to enable electric mobility is the installation of direct current fast charging (DCFC) stations, hereby referred to as fast-charging stations; These have the capability to obtain 80% of a full charge in half an hour. Although not yet comparable to the refuelling time of a traditional internal combustion engine (ICE) vehicle, fast charging capacity significant improves EV ease-of-use and the technology to accept even higher rates of charge to reduce idling times are being developed [7]. It is estimated that to expand the adoption of electric vehicles in the United States, 45,000 DCFC stations must be installed by 2025, an increase of almost 40,000 from the 5,500 which are currently publicly available [8].

1.2 Aims and objectives

Although the benefits of transport electrification and the potential of fast-charging to promote the transition to decarbonised vehicles are clear, there are certainly barriers which exist to limit the implementation of such technologies. While fast-charging is a ubiquitous solution to improve usability of EVs, a limited business case arising from high capital and operational costs, plus uncertainty regarding negative grid impacts have stifled widespread expansion of such infrastructure. An important issue for many communities attempting to transition to electric mobility is the lack of case studies focused on areas that are not highly-populated and urbanised. Such a limited scope is reasonable when considering the priority to decarbonise high-density communities producing significant carbon emissions; nevertheless, an understanding of the impacts of unique lifestyles in atypical environments and climates is crucial to promoting an equitable transition to electrification. The singular travel habits and behaviours of residents within these areas will subsequently produce a different use case for EVs and business case for fast-charging stations, which must be considered by local policy makers and regulators. Unfortunately, very few studies have focused on end user behaviour and driving schedules when assessing EV use, utilisation of charging infrastructure, and EV impacts on the grid system. This is a result of a limited implementation of agent-based models (ABMs) in studies of electric vehicles, and certainly those which consider daily travel itineraries of end users.

Stemming from the identification of these gaps, this study aims to understand the systemic challenges with transport electrification and expansion of public fast-charging infrastructure as perceived by the stakeholders within a unique EV system. As a result, it intends to offer specific, relevant guidelines and recommendations through the implementation of an agent-based model that focuses on individual driving behaviours of residents for a variety of activity types. The model will focus on a case study of the Municipality of Anchorage (MoA) in Alaska, which is currently rapidly gaining interest in transport electrification but has many barriers to overcome for EVs to become mainstream. With the help of local researchers, this study was designed to answer the following questions:

1. What are the significant barriers to EV adoption and the expansion of public charging (with a focus on fast-charging) infrastructure in Alaska, as perceived by major stakeholders?
2. What is the travel behaviour of MoA residents, what are their concerns regarding electric mobility, and what are their requirements for charging?
3. What are the limitations of the existing public charging network and what interventions can improve them?
4. Are there simple strategies to mitigate negative grid impacts of future EV loads?

To answer these questions, the following objectives are outlined:

(A) Provide an overview of the existing literature on the EV landscape, with general background information, consideration for consumer preferences and concerns, and a summary of existing policy mechanisms and their effectiveness. Additionally, address fast-charging specifically, focusing on technical and economic barriers to the adoption of DCFC infrastructure.

(B) Present background information on the case study of Alaska and identify the modelling framework being employed.

(C) Develop a multi-stakeholder approach to understand the local challenges with electrification from a variety of perspectives.

(D) Develop a modelling methodology within the determined framework in (2) to analyse the feasibility of meeting specific driving needs with electric vehicles, the utilisation of existing and potential future charging infrastructure, and the impacts of increased EV adoption on the local electrical grid. This should include:

- An accurate representation of the local environment and residential population, including socio-demographics, household characteristics, and travel patterns.
- A realistic determination of energy use of vehicles within the model environment.
- A defendable algorithm for determining agent charging behaviour considering the state of the existing charging infrastructure.
- Quantifiable characteristics of each simulation which can be used to compare results.

(E) Apply the methodology to the described case study and generate recommendations for stakeholders.

1.3 Thesis structure

Chapter 2 addresses points (A) and (B) through a state-of-the-art overview of the existing literature on transport electrification and fast-charging, providing a foundation for relevance of the study and the formulated methodology.

Chapter 3 addresses points (C) and (D), describing the methodology for the stakeholder engagement and the core structure of the agent-based-model. The source information for agent characteristics are described as well as the core logic for their behaviour within the model is explained.

Chapter 4 summarises the results of the stakeholder engagement and their implications on the characteristics of the agent-based model and the scenarios considered. Subsequently, the modelling methodology is applied to the case study (Municipality of Anchorage).

Chapter 5 and 6 conclude the report with an analysis of the results reported in chapter 4 and their implications for stakeholders and policymakers, addressing point (E). Additionally, the limitations of the methodology are discussed and considerations for future work are presented.

2 Literature Review

2.1 Stakeholders within transport electrification

This section considers the general stakeholders for a transport electrification system, which are outlined in Figure 2.1. Stakeholder roles are discussed and their impacts on charging infrastructure deployment is considered, as it is most relevant to the topic of this report.

2.1.1 Primary stakeholders: EV owners, manufacturers, electricity suppliers, and grid operators

The EV environment has four major stakeholders: EV owners, EV manufacturers, grid operators, and electricity suppliers. The EV owner has one of the most important roles to play within the system as their preferences and behaviours inevitably influence policy and investment strategies taken by other stakeholders. Although their role is considered the most straightforward, it is also the most critical in determining the value inherent in the EV charging ecosystem and the utilisation of electric vehicle service equipment (EVSE). Additionally, as seen in section 3, the factors for influencing consumer behaviour can be complex and actions may not always conform to the assumptions made by statistical models. While many studies regarding electric vehicles assume that meeting the transport demand is the primary concern of the consumer, it has been shown that mobility is also linked with socio-demographic and contextual conditions, such as relaxation and leisure, that electric transport may not currently support [5, 9]. It has also been identified that even considering a system which can provide all expectations of mobility, through a robust charging network for example, a lack of awareness in non-EV users was a significant roadblock to interest toward electric vehicles [10]. While consumer behaviour is discussed in further detail in section 3, it is crucial to point out that EV preferences and perceptions are an important barrier to EV adoption and highlight the importance of stakeholder cooperation in the transition to electric mobility.

The stakeholder with direct influence on the perception and utility of electric vehicles by the consumer is the EV manufacturer. As the EV manufacturer responds directly to consumer driving needs, they are one of primary drivers of innovation within the EV space and play a key role in enhancing the usability and performance of electric vehicles. When considering the breadth of available EV models, an importance concern that will need to be addressed by manufacturers is the use case outside of highly populated, urbanised environments. While many compact and sedan vehicle models exists, there are very few large vehicle types, such as trucks and SUVs, or vehicles for different terrains, such as four-wheelers and snow machines. The future of EV manufacturing will require the expansion of use cases for electric vehicles, which will simultaneously address concerns regarding equity within transport electrification, as many rural communities are the ones which require additional consideration on this topic.

Another key stakeholder in the EV web is the grid operator. They can be as large as a national or regional grid operator and distribution network operator (DNO), or as small as a local, vertically-integrated utility in a small town or rural setting. Regardless of size or scope, the role of the grid operator remains the same: provide secure, reliable electricity to suppliers at competitive prices while maintaining existing assets and providing maximised returns to investors. With the progressive injection of electric vehicles into the market, management of grid security will become an important task for the grid operator. As discussed later in the report, uncontrolled EV charging and inconsiderate charging infrastructure placement can negatively impact grid assets and produce costly upgrades [11]. As a result, grid operators are incentivised to be involved in facilitating and managing the proper electrification of the transport sector.

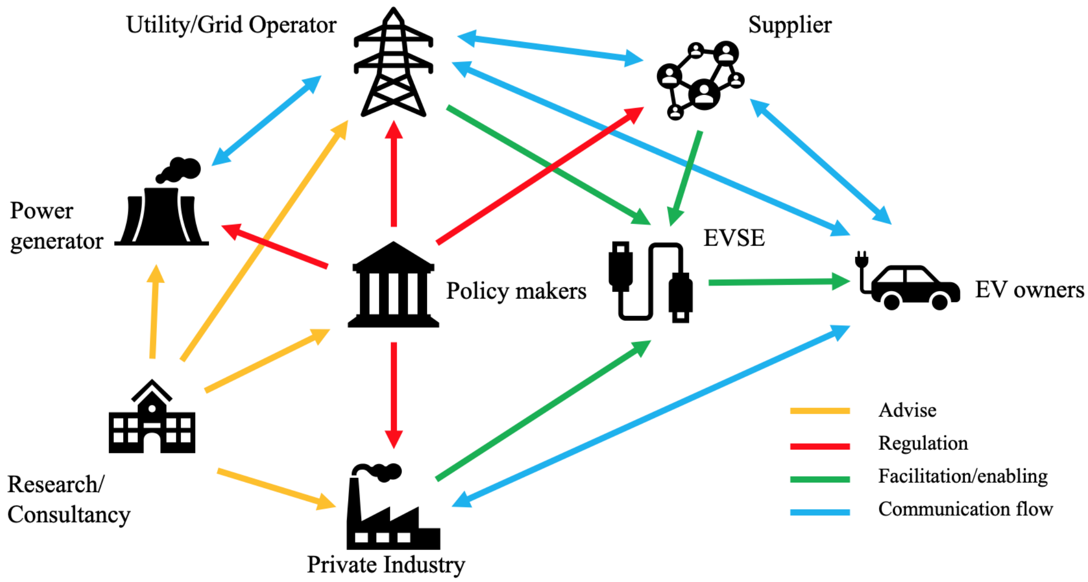


Figure 2.1: Simple diagram of stakeholder relationships within an EV landscape. Adapted from Palomino & Pirvania [4].

The final primary stakeholder within the EV system is the electricity supplier, whose role is to provide all consumers in a given area with electricity at competitive rates. In the transition to electric vehicles the supplier plays a crucial part in the charging landscape, as the imposed rate structure (residential and commercial) is a key determinant in the economics of public charging infrastructure investments and charging behaviour of individual consumers [2, 12, 13]. If future electricity grids will continue to increase the penetration of high-intermittency renewable generation and contain a high level of electric vehicles, retailers will be required to increase their involvement in controlling electricity flows through demand-side management and smart charging.

2.1.2 Secondary stakeholders: Researchers, policy makers, and private industry

Secondary stakeholders of the EV landscape include researchers, policy makers, and private industry. As transport electrification strategies are still under development, research, from a technological, economic, and policy perspective plays an important role. Stakeholders involved in research can be universities, research institutions and organisations, and private consultancies. As the performance of electric vehicles and economic and regulatory landscapes are region-specific and case-sensitive, research can provide both general insights and individual recommendations to determine the proper pathways for electric mobility. While research indicates potential pathways, policy makers facilitate those pathways through taxation, incentivisation, and encouragement. The final stakeholder is private industry, which incorporates EV manufacturers (considered previously), battery manufacturers, and charging station providers. Battery production is the most carbon intensive process in the value chain of electric vehicle manufacturing, and poses ethical issues with the mining of necessary materials as well as supply chain issues regarding the relative scarcity of certain materials. This is discussed further in section 2.3.1. Lastly, the expansion of charging infrastructure will require a variety of locations, such as workplaces, supermarkets, and other places of consumer aggregation, to manage charging stations. Businesses and workplaces are thus likely to become important enablers to consumer preference for EVs and cooperation will be required to maintain system interoperability.

2.2 Benefits provided by electric vehicles

This section outlines the benefits provided by electric vehicles, both in their inherent operation and through their connection to the electrical grid. It must be noted that certain benefits have requirements that are currently not satisfied, such as high EV penetration or the existence of a smart, flexible network. Nevertheless, it is important for all benefits to be considered as they will undoubtedly influence the evolution of the power grid and future supply-demand balance.

2.2.1 Environmental

The clearest advantage of EVs lies in the absence of tailpipe emissions and the potential displacement of fossil fuels. A typical vehicle with an internal combustion engine currently produces 4.6 metric tons of carbon dioxide annually [3]. Although improvements in fuel economy will continue to minimise the carbon footprint of driving, the production of carbon dioxide cannot be eliminated as it is an inherent artifact of the combustion process. Besides carbon dioxide, pollutants such as methane and nitrogen oxides are also generated through combustion. While the emissions of the additional products are small compared to carbon dioxide, they have a higher global warming potential (GWP). The lack of tailpipe emissions also has implications for air quality. Incomplete combustion within ICE vehicles produces air pollutants, such as particulate matter and sulfur oxides, that have adverse impacts on human health [3]. While it is obvious that electric motors produce no such pollutants, it is important to consider the air quality impacts of the entire energy generation supply chain. If the carbon intensity of the grid is low due to incorporation of renewable energy, electric vehicles are especially beneficial by displacing the direct utilisation of fossil fuels, such as diesel and petroleum, by ICE vehicles. However, electrification of transport without parallel decarbonisation of energy generation can minimise the resulting environmental benefits, and in some cases, can act to harm air quality, as will be discussed in section 2.3.1..

2.2.2 Grid stability

Increased electric vehicle adoption and the subsequent rise in electricity demand has obvious economic benefits for utilities and network operators. Additionally, the connection of EVs to the grid system can provide numerous other advantages, especially with increased intermittent, renewable generation in the energy mix. It is important to note that many technological benefits of electric vehicles require a robust, flexible electricity network, the infrastructure for which is not yet developed in many areas. In addition, positive impacts from EVs will only begin to be realised when their penetration levels rise to significant levels.

2.2.3 Peak shifting

Since peak electricity demand occurs in the afternoon after working hours, plugging in EVs at this time can exacerbate the peak load and strain the existing network infrastructure. However, shifting EV charging, especially in a grid system with intermittent sources of generation, can minimise costly peaker plant operation, reduce curtailment of renewable resources, and increase existing asset utilisation [14, 15]. Shifting charging periods to times of excess capacity, such as during the day when solar power is high, can add revenue to utilities and avoid increases in peak demand. In the case of California, it was shown that existing fast charging demand profiles aligned with times of high solar curtailment, allowing better utilisation of low marginal cost electricity and potentially avoiding or delaying investments in additional infrastructure [8].

2.2.4 Demand response and vehicle-to-grid (V2G)

As electric vehicles are connected to the grid when charging, their impact on the network can be controlled to ensure stability. Demand response involves regulation of vehicle charging in response to energy supply. If there are spikes in demand or disruptions in generation, charging can be turned off to maintain network integrity. Likewise, when renewable generation comes onto the grid, charging can be turned on. Similarly, vehicle batteries can act as sources of energy storage used to provide security and stability to the electrical network. Such a mechanism is called vehicle-to-grid (V2G) , in which EVs actually **supply** electricity to the grid when demand is high. This benefits utilities and network operators by eliminating the ancillary costs of requiring standby peaker plants and could also provide a source of revenue for EV owners [16, 17]. Zhao et al. [18] considered the benefits of V2G ancillary services for electric trucks in multiple U.S. cities and found that lifetime ownership revenue exceeds ownership costs by $20,000-$30,000. Noel & McCormack [19] showed that if all conventional school buses in a U.S. fleet were converted to electric buses, V2G services could lead to $38 million in net present savings.

2.2.5 Battery second life

The ability of EV batteries to store energy is not limited to their time powering an electric vehicles. Even after the initial lifespan of a battery in a vehicle is complete, approximately 70-80% of the charging capacity is maintained [20]. Wu et.al [21] concluded that batteries sold at an optimum capacity of 77% can achieve a second life value of $100/kWh and reach Pareto improvement. Nevertheless, grid scale benefits from battery second life are only realistic with significant penetration of electric vehicles. However, even small-scale energy storage, such as for a single fast-charging station, has the potential to reduce future requirements for infrastructure upgrades. Research into the safety, feasibility, and cost-effectiveness of battery second life applications are still in the early stages and current lack of regulation in this area hinders large-scale applications [22]. As more electric vehicles penetrate the market, battery end-of-life considerations will likely become an important concern, and the potential for second life utilisation will be central to minimising the environmental impacts of batteries.

2.3 Challenges posed by electric vehicles

2.3.1 Environmental

While it is clear that a lack of tailpipe emissions may make electric vehicles an obvious improvement from traditional combustion vehicles, their environmental impact is not negligible. The operational emissions of EVs are regionally variable and directly dependent on the carbon content of grid electricity. In China, it has been shown that EVs reduce GHG emissions but increase particulate matter (PM), nitrogen oxide (NOx), and sulfur oxide (SOx) emissions [23] due to highly carbon intensive energy generation. Similarly, in the state of Texas, reliance on coal results in EVs indirectly emitting much more sulfur dioxide than internal combustion vehicles [24]. Hence, it is sometimes the case that electric vehicle adoption simply transfers the emissions burden upstream in the electricity supply chain, shifting the impacts to rural communities which are typically in closer proximity to power plants.

Another important factor to consider is electric vehicle manufacturing, which has comparable emissions to those of internal combustion engine (ICE) vehicles [25]. A major contributor to manufacturing emissions is the production of the battery, although its exact carbon intensity is subject to high uncertainty and is dependent on battery chemistry [26]. While a recent review of life-cycle greenhouse gas (LCGHG) emissions of EVs by Ambrose et. al [27] showed that in the U.S., electric vehicles have 35-50% less LCGHG emissions than ICE vehicles, many factors have the potential to minimise the emissions savings incurred. Trends promoting larger batteries to mitigate range anxiety, low utilisation of EVs, and advancements in ICE fuel efficiency create a complex environment for determining overall benefits of electrifying transport.

Finally, it is also worth noting the raw material requirements for electric vehicle battery manufacturing; the main metals required are nickel, cobalt, and copper. The relative scarcity of cobalt will make prices volatile [28]; heavy geographical consolidation of mining operations and battery manufacturing in regions like China and Japan could create market instabilities and supply risk [22]. Secondary production of raw materials through recycling of batteries has the potential to mitigate investment risk, however current recycling rates are inefficient and insufficient to support future demands for raw materials, and even with higher efficiencies of recycling, cobalt in particular is still required from primary production [29].

2.3.2 Technological

Although the potential benefits of large-scale deployment of electric vehicles can be significant, technical and logistical barriers exist which make increased penetration of electrified vehicles difficult to achieve practically. Using real data from 39 residential feeders in northern California, it was determined that uncontrolled EV penetration of one vehicle per household meant that 58% of distribution feeders exceeded their voltage limits, with the peak daily demand increasing by 64% [30]. Uncontrolled charging in the Sacramento area of California at 5% EV penetration levels resulted in grid upgrade costs of $150 per vehicle [31]. Mitigation of grid upgrades requires a smart, flexible network with control mechanisms to manage EV charging, and such technologies are currently under development and not yet deployed at grid scale.

Electric vehicle penetration also faces challenges with consumer acceptance. Financial and social incentives have not always been successful in spurring consumer transition from traditional ICE vehicles, and high vehicle costs and range anxiety hinder widespread adoption to electric vehicles [32]. Even after a Danish EV trial of a variety of households seemed to indicate EVs can meet all basic driving needs, only an insignificant fraction of participants decided to adopt an electric vehicle upon completion of the trial [5]. Although the participants found techniques to complete all daily tasks, the researchers of the trial found that participants objected to the EVs because the leisure and freedom normally associated with driving was lost. Stringent routine planning and farsightedness were instead required to reduce anxiety related to running out of battery power. For EVs to penetrate the consumer base beyond the early adopters and environmentally-conscious, usage patterns must become similar to those of traditional ICE vehicles, which requires robust and rapid public charging infrastructure to be implemented. While increasing non-residential charging opportunities is certainly one of the top methods to improve the usability of electric vehicles, the concerns of consumers regarding electric mobility is multi-faceted. Understanding consumer needs and preferences is crucial to a successful transition to transport electrification, and hence is investigated further in the section 2.4.

2.4 Key factors for influencing electric vehicle adoption

This section aims to outline the important determinants for consumers when deciding on purchasing electric vehicles and the effectiveness of policies to mold public opinion and influence consumer behaviour. Examples of prior and existing policies promoting electric vehicle uptake will be presented and their effectiveness analysed through case studies of Nordic countries and the United States. These examples were chosen because they represent the most advanced and the largest potential EV market, respectively, and thus can serve as guidelines for future policy decisions. While these examples can certainly serve to inform and sway the direction of future policy, it is worth mentioning that many up-and-coming EV systems will likely require innovative solutions that may not find common ground with historical policies.

2.4.1 Purchase price and operation

The purchase price is a major determining factor in a consumers decision to adopt an electric vehicle, with a secondary consideration being the operational cost (i.e. charging and maintenance). In a review published by Liao, Molin, and Wee [33], the financial burden of an electric vehicle was shown to be a highly influential variable and was severely negatively correlated with EV preference. However, lower operational cost was seen as a potential driver of adoption, although most consumers do not place great significance on this aspect [34]. It is also important to note that the price to charge an electric vehicle is regionally-dependent, and under certain circumstances, powering a vehicle using grid electricity can actually be more expensive than fuelling with petrol. Figure 2.2 shows the breakdown of levelised cost of charging (LCOC) for each U.S. state.

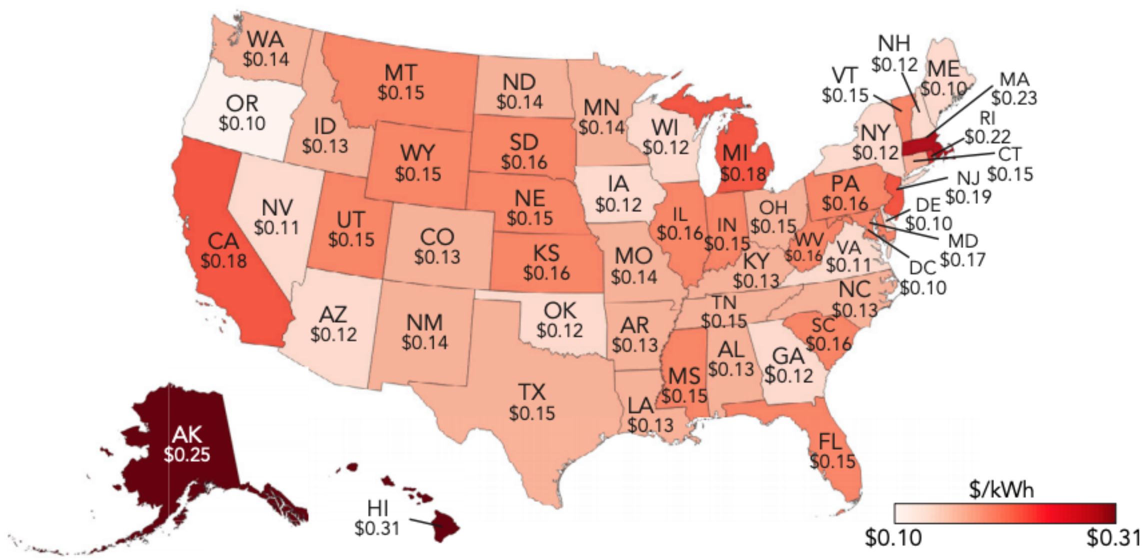


Figure 2.2: U.S. state breakdown of the levelised cost of charging. Taken from Borlaug et al. [35].

The variation in LCOC can be attributed to the price of electricity, cost of EVSE installation, utility rates, and the available public charging infrastructure, all of which will be discussed in the report in further detail. It is interesting to note that even in states with high LCOC values, fuel cost savings may still prove EVs profitable if the price of gasoline is also high. Figure 2.3 shows the variation in fuel cost savings across all states in the U.S. based on different charging cost scenarios. It is clear that states with high gasoline costs will see increased profitability of EVs, but it is important to understand that policy mechanisms and utility rate structures have an important role to play in enable electric mobility, even under circumstances when it might not be initially favorable.

In cases where the total ownership cost of electric vehicles is already cheaper than conventional fossil fuel vehicles, it has been shown that consumers are concerned more with the existing expense as opposed to potential lifetime savings [36]. Battery costs, which constitute a significant portion of total EV cost, are declining more rapidly than previously predicted [37] and can potentially be cost-competitive with ICE vehicles by 2025 [38]. As a result, it can be seen that the upfront cost of an electric vehicle is slowly becoming less of an issue, and it may be possible for incentives to transition to other burdens.

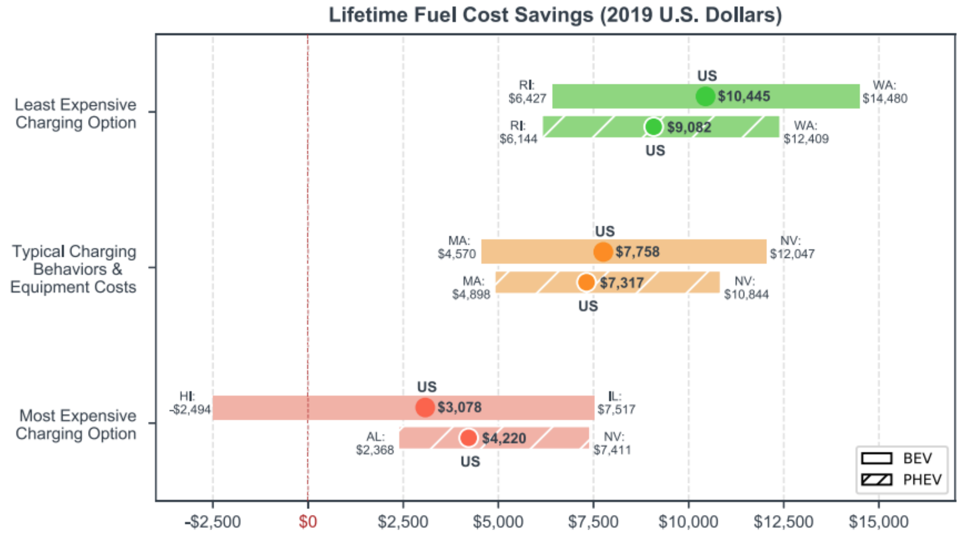


Figure 2.3: Lifetime fuel cost savings considering different charging cost scenarios. Taken from Borlaug et al. [35].

2.4.2 Range anxiety

As previously mentioned in section 2.3.2, there are technological issues currently making electric vehicles less desirable than fossil fuel vehicles. The most frequently concern with consumers is *range anxiety*, which is the fear that an electric vehicle will not be able to fulfill normal driving needs. This fear is significant in non-EV users, while the relationship with existing EV users is less clear. Studies have shown that range anxiety can be much less prominent in EV users, who showed a trend of decreased anxiety with time [39, 40]; on the other hand it has also been observed that after trialling electric vehicles for a few months, driving range was valued much higher than at the beginning of the study [41]. Mitigation of range anxiety is ongoing: EV battery capacities are constantly improving, and by 2030 the average driving range is expected to reach 350-400 km [1]; additionally, charging infrastructure continues to expand globally, with publicly accessible chargers increasing in number by 60% from 2019 to 2020 [1]. Although 82% of those are in China, policies and further investment are spurring growth in other countries such as the United Kingdom and the United States. As the technology of electric vehicles continue to improve, the allowable electric mobility will become less contingent on battery capability, and more on the robustness and capacity of public charging infrastructure.

2.4.3 Charging infrastructure

The expansion of public charging infrastructure is critical in promoting the transition to electrified transport as it can alleviate range anxiety and enhance mobility. Although 50-85% of charging occurs at home [42, 43], a strong relationship exists between the number of available public charging stations and the number of EV drivers (Figure 2.4). In addition to the existence of available charging, proximity is an important concern for consumers as usage of electric vehicles must be perceived to be similar to existing fossil fuel vehicles [44].

The main locations for charging, ranked from highest to lowest utilisation, are: (1) home or residence, (2) workplace or commute location (i.e. supermarkets), (3) non-work public areas, and (4) travel corridors [42]. The availability, speed, and cost of charging at different locations has a significant impact on charging behaviour. Although charging at home is the preferred method for existing EV users and can be the most influential factor when motivating EV purchase [10, 45, 46, 47], general access to outlets in

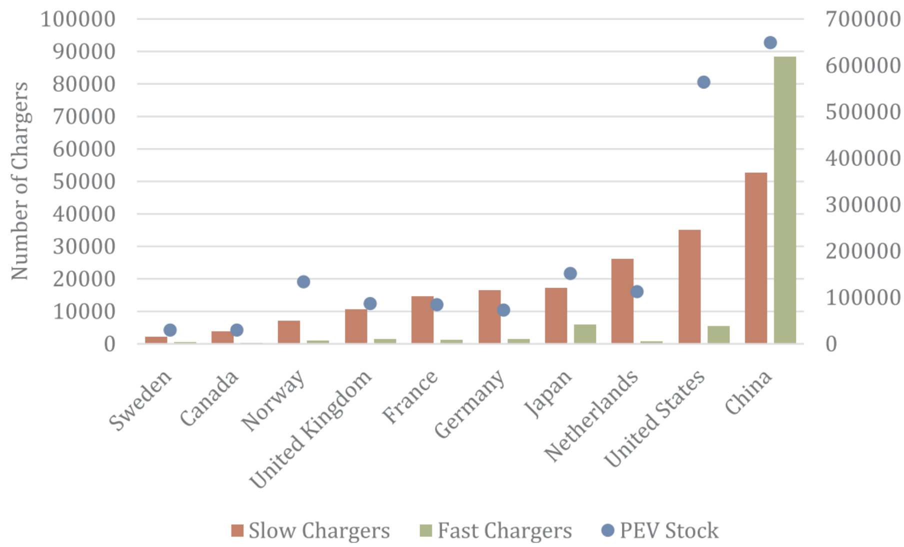


Figure 2.4: Country comparison of available charging infrastructure and total vehicle stock. Taken from Hardman et al. [42].

residential ares is deceptively lower than expected. Even in the United States, where 74% of households have access to a garage for vehicle storage, 52% do not park within 20 feet of an outlet, out of which 9% did not own a vehicle [2]. Hence, 43% of of those households would either depend on public charging or need installations to occur to be able to charge from home. This indicates that increasing the attractiveness of electric vehicles could require extensive investment in charging infrastructure, whether in residential or public areas, to spur the transition to e-mobility. The chosen allocation of investment will likely be the primary determinant of charging location, at least in areas with low access to household outlets. For example, Tal et al. [12] found that likelihood of home charging increased by 15% if there was access to level 2 (3.6-22 kW) charging or if the cost to charge at home was the cheapest option. Workplace charging was undesirable in a variety of scenarios: congestion for charging, requiring to swap parking spaces and charging time limits. However, free workplace charging increased the probability of charging during work by almost 10%.

In terms of criteria for public charging placement, important trends can be extracted to help guide policy-making and proper incentives. An important distinction to make when considering user preference for charging infrastructure, which can turn out to be problematic for policy, is between existing EV users and interested non-users (Figure 2.5). In a study by Philipsen et al. [6], both EV users and non-users viewed service stations as critically important locations for charging, indicating that charging and traditional fuelling are linked activities and that all consumers are generally unwilling to accept externalities to charging. However, the important results lie within the differences; interested non-users ranked the remaining possible charging locations with a higher score than existing users, all at a statistically significant level. The discrepancy in value may be problematic for policy design and investment allocation; however, the results also indicate that addressing the concerns of non-users through proper communication and education can serve to improve the efficiency of technology spread.

Other notable criteria uncovered by Philipsen et al. [6] include the overall unwillingness of potential users to accept drawbacks to daily routines, such as vacating parking spots after charging sessions and waiting times. Dual use of time during charging and around-the-clock availability were both rated as important to potential users, which contradicts the earlier preference for service station charging placement but verifies the notion to limit drawbacks.

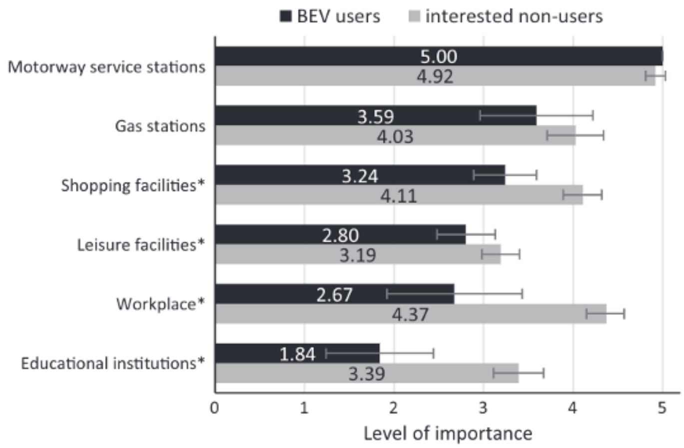


Figure 2.5: Average importance of potential charging locations, with a (*) representing statistical difference. Taken from Philipsen et al. [6].

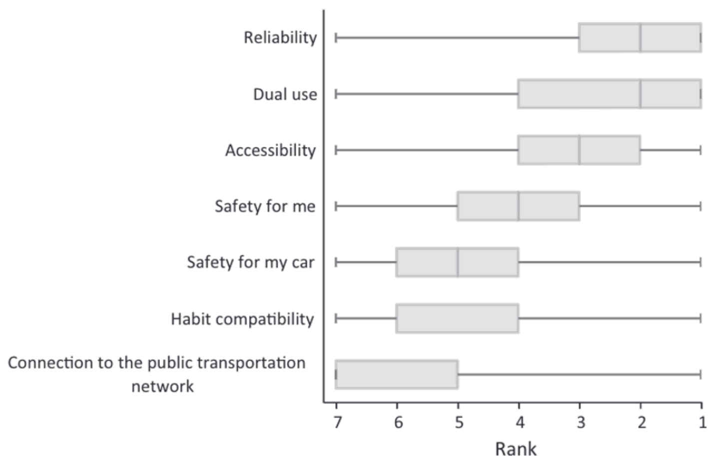


Figure 2.6: Average importance of charging station characteristics. Taken from Philipsen et al. [6].

2.4.4 Summary of consumer concerns

To summarise, the main concerns for consumers regarding EVs are: the investment cost, both capital and operational; range anxiety, which is a fear of EVs being unable to meet normal driving needs; and the lack of a robust public charging infrastructure. Of these, a limited public charging network is the key barrier to electric vehicle adoption, as it directly impacts range anxiety and reduces the range of activities supportable by EVs. While deployment of charging infrastructure is growing, it is important to also consider the speed at which charging occurs. Consumers are shown to be unwilling to accept drawbacks and expect an experience similar to what they are currently accustomed to. Hence, it is clear that fast-charging opportunities, which can provide a similar waiting time to fuelling an ICE vehicle, are vital to mainstream adoption of electric vehicles. Fast charging impacts, planning, and economics will be discussed in further detail in sections 2.5 and 2.6.

2.4.5 Policy incentives and their effectiveness

With all of the barriers to EV uptake discussed in section 2.4, policy incentives are a potentially key instrument to improve the attractiveness of electric vehicles. Still, it is important to determine whether policy actions are merely keeping a technology afloat or truly promoting a transition that could evolve to be self-sustaining. As the technology and cost of electric vehicles improves, the development of proper policy mechanisms is taking center stage, and the effectiveness of past policies are being looked at to advise the decision-making of the future. In this section, case studies of Nordic countries and the U.S., the most advanced and biggest EV markets, respectively, will be examined to extract insights regarding effective and ineffective policies to promote electric vehicle uptake.

Nordic countries

Nordic countries have assumed a united front with regards to climate change and societal decarbonisation, although their paths towards that goal and eventual results have been unique and independent. An interesting comparative analysis was performed by Kester et al. [32], in which a variety of stakeholders spanning multiple sectors and industries from 5 Nordic countries (Table 2.1) were interviewed to gain insights on policies and their perceived success.

Table 2.1: Characteristics of the study performed by Kester et al. [32]

Characteristic	Value
Interviews conducted	227
Countries considered	Iceland, Finland, Sweden, Denmark, Iceland
Sectors included	Government agencies, regulatory authorities, research institutions, industrial players, auto manufacturers, EVSE companies

The results from the study are outlined in the bullet points below:

- Creating cost competitiveness for EVs was suggested through three mechanisms: direct financial incentives, secondary incentives (i.e. free parking, high-occupancy vehicle (HOV) lanes, etc), or increasing purchase cost of ICE vehicles.
- Most individuals (spanning all countries) preferred taxation over subsidies as subsidies were considered uncertain in their consequences and unsustainable.
- Participants preferred parking and driving benefits but also understood they could have negative outcomes (such as congestion); such policies would then be very unpopular to remove in the future.
- "Overarching" policy, such as investment in public charging infrastructure, was seen as more effective and beneficial than "individual" policies, such as subsidies or tax breaks. This is because overarching policies provide a social benefit as opposed to an individual benefit. However, it was noted specifically that investment in charging infrastructure is not economically viable.
- Consumer awareness was noted as an important barrier with a desire for governments to disseminate clear, useful information to consumers to create interest and offer guidance.
- Finally, policy suggestions revolved around consistency, clarity, and planning. Stakeholders condemned the short-lived political nature of EV policy, stating that it was a barrier to sustained transitional pressure. A clear policy signal was mentioned as crucial to instigate communities, businesses, and local authorities but a long-term phase out plan is required for the policy to be successful.

The results show that discussion regarding proper policy mechanisms for electric vehicle uptake must be had with all relevant stakeholders. Furthermore, effective government policy hinders on consumer awareness and proper dissemination of information, otherwise the intended effects might not be realised. It was interesting to note that negative feedback mechanisms, such as taxation, were preferred over subsidies; such policies, although potentially more effective, will be difficult to implement politically. It is also important to consider the bearer of costs: governments bear the costs of subsidies and alleviate consumer costs; meanwhile taxation, at least as technology matures, increases consumer costs but also provides revenue for the government to help fund more general policies, such as charging infrastructure investments, to improve the benefits of transitioning to a new technology.

Although analysing stakeholder perspectives in hindsight can provide key insights, it is also important to discuss which policies were actually implemented. In Norway, incentives were mainly social benefits, such as bus lane access and free parking, and cost exemptions and reductions for individual purchase of EVs, as early models had significantly lower quality. Later, in the early 2000s, policies transitioned to promote charging infrastructure development, as such projects were not economically viable. The most effective, according to a review by Figgenbaum, Assum, and Kolbensvedt [48], were the value-added tax (VAT) exemption introduced in 2001 and providing bus lane access, introduced in 2003 and 2005. While incentives for EVs were introduced in the early 1990s, it is worth noting that EV penetration did not begin to rise significantly until the early 2000s [48]. This indicates that incentives alone were not sufficient to promote EV uptake, likely because the technology had not reached sufficient maturity to become attractive to consumers and the charging infrastructure was not in place for their utilisation to become relatively convenient. As it stands, EVs in Norway held a 54% market share in 2020, but incentives for their purchase and use will continue through 2022 [49] after which they will be re-evaluated. VAT exemptions and bus lane usage are still implemented, and a toll exemption of 50% was implemented in 2019. It is worth noting that extensive fast charging networks have been developed in Norway, and consumers have been willing to pay, on average, three times more than residential electricity rates [49].

United States

The United States is an interesting case because incentives can be provided on a federal and state level. From a federal standpoint, minimal action has been taken to directly promote electric vehicles. The Corporate Average Fuel Economy (CAFE) standards were enacted in 1975 after the oil crisis caused rising fears regarding U.S. dependency on foreign oil. These standards were not meant to affect consumer decision-making, but rather influence automakers to produce higher efficiency vehicles through imposed penalties. The constraints were initially annually consistent, but were modified in 2012 to increase efficiency on an annual basis. These standards, in conjunction with Environmental Protection Agency (EPA) emissions standards introduced in 2011, are the main policies influencing transport carbon emissions in the U.S..

These policies do not directly influence the adoption of electric vehicles; nevertheless, it has been noted that increased policy stringency by 2025 could force manufacturers to pursue electrification [50] but it is also possible the transition will favor plug-in hybrid vehicles as opposed to 100% electric transport [51]. Since CAFE penalisation is based on the footprint of the vehicle (wheelbase multiplied by average track width [51]), it is possible that long-term effects include a shift in manufacturing towards larger footprint vehicles (which have less stringent penalties) and undermine the goals of the policy. Analysis by Sen, Noori, & Tatari [52] using an agent-based model, however, indicated that CAFE regulations can be successful in increasing EV penetration while reducing the share of ICE vehicles; the effect is increased by coupling policy with financial incentives. Certain manufacturer agents within the model did transition to higher footprint vehicles to avoid penalties, but also saw the lowest profits.

Uncertainty exists regarding the effectiveness of the CAFE and EPA policies in lowering transport emissions and transitioning to electric mobility; nevertheless, researchers suggest such policies can be effective and consistently regard the expansion of public charging infrastructure as a key policy mechanism to further promote EV uptake [52, 53].

With regards to state-level policy regarding transport electrification, there is large variety in the intensity of government incentives. The most active states, such as California, have implemented zero emissions vehicle (ZEV) policies and some form of incentivisation to promote electric vehicle penetration into the market; other states, such as Colorado, simply provide incentives, either direct or indirect, to promote electric vehicle purchases; many states have no policy in place whatsoever. Figure 2.7 shows the U.S. states with the highest consumer benefits and their corresponding EV vehicle share, while Figure 2.8 ranks U.S. states by highest EV market share and displays their consumer benefits.

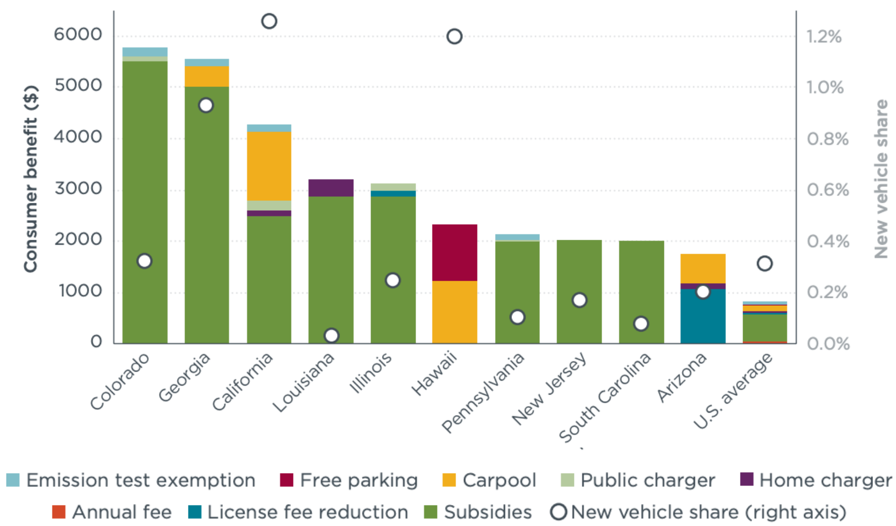


Figure 2.7: Consumer benefits and corresponding EV market share for U.S. states with the highest total incentives. Taken from Jin, Searle, and Lutsey [54].

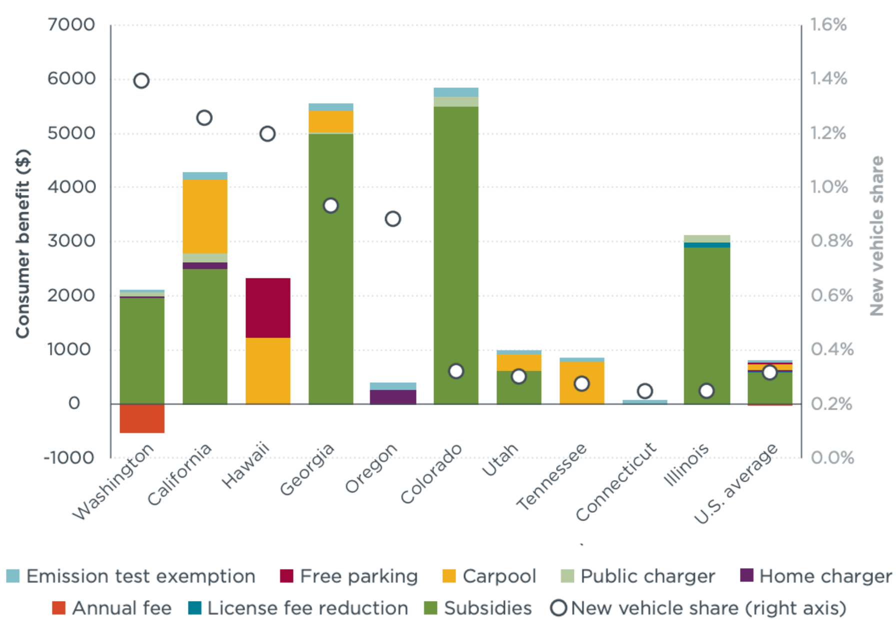


Figure 2.8: EV market share and corresponding total incentives for U.S. states with the highest EV market share. Taken from Jin, Searle, and Lutsey [54].

It is interesting to note that the states with the most benefits are not necessarily those with the highest share of electric vehicles. Figure 2.7 shows that states with subsidies providing the overwhelming majority of the benefits, even if the total monetary amount is high, do not greatly influence EV uptake. An example is Colorado, having the highest consumer benefit but with very low EV market share. Meanwhile, states with a variety of benefits tend to impact consumers more even when the total value of the incentive is relatively low, such as the case with Hawaii. Figure 2.8 similarly shows that incentives are not the only factor influencing consumer decision-making. Contrary to the trends seen in Figure 2.7, we can see outliers such as Washington and Georgia, which have a high EV market share with low incentivisation dominated by subsidies.

The holistic U.S. assessment performed by Jin, Searle, and Lutsey [54] determined that subsidies, carpool lane access, and emissions test exemptions were significantly correlated with EV sales, with subsidies exhibiting the strongest relationship. Although subsidies, as shown in the previous figures, were the most ubiquitous in their presence, their influence on EV sales was almost identical in magnitude to the effect of carpool lane access. This could be an indication that more emphasis placed on indirect, social incentives could further enhance the attractiveness of electric vehicles without the need to increase government spending. As a final note, Jin, Searle, and Lutsey performed a benefit-cost analysis which concluded that the most cost-effective policy to benefit consumers was investment in public charging infrastructure. While this does not consider the economics of implementing a charging network, it does reiterate the importance of public infrastructure in successfully electrifying the transport sector. This study, although representative of policies in all U.S. states, is limited in scope as only policies with monetary value were analysed; thus many potential benefits were ignored for the sake of understanding macro trends. Further research into the outlier states could provide valuable insights into consumers motivations and preferences that lie outside the current scope of understanding.

2.4.6 The need for fast-charging

In summary, policy mechanisms are key in spurring consumer uptake of electric vehicles; even so, monetary incentives alone may not be enough to trigger a transition, and secondary benefits such as free parking and access to carpool lanes should be considered. Additionally, it was clear that subsidies and tax exemptions in the early development of electric vehicles were insufficient because the technology had not developed to an extent which made electric vehicle use comfortable and easy. However, technological development has improved significantly in recent years, lowering costs and reducing range anxiety. Hence, it can be surmised that an increasingly important barrier to EV adoption is charging infrastructure access, specifically fast-charging, which can create a driving experience similar to what is currently in place.

As is the case in most high-level assessments, such as the one performed by Jin, Searle, and Lutsey [54] in the U.S., the analysis reduces individuality of circumstance to provide an overall picture of the population. While eclectic incentivisation through primary and secondary benefits are likely to see success in highly-populated urban areas, their effectiveness is minimal if not non-existent in more sparsely populated, rural areas. This points to a clear need for research on unique use cases of electric vehicles, such as Alaska. While general studies, like those described in this section, may serve policymaker needs in communities which fit the general mold of an interconnected, urbanised environment, it certainly does little to provide guidelines for areas which do not. However, it can be surmised that particular barriers to adoption will be ubiquitous for all communities, as is certainly the case with a lack of public charging infrastructure. In fact, the lack of infrastructure barrier may actually be more prominent in less urbanised areas, as the travel distance tends to be higher on average than in highly populated cities [55]. With increased travel distance, the driving experience becomes more important, which drives the need for expansion of fast-charging specifically. As such, subsequent sections of the literature review will focus on the technical and economic aspects of fast-charging infrastructure, addressing its impacts on electric vehicles and the grid, as well as the factors influencing capital and operational costs.

2.5 Fast charging impacts and demand

2.5.1 Fast charging in context

One of the consumer benefits of an electric vehicle is the ability to charge the battery at any location with an outlet. While basic driving needs can be satisfied by residential charging, range anxiety can only be mitigated by a robust public charging infrastructure. As seen in Figure 2.9, growth in electric vehicle sales and investment in public charging stations are closely linked.

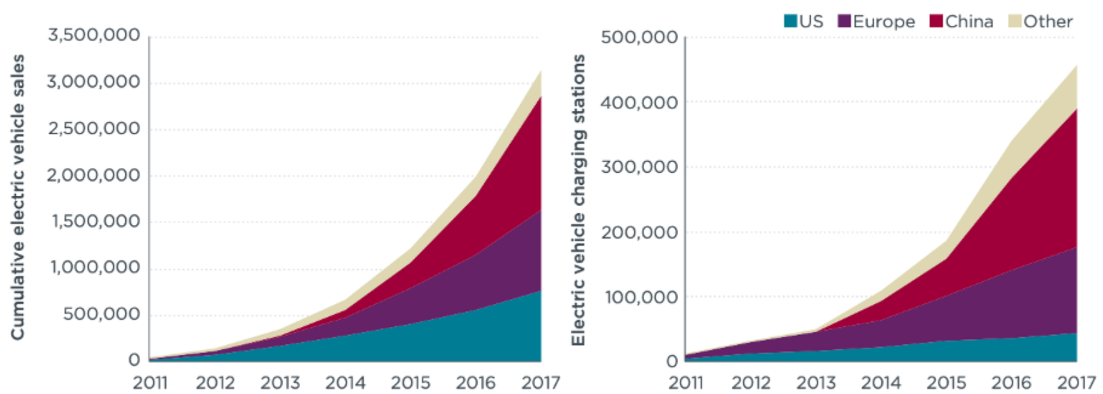


Figure 2.9: Global electric vehicle sales and charging station deployment. Taken from Nicholas & Hall [2].

Although charging infrastructure and electric vehicle penetration are certainly positively correlated, areas with limited infrastructure and low electric vehicle counts are plagued by the "chicken or the egg" dilemma. Consumers are not willing to purchase an electric vehicle without existing infrastructure to support their daily travel needs; conversely, private and public entities are hesitant to invest in charging infrastructure with the uncertainty regarding the consumer transition to electric mobility. Regardless of which party makes the first move, the need for charging infrastructure is undeniable for the penetration of electric vehicle into the transport sector. For acceptance of electric vehicles to move past the initial phase of early adopters and attract interest from public and private bodies, the utilisation of EVs must be comparable to ICE vehicles [6]. Thus, charging infrastructure must be both ubiquitous and have rapid vehicle turnover. DCFC stations, which provide 50 times the power of a typical residential outlet, are a potential solution. Such chargers can deliver $60 - 300$ miles of charge in half an hour, which, although not yet comparable to ICE vehicles, significantly improve the mobility of electric vehicles. Table 2.2 provides an overview of the important characteristics of different charger types. This section considers the grid and battery impacts of DCFC and how they can be mitigated and examines the planning and layout of DCFC infrastructure deployment. Certain aspects, such as grid upgrade costs, are regional and climate-dependent; however, general trends can still be extracted and provide insight into the benefits of DCFC expansion and potential barriers to its implementation.

Table 2.2: General characteristics of different electric vehicle charging options. Adapted from Levy, Riu, & Zoi [8] and Nicholas & Hall [2].

Charger type	Voltage	Typical power	Approximate charging time
Level 1 (L1)	120 V AC	1.2 - 1.8 kW AC	20 hours
Level 2 (L2)	200 - 400 V AC	3.6 - 22 kW AC	5 - 6 hours
DCFC	400 - 1000 V AC	50 kW or more	60 - 90 minutes

2.5.2 Fast charging grid impacts

Even at significant penetration levels, it has been estimated that the load presented by electric vehicles will constitute a minor portion of the overall electrical demand [56]. This signifies that electric vehicle charging will not impact generation capacity; however, the impacts of fast charging on distribution networks can be significant. As mentioned in section 2.3.2, even basic level 1 and level 2 charging, when uncontrolled, magnify peak demand and can overload transformer buses at low EV penetration values. Fast charging, although used less frequently than level 1 and level 2 chargers, can have similar impacts due to high power requirements. Improper placement of fast charging stations diminishes the reliability of the network by reducing voltage stability and increasing power losses, which can result in economic losses for the utility [11]. Even with proper placement, considering strong and weak buses in the system, a certain penetration of fast charging stations will require network upgrades. Although a general statement cannot be made regarding the installed peak capacity at which network upgrades will be required, case studies are useful in approximating potential limitations of existing network infrastructure. In the United States, it has been shown that while transmission infrastructure can handle fast charging load in all but a few exceptional hours during the year [57], the distribution network and final transformers will likely need upgrades with an additional 1,200 kW load from fast chargers [2]. There are a variety of solutions to mitigate the negative impacts of fast charging stations on the distribution network, all of which will be discussed in this section and the subsequent. A quick summary is provided here.

- A proper layout of stations considering user needs and grid capacity (section 2.5.4).
- Implementing time-of-use rates to deter charging during peak demand as a form of smart charging (section 2.6.2).
- Combining fast charging stations with battery storage; the battery can be charged during low utilisation and discharged during peak hours to minimise grid reliance. This option can also be combined with on-site solar generation (section 2.6.3).

2.5.3 Fast charging battery impacts

Fast charging is an attractive method to increase electric vehicle penetration as it enables long-distance travel and quick recharge, but its consequences on battery durability and lifespan must be considered. The main concern with DCFC is the increase in battery temperature from the high currents required to quickly charge the battery, which can be further exacerbated if the vehicle is operated in hot climates. As temperature has a direct effect on charging and discharging rates of the battery [58], its management plays a significant role in maintaining proper battery function and elongating its lifetime. Lithium-ion batteries, the most frequently utilised chemistry of electric vehicle batteries, are especially prone to temperature degradation due to their high energy density and self-heating properties at certain temperatures [59]. As a result, manufacturers developed battery thermal management systems (BTMS) to manage and regulate battery temperatures which are now present in every electric vehicle.

Many studies have been performed which investigate the effects of DCFC on battery degradation. It has been found that even under unrealistic use profiles for fast charging, such as when only DCFC is used to charge the battery, BTMS mitigates the negative impacts and little to no differences in performance are seen when compared to level 2 charging [60]. However, fast charging does significantly affect maximum battery temperature, which can exceed proper operational limits during specific driving behaviours even if passive cooling BTMS is employed [61]. In cold temperature environments, BTMS is used to heat the battery to maintain operation within safe limits. In such circumstances, lithium plating becomes the predominant issue with fast charging. Lithium plating occurs when metallic lithium forms around the anode, which can result in malfunction [62]; literature on such effects has identified that fast charging below 10°C can result in noticeable lithium plating on the battery [63] and reduce longevity.

2.5.4 Fast charging demand and planning

Enabling electric mobility certainly requires optimisation of public charging infrastructure to meet consumer needs and minimise negative grid impacts. With regards to fast charging stations, many studies have been performed which attempt to determine the optimal number and location of fast charging stations, utilising a variety of methodologies and assumptions.

Electric vehicle charging infrastructure must, first and foremost, meet a certain user demand, with consideration for technological and economic constraints. As the user is the central focus, it is important to distinguish between the user types, of which three are discussed extensively in the literature [64]:

- Public transportation users, such as buses, have simple design requirements for enabling electrification. Consistent and fixed routes reduce the uncertainty surrounding travel behaviour. Planning of charging stations will depend on the size of the fleet and daily utilisation of vehicles.
- Ride-hailing service users, such as taxis, have more complex travel patterns but must also follow strict guidelines. Thus, it is possible that issues with low utilisation of fast charging infrastructure within cities can be mitigated with electrification of ride-hailing [65].
- Private vehicles, which constitute the majority of the vehicle fleet. Charging considerations for private users are complex and tend to require more assumptions than the previous two groups. This is because usage patterns for private users are more diverse and location-specific, and thus planning to meet private charging needs is difficult to generalise.

This section will focus on modelling options for private vehicle electrification due to the volume of available literature and the understanding that investments in charging infrastructure to meet private vehicle demand will inherently provide co-benefits to all user groups. This section will outline the considerations required for modelling fast charging demand and layout, providing historical context and discussing future potential.

Location optimisation of charging stations

There are two main schools of thought with regards to optimal placement of charging infrastructure [64]. A **node-based** approach is one in which locations (nodes) are assigned an electricity demand that must be met by charging stations of a certain capacity. Nodes can be any potential source of electricity demand, such as an individual driver or a bus depot, but in a basic framework they are stationary. A **flow-based** or **path-based** approach, however, assigns to each driver a origin-destination pair, and places charging stations in optimal locations based on demand density and battery trip requirements. Figure 2.10 provides an overview of the models associated with the two approaches, which will be discussed in further detail in their own subsections.

Node-based modelling

The Set Covering Location Model (SCLM) and Maximum Covering Location Model (MCLM) are frameworks that attempt to maximise the number of nodes whose demand can be met by a particular set of stations [66]. Thus, the key determinant within these models is distance between nodes and charging stations, which is set to a fixed parameter and is the main determinant for station citing [67]. The difference between the SCLM and MCLM methodologies is that in SCLM, demand magnitude is not considered and the importance lies in all nodes being covered; on the other hand, MCLM allows nodes to remain uncovered, which can be used to analyse more realistic scenarios such as optimising coverage with budgetary constraints and/or fiscal incentives [64].

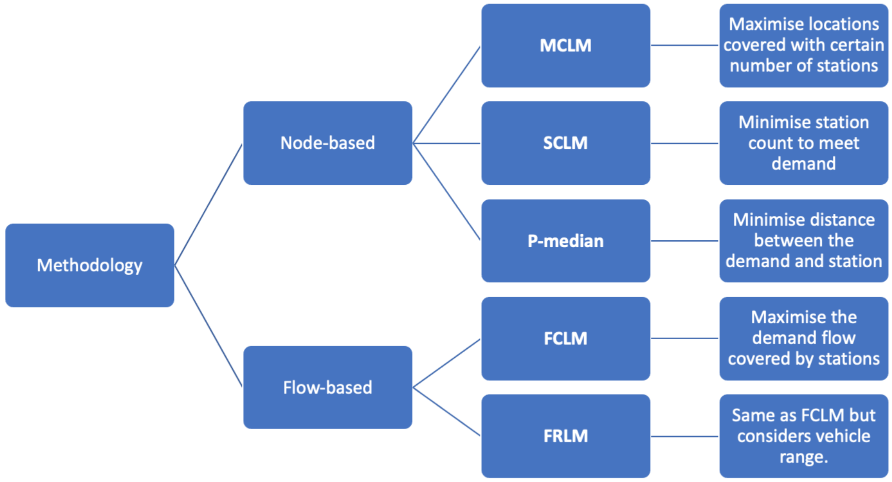


Figure 2.10: Overview of modelling methods and associated models. Modified from Metais et al. [64].

The goal of the p-median model, meanwhile, it to minimise the total cost of facility deployment, restricted to p facilities. Each node is assigned to a single facility and there is the capability to fix a maximum capacity to a facility that caps the allowable demand it can meet. As determined in a review by Metais et al. [64] this methodology is the most widely-used in location optimisation problems, and has been mainly used to either minimise distance to charging stations or minimise infrastructure costs for a particular demand. However, this modelling framework has also been utilised in unique ways, such as by Jia et al. [68] to forecast both the slow and fast charging requirements of Beijing.

Node-based modelling approaches are beneficial in that they require little data to provide a baseline estimate of charging infrastructure needs, and can be modified in their complexity to consider multiple parameters such as charging speed and facility capacity. Nevertheless, these models are restricted in their application as they consider electricity demand as static and thus lack robustness in understanding driving behaviour and vehicle range capacities. Node-based approaches could have a niche application in rural areas where mobility is limited and demand could be assumed as static with limited deviation from reality.

Flow-based modelling

The simplest version of a flow-based model is the Flow-Capturing Location Model (FCLM) , which was conceived by Hodgson [69] and improves on the MCLM by considering origin-destination pairs and flows instead of static nodes. The Flow-Refueling Location Model (FRLM) was developed uniquely for alternative-fuel vehicles by considering the specifications and limitation of a vehicle when determining the number of facilities that are required to fulfill the charging needs for a particular pathway [70]. Researchers have since modified the original model to consider different factors, such as capacity constraints on facilities [71], path deviation to charge [72], and uncertainty with EV charging demand [73].

Although it is clear that the flow-based approach is more robust than the node-based method, there are still shortcomings. Flow-based models do not consider time constraints for charging, and assume similar behaviour to ICE vehicles [64]. It is possible to combine node- and flow-based models into a single analysis to improve robustness, as done by Sun et al. [74] considering both nodes of slow charging and flows of fast charging, however stochastic consumer behaviour and uncertainties in demand remain unexamined and thus produce simplified results.

2.5.5 A novel approach: agent-based modelling

An important consideration when planning public infrastructure investment, as alluded to in section 2.4, is consumer behaviour and preference, as technological adequacy alone may not be sufficient determine utilisation of charging assets. Hence, agent-based approaches have been developed which can model individual decision-making processes. In such a framework, individual "agents" and their interactions within a population are simulated, which addresses demand uncertainty and allows behaviour modification through future actions and changes [75].

Although theoretically, agent-based simulations could perfectly model real-world scenarios, limitations in data collection and computational power diminish the robustness of agent-based models. Additionally, this framework presents uncertainty, present through random elements within the model. It can be the case that running multiple iterations with many random variables will produce significantly different results [76], which undermine the conclusions reached and the reproducibility of results.

Specific applications of agent-based models for EV research has been focused mainly to simulate the diffusion of electric vehicles within a population through policy interventions [77, 78], assess the impacts of electric vehicles on the electrical grid [79], or determine strategic placement of charging stations within an urban setting [80]. However, a majority of such models lack an accurate representation of the behaviour and characteristics of local residents, choosing instead to generate basic, high-level decision-making criteria which may limit the scope of the results and the implications of the suggestions provided. This is especially important when considering using agent-based models to understand public charging infrastructure utilisation and forecast the charging needs of a population. Additionally, the case studies are restricted to high-density urban environments, failing to encompass the wide variety of use cases of electric vehicles. It is clear that while agent-based modelling can serve to enhance decision-making with regards to electric vehicles, the implementation of this modelling technique is limited and its application to transport forecasting is yet to be determined. However, a study performed by Pedro, Hardy, and van Dam [81], which stemmed from the master's work done by Maria Pedro, a former student of the Sustainable Energy Futures course at Imperial College London, does present a case study with relevance to the goals of the current project. In this work, the characteristics of local residents in Swindon Borough of the UK were used as inputs to the agent-based model, and with stakeholder involvement, created an accurate representation of all aspects of an EV system, modelling the impacts of increased EV penetration on the charging infrastructure and the electrical grid, and considering systemic interventions to mitigate the risks.

2.5.6 Summary and application

To summarise, Table 2.3 lists studies compiled by Nicholas & Hall [2] in their analysis of early fast charging adoption. The review shows that there is significant uncertainty regarding the required fast charging infrastructure investment based on the considerations and assumptions made. However, the authors did indicate a trend of higher BEV/DCFC ratios with time. Even though most of the identified model types are agent-based, different papers analysing the same region (i.e., California) came to vastly different conclusions regarding the required fast charging infrastructure to support transport electrification. This is indicative of the immaturity of modelling charging requirements, a conclusion with which the authors agree, and should be considered an important area of research moving forward. It also confirms the need for new studies to consider the characteristics and behaviours of the residents being represented in the models, as making high-level assumptions will likely lead to highly variable results. While it appears that agent-based models may be best suited for studying EV systems, the impactfulness of conclusions reached using this methodology is limited if agents do not properly represent the population being studied. Furthermore, the compiled assessment indicates a clear lack of research focused on rural travel needs, with only one study, by Wood et al. (2017), assessing both urban and rural charging infrastructure.

Table 2.3: Studies identifying fast charging requirements and key assumptions made. Column 3 in parenthesis shows whether (network coverage, service capacity) are considered. Adapted from Nicholas & Hall [2].

Study	Region	Model Type	BEV/ DCFC ratio	Notes
Bedir et al., 2018 [82]	California	unknown (Y/Y)	29-80	Uses California household travel data to determine charger location and capacity
Cuijpers et al., 2016	Netherlands	unknown (Y/Y)	1,409-2,331	Considers scenarios of uptake with autonomous, renewable vehicles. Only includes corridor fast chargers.
Genovese et al., 2017	Italy	unknown (Y/Y)	190	Uses GPS data to estimate fast charging needs for Rome electric vehicle drivers.
Gnann et al., 2016	Germany	agent-based (N/Y)	100-556	Models fast charging needed to prevent queuing with various charging speeds, to reach 1.5 million BEVs.
Ji et al., 2015	California	agent-based (Y/Y)	593	Models demand in California considering different vehicle ranges and charging technologies.
Jochem et al., 2016	Germany	FRLM (Y/N)	152	Models demand for DCFC along the Autobahn based assessed costs.
Marcon, 2016	Canada	N/A (Y/N)	1,072	Focuses on profitability of stations in different settings.
Melania, 2014	California [83]	agent-based (Y/Y)	667-1815	Plans infrastructure to accomplish California's EV uptake goals for different scenarios.
Metcalf, 2016	California	N/A (Y/Y)	563	PG&E utility assesses DCFC grid impacts in California and mitigation strategies.
Nicholas et al., 2013	California	agent-based (Y/Y)	169	Assumes fast charging as only public charging option for statewide travel across California from survey data.
German NPE, 2015	Germany	N/A (N/Y)	141	Creates comprehensive set of recommendations to enable 1 million BEVs in Germany.
Reuter-Oppermann et al., 2017	Germany	FRLM (Y/Y)	152-1,639	Compares coverage and capacity approaches to the needs of the German Autobahn up to 2030.
Wood et al., 2017	United States	agent-based (Y/Y)	300	Models urban and rural needs. Shows that home and workplace charging are primary.
Xie et al., 2018	California	FRLM (Y/Y)	583	Examines inter-city travel and shows that multiple chargers per station is preferred.

2.6 Fast charging costs and business case

This section outlines the costs associated with the full life cycle of a fast charging station. Installation and operational costs are discussed with consideration for potential areas of improvement and cost-reduction strategies. It is important to discuss the economics of fast charging as recovering capital costs from installation is more complex than level 1 and level 2 chargers. Thus, although fast charging provides clear advantages for the consumer, poor foresight when planning infrastructural investments can financially harm both the consumer and operator. The three major categories for fast charging station cost are operations, equipment, and development, which constitute 30%, 35%, and 35% of the total cost, respectively [8]. Each of the components will be discussed with consideration for potential areas of improvement, and cost reduction strategies are extracted from the literature which can increase the profitability of fast charging stations in future installations.

2.6.1 Installation and development costs

DCFC stations require specialised equipment such as AC-DC and DC-DC converters and a complex safety system to handle high power flows and transform grid electricity into scaled DC usable by electric vehicles. Fast charging stations must also adhere to strict vehicle and industry safety standards to ensure safe utilisation and maintain trustworthy operation [8]. As a result, installation is much more significant than for simple level 1 and level 2 chargers, requiring planning, permitting, and specialised expertise to achieve. Table 2.4 shows comparative installation costs between different charging levels, clearly indicating that DCFC stations are multiple orders of magnitude more expensive than level 1 and level 2 stations.

Table 2.4: Purchase cost of charging equipment of different speeds in the U.S. Adapted from Metais et al. [64, 84]

EVSE Type	Average public installation cost	Average home installation cost
Level 1	$4,000	$400-$900
Level 2	$6,000	$680-$4,100
DCFC (50 kW)	$73,000	Not available
DCFC (150 kW)	$120,000	Not available
DCFC (350 kW)	$205,000	Not available

Installation of a DCFC station can be split into two categories: equipment procurement and development. Equipment includes charger hardware, grid interconnection, and software, which comprise 84%, 12%, and 4% of the equipment cost, respectively. Meanwhile, 80% of development cost is for labor, with the rest composed of permits, taxes, and engineering design [8].
While the general installation cost structure is similar across charging speeds, the magnitude, as shown in Table 2.4, can vary significantly. While it is clear that cost of installation will rise as charging speed increases (i.e. from 50 kW to 150 kW chargers), the relationship is non-linear. Nicholas, in a review of multiple studies [84, 85, 86] showed that installation of a 50 kW charger requires $45,000, while a 350 kW charger requires $65,000, a 45% increase for a 7-fold improvement in power output. It is also important to also consider how costs scale as the number of chargers and/or charging ports per site increase; estimates from Ribberink et al. [85], the Electric Power Research Institute (EPRI) , and the Rocky Mountain Institute (RMI) [86] have indicated that per charger installation costs fall both when more chargers are installed per site and more charging ports per charger are available [84]. An example of installation costs per 50 kW charger as a function of number of chargers per site is presented in Table 2.5.

Table 2.5: Installation cost per 50 kW charger by number of chargers per site. Adapted from Nicholas [84].

	1 charger	**2 chargers**	**3-5 chargers**	**6-50 chargers**
Labor	$19,200	$15,200	$11,200	$7,200
Materials	$26,000	$20,800	$15,600	$10,400
Permit	$200	$150	$100	$50
Taxes	$106	$85	$64	$42
Total	$45,506	$36,235	$26,964	$17,692

These values can serve as an important baseline for understanding the dynamics of investment requirements for different fast charging scenarios. It is important to note that the results shown cannot be extrapolated to a specific site, especially when considering upgrades to a 350 kW system. Such high power demands will almost certainly be met with costly grid upgrades, the magnitude of which can vary tremendously. A study performed by Ribberink et al. [85] estimated installation costs at three separate sites in Ottawa. Sites A and B showed minimal marginal cost transitioning between 50, 100, and 150 kW power capacities and reasonably higher costs for a 350 kW installation; conversely site C exhibited exuberantly higher installation cost for a 350 kW charger (Figure 2.11), rising to over $120,000 for a 4-charger installment due to costly grid upgrades.

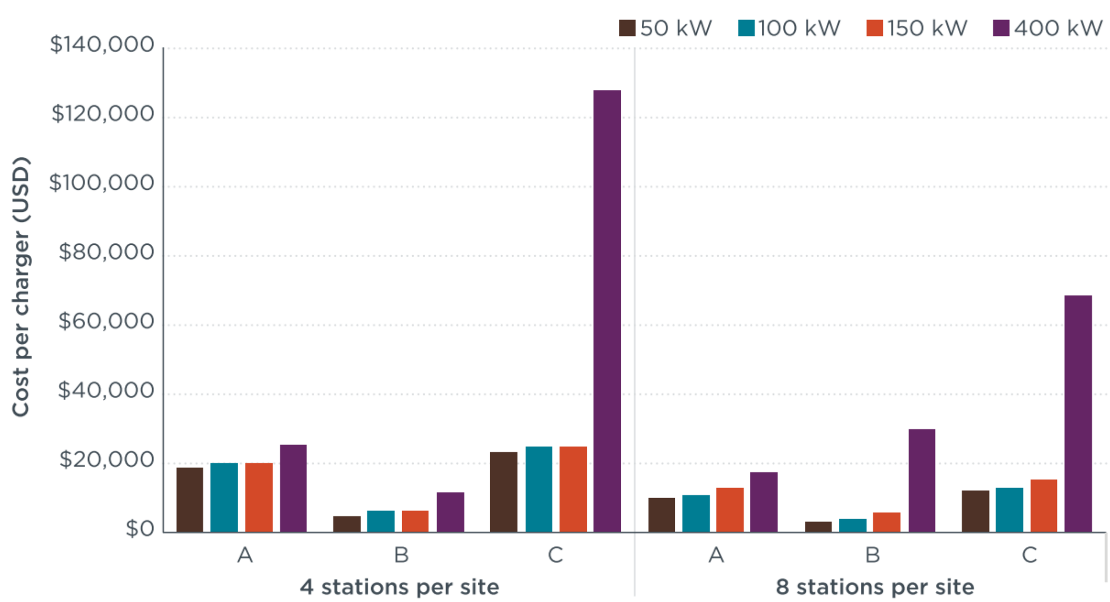


Figure 2.11: Installation cost estimates for chargers in three different locations. Data from Ribberink et al. [85]. Taken from Nicholas & Hall [2].

In summary, installation costs make up a significant portion of the overall cost associated with a fast charging station, and are much more significant than for level 1 and level 2 stations. As a result, it is important to understand the expected utilisation of the station and if investment in fast charging is the proper route to take, taking into consideration charging speed, number of stations, and number of charging ports. It is also important to note that economies of scale and new technology emergence will continue to lower the installation capital requirements; progressive deployment experience can continue to reduce costs through standardisation and streamlining of approvals and permits.

2.6.2 Operational cost and utility charges

The success of a charging station, regardless of power level, even upon completion of installation, is not guaranteed. This is especially true for DCFC station considering the need to recover much higher initial investments, as discussed in the previous section. The cost of electricity procurement and utilisation by EV users are critical metrics for determining a station's profitability, and they are linked properties. 51% of the operational cost of a fast charging station result from electricity procurement [8]; hence, if the costs to obtain electricity from the grid are high, the price to charge at the station will inevitably increase. This has the potential to not only reduce utilisation, but deter the transition to electric mobility in general by increasing cost disparity between usage of fossil fuel and electric vehicles.

It can thus be seen that the utility charges for providing electricity to the charging station are monumental in determining its economic viability. Rates charged by utilities vary widely by region, however, most current rate structures are inhibitory to fast charging deployment. It is also important to distinguish between occasional and frequent users. Occasional users of fast charging, such as during infrequent long-distance trips, are likely to be willing to pay a significant per kWh fee. On the other hand, frequent users that rely on fast charging for mobility would require more price parity to a gasoline vehicle [2]. Thus, the location of a station is also important in determining the proper rate structure to maintain profitability.

Time-of-use rates

The rate structure most widely considered as enabling to fast charging infrastructure is *time-of-use* (TOU) electricity rates [2, 7, 42, 84]. Under this structure, two or three pricing tiers exist within the day, with prices also varying by season and weekends. The highest electricity price will be charged during peak demand, hence incentivising electricity use during so called "off-peak" periods when prices are lower. In the context of electric vehicles, off-peak charging is an important principle: basic rate structures promote uncontrolled charging [87], which tends to occur **during** peak hours of the day, enhancing peak demand and causing negative consequences to grid integrity [30, 31, 88]. Not only can TOU rates maintain grid security through off-peak electricity usage, they simultaneously increase utilisation of existing grid assets, and in the case of intermittent renewable generation, can increase the capacity factor and provide increased revenue to grid operators through utilisation of low marginal cost energy sources [88].

An extension of TOU rates are dynamic rates, in which utilities are able to modify prices even more frequently to better reflect grid capacity, wholesale prices, and carbon intensity of generation [89]. Although dynamic rates are a novel idea with limited practical employment, there is potential that such a scheme may provide higher profits for utilities and better meet user charging needs [90]. It is worth noting that although TOU and dynamic rates have the best potential to promote DCFC and electric vehicle uptake, without a shift in consumer behaviour, the benefits of such schemes are not full realised. Muratori, Kontou, and Eichman [91] performed a holistic analysis of DCFC costs across 7,500 electricity rates in the U.S. and showed that at low utilisation, on-peak charging using a TOU rate resulted in electricity costs of \$1.5/kWh, an order of magnitude higher than off-peak charging . Shifting consumer behaviour and obtaining the highest benefits from EVs is likely to be best served through a combination of proper rate structures and smart charging mechanisms [89].

Discouraged rate structures

Although TOU rates are seen as enabling to transport electrification while minimising grid impacts, most utilities, especially in the U.S., still implement a flat rate scheme, either with or without demand charges [91]. Demand charges are costs independent of total energy use and are simply proportional to the peak demand over a certain billing period. While demand charges can encourage energy efficiency, for DCFC stations, which have high power demands for short periods, demand charges can account for a large portion of overall bills and negatively influence economic viability [89]. Especially at low utilisation, demand charges tend to account for a high proportion of total costs [4, 7, 91] and result in fast charging stations being unprofitable [13]. As utilisation rises, peak demand charges become less influential in the electricity cost of charging stations, and demand charge rates result in lower electricity cost compared to a simple flat rate structure [91]. Hence, it may be worthwhile to consider a charging business model where a TOU rate applies in early deployment and low utilisation, and transitions to a demand rate when such charges are spread over much higher energy procurement.

2.6.3 Improving the economic viability of fast charging stations

In the current environment, considering capital expenditures and possible revenue streams, public fast charging stations are not economically viable [13]. The most significant factors influencing profitability of DCFC stations are high costs (costly grid upgrades and/or unfavourable electricity rate structure) and low utilisation. Thus, it is important to consider mechanisms by which profitability can be increased. This section considers technological business model solutions which could improve the economic viability of charging stations through the factors mentioned prior.

Maximising positive grid interactions

Regardless of the electricity rate structure under which a fast charging station operates, electricity prices will be a major determinant of economic profitability. Hence, a fast-charging station which can obtain its electricity at the lowest prices will be able to reduce operational costs; this can be achieved through a combination of on-site generation, which reduces reliance on grid electricity, and battery storage. Such a solution would not only benefit the economic viability of the fast charging station by minimising demand charges [92], but reduces the potential negative grid impacts of the station itself through peak shaving [93]. Once in operation, the battery storage can provide grid services such as ancillary service [94] and demand response [95], hence increasing utilisation of existing grid assets and reducing grid upgrade requirements. Localised generation would come in the form of photovoltaic (PV) panels which simply act to reduce grid dependence and further improve the net operational revenue.

Muratori et al. [92], considers technological solutions, specifically PV panels and battery storage, to mitigate costs associated with fast charging stations using over 7,000 rate structures across the U.S. under different load scenarios. The results indicate that all sites which chose to install PV panels (to minimise energy charges) and battery storage (to minimise demand charges) saw reductions in operational costs compared to the baseline; nevertheless, a large majority of stations which chose technological installations were PV-only, as not all locations with demand charges proved battery storage investment economical. Another interesting solution proposed by the researchers was co-location with a commercial load, such as a businesses. The benefits are a result of a reduction in fixed costs and demand charges (if peak loads did not coincide), and were more profound with small stations with low utilisation. However, a reversed-tier rate structure in which electricity costs rise with increased demand, made co-location non-viable. Identical results were obtained by Yang & Ribberink [96] with more consideration placed on the payback period of PV and battery storage investment; they found that current costs of storage are prohibitive and payback periods are not reasonable. However, they noted that as prices for PV and batteries continue to drop, such endeavours may become more favourable in the future. Additionally, the researchers noted that although it may not be favourable to install localised generation and storage, it may still be a more attractive option than the potential grid upgrades and high demand charges incurred for a normal installation. The benefits and economic potential of technological solutions to reduce reliance on the grid will require detailed quantification of upfront cost and expected utility charges to determine their viability. In any case, it is likely that additional financial support is required for fast charging endeavours to be realised.

Business models

Overarching business models for DCFC stations are difficult to define because of how important economic factors differ by region, with stakeholders being exposed to different pricing mechanisms (petrol and electricity), travel dynamics, and consumer preferences. Most studies related to fast charging economics focus their scope onto a single stakeholder, such as the consumer or the charging station operator, and fail to understand the potential implications for the entire value chain. While studies have focused on particular stakeholders, the value chain for electric mobility is more complex and as such improper assessment may result in novel benefits, but also additional barriers to adoption [97]. For example, a novel TOU rate was examined in California which had the potential to lower consumer bills by 65% [98], which is likely to make fast charging an attractive option. However, no analysis was done regarding the impacts of lower revenue on the utility, and what interactions play out regarding selling electricity at a lower price with the potential for higher utilisation. Thus, it is important for business models to analyse multiple stakeholder perspectives of a potential action to minimise uncertainty and provide a more integrated solution, and such approaches are scarce in the literature.

An analysis by Serradilla et al. [99] utilises a Rapid Charge Network (RCN) model for the UK which involves a central *Electro-mobility service provider* (EMSP) , which has a direct relationship with the consumer in providing charging services. Within the model, the EMSP is partnered with site owners, which provide the location on which the stations are installed; EVSE suppliers, which install the necessary chargers; and charging service operators, which handle the performance of the chargers by providing software, hardware, and technical knowledge. The results, based on assumptions regarding the growth of the EV market, indicated that investment in fast charging was profitable if the consumer pays a mark-up factor of 3.3 over the residential electricity price. The RCN model serves as a good example of a multi-stakeholder assessment which minimises uncertainty and provides a clearer path for policy intervention that, with great confidence, can understand the impacts on both consumer attractiveness to EVs and the players in the public charging domain.

A similar approach was taken by Nigro, Welch, & Peace [13] in which the EV markets in Washington (low electricity prices) and New York (high electricity prices) were examined and different interventions analysed from the perspective of multiple stakeholders. Two alternative business models are proposed:

- **Sales boost business model** - An automaker subsidises the installation of fast charging stations, which are operated by third-party hosts. This was shown to improve the net present value (NPV) of the operation but did not result in profitability for either stakeholder, except for the owner-operator when large percentages of upfront cost were subsidised (in both locations). Even so, the NPV was below $20,000 over a 10-year period.

- **Revenue sharing business model** - Businesses in a desirable location for travel pool funding to subsidise charging infrastructure ownership on an annual basis. They also provide the sites to host the charging stations. Under this scenario, the profitability of the business (retailer) is significant, however the owner-operator still maintains a negative NPV. Raising the price of electricity by 30% allowed for a payback period of 9-10 years for the owner-operator.

These examples highlight the need for integrated business models that can quantify the benefits and barriers for multiple stakeholders within the fast charging framework. They also address the need to quantify indirect benefits from fast charging station deployment, such as what is seen with traditional fuelling stations offering shopping opportunities during idle times.

2.6.4 Summary: Considerations for investment in charging

- **Installation costs for fast charging are currently high.** The necessary equipment and safety measures needed to provide high power charging to electric vehicles, as well as the likely grid upgrades required make fast charging stations a costly endeavour. While local generation and energy storage can mitigate grid infrastructure upgrades, the costs for their installation are too high in most cases to prove economically viable.
- **Utility rate structure and electricity price are key determinants of operational viability.** Time-of-use rates are considered enabling to fast charging use and have potential to benefit the grid. Demand charges, on the other hand, tend to inhibit fast charging, especially in low utilisation, because of infrequent, high power demands.
- **Business models must consider multiple stakeholder perspectives.** It appears that without policy support, there are only a handful of use cases where fast charging stations are independently viable. However, proper policy support can only occur if many stakeholder positions are quantified. Further studies must be more aggregated in their approach to determining the benefits and costs associated with public charging infrastructure installation.

2.7 Case study: Alaska

2.7.1 Overview of the energy system

The state of Alaska, from an energy perspective, can be considered an independent, islanded system. However, within Alaska, each community or cluster of communities cannot be described in unifying terms. 150 of Alaskan towns are islanded microgrids, with minimal interconnection between them [100]. For such areas, diesel generators typically supply electricity and heating demand is met with biomass or diesel oil, with limited investment in small-scale renewables. An important exception to this paradigm is Southeast Alaska, which has abundant hydropower resources and can generate zero-carbon electricity.

A single electricity transmission network exists within the state, called the “Railbelt”, which provides power to 65% of Alaskan inhabitants living within six vertically integrated utility areas [101], all of whom are rate-regulated by the Regulatory Commission of Alaska (RCA). Although the utility areas are interconnected, they are not managed as a regional grid. As a result, transmission tariffs are compiled when energy is transferred across utility boundaries, making cooperation less attractive. Most electricity within the Railbelt is sourced from natural gas, with the rest generated by a mixture of coal, wind, hydropower and small-scale solar. Although total energy consumption in Alaska ranks 40th among U.S. states, per-capita consumption is 4th as a result of high heating demands during long, harsh winters [100].

Fossil fuels

Fossil fuel development within Alaska has historically been a major driver of the state economy. Revenue generated by oil extraction has allowed the state government to function without support from state sales or income taxes and provides residents with an annual royalty check from state investment revenues. The vast majority of petroleum extraction occurs in the Prudhoe Bay oilfield in the North Slope. Although natural gas is also present in the field, 90% of extracted gas must be re-injected as no pipeline exists to transport the fuel to market. As a result, a majority of Alaskan communities rely almost exclusively on petroleum-based fuels to meet their heating demand. Important exceptions include Fairbanks and Southcentral Alaska. The Fairbanks area has local coal production which is used for driving coal-fired power plants and the Kenai Peninsula, Anchorage, and Matanuska Valley areas within Southcentral Alaska have a natural gas distribution network from gas extracted from the Cook Inlet gas fields.

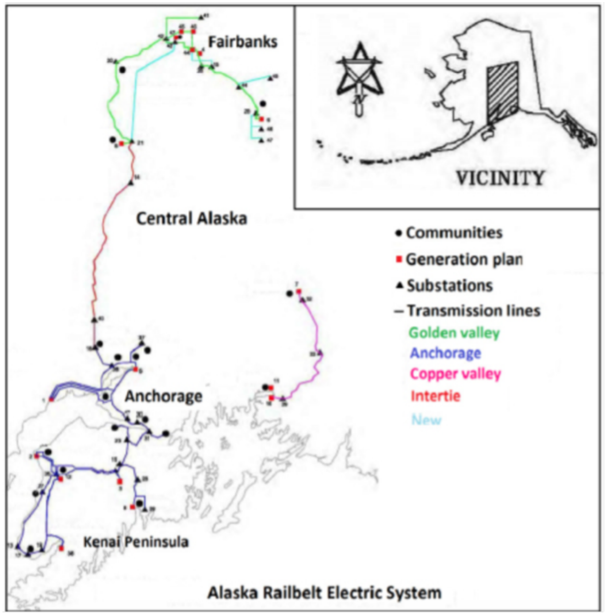


Figure 2.12: The Alaskan Railbelt system. Taken from Wender [102]. Modified from Dale [103].

As the Prudhoe oil fields have matured, oil production has steadily declined. Although millions of acres of land exist in the Arctic National Wildlife Reserve (ANWR) with potential minable resources, conservationists and Alaska native organisations have fought to maintain protections prohibiting oil and gas exploration in the area. An important development has been the Federal Energy Regulatory Commission (FERC) approval of a natural gas pipeline to bring the stranded natural gas in the North Slope to market [104]. Such a pipeline would be able to provide cleaner fuel for heating to northern communities currently reliant on wood fuel and diesel. The multi-billion-dollar project is currently being challenged in court by environmental groups, and investors are unsure whether the Biden administration will provide federal funding considering their stance on progressing the renewable energy agenda.

Renewables

While Alaska is known for its abundant fossil fuel resources, it also contains significant renewable energy opportunities. As rural communities attempt to transition away from costly diesel fuels and lower their carbon footprint, small-scale renewable installations are beginning to see rapid development. Alaska's large land area and unique landscapes provide eclectic geographical opportunities for different renewable resources:

- Wood is an important source of heat in many parts of Alaska and interest in using biomass within a central heating system in rural communities has grown. An example of this is the city of Galena, which heats a local academy campus with wood pellets, displacing 200,000 gallons of fuel oil each year [105]. Other potential sources of energy generation from biomass include using fish oil from large fish processing plants to produce electricity and recycling cooking oils and animal fats to help offset diesel in transport fuel mixes.
- Hydropower currently generates a quarter of Alaska's electricity and there are many small-scale projects currently under investigation all across the state. However abundant, hydro projects are difficult to approve as they have high potential for negative environmental impacts [105].
- Alaska's high latitude implies extreme seasonal variability in available solar energy. Minimal solar energy is available during the winter months; however, clear skies, dry air, long days, and relatively

cool temperatures mean that solar installations can exceed their rated capacities during the spring and summer. Projects such as Solarize Anchorage have utilised federal incentives and economies of scale to expand decentralised solar generation along the Railbelt [105].

- Wind power is very abundant along Alaska's coastline, and has potential to offset low solar output during long Alaskan winters. Although the interior of the state has very site-specific applications of wind generation, wind-diesel hybrid systems are starting to become popular in an attempt to maintain system stability while reducing diesel fuel consumption [105].

While Alaska certainly has potential for expanding renewable energy generation, there are many barriers to widespread implementation. A lack of interconnection within Alaska implies that communities must seek unique and individually tailored sustainable solutions, which can act to deter rapid penetration of renewable generation. Additionally, rural systems typically have high redundancy within the generation infrastructure to maintain security of supply, especially during the wintertime. As a result, small-scale renewables are usually difficult to justify financially, and limited local expertise in novel renewable technologies reduces confidence in their operational success. However difficult decarbonisation of rural energy systems will be, the Railbelt is a system that has high potential for decarbonisation with proper motivation and incentivisation.

2.7.2 Electric vehicles in Alaska

Recent years have seen an expansion of electric vehicle penetration in the state of Alaska. While electric vehicle purchase is currently restricted to early adopters and environmentalists, there is great interest in electrifying transport in Alaska. This provides a great opportunity to better understand the dynamics of electric vehicles in an Arctic climate with unique travel habits and requirements. This section briefly summarises the existing electric vehicle environment in Alaska as context for the discussion.

Current electric vehicle penetration

There are currently close to 1,400 registered electric vehicles in the state of Alaska, a majority of which are being used in Anchorage and Juneau [106]. Interestingly, almost entirely through anecdotal sharing of experience, electric vehicles have even managed to penetrate Fairbanks in the northern reaches of the state. Even under harsh winter conditions and decreased driving ranges, EVs have received positive reviews and could be more cost-effective to fuel compared to petrol vehicles [107]. There are ongoing demonstration projects which are testing the economic and technical performance of electric vehicles in three Alaskan communities [108]: (1) Three electric trucks for public services are being tested in the Anchorage area; (2) An electric school bus with a solar-powered charging depot are being tested in Tok; and (3) An electric public transit bus is being tested in Juneau. Even though electric vehicles are present in communities spanning most of Alaska's range of geographies and climates, there is a lack of research in and significant concern regarding EV capabilities during the winter-time. For interest in EVs to grow, there must be a body of knowledge which affirms reliable performance of electric vehicles in cold climates.

Charging infrastructure

Anchorage and Juneau also boast the majority of the 69 public charging stations installed in the state of Alaska. EV charging stations that have been installed by utilities tend to be free to use; the rest of the stations have been installed by businesses and required credit card payment to use. The Alaska Energy Authority, in July of 2021, approved the distribution of nearly $1 million to 9 collective site hosts across Alaska for the installation of new fast charging stations [108]. The locations of sites approved for the funding are listed in Table 2.6, and are expected to be operational in 2022.

Table 2.6: Characteristics of successful site host applicants for new charging stations through the VW settlement.

Community	Chargers	Amount awarded
Seward	1 DCFC and 1 L2	$109,000
Homer	1 DCFC and 1 L2	$110,000
Soldotna	1 DCFC and 1 L2	$110,000
Cooper Landing	1 DCFC and 1 L2	$110,000
Anchorage (MoA)	1 DCFC	$110,000
Chugiak (MoA)	2 DCFC and 1 L2	$110,000
Trapper Creek	2 DCFC and 1 L2	$110,000
Cantwell	1 DCFC and 1 L2	$86,000
Healy	2 DCFC and 1 L2	$106,000

An additional development is the proposal filed by Railbelt utilities in June 2021 to the RCA to reduce the high demand charge for fast-charging stations. Addressing the lack of available charging infrastructure and their operational cost are important steps in increasing the attractiveness of EV transport in Alaska considering the long distances required for travelling between communities.

Utility incentives and rate structures

Utility rate structures have been listed as an important barrier to the expansion of charging infrastructure in Alaska [108]. Juneau is currently the only community which offers a time-of-use rate structure for EV users with a level 2 charger installed at home to incentivise EV uptake while mitigating potential peak demand spikes. Chugach Electric, an Anchorage utility, provides credits for commercial customers to promote purchase of level 2 charges and residential customers to provide data on personal level 2 charging. For utilities to embrace the transition to electric vehicles there must be consideration placed on the potential negative impacts of these vehicles on the grid system, specifically for identification of potentially weak distribution links that may suffer costly grid upgrades with improper charging loads.

2.8 Literature review summary

2.8.1 Current status of electric mobility and fast-charging

This review has examined the state-of-the-art literature with regards to transport electrification through the lens of consumer preferences and public fast charging deployment. The main findings of the literature is summarised as follows:

- Purchase price, range anxiety and lack of charging infrastructure are the primary complaints noted by drivers regarding electric vehicles. Although purchase price can be simple to mitigate through price subsidies, monetary incentives, while important, are not likely to work in isolation. Consumers are more likely to react to indirect social benefits, such as carpool lane access and free parking. These interventions have potential to improve the *purchasing* of EVs, but have not solved operational concerns. It is also important to note that studies of consumer preferences and policy interventions have been limited to high-level aggregate analyses or case studies of highly-populated urban areas. Such literature is likely not influential to communities which do not fit such a mold, such as those in more rural, low-density areas. However, a general expectation is that the most critical, and obvious, desire of any consumer is for the driving experience of an electric vehicle to not deviate significantly from traditional driving using ICE vehicles. Hence, investment in robust public charging infrastructure, specifically DCFC infrastructure, is essential for the transition to electrified transport under any circumstance.

- Before deployment of fast charging infrastructure is considered, the potential impacts to the grid network must be determined and mitigated. In addition, understanding consumer travel patterns and driving behaviour is a key factor in the optimisation of the quantity and distribution of charging stations. A variety of modelling methods are available, and the assumptions considered by researchers play an important role in the final determination of infrastructure requirements. Optimisation modelling of infrastructure requirements is key as it determines the magnitude of investment required. While agent-based modelling is likely the best approach to understand EV systems and forecast impacts on the grid and utilisation of charging infrastructure, current implementation has lacked consideration for local resident characteristics and travel patterns.
- Significant barriers to the deployment of fast charging infrastructure are high upfront costs, undesirable rate structures, and low initial utilisation. Outside of a few use cases, the literature indicates that, as a result of these barriers, fast charging investment is not economically viable. Time-of-use rates, local PV generation, and energy storage have potential to improve the profitability of fast charging stations through reductions in operational costs, but initial installations will likely need significant government support to result in profitability. On a positive note, if fast charging availability spurs uptake of electric vehicles, increased station utilisation, upfront cost reductions through experience and process streamlining, and advancements in battery storage technology will likely continuously improve fast charging profitability.

2.8.2 Research gaps and potential questions

Lack of diverse EV use cases

An important research gap within the general landscape of transport electrification is the lack of diverse EV use cases. Although a clear priority should be placed on EV diffusion into high-density urban areas producing high quantities of carbon emissions from travel, the lack of research into alternative use cases produces an equity issue within electrification. This is especially important considering the unique challenges faced by rural communities, such as long travel distances in a limited road network, a basic grid infrastructure, and low population density, which likely make transport electrification much more difficult than in the case studies presented in existing literature. As such, an important area of future research needs to be alternative EV use cases, with a clear focus placed on the travel behaviour and habits of local end users.

Modelling shortcomings

While agent-based modelling is becoming a popular tool to analyse transport scenarios and specifically, electric vehicle systems, there is limited utilisation of real-world data to accurately represent the behaviour and travel patterns of the residents being simulated. This is especially important when using agent-based models to quantify and forecast the fast-charging infrastructure needs of a particular area, as agent-based models within the literature focused on this topic have a low level of cohesion. However, the benefit of an agent-based modelling approach for simulating EV systems is that incorporating local behaviour and complexity is not difficult to implement, requiring collaboration with local stakeholders and the compilation of relevant population data, as was done by Pedro, Hardy, and van Dam [81].

Business model improvements

An important area of research that has received significant attention is the fast charging business model. However, it was found that most analyses investigated a single stakeholder, and many potential benefits and barriers of EVs were thus not considered. Due to the novel and complex nature of the EVSE value chain, business models must consider the benefits and costs for multiple stakeholders to have an accurate understanding of the profitability of DCFC stations and to enable the employment of proper policy mechanisms to address key financial barriers. Additionally, indirect sources of revenue for charging station owners should be explored, such as the potential for integration of their business with other services, as is typically done with traditional fuelling stations.

Dynamic rates

Dynamic charging rates are a novel approach to electricity pricing that may serve a similar role to demand response, molding charging behaviour to maximise existing grid utilisation. However, user studies of the benefits of dynamic rate structures is limited, and the willingness of consumers to agree to a more complex rate structure is unknown. A study considering these factors would involve performing a comparative analysis between TOU and dynamic pricing structures for fast chargers, taking into consideration different penetrations of EVs, how such a scheme would impact utilities and end users, and what potential technological requirements are needed. An agent-based modelling method could be employed to understand the interaction consumers may have with such a dynamic pricing structure.

2.8.3 Opportunities for an Alaskan case study

Alaska certainly provides a unique use case for electric vehicles with relatively low-density populations living in areas located long distance apart, in addition to the harsh conditions faced by its residents during the winter months. As such, a case study of an EV system within Alaska certainly addresses the lack of EV use cases gap uncovered in the literature review. As the Alaskan electric vehicle environment is still in its infancy, many potential research questions are possible to discuss in a variety of topics. Of particular interest is the Railbelt electricity system, which is the only large, interconnected transmission network in the state. Considering the gaps in the literature noted above, potential research topics are listed below:

1. A case study within Alaska can be chosen to employ a systemic approach which aims to understand the barriers with public infrastructure deployment through the perspective of multiple major EV stakeholders, including end users, which can be supported by an agent-based model of drivers.

2. A noted barrier to fast charging infrastructure expansion is the inhibitory utility demand charge; an analysis could be done utilising the experience of other U.S. states by comparing the economic impacts of existing alternative rate structures, as well as the one currently proposed, on the consumer and utility in Alaska. A dynamic pricing scheme could also be considered.

3. As the Railbelt, compared to other systems, could be labelled a microgrid, are there unique advantages and/or disadvantages of the Railbelt grid management structure to fast charging deployment? How can the disadvantages be mitigated?

4. What role should a vertically integrated utility play in the transition to transport electrification? What are the economic implications of full utility control over fast charging, smart control, and demand response mechanisms?

Overview of the case study

Through discussions with Alaskan researchers as part of the preparatory work for this thesis, research topic (1) was chosen as it simultaneously addresses the gaps of limited EV use cases within the literature and the lack of local considerations in agent-based modelling implementations. The chosen community for the case study of this project will be the Municipality of Anchorage (MoA), shown in Figure 2.13. The justification for this is that the MoA currently has the second highest EV penetration in the state of Alaska, and being the most populated city, has the greatest potential for EV growth. With two site hosts in the MoA receiving VW grant funding to install fast-charging stations and the anticipated ruling on the demand charge issue, there is increasing momentum towards transport electrification in the region. The methodology will include: conducting stakeholder interviews to determine commonalities and differences in opinion between the major players in the EV landscape; distributing a survey of MoA residents to understand travel behaviour and charging preferences; and developing an agent-based model of MoA drivers, using insights from the interviews and survey, to simulate EV load and public charging network utilisation. The details of the methodology is discussed further in Chapter 3.

Modelling backbone

As discussed in the literature review, the agent-based modelling approach employed by Pedro, Harvey, and van Dam [81] used characteristics of the case study population to accurately model their behaviour and emphasized local stakeholder opinions in the analysis of the EV system. Since a similar approach is developed for the Alaskan case study, the model developed by Maria Pedro for her work will be used as the backbone for the model design in this report. However, significant changes will be made to tailor the model to the unique characteristics of this particular case study. These will be discussed further in Chapter 3.

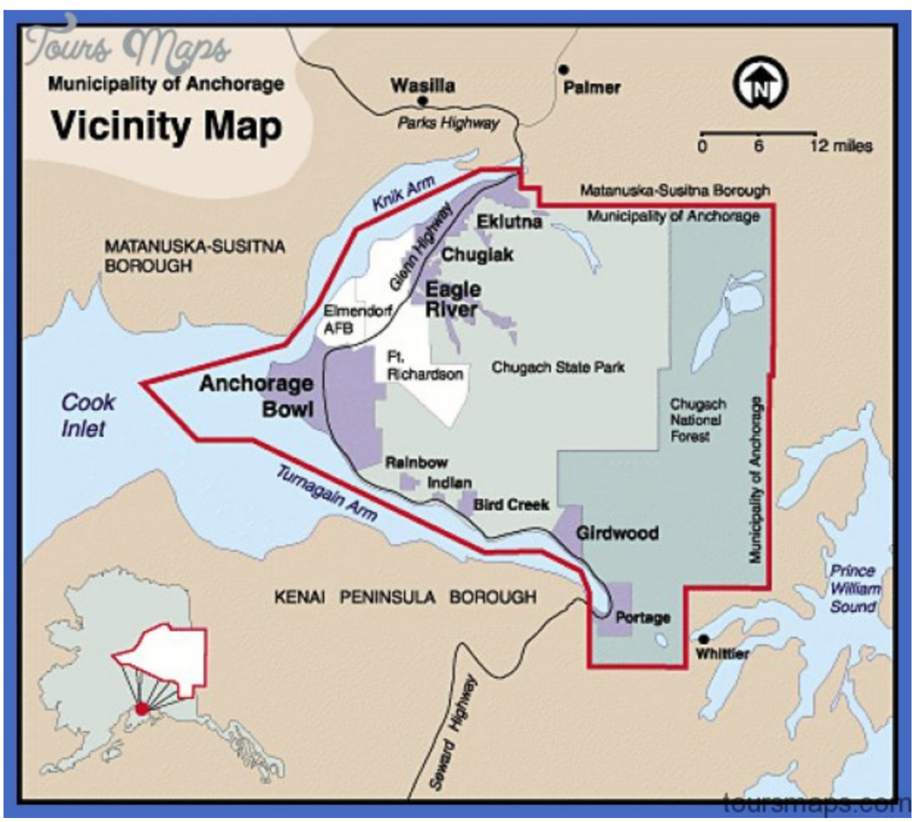


Figure 2.13: Map of the municipality of Anchorage, Alaska [109].

3 Methodology

3.1 Introduction

To understand the barriers to charging infrastructure expansion in Alaska, a three-pronged approach was chosen which seeks to understand the problem from multiple perspectives and viewpoints. The Municipality of Anchorage (henceforth MoA) was identified as a case study for this project as it is the most densely populated area of Alaska, has the highest penetration of electric vehicles in the state outside of Juneau, and has been gathering significant interest in electric mobility in the past few years. Firstly, stakeholder interviews were conducted to identify commonalities and differences in opinion between the major players in the Alaskan EV infrastructure landscape regarding the current status of public charging infrastructure in Alaska and the necessary next steps which need to be taken to promote electric mobility. Section 3.2 will outline the interview process and identify which participants were secured for this study. Appendix A contains the questions that were asked of each stakeholder type. Secondly, a survey of MoA drivers was distributed to understand day-to-day and recreational driving behaviour of residents and their preferences regarding charging infrastructure. Section 3.3 will present the survey in further detail and the list of questions is available in Appendix B. Finally, an agent-based model of the Municipality of Anchorage was developed to understand driver mobility, EV load, and current and future utilisation of the public charging network. Section 3.4 gives an overview of the model and defines the variables within it. Afterwards, Section 3.5 gives an account of how the model environment was rendered, outlining the source data and assumptions used. Section 3.6 describes the characterisation of the agents within the model; as a function of their characteristics, a definition of the agent's behaviour in a given simulation is provided. Finally, Section 3.7 lays out the scenarios consideration process.

3.2 Stakeholder interviews

3.2.1 Overview

The EV landscape, for the majority of Alaska, is still in its infancy. The prospect of transport electrification and expansion of the EV fleet is a topic that has only begun to be discussed in the MoA within the last few years. Before then, early adoption of electric vehicles has occurred mainly through word-of-mouth, with limited policy or regulatory interest in the matter. In 2020, the state government, specifically the Alaska Energy Authority (AEA) , promoted the creation of the Alaska EV Working Group, which is a coalition of stakeholders that meets quarterly to discuss the issues surrounding EV adoption and public charging infrastructure in Alaska. It was from these stakeholders that interviewees were selected, in an attempt to represent the wide breadth of players within the electric mobility landscape and specifically those operating in the MoA.

3.2.2 Goals and approach

For the purposes of this study, the goal of the interviews were to understand the viewpoints of an eclectic group of stakeholders within the EV environment in the MoA; these viewpoints had the potential to influence the types of scenarios presented in the agent-based model. As a result of the limited time frame of the project, a total of 5 interviews were conducted, each with a different stakeholder type. Interviews were procured with: a private charging station installer, a utility representative, a state energy agency representative, an elected state representative, and 3 local researchers.

The interview was designed to begin broadly, discussing the importance of transport electrification to meeting climate goals, and worked into more detailed questions regarding the barriers to EV adoption and expansion of fast-charging infrastructure. Recent developments such as the rate design modification proposal and other potential policy solutions were discussed. The interview concluded with questions on the roles of different agencies in spurring charging infrastructure investment and the importance of modelling to make calculated investment decisions. The general interview flow is defined below, although it should be noted that the interviews were discussions and sometimes did not move according to this exact format. In addition, each interviewee had supplementary questions which were specific to their area of expertise. The exact list of questions asked to each interviewee is listed in Appendix A.

1. What is the importance of transport electrification in meeting climate goals?
2. What are the barriers to EV adoption in Alaska?
3. What are the barriers to public charging infrastructure expansion in Alaska?
4. How has existing policy been effective?
5. What other policy solutions are needed?
6. Who should be responsible for spurring the growth of infrastructure and EV penetration?

3.3 Driver survey

3.3.1 Overview

An online questionnaire was developed with the main goals of understanding driving behaviour and charging preferences, to potentially use as input into the agent-based model and as a reference for future policy-making decisions. The survey questions were heavily influenced by Philipsen et al. [6]. The logic and flow of the driver survey is presented in Figure 3.1.

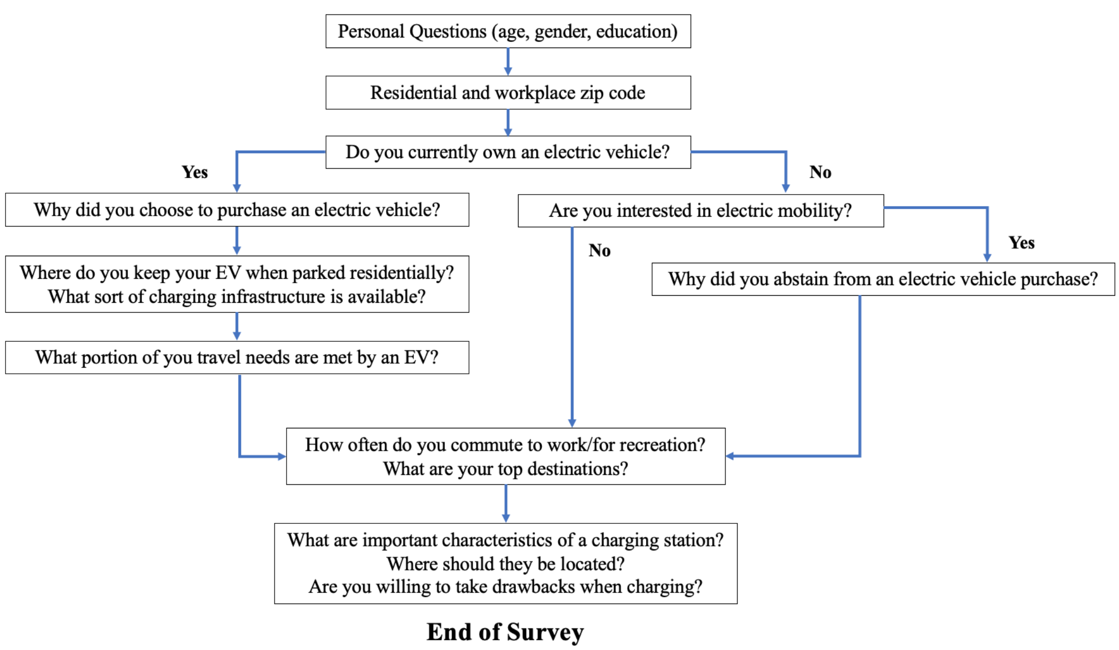


Figure 3.1: Flow and logic of MoA driver survey.

3.3.2 Questionnaire

The inclusion criteria for survey participants were being over the age of 18 and a resident of the Anchorage municipality. The survey consisted of three main sections. Firstly, personal information was collected regarding age, gender, education level, residential/workplace zip code, and whether or not the individual owned an EV. Specific questions would then become visible depending on the response to the EV question. Secondly, travel behaviour information was collected, including travel frequency and popular destinations. Lastly, questions about charging preferences rounded out the survey. The logic-based questions and questions regarding travel behaviour and charging preferences are described in further detail below. As a general rule, any questions with a 6-point Likert scale provided an ”other” option aside from the given criteria which the participant could specify.

Logic-based questions

The question of EV ownership introduced logic which would either redirect an individual to answer more personal questions regarding their own EV use, or a question asking if they are interested in electric mobility and potentially owning an EV in the future. If the individual does not own an EV and is interested in electric mobility, they are redirected to a question with a 6-point Likert scale ranging from ”no importance” to ”utmost importance” on why they have currently **abstained** from an EV purchase. The evaluation criteria were: (1) High upfront cost, (2) Lack of public charging infrastructure, (3) Range anxiety, and (4) Cold weather performance. If the individual was an EV owner, they were redirected to a question with the same 6-point Likert scale regarding their reasons **for** purchasing an EV. The evaluation criteria for this question were: (1) Air quality concerns, (2) Carbon emissions, (3) Lower operational costs, (4) The driving experience (responsiveness, silence, etc.), (5) Tax incentives, or (6) Convenience of residential charging. Additional questions in this section included the parking situation at the residence (which is important to consider in the winter) and questions regarding what portion of driving needs are met by the EV.

Travel behaviour

All groups were then redirected to the second section, which regards travel behaviour. The questions in this section ask about commuting frequency to work and for recreation during a typical week in the summer (May - September) and the winter (October - April). Additionally, the locations of the top 5 destinations for recreation and the frequency of visitation (at any scale) were inquired.

Charging preferences

The final section of the survey regarded charging preferences and contains 3 questions, all of which have a 6-point Likert scale. The first question asks about the importance of various locations to becoming site hosts for chargers. The options are: (1) Fuelling stations, (2) Workplaces, (3) Shopping centres, (4) Leisure centres (hotels, recreational areas, etc.), and (5) Educational institutions. The second question asks about the importance of various characteristics of a charging station, specifically: (1) Dual use, (2) Reliability, (3) Accessibility, (4) Habit compatibility, (5) Cost parity, (6) Personal safety, and (7) Vehicle safety. These characteristics were defined for the respondents, and are summarised in Table 3.1.

Table 3.1: Characteristics of a charging station considered in the driver survey.

Characteristic	Description
Dual use	Combining charging with a secondary activity, such as shopping.
Reliability	It is not difficult to find a charging station and there are no errors during operation.
Accessibility	Charging stations are centrally located and easy to access.
Habit compatibility	It is already habitual to visit the location and there is no need to acclimatise.
Cost parity	The cost of charging is comparable to the fuelling cost of an ICE vehicle.
Personal safety	There is a sense of safety from crime as the vehicle charges.
Vehicle safety	It is not threatening to leave the car to charge at the location.

3.4 Model description

An agent-based model consists of three major components: the environment of the model, the composition of grid cells (henceforth named "patches"), and the inhabiting agents. The agents are entities which exist inside the environment of the model, moving between grid cells and interacting with one another. Their behaviour is influenced by all the elements within the model: their personal characteristics and the characteristics of other agents, the properties of the grid cells, and the parameters set by the modeller. This section will focus on the parameters which determined agent movement within the model during a simulation.

The software that was used to develop the agent-based model is Netlogo [110] because of its simple programming language, extensive documentation, and a wide variety of example models. Additionally, as the model required the use of geo-spatial data to accurately represent the MoA environment, the user-friendly interface that NetLogo provides with QGIS [111] is further evidence of its usability for this particular project. As mentioned at the end of the literature review, the basic framework for the model consisted of the backbone of an agent-based model developed by a previous master's student of the Sustainable Energy Futures program, Maria Pedro. Her model characterised residents of Swindon Borough (UK), developing specific schedules using resident characteristics to simulate the impacts of EVs on the local power network [81]. The design aspects of the model which served as an example for this project are:

- The methodology and functions to import shapefiles and render the model environment within NetLogo.
- The functions to import and read Microsoft Excel [112] csv files which characterise agents into NetLogo.
- The framework for developing agent schedules and proper actualisation of the simulation.

While the backbone of the model was very similar in design to the one produced by Maria, important aspects of the environment, agents, and schedules were modified to fit the case study presented in this report. Specifically, these were:

- The prior model used a straight-line approximation when agents moved between locations. However, as the MoA has a boomerang shape, the agents needed to be restricted to movement along the road network. This also required a unique way to calculate the distance between locations, as NetLogo inherently only contains the functionality to calculate straight-line distance.
- In the prior model, agents would drive to the nearest charging station, and if it was occupied,

would drive to the next nearest available one. With the state of the existing infrastructure in the MoA, which is minimal, this approach is not realistic. New charging logic was developed that more accurately represents a residents' decision-making under such circumstances.

- A new weekend destination schedule was developed as many residents in Alaska enjoy hiking. As such, hiking destinations within the MoA were incorporated into the model and into the agents' travel plans on the weekend.

3.4.1 Model overview

The goal of the model is to determine the EV load of drivers in the MoA and the utilisation of the public charging network based on the travel behaviour of electric vehicle drivers for a typical weekday and weekend using the current and potential future fleet of EVs. The differences in energy use by vehicles in the summer and winter were also considered.

First, the boundaries of the environment were set as the physical border of the MoA, within which the 5-digit zip code delineations were imposed. Further additions, such as roads, residential areas, workplaces, and schools were imported, which will be discussed in greater detail in Section 3.5. Importantly, the existing charging stations as well as those approved by the recent allocation of VW-settlement funds by the Alaska Energy Authority (AEA) were deployed. These charging stations would be those available to all agents if they required charging during their daily routines. Finally, the agents were given characteristics such as household type, number of vehicles, and occupation, which would determine their schedules and subsequent behaviour during the simulation of a typical day. The schedules and agent behaviour is discussed in more detail in Section 3.6.

In this particular case, half-minute time-steps were set based on the the representation of the MoA within the model framework; specifically, the actual real-world distance between patches, and an assumed average driving speed. A description of all calculations made for the model is available in Appendix C. Figure 3.2 gives a high-level overview of the model initialisation, main procedures, and the resulting data, describing the basic commands that guide an agent's behaviour.

3.4.2 Model state variables

Table 3.2 identifies the state variables which govern the movement of the agents within the agent-based model. The *SOC-static-drop* parameter is what constituted the difference between a summer and winter simulation, as the static drop in charge was set to zero in the summer. The exact calculation of the state variables is described in Appendix C.

Table 3.2: State variables of the agent-based model.

Variable name	Description	Value	Static?
Tick	Time-instance within the model	0.5 minute	Y
SOC-drop-patch	Charge consumed when driving per time instance	0.25%	Y
SOC-static-drop	Charge consumed while idle per time instance	0.005%	Y
Charging-speed-L1	SOC gained when charging at L1 charger	0.02%	Y
Charging-speed-L2	SOC gained when charging at L2 charger	0.2%	Y
Charging-speed-L3	SOC gained when charging at L3 charger	0.8%	Y

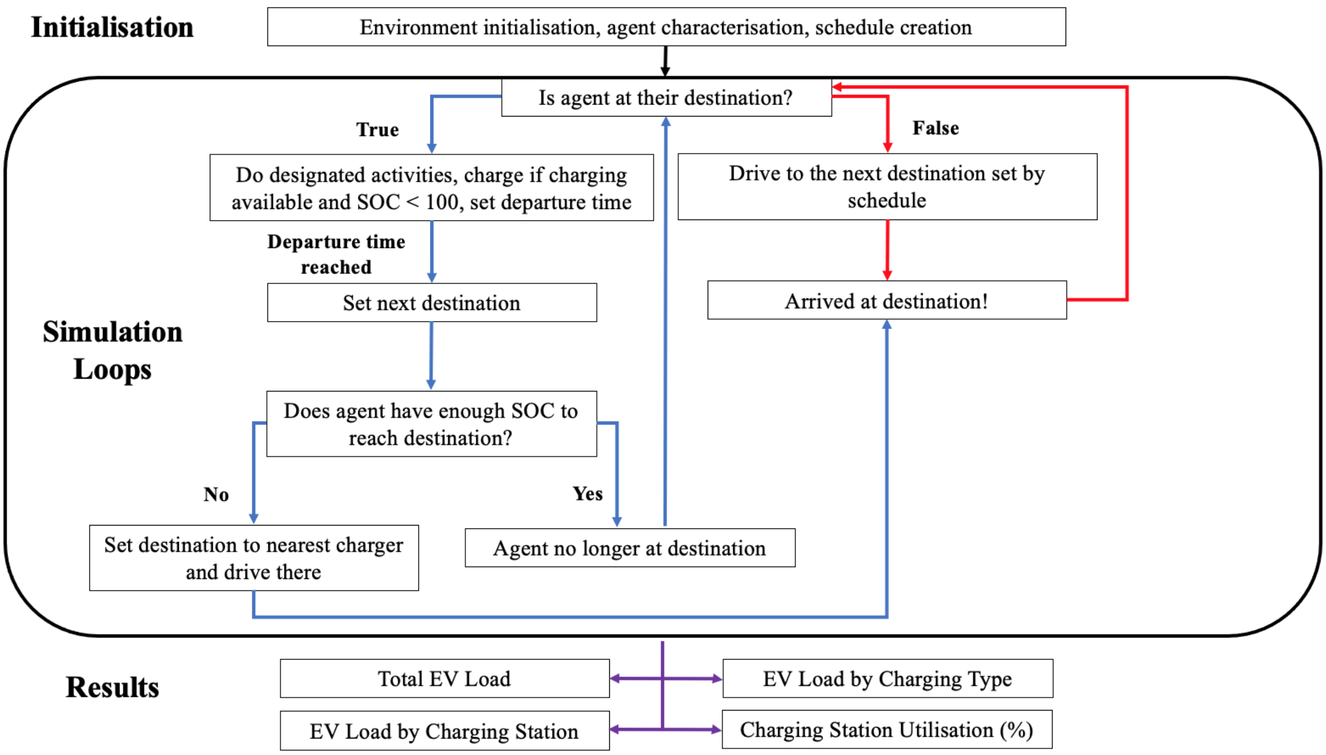


Figure 3.2: Overview of agent-based model logic.

3.5 Model environment

3.5.1 Layout

The environment of the model was created entirely using online data hosted by the Municipality of Anchorage supplemented by datasets generated by the graduate student from publicly-available information. The GIS datasets are managed and updated through a partnership between municipal departments and the Geographic Data and Information Center [113]. Firstly, a general boundary of the MoA was rendered, after which zip code delineations were overlaid and color-coded. The important data sets which were accessed comprised of: residential areas, land-use areas (a subset of which would become workplaces), the road network, and schools. The publicly-available data was supplemented with the trailhead locations of the 10 most popular hikes around the Anchorage area (validated by responses given in the driver survey) and data of currently installed and approved charging stations. A total of 11 charging stations were considered for the baseline scenario, 9 of which are currently accessible and 2 which plan to be installed in 2022. Each patch was thus assigned a parameter to determine its location (zip code) and its purpose (residence, workplace, street, hike, or charger). These delineations were made clear through color-coding and resulted in a realistic representation of the MoA, as seen in Figure 3.3. The distribution of charging stations and an indication of distance within the MoA is visualised in Figure 3.4. Three Bears Alaska is unique as its a single station split into 2 as it has multiple ports of different charging speeds (1 L2 and 1 L3), which was not possible to assign to a single station within NetLogo.

Figure 3.3: Comparison of NetLogo and QGIS rendering of the Anchorage Bowl within the MoA. Zip codes are not color-coded in QGIS and only the outlines of land-use areas are color-coded in NetLogo.

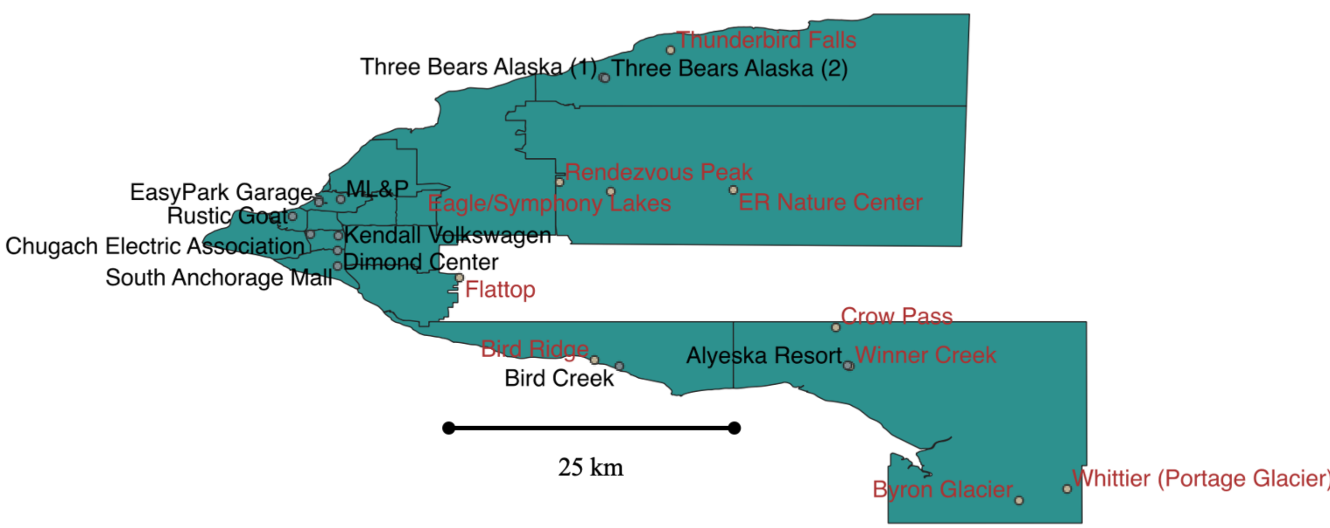


Figure 3.4: Locations of charging stations (black) and hiking areas (red) in the MoA considered within the agent-based model. Bird Creek is a charging station mentioned by Tesla as a site of interest, and is considered in one of the modelled scenarios.

3.5.2 Patch state variables

The variables defining the patches within the agent-based model are static for all cells except those representing chargers. The chargers are defined by their name, charging speed and the number of available ports. The status of a charging station is dynamic with each time-step, and depends on the number of EVs charging at that station.

A unique configuration was required for patches representing streets to allow agents to move across them. The **nw extension** of NetLogo allows the formation of a network through links, however links can only be created between turtles (called nodes) and not patches. Thus, producing a navigable street network required the following: (1) first, certain patches were assigned as streets; (2) then, each street patch would **sprout**, or generate, a street node which would "sit" on the patch; the street nodes would hence mimic the street patches; (3) finally, each street node would create a link with the two nearest other nodes, thus creating a network. Subsequently, every patch within NetLogo is assigned a parameter named *node-nearest-street* which represents the nearest street node by straight line distance, used for calculating distance within the model. A comprehensive list of state variables for patches is presented in Table 3.3.

Table 3.3: State variables governing patches of the agent-based model.

Variable name	**Description**	**Domain**	**Static?**
zipcode	Zip code its contained in	99501, 99502, etc.	Y
residence?	Identifies residential areas	True/False	Y
street? and street-node?	Identifies streets (patch or node)	True/False	Y
centre?/commercial? industrial?/centre?/school?	Identifies workplace area or schools (school can be either)	True/False	Y
trailhead?	Identifies trailhead	True/False	Y
node-nearest-street	Identifies the nearest street node to a patch	single patch identifier	Y
charger?	Identifies charging station	True/False	Y
charger-name	Identifies location of charging station	Dimond Mall, Alyeska, etc	Y
num-charging-ports	Sets number of available charging ports at charging station	whole number	Y
charging-speed	Identifies the charging speed of charging port	L1/L2/L3	Y
num-EVs-charging	Sets the number of EVs occupying a charging station	$\leq$ num-charging-ports	N
charging-demand	Power drawn from a charging station	kW	N

3.6 Model agents

3.6.1 General resident characteristics

The total population of the Municipality of Anchorage was described using the public dataset of population estimates provided by the MoA Department of Labor and Workforce Development (Figure 3.5). The latest estimates of 2021 along with 5-year updates are available, and can be accessed within the model.

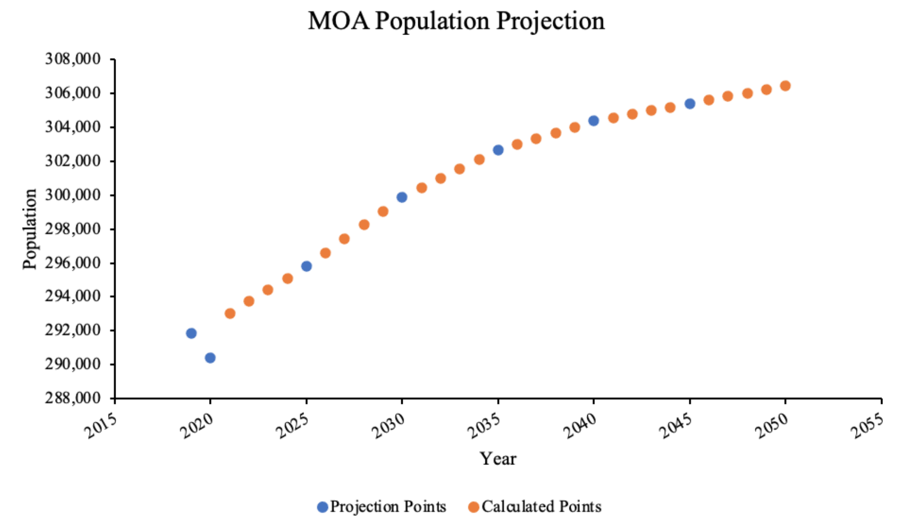


Figure 3.5: Annual extrapolation of MoA population using publicly-available data [114].

However, only those aged 19+, using demographic proportions available from the most recent 2019 ACS estimates of the U.S. Census [115] are actually initialised within the model. This is done to represent only the subset of the population which can be guaranteed as drivers. This subset of residents is distributed through the residential areas within the MoA using the zip code population distribution proportions provided by the 2019 ACS estimates (Figure 3.6). As a result, approximately 195,000 residents are initialised for the 2021 simulation year.

Although there are numerous potential characteristics which could identify an agent, only those that played a major role in defining daily schedules were considered (Table 3.4). These were: employment status, worker type, household type, and the number of cars owned. The worker type was the link between the land-use areas defined for the Anchorage municipality environment and the employee agents that populated it. The household type determined the presence or absence of dependent children and the age bracket of the household. The household delineations, again retrieved from the 2019 ACS estimates, were: Family with kids, Family with elderly, Living alone, and 65 and older. The number of owned vehicles is an important metric as it was the major prerequisite for electric vehicle ownership eligibility.

A second set of agents within the model are the street nodes, whose initialisation was described in the previous section. Street nodes are not residential agents, carrying none of the characteristics described in Table 3.4, and do not move around the model environment nor interact with other agents. This set of agents, however, is important because their initialisation allows for the movement of drivers to be restricted along the street network. The network extension contains specific functions that allow calculation of paths through the street nodes, always finding the shortest path between two points. The calculation of the path in turn allows for the movement of drivers to be restricted to the proper patches, and furthermore gives an accurate calculation of the loss of charge for an electric vehicle.

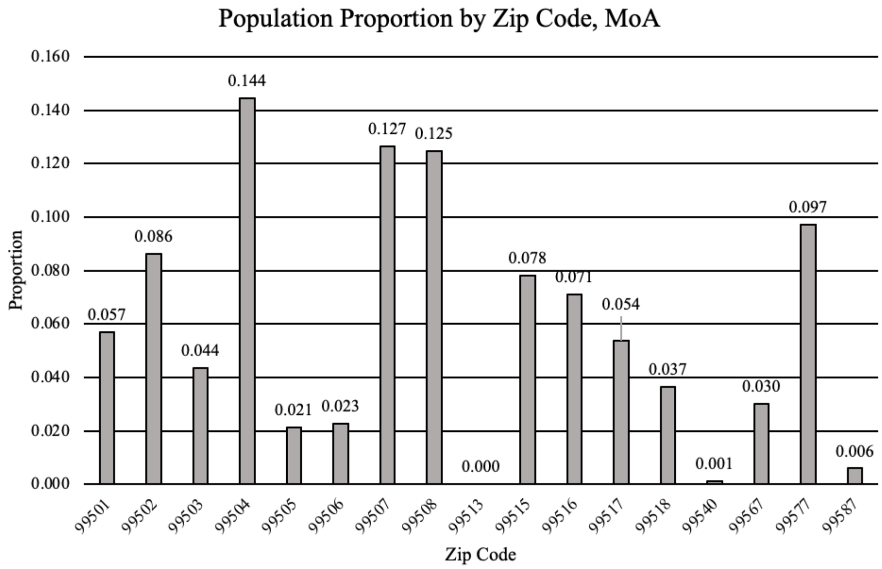


Figure 3.6: Population proportion of the Anchorage municipality allocated by zip code area according to 2019 ACS estimates of the U.S. Census [115].

Table 3.4: Initialised variables of agents within the agent-based model.

Variable	Description	Source
housexy	House coordinates	2019 ACS estimates (U.S. census) [115]
is-worker?	Boolean determining employment	MoA labor statistics [114]
household-type	Determined household type	2019 ACS estimates (U.S. census)
with-kids?	Set true if household-type = "Family with kids"	Calculated within model
num-vehicles	Number of vehicles available	2002 Anchorage Household Travel Survey [116]
employment	Sets worker type based on land-use areas	MoA labor statistics
EV-driver?	Identifies EV drivers	Vehicle registration data trends [117]
commuter?	Identifies drivers from Matanuska-Susitna Borough	Alaska DMV Data obtained from Alaskan researchers
nearest-street	Identifies nearest street node to current location	Set dynamically within model
range-anxiety-factor	Sets state-of-charge limit for agents	Set statically within model
residential-charge?	Determines if agent can charge at home	Set statically within model
workplace-charge?	Determines if agent can charge at workplace	Set statically within model

3.6.2 EV drivers and fleet

The number of EV drivers within the MoA present for a given simulation year were approximated from the Anchorage Department of Motor Vehicle (DMV) data visualised by the Chugach Electric Association (MoA utility) [117], and only BEVs were considered. From the plot an approximation for the annual growth rate was set at 67 vehicles with the number of initialised EVs during a 2021 simulation year being approximately 225 vehicles. The growth rate is assumed to be constant for future years. Commuters from the Matanuska-Susitna Borough (MSB), a community north of the MoA, were also considered within the model, as the Alaskan researchers cited that there is a good portion of their residents which are employed in the MoA; additionally, recreational destinations, especially Girdwood/Alyeska, are also popular amongst MSB residents. The number of EVs in the MSB in 2021 was approximately 70 vehicles, all of which are assumed to commute to the MoA for work during the weekday. However, only a subset of the total EVs choose to visit a hiking location on the weekend. Travel behaviour of commuters is described in further detail in Section 3.6.4.

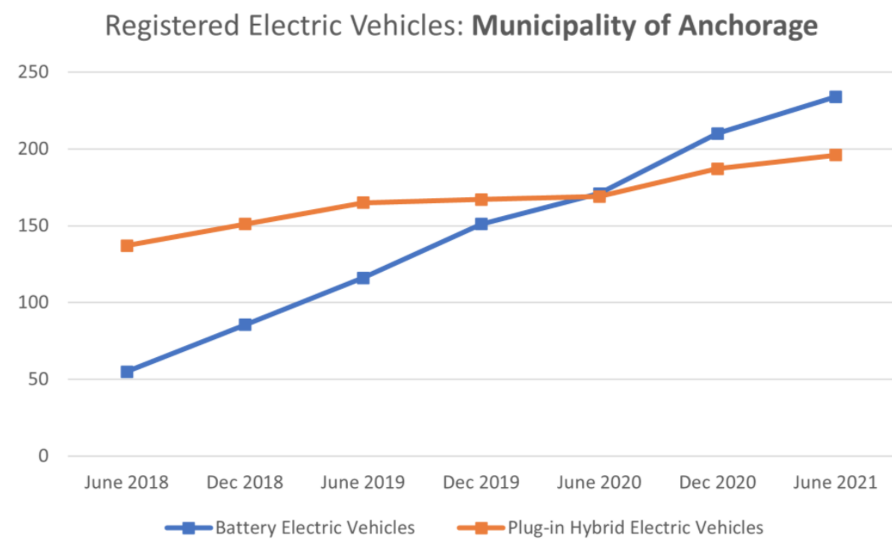


Figure 3.7: EV Growth in the MoA. Taken from Chugach Electric Association [117].

The residents which are eligible to become EV owners are those that have 2 or more vehicles and were not members of the "65 and older" household type. Although retired individuals are likely to become early adopters because of their simple lifestyle and lack of long-distance travel, these individuals were not considered for the purposes of this study. The total number of EV drivers was subdivided into the separate zip codes using the general population proportions obtained from the 2019 ACS estimates, at which point allocation to individuals that fit the prerequisites for adoption was random.

For simplification purposes, a single standard was chosen for the EV model present in the simulation. A Chevy Bolt was selected due to its popularity in Alaska [63]. Although a typical Chevy Bolt has a battery capacity of 60 kWh, as most Alaskans purchase secondhand vehicles, a reduced capacity of 54 kWh was set within the model using an average annual battery loss of 2.3% for a 2017 Chevy Bolt [63]. For simplification, vehicles were considered to drive at a constant speed of 30 mph, as this allowed for an approximate time-step of 0.5 minutes per tick.

Due to a lack of public charging infrastructure in the MoA, at was assumed that any resident assigned as an EV driver would have access to residential charging. 68% of residents were assigned level 2 charging and 32% level 1, which were values obtained from driver survey results (section 4.2.1). Additionally, an option to set workplace charging availability is present within the model; however, this infrastructure is severely limited within the MoA and it was assumed that no residents had access to workplace charging in the baseline scenario.

Finally, each EV driver was randomly assigned a range anxiety factor which arbitrarily ranged from 15% - 30% of their total state-of-charge. If the remaining charge upon reaching a destination that was not a hike was expected to fall below this value, an EV driver would choose to look for a charger.

3.6.3 Initialisation

Upon rendering the environment, the model agents can be initialised. Each agent is initially placed randomly into a residential zone within their assigned zip code area. Residents are then characterised by their employment, household type, and number of vehicles. EV owners are then determined and assigned a state-of-charge (SOC) and a random range anxiety factor from 15% to 30%.. Residents with level 2 residential charging begin with an SOC of 100, while the rest of the agents (those with level 1 infrastructure or commuters) begin with an SOC of 75. This was done because, due to minimal available public charging and no workplace charging, it cannot be assumed that an individual can recuperate a full charge on residential Level 1 charging alone. While MoA residents are first initialised, then characterised, all commuters (n=70 in 2021) are right away initialised as working EV drivers with no kids and no access to residential charging (as their actual home is outside the MoA). All MoA residents are initially generated to create a full distribution of potential EV drivers; however, only EV drivers remain present for the simulation run as they are of primary interest to the study and elimination of the majority of residents significantly reduces the model run-time. Furthermore, initialising the entire population gives the opportunity for future simulations with a higher penetration of EVs. The model is set up to begin the simulation at 5 am as the vast majority of trips within the MoA begin after this time [116].

3.6.4 Travel behaviour

As the focus of the model was to understand the impacts of travel patterns on public charging station utilisation, the schedules of agents were meticulously defined. The 2002 Anchorage Household Travel Survey [116] was the source of travel data for the MoA, and included information on trip purpose and trip departure times, which were the determining parameters of scheduling functions within the model. The charts used to determine schedules are available in Appendix C. As determined by the report, the main travel purposes for residents with personal vehicles were, in order of decreasing frequency, to/from work travel, to/from school travel, shopping (commercial area), and recreation. As such, weekday travel was governed primarily by employment and household characteristics, with no time for recreational activities, which were reserved for the weekend; the exception to this was if an agent was unemployed. This section gives a description of the weekday schedules for the different agent types within the model as well as the general weekend itinerary applied to all agents.

Weekday: employed agents

All employed agents begin the simulation at their home location, designated by the *housexy* variable. Those with kids set their first destination to the nearest school to their home, and set a departure-time between 7 and 8 am (between ticks 240 and 360). Upon arriving to school, they are given a 15-minute window to drop off their kids, after which they travel to their designated workplace. If the agent does not have children, they travel directly to their workplace from home, with their departure time set as a normally distributed variable between the hours of 5 am and 11 am (ticks between 0 and 720) with the mean being the peak travel hours of 7-8 am.

If an agent has kids, they leave work between 2 and 3 pm (ticks 1080 and 1200) to pick up their children, then either go back home or go to the nearest commercial area. This is set arbitrarily by a probability value, with a 30% chance of going to a commercial area and 70% chance of going directly home. Agents without children leave work between 3 pm and 8 pm (ticks 1200 and 1800) and have the same probability of choosing a commercial area or home to travel to. All agents not home by 9 pm for any reason are forced to return at that time.

Weekday: unemployed agents

All unemployed agents begin the simulation at their home location, designated by the *housexy* variable. Those with kids follow the same itinerary as employed agents with regards to picking up and dropping off children, however upon dropping of their children, 30% go to the nearest commercial area, while the rest go home. Upon picking up their children from school, if they have already been to a commercial area, they go straight home. Otherwise, they have a 30% probability once more of going to the nearest commercial area.

Unemployed agents without kids have three options: go to the nearest commercial area (30% chance), go on a hike (40% chance), or stay home (30% chance). The probability values are again set arbitrarily; in any case, all agents are forced return home at 9 pm.

Weekend: all agents

All agents during the weekend follow a similar itinerary to those of unemployed agents without kids during a weekday. However, the probability of going on a hike increases arbitrarily from 40% to 60%, with the resulting probability of remaining home dropping to 10%. Commuters, on the other hand, have a 20% probability of staying home (which corresponds to not driving to the MoA), a 40% chance of driving to Girdwood/Alyeska for recreation (to account for its popularity), and a 40% chance of choosing a hiking destination randomly. These values were chosen arbitrarily.

3.6.5 Charging behaviour

As EVs must endure a harsh climate when operating in Alaska during the winter, their performance and, as a result, the charging behaviour of their drivers, will be unique. The cold weather performance of an EV is considered with the *SOC-static-drop* parameter, which is set to 0 for a summer simulation and 0.005% for a winter simulation. This value corresponds to a drop in the state-of-charge when a vehicle is idle from using power to maintain the temperature of the battery. This factor is also considered in the amount of SOC gained during charging. During the winter simulations, the charging speed at a given charger will equal the raw charging speed with *SOC-static-drop* subtracted. This static drop in SOC is assumed to be known to all EV drivers in Alaska and is inherent in their range anxiety. Hence, when planning trips, EV driving agents will consider whether a particular trip to a destination will drop their state of charge to below their range anxiety factor; if it does not, they will drive to the destination; if it does, they will decide to charge first. The only exclusion to this rule is for agents travelling to a hiking destination. Such agents require their state-of-charge to be sufficient for a return journey. However, this calculation is run whilst they are at a charger, and in the case of a winter simulation, does not account for the loss of charge when parked. This was done to simulate imperfect decision-making by EV drivers.

When determining a location to charge, the agent will first search for the nearest unoccupied charging station, which is any station where the number of charging ports (set by *num-charging-ports*) is greater than the number of vehicles currently charging there (set dynamically by *num-EVs-charging*). If such a station exists, they will drive there. If there are no such stations (all stations are fully occupied), the driver will find the nearest occupied station and drive to it.

Once an agent has arrived at a charging station, they must reassess the occupancy of the station, as well as determine if other vehicles are already waiting to charge. Within the model, there is no mechanism by which an agent can ascertain the occupancy of a station whilst en route, due to difficulties in implementation within the model. The logic by which a vehicle at a charging station determines the next course of action is outlined in Figure 3.8.

If an agent arrives and a charging port is unoccupied and there is either no queue, they will begin charging (by setting *charging?* to true), which sets a port as occupied (adding 1 to *num-charging-ports* of the station patch), until their state of charge has reached an acceptable point (set by *acceptable-SOC*), the value for which depends if the destination is a hike or not (as discussed previously). At this point, the agent will stop charging (by setting *charging?* to false) and free up the charging port for other agents (subtracting 1 from *num-charging-ports* of the station patch).

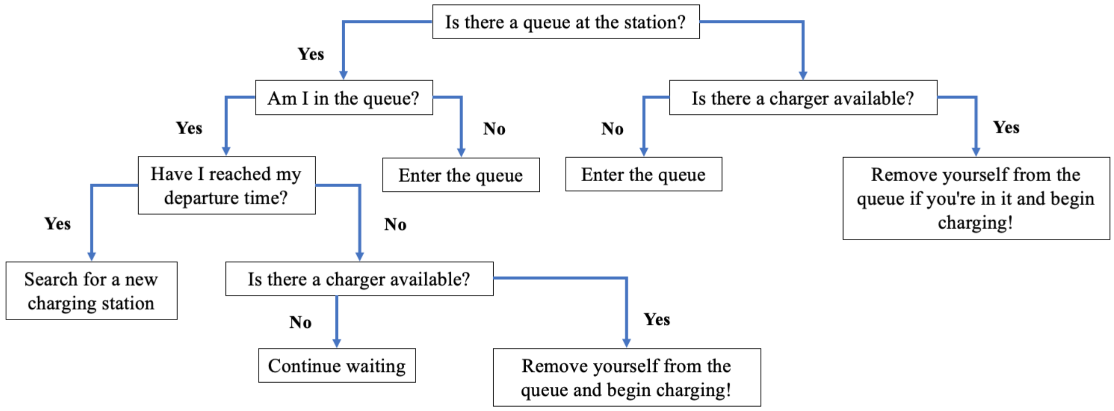


Figure 3.8: Logic for agents within the agent-based model attempting to charge.

However, if an agent arrives and all charging ports are occupied or a queue has already formed, the agent will add themselves to it and set a new departure time. The departure time is set to the current tick count plus the parameter *waiting-time*, which is set to an arbitrary value of 30 ticks (15 minutes).

For vehicles already in the queue, the vacancy of the station as well as their position within the queue is reassessed with every passing tick. If a station opens up during the waiting period, only the agent first in the queue will be able to start charging, and in doing so remove themselves from the queue. If the agent has reached their departure time before beginning to charge, they will start searching for a new station. The agent will only leave their current location if they have enough charge to reach the next available/unavailable station. If they do not have enough charge, they will remain at the station until a port becomes available and they are first in the queue. This way, a vehicle can only get stranded if they do not have enough charge to reach the first station nearest them when at a destination. All dynamic variables which control an agent's behaviour are outlined in Table 3.5

Table 3.5: Dynamic variables of agents within the agent-based model.

Variable	Description
nearest-street	The nearest street node to the current location of the agent.
destination	Sets destination of agent
destination-2	Saves initial destination of agent if not enough charge to reach it
path	A list of street-nodes between an agent and the nearest street-node of its destination.
charging?	Boolean setting an agent's charging status
departure-time	Time (in ticks) at which an agent leaves their location to drive to their destination
arrived-at-destination?	Boolean setting an agents' location reference
SOC	State of charge of the EV battery
SOC-needed	Determines the necessary charge to reach the destination.
acceptable-SOC	Determines the SOC at which to stop charging. Set to SOC-needed + range-anxiety-factor if destination is not hike-location, otherwise set to 2 * SOC-needed

3.6.6 Calculation of distance and travel path

The default function for calculating distance within NetLogo is called **distance**; however, this function calculates the straight-line distance, outputting the number of patches in a direct line between two points in the grid. As the model required agents to accurately calculate distance to properly represent the loss of charge when travelling to a destination, a unique function was designed to consider the distance travelled specifically along the road network. The logic for the new distance function, named **distance-calc**, goes as follows:

1. A function inherent to the nw extension, called **nw:turtles-on-path-to** outputs a list of turtles between two locations along a network of turtles, always finding the shortest path (shortest number of turtles). In this model, it will output the list of street nodes between two locations along the road system.
2. To begin, an agent will create a link to the nearest street node to its current location.
3. The agent will use **nw:turtles-on-path-to** to calculate the number of turtles between it and the *node-nearest-street* parameter of the destination patch, and assign it to a local variable.
4. The first two items of the list, corresponding to the agent and the nearest street node, are removed, since the distance between the turtle and the nearest street node is not considered for simplification.
5. The length of the subsequent list is returned.

When an agent is determining if it can reach the next destination, the length of the list is multiplied by *SOC-drop-patch* to determine how much charge will be required.

The function **nw:turtles-on-path-to** is also used for agent movement. Steps 1-4 of **distance-calc** are identical for this process, except, the list is assigned to the parameter *path*, after which the agent is moved to *nearest-street* without any drop in SOC. If the length of *path* is greater than zero, with each passing tick the agent will move to the first item of *path* (which is the next nearest street-node), and then remove it from the list. This ensures that before the next tick, the first item of the list is always the **next** node that needs to be reached. With each passing tick the SOC of the agent drops by *SOC-drop-patch*. Once the length of *path* is zero, the agent knows they have reached *node-nearest-street* of their destination, and they move to the actual destination patch without losing any SOC. The simplification of not considering the distance between a patch and the road network is acceptable because that distance relative to the total distance moved by agents along the road network is very small.

3.6.7 Assumptions

The assumptions implemented on the characteristics and behaviours of the agents can be summarised as follows:

- A single EV model is considered for all agents.
- Agents always chose the shortest distance to their destination.
- Driving distance **to** the road network is not considered in calculating loss of charge.
- Agents with children live nearest the school their children attend, and only frequent the nearest commercial area to their current location.
- A static loss of charge is considered for idle vehicles, which only applies to the winter months (0.005%) and for vehicles not at their residence (all agents assumed to have garages).
- Only the 10 most popular hiking locations are included in the model.
- Agents are unaware of the occupancy status of the nearest charging station whilst en route to the station. They receive occupancy information before embarking and upon arrival.
- Agents have no mechanism by which to know how long a charging port will stay occupied.
- All EV drivers have access to residential charging unless they are commuters.

3.7 Scenario creation

The scenarios considered within the model were meant to answer research questions (3) and (4) as outlined in the introduction, which are:

- What are the limitations of the existing public charging network and what interventions can improve them?
- Are there simple strategies to mitigate negative grid impacts of future EV loads?

As such, two sets of simulations were run to provide insights on these questions.

3.7.1 2021 scenarios

The 2021 scenarios consist of baseline simulations of a weekday and weekend in the summer and winter to use as a comparison prior to implementing interventions. A second set of weekday and weekend simulations in the summer and winter were then run after weak points within the charging infrastructure network were identified from the baseline scenarios. Specifically, the addition of a fast-charging station near the Bird Ridge hiking location and a supplementary level 2 charging port placed at Alyeska Resort were considered. The Bird Creek station has real-world implications as it was mentioned as a potential site of interest for charging stations by Tesla (to the Alaskan researchers).

3.7.2 2025 scenarios

The 2025 scenarios considered the impacts of continued EV growth within the MoA. The first scenario, named the baseline, investigated maintaining the same EV: charging-station ratio for the growing EV population, following the trend of placing new stations in commercial areas. The interventions employed in the 2021 scenarios will also be analysed in their effectiveness at handling an increased EV population. Further simulations analysed adding workplace charging infrastructure as a method to help mitigate peak demand in the evening. This was due to the utility representative noting that investment into smart-charging technology is not currently economically feasible. 5%, 10%, and 25% availability of workplace were modelled.

4 Results and Analysis

4.1 Stakeholder Analysis

This section presents the results from the stakeholder interviews. Although the sample size of the interviews was small, the responses obtained in the interview process are still valuable as the diversity of stakeholders was maintained. The main themes discussed during the interviews will be summarised in the following subsections, concluding with how the responses provided will influence the agent-based model implemented for the Municipality of Anchorage (MoA).

4.1.1 Barriers to EV adoption in Alaska

There was general consensus between stakeholders regarding the main barriers to electric vehicle adoption in the State of Alaska. The three major barriers noted by all interview participants are outlined, after which additional issues raised by certain interviewees are mentioned.

Considering the unique travel habits and recreational activities of Alaskan residents, a common barrier named was the lack of diverse EV models on the market. A few interviewees cited speaking directly with end users who are waiting for an electrified SUV or minivan to consider the switch, and all participants believe an availability of four-wheel-drive vehicles and trucks would significantly boost interest in EV adoption. An additional challenge lies in the EV market. As stated by the state energy agency representative, many people drive used vehicles; unfortunately, the market for used electric cars in the MoA and other areas in Southcentral and Interior Alaska is almost non-existent and shipping used vehicles from other U.S. states is costly and time-intensive. This is in contrast with Juneau, the city in southeast Alaska with the highest EV penetration in the state, which has a direct connection to Seattle, Washington and can more easily procure used vehicles from a more saturated market via the Alaska Marine Highway ferry system.

A second major barrier cited is poor public perception of electric vehicles, specifically a lack of understanding of utilisation and performance. A major concern of the public is cold-weather performance, and while there are few case studies on the topic, for most drivers the negative attitude is likely a misconception. While it certainly is a consideration in northern communities with more sever winters, such as Fairbanks, the stakeholders believe winter performance anxiety in communities such as the MoA stem from a lack of understanding and access to information on the capabilities of an electric vehicle. This issue is an important one that is of primary concern to industry and policy makers. The utility representative described a potential future program in which rate payers would have the ability to test-drive electric vehicles once per year for free; however, this would first require local car rental companies to offer electric model options for drivers, which is not yet the case. The state energy agency considers public outreach and education as a key aspect of their ongoing involvement in transport electrification. A recent development in August 2021 was an EV ride-and-drive event as part of the EV car show they co-sponsored to bring together manufacturers and prospective EV drivers in the MoA to test out different models and better understand the benefits of electric vehicles. With regards to cold climate performance, the researchers disclosed that a one-year study is currently underway to investigate the performance of electric vehicles and battery degradation in the extreme winter conditions of Fairbanks, Alaska. The results for this are expected to be provided by participants at the end of 2021 for data analysis.

The final barrier, which was mentioned by all participants as one of the most important, is the lack of available public charging infrastructure, and more specifically, DCFC stations along the travel corridor. Although it was noted that approximately 90% of charging occurs at home and general daily travel needs can be met mostly without reliance on public infrastructure, the presence of an infrastructure network does enable long-distance mobility, which is a necessity due to the large distances between Alaskan communities. It was also mentioned that fast charging speeds are essential for the electrification of large vehicles such as heavy-goods vehicles. Range reductions from carrying heavy loads in conjunction with cold temperatures will require more charging events and charging speed will need to be high, certainly higher than 50 kW as mentioned by the private installer, to maintain the same level of service. The challenges with overcoming the barrier of public infrastructure and the roles of different agencies in enabling its availability and expansion is expanded on further in subsequent sections.

Other barriers which were mentioned in discussion were:

- The existence of a unique use case of populations which live in rural areas and isolated communities. The issue of model availability is exacerbated as these areas usually lack a cohesive road system and most driving occurs using four-wheelers and snow machines, for which limited electrified options exist. Additionally, it is unclear how their limited electrical infrastructure and generation capacity would cope with the additional load from electrified vehicles.
- Transport electrification in communities with grid electricity of high carbon intensity does not address the underlying goal of reducing transport carbon emissions, and in fact exacerbates it.
- A lack of political clarity regarding the energy future of Alaska and its relationship to climate action. Currently no state climate mitigation strategy is in place, and subsequently, no plan to transition away from fossil fuel generation and ICE vehicles. The researchers believe this deters the conversation regarding EVs and their potential economic benefits.
- Alaska is characterised by low population size and low population density, which is an issue when attracting funding for infrastructure requiring high capacity utilisation (such as roads and airports). The concern is heightened when attempting to implement broad geographic coverage of a service, as is the case with fast-charging infrastructure.

4.1.2 Barriers to fast-charging infrastructure expansion

After the discussion on the barriers to EV adoption in Alaska, the focus shifted to the barriers to expansion of public fast-charging infrastructure.

The lack of a business case for fast-charging stations is cited as the most significant barrier to adoption. In the case of Alaska, the lack of economic viability is a result of a high demand charge, significant capital and installation costs, and expected low station utilisation. The high demand charge is an issue that has taken the priority with regulators in Alaska, with a proposal filed in June 2021 by Alaskan utilities to the Regulatory Commission of Alaska (RCA) which would implement a unique rate structure based on a determined load factor (set by each utility individually) for fast-charging stations, reducing the demand charge and improving the operational costs for site hosts. A positive ruling also has the potential to spur outside investment; as noted by the researchers, discussions with Tesla indicated the demand charge as their primary concern with investment into transport electrification in Alaska. Tesla also mentioned (to the researchers) their interest in placing a fast-charging station in the Bird Ridge area.

While the rate structure improves the operational costs of a charging station, investment is required to alleviate the high capital burdens of a fast-charging station for potential site hosts. A step in the right direction has been the allocation of Volkswagen (VW) settlement funds by the Alaska Energy Authority to the installation of 15 new fast-charging stations at 9 sites along Alaska's most travelled highway corridor. Each successful recipient was awarded approximately \$110,000 towards the installation of a station, which, according to state energy agency, constituted approximately 64% of the capital requirements of installation on average.

One big question considered by most participants for the future of investment into public charging infrastructure is whether to network future charging stations. Networking allows for a site host to charge a consumer for charging; data collection on station utilisation; routine maintenance, troubleshooting and repair to be performed remotely by the manufacturer; and an EV driver to determine the availability of the charger remotely. Additionally, the data collected from networked stations has added value for understanding initial station utilisation which could influence future policy-making decisions. On the other hand, it also increases capital costs significantly, which can vary widely, as much as 10-fold for a level 2 station, according to the state energy agency. Networking also requires a cellular connection, which is not available along many sections of the travel corridor. A big concern for the private installer is the high price being charged by private charging locations in the MoA, which they believe is too high, even for a level 2 station. However, the state energy agency commented that the pricing scheme, at least for publicly funded chargers, is set to a level which intends to simply recuperate the capital investment without a profit margin. While the stations approved for the VW grant funding were required to be networked for this purpose, there is extra money left over for additional stations that the state energy agency is considering to fund the installation of non-networked level 2 stations as appropriate in communities with small, islanded road systems, and areas that lack cell connectivity.

Interconnection cost is another major component of the capital investment, which is certainly an issue along the road network. However, interconnection cost can reach significant magnitudes even in urban settings. The utility representative and the private installer both identified the lack of 3-phase distribution along the travel corridor as a barrier which restricts the number of economically feasible EV charging station locations. The high costs of the station are coupled with an expected low utilisation, especially of stations located along the travel corridor, even at higher penetrations of vehicles. As mentioned in the previous section, the low population density, low driver count, and high travel distances between communities means that even with a higher penetration of EVs, travel along the corridor is simply not frequent enough for stations to be economical when considering passenger travel. It will almost certainly be the case that the value of such installations will have to come through the lens of social and network benefit instead of an expected return on investment. There may also be additional secondary revenue for the site host through increased traffic at their location.

While high capital costs are more certainly the primary barrier to the proliferation of charging stations, this issue is not unique to electric vehicle infrastructure and is a characteristic of any new technology. While a general consensus of stakeholders is that the state of Alaska is currently in too poor of a fiscal situation to directly invest in and promote new technologies, an important roadblock remains the lack of political clarity on the energy future of the state. Although the MoA has formulated a climate action plan with a high importance placed on transport decarbonisation, there is no cohesive environmental policy at a state level, which the researchers believe plays a major part in diminishing interest from industry and halts meaningful conversation about future investment. An example that was provided was that, while the maximum allowable proportion of VW funds was allocated to EV infrastructure (15%), the majority was used for improving diesel efficiency for vehicles and prime movers. While the usage of funds was left up to applicants (as long as it met usage requirements), it sets a precedent for the priorities of Alaska's energy future, which currently does not appear to be a reduction in fossil fuel reliance.

Additional barriers mentioned by the interviewees include:

- A wintertime issue of charging stations is the additional cost of maintaining operability in cold temperatures. A site host must consider the additional cost of keeping a station operational in the cold temperatures especially at low penetration of EVs.
- Land acquisition along the road network is not always a straightforward process.
- A lack of maintenance expertise in certain areas and difficult access to locations along the road network will mean that stations will likely have a lengthy downtime when issues arise.

4.1.3 Investment responsibilities

It is a general understanding amongst stakeholders that the current financial status of the state government prohibits direct investment into charging infrastructure. However, all stakeholders agree that the role of government is important in promoting new technologies, especially during the early stages. Speaking with a member of the state energy committee provided helpful insights on what the future of government policy and aid could be in the realm of clean generation and transport decarbonisation. They believe that the government has the opportunity to recognise a public good and improve the transport infrastructure, facilitate a cleaner environment, and invest in a promising new technology. The most direct way to do this, in their opinion, would be public education and creation of a basic network of charging infrastructure, which certainly address the major issues mentioned previously. In their mind, this would provide the necessary backbone for market expansion both in consumer interest and private sector investment. Unfortunately, the representative concedes that in the short-term, certainly within the next 5-year window, the state fiscal issues will not be solved, and investment is highly unlikely.

As a result, the most important question is posed; who should be responsible for spurring the expansion of charging infrastructure through investment? In the eyes of the utility representative, the utility's role should be as a facilitator, allowing the private sector to be the main instigator but providing assistance in planning and implementation. Examples cited by the utility representative include the existing financial programs to promote level 2 installations in residential, workplace, and commercial locations through a monetary credit, as well as the programs mentioned earlier for fleet operation services such as car rental companies, or Uber and Lyft. When asked about potential investment in smart-charging technology to control peak loads at higher EV penetrations (as a consideration for the high residential charging proportion), the utility representative noted that although it has been a consideration, the capital costs are currently too high and such a project is unfeasible. An additional point that is made regards the regulation of utilities in Alaska; as they are rate-regulated, large infrastructure investments must be shown to be prudent investments if the utility wishes to recover the project costs through electricity rates. The views of the utility representative indicate that the current environment does not warrant direct utility involvement, and at this stage they are focused more on barrier removal through the aforementioned programs and the utility-proposed rate design modification. Similarly, comments by the private installer considered the nature of utilities; as they are cooperatives with each customer being a member and owner of the business, direct investment into charging infrastructure at low penetrations of EVs, potentially increasing rates, would likely be viewed negatively by the majority of consumers, who drive ICE vehicles.

The position of the researchers, on the other hand, is more deterministic, as they consider the transition to electrified transport to be a "when" and not "if" issue. The role of a utility, in their mind, should be more proactive, considering the potential growth in demand and revenue and how much incentive can be provided to bring down fixed costs. An example given was to invest in charging infrastructure at the airport to promote electrification of the taxi fleet, which as a population has much more per vehicle mobility and would consume much more kWh per day than a personal private vehicle. Additionally, the role of the board of directors was highlighted in the decision-making process of a utility. The Golden Valley

Electric Association utility (which operates outside the MoA) was cited as a cooperative which is moving forward with installation of a few charging stations as a result of pressure by the board of directors. Chugach Electric Association (MoA utility) has made progress through a recently-implemented "Triple Bottom Line" policy which requires social and environmental consideration in investment decisions, but other stakeholders believe the utility has more power to wield to spur the expansion of infrastructure which would inevitably pay the most dividends to the utility and its ratepayers.

4.1.4 Summary and extracted insights

The interviews with stakeholders revealed similarities regarding the biggest challenges facing the movement to electrify transport, but also differences in how the challenges should be mitigated. It is clear, however, that the major stakeholders consider a lack of education and awareness and limited public charging infrastructure to be the two significant barriers which can be overcome through political and regulatory action. Table 4.1 summarises the considerations made by each interviewed stakeholder, highlighting their perceived barriers to EV adoption, their goals, and their actions to achieve their goals/ mitigate perceived barriers.

With regulatory change to reduce the demand charge currently on the docket with the RCA, Alaska is at an important crossroads in the movement to electrify transport. If the new rate design structure is passed, the expectation is that it will spur interest from large-scale private installers to move into Alaska and help with the expansion of fast-charging infrastructure, as the Alaska state government is in no capacity to do so. The extent to which utilities will play a role in this transition is yet to be determined; although other stakeholders consider them to be the greatest beneficiaries and hence believe they should be primary players, most utilities do not currently want to get involved. If the new rate design does not have the expected consequences, public engagement may become a key determinant of local stakeholder investment into transport electrification.

From the interviews, a few insights will be used as part of scenarios tested within the agent-based model. As the researchers mentioned the Bird Ridge area as a prospective location for a charging station, its impact on local mobility will be assessed as an intervention. Additionally, as the utility mentioned high upfront cost of smart-charging technology, investment into workplace charging as an alternative will be investigated to determine the impact on peak evening demand.

Table 4.1: Summary of stakeholder perceptions, focus, and actions.

Stakeholder	Perceived barrier(s)	Primary focus	Current action(s)
Researchers	Lack of regulatory/political clarity Lack of EV models Lack of infrastructure Public perception	Public education, EV research	Research on winter battery degradation
Utility representative	Lack of EV models Public perception Lack of infrastructure	Reduction of capital costs and demand charge	Incentives to install L2 chargers and test-drive EVs, proposal for new rate-design structure
State energy agency	Public perception Lack of infrastructure Cold weather performance	Lowering electricity costs and public awareness	Distribution of government grant funding and public education
Installer	Lack of infrastructure	Expansion of fast-charging infrastructure	Operation of recently-installed fast-charger, investigating new potential sites
State government representative	Lack of infrastructure Public perception	Spur investment, employ systems approach of sustainability in energy policy	Promoting investment into renewable energy generation, no direct action with regards to EVs yet

4.2 Driver survey

4.2.1 Participants

A total of 215 participants completed the survey, with 19 (9%) being current electric vehicle owners. Out of the 196 non-EV users, 137 (70%) indicated interest in purchasing an electric vehicle. 44% of respondents were male, 54% were female, with 4 individuals (2%) reporting as non-binary or undisclosed. The age distribution and highest education level of participants are outlined in Figure 4.1.

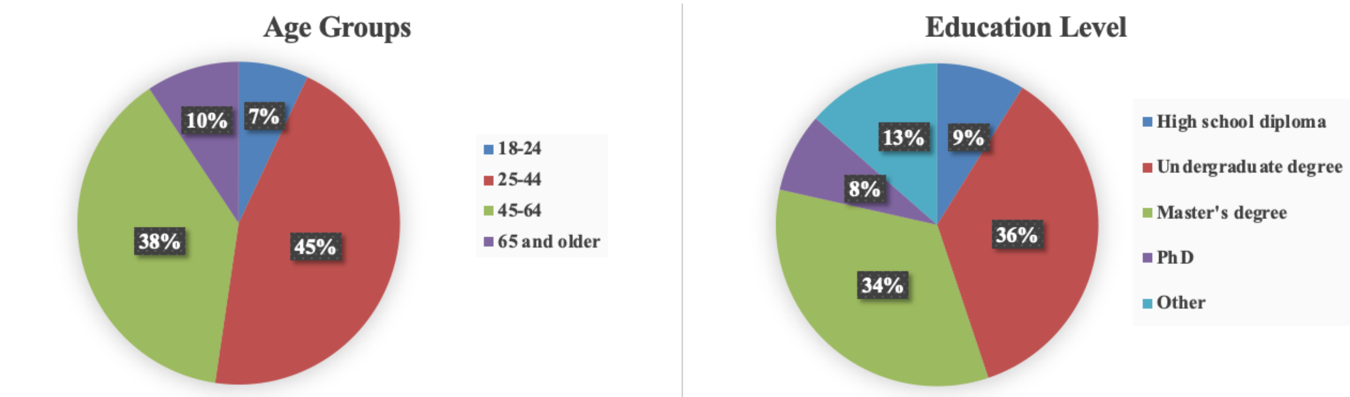


Figure 4.1: Age groups and highest education level of participants in the MoA driver survey.

From the EV users, all respondents had access to residential charging, with 13 (68%) and 6 (32%) indicating having level 2 and level 1 charging at home, respectively. Similarly, 15 (79%) participants had an indoor space to park their vehicle at home (such as a garage), while 4 (21%) parked outside. With respect to driving needs, EV users indicated that, on average, 85% of charging needs are met by residential charging, 94% of daily travel needs are met by their EV, and only 60% of recreational travel needs are met by their EV.

An important metric considered was the residential distribution of respondents to determine if the sample accurately described the population. A comparison between survey proportions and U.S. census proportions, which can be found in Table B1 of Appendix B, indicates that the sample is not representative of the population. For the analyses done on Likert scale questions, a chi-squared test was employed to determine if significant differences existed between groups. For questions specific to either EV owners or interested non-users, male and female responses were compared. For general questions to all respondents, the responses between EV owners and interested non-users were compared. Additional consideration in general questions was given to age groups.

4.2.2 Participant motivations

For those respondents who were EV owners, an additional question was asked to determine the particular motivation behind the decision to buy an EV. Similarly, for those respondents who were not EV owners but interested in electric mobility, a question was asked regarding their reasoning behind abstaining from an electric vehicle purchase. The responses were separated by sex to determine if any statistically significant differences existed between the motivations of males and females. The results for these questions are presented in Figures 4.2 and 4.3.

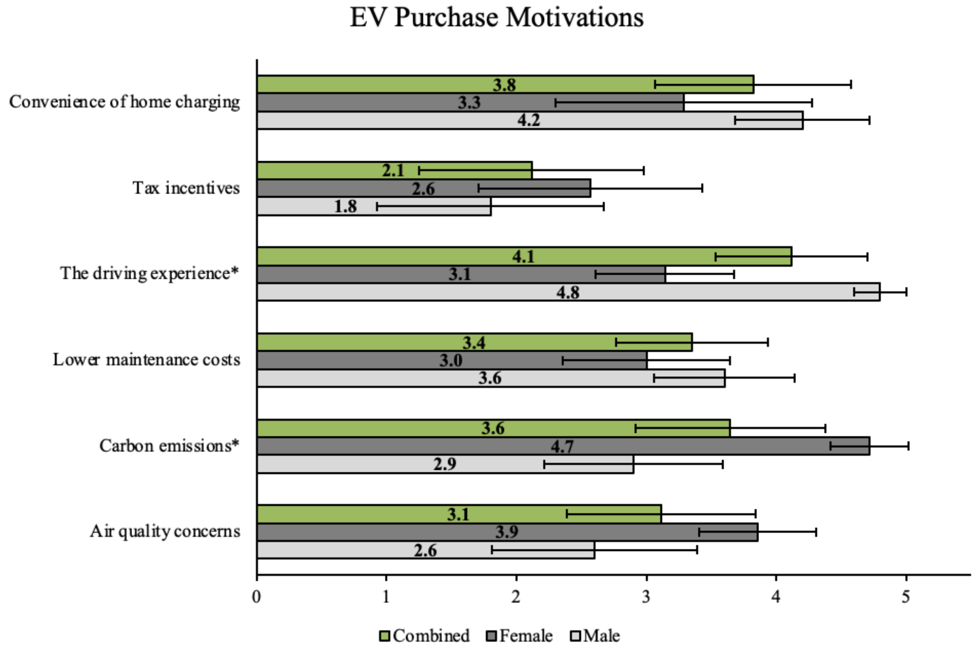


Figure 4.2: Average importance of considered factors when making an EV purchase (min=0, max=5) with 95% CI. Categories with an asterisk indicate a significant difference between the two genders.

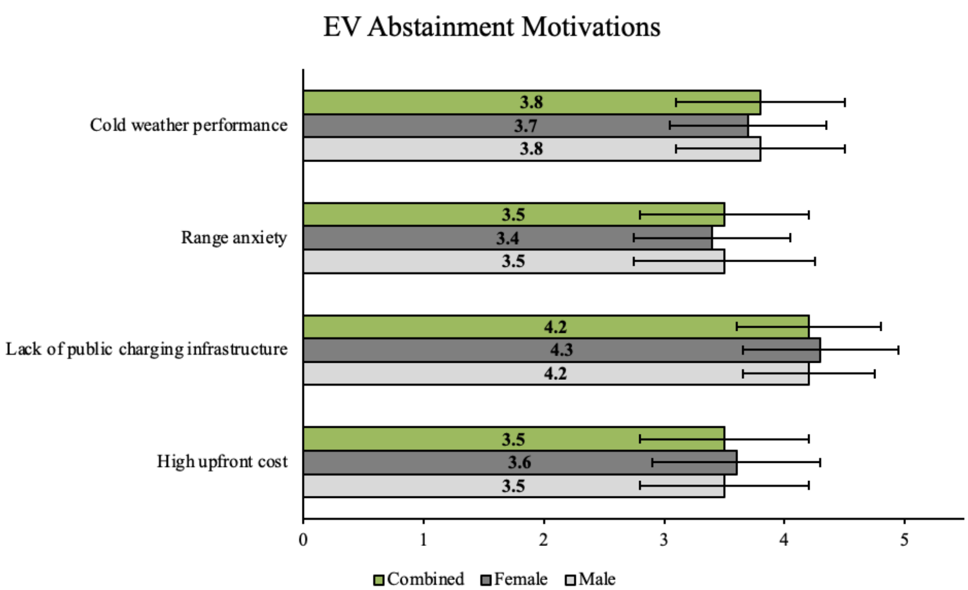


Figure 4.3: Average importance of considered factors when abstaining from an EV purchase (min=0, max=5) with 95% CI. Categories with an asterisk indicate a significant difference between the two genders.

Interestingly, the driving experience was rated the highest overall factor for vehicle purchase (mean=4.1), carried mainly by the extremely high ranking given by males (mean=4.8). For females, however, the driving experience was the second least significant consideration (mean=3.1), with only tax incentives (mean=2.6) receiving a lower score. Tax incentives was the least considered factor for both genders (mean=2.1). The top motivations for females appear to be environmental impacts, with air quality concerns (mean=3.9) and carbon emissions (mean=4.7) constituting the top two considerations; meanwhile males appear to consider the technical and economic benefits of their purchase, ranking driving experience, home charging, and lower maintenance costs as their primary motivations.

With regards to the sample of interested non-EV users, the responses between males and females were almost identical. The most important consideration was the lack of public charging infrastructure (mean=4.2), which echoes the sentiments of the major stakeholders within the transport electrification space. The other three considerations received very similar scores, with cold weather performance (mean=3.8) slightly edging out range anxiety and high upfront costs (mean=3.5 for both). A total of 24 additional responses were provided in the "Other category", each of which received either a score of 4 or 5: 7 responses (29%) mentioned the lack of servicing expertise in Alaska, and the resultant uncertainty surrounding repair and battery decommission; 5 responses (21%) related back to a lack of mobility from limited charging infrastructure; 5 responses (21%) cited a lack of model diversity to meet specific driving needs and the lack of used models in the Anchorage area; 4 responses (17%) noted the carbon footprint of EV manufacturing and the sustainability of mining rare earth metals for batteries; and the rest of the responses indicated a lack of existing urgency to replace their current ICE vehicle. The relatively high marks placed on each category, including the number of highly rated additional concerns raised by this sample of drivers shows that while charging infrastructure may be the most significant barrier to adoption, all aspects of an electric vehicles' life cycle, from upfront cost and manufacturing emissions, to maintenance and repair, to how vehicle components are reused and recycled, will need to be addressed to comprehensively see a change in attitude regarding transport electrification in Alaska.

4.2.3 Travel behaviour

An important aspect of the driver survey was to understand driving behaviour and frequent destinations of residents within the MoA. The first task was to see if any differences exist between the typical driving habits of EV users and non-users, which is depicted in Figures 4.4 and 4.5. As can be seen, the values for both work and recreational commuting are very similar, with non-EV drivers having a tendency to drive more frequently to work; recreational travel habits between the two groups are very similar. Additionally, very little seasonal difference in travel behaviour is observed, with recreational travel slightly increasing during the summer months, which is expected. Remembering that EV users identified their EV meeting 60% of their recreational travel needs, these results show that EV drivers are still reliant on their secondary ICE vehicles to meet recreational travel needs, and further supports the claim that a lack of charging infrastructure along the travel corridor is a major barrier to further uptake of electric vehicles.

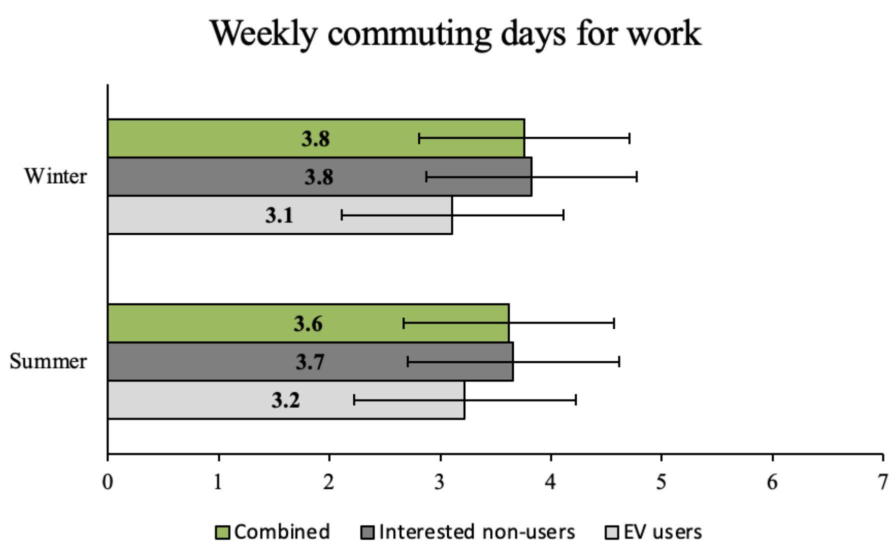


Figure 4.4: Comparison of average summer and winter weekly commuting days to work (min=0, max=7) with 95% CI.

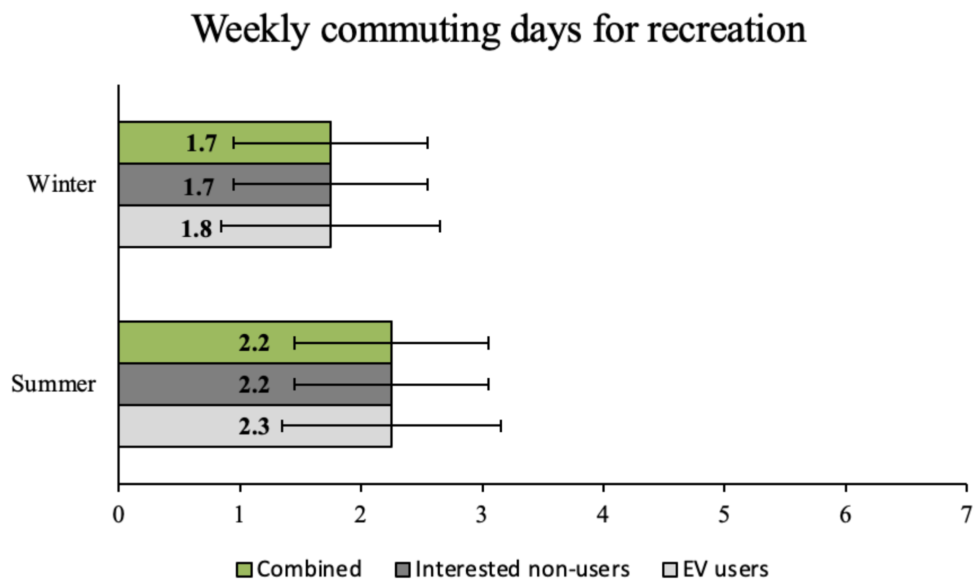


Figure 4.5: Comparison of average summer and winter weekly commuting days for recreation (min=0, max=7) with 95% CI.

Survey participants were additionally asked to list their top 5 destinations along the travel corridor and the frequency with which they travelled there. The format of responses was left to the discretion of the respondent, however all responses were annualised to allow for a sound comparison. A total of 165 responses were recorded for this question, and the destinations were split into town destinations and recreational areas. The results of the analysis is visualised in Figures 4.6 and 4.7. It is worth mentioning that "recreational destinations" are those uniquely identified as areas for activities such as hiking, camping, fishing etc. Although uniquely identified, it is highly likely that travel to the town destinations also corresponds to a recreational activity, albeit more formally or for a longer duration.

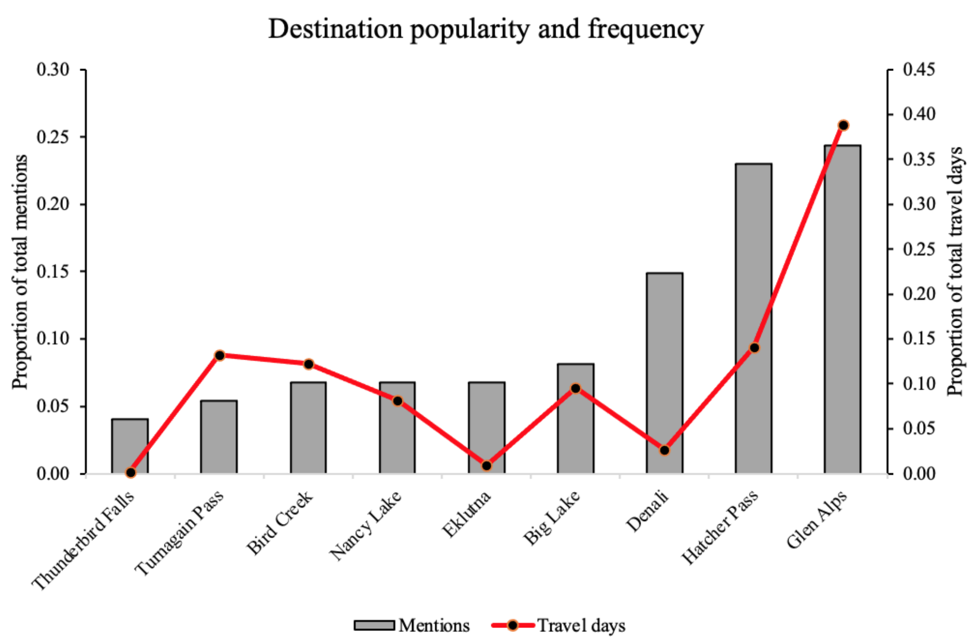


Figure 4.6: Proportion of total mentions and travel days of recreational area destinations.

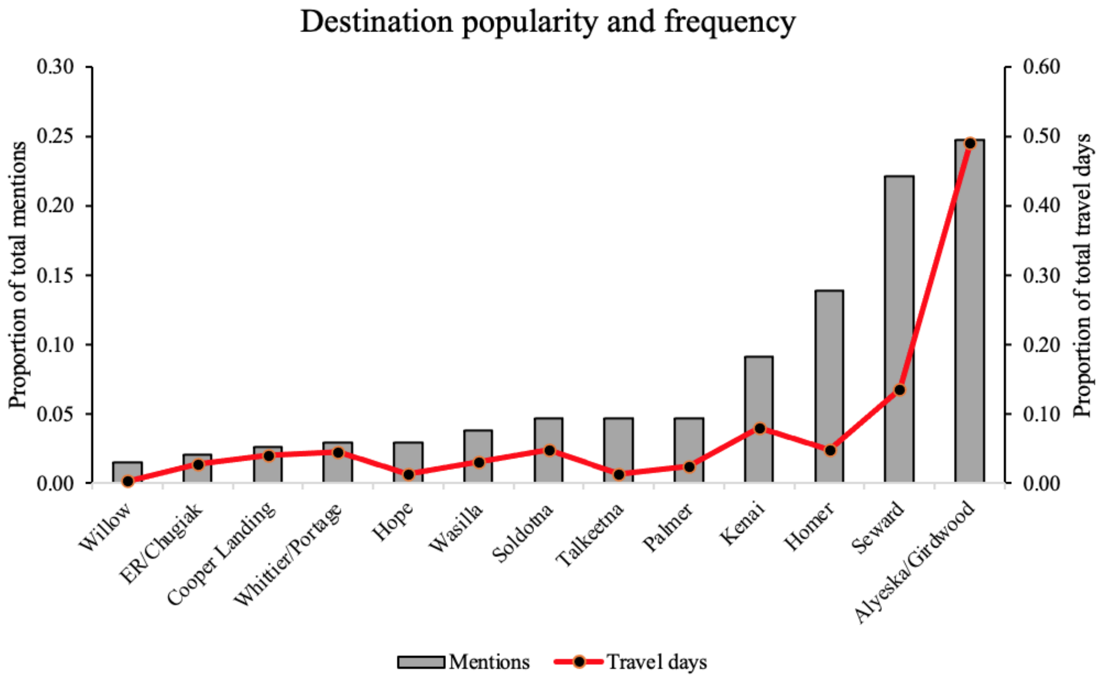


Figure 4.7: Proportion of total mentions and travel days of town destinations.

The important distinction between recreational and town destinations becomes clear in these figures, as there is a much more distinct relationship between the total number of times a town destination is mentioned by respondents and the frequency of travel; the popularity of and frequency of travel to a particular town is correlated. By far the most popular destination is Girdwood, which sits right on the base of Alyeska mountain in the southern portion of the MoA. Mentioned by 25% of respondents and accounting for almost 50% of all travel days, the location is popular both in the winter, for skiing ans snowboarding, and during the summer, for hiking, biking, and camping. A close second is Seward, which is mentioned by 22% of participants but accounts for a much smaller 14% of all travel days.

On the other hand, recreational destinations do not follow a simple linear relationship. Certain destinations, such as Turnagain Pass, have a very low proportion of mentions (5%) but hold a high proportion of total travel days (13%). The same is true for Bird Creek and Big Lake. On the other end of the spectrum is Denali National Park, which reserves 15% of mentions but holds less than 5% of total travel days. Out of the recreational destinations listed, Bird Creek and Glen Alps are locations within the MoA, and will be included in the list of hiking spots available within the agent-based model.

To consider the effects of distance on travel, the average number of travel days was plotted as a function of the destination distance (Figure 4.8). As can be seen, there is a weak relationship between distance to the destination and the travel frequency, with a slightly stronger correlation for populated town destinations. However, it can be observed that popular destinations by mentions, such as Denali National Park and Homer, almost certainly have low travel days because of the large distance between them and the Anchorage municipality. This indicates that recreational travel is linked to certain destinations based on the unique activities that are offered there. This certainly explains the popularity of Turnagain Pass and Hatcher Pass, which are hubs for backcountry snow sports located within a relatively short distance of the MoA.

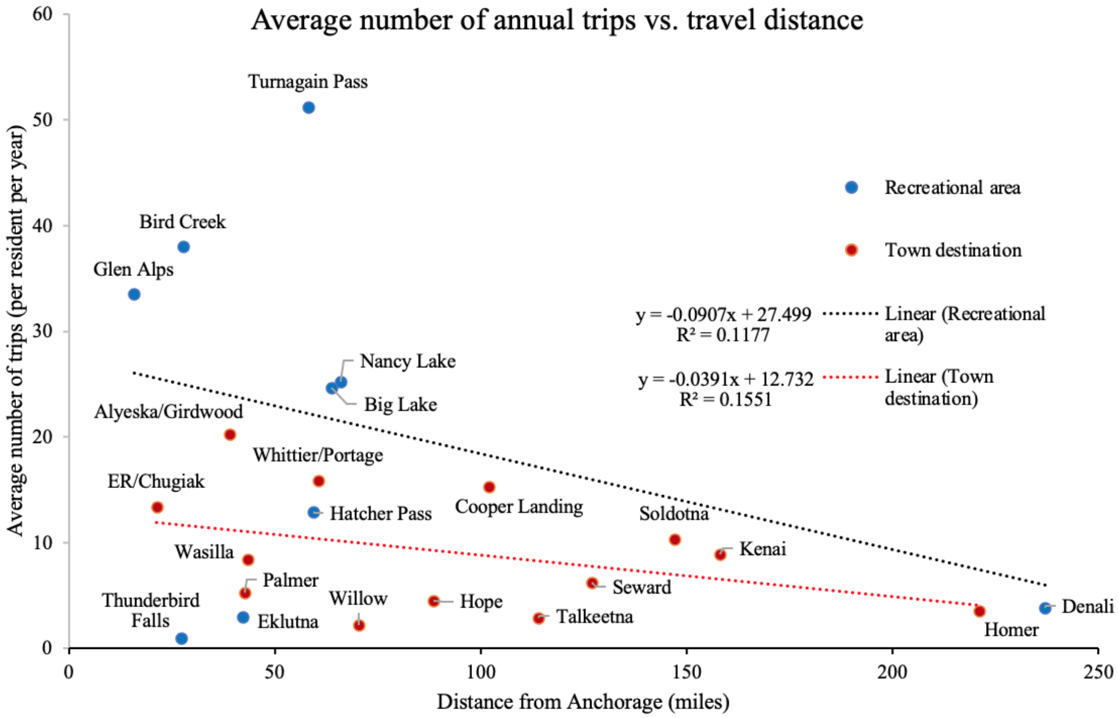


Figure 4.8: Average number of travel days plotted as a function of distance for all destinations.

Figure 4.8 also highlights that the destinations with the highest average travel days per person are recreational areas, which provides challenges from the perspective of charging station installation. These areas are located at a significant distance from the distribution network, complicating the feasibility of destination charging. However, their relatively short distance from the MoA could indicate that servicing a majority of such trips would not require many stations, and proper placement with a sufficient number of chargers could certainly increase EV mobility for recreation. An important consideration for station installers would be the trade-off between high charging speed (with low number of ports) and high number of points (with low charging speed).

4.2.4 Charging preferences

The final section of the survey gathered insights on the important characteristics of a charging station, comparing the views of interested non-users and current EV-users. Figure 4.9 shows the scores given to different potential charging station locations by MoA residents. Although none of the categories provided have statistically significant differences, a few observations can be made regarding the viewpoints of the two groups. Firstly, the category with the clearest difference of opinion was fuelling stations, which non-users ranked as one of the locations of highest importance (mean=4.2), while EV users gave them the lowest importance value (mean=3.4). This may indicate that for non-users, the act of charging is still linked with the activity of fuelling a vehicle. Workplaces (mean=4.2) and leisure centres (mean=4.1) were rated highly by both groups, which is reasonable since work and recreation are the activities in which the vehicle sits idly for the longest period of time. Surprisingly, commercial area charging had the lowest overall rank (mean=3.5), with even educational institutions (overall mean=3.8) receiving more consideration from both EV users (mean=3.7) and non-users (mean=3.8).

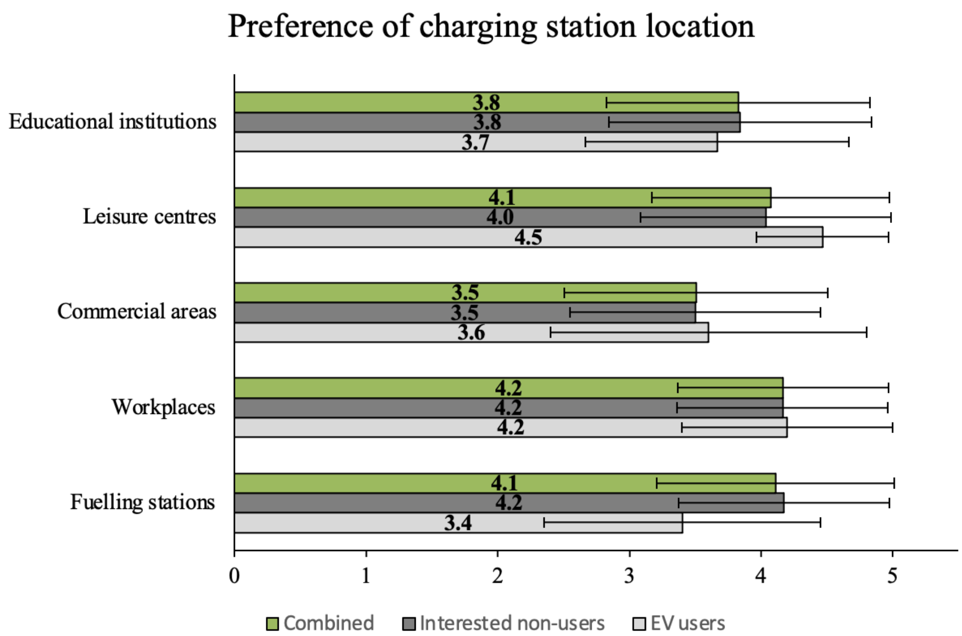


Figure 4.9: Average importance of different locations to host charging stations between EV users and non-users (min=0, max=5) with 95% CI.

A comparison of age groups (Table 4.2) did not yield significant differences either, however, the average values were slightly more profound. Respondents aged 65 and over placed similar importance to all possible locations, giving a mean mark above 4 to each one. The highest overall value was placed on workplaces (overall mean=4.2), however all groups but age class 45-64 ranked fuelling stations as the most important location. Educational institutions were ranked extremely high by young adults aged 18-24 (mean=4.5), while leisure centres ranked the highest for those aged 45-64 (mean=4.3).

Table 4.2: Average importance of different locations to host charging stations by age class (min=0, max=5) with 95% CI.

Location	Overall average	18-24	25-44	45-64	65 and older
Gas stations	4.1 ± 1.00	4.8 ± 0.95	4.2 ± 1.00	3.9 ± 1.05	4.3 ± 1.10
Workplaces	4.2 ± 0.95	3.8 ± 1.00	4.0 ± 0.95	4.4 ± 0.95	4.6 ± 0.95
Commercial areas	3.5 ± 1.00	3.8 ± 1.20	3.3 ± 0.95	3.5 ± 0.95	4.5 ± 1.05
Leisure centres	4.1 ± 0.95	3.9 ± 1.15	3.9 ± 0.95	4.3 ± 0.90	4.3 ± 1.10
Educational institutions	3.8 ± 1.00	4.5 ± 1.05	3.6 ± 1.00	3.8 ± 1.00	4.4 ± 0.90

Secondly, the importance of the characteristics of a charging station were examined. Figure 4.10 shows the average responses between interested non-users and current EV users. There is very little difference between the responses, with all aspects being rated highly by the survey participants. The biggest difference was observed in cost parity and dual use: non-users ranked cost parity higher (mean=3.9) than EV users (mean=3.5), while dual use was considered more important for EV users (mean=4.1) than non-users (mean=3.6). Reliability and accessibility ranked the highest in both groups, which validates the concerns regarding cold weather performance of stations and the importance placed on fuelling stations, as they are the most accessible service along the travel corridor. It similarly validates that major concerns of interested non-users, which ranked range anxiety and lack of infrastructure as their main reasons from abstaining from EV purchase.

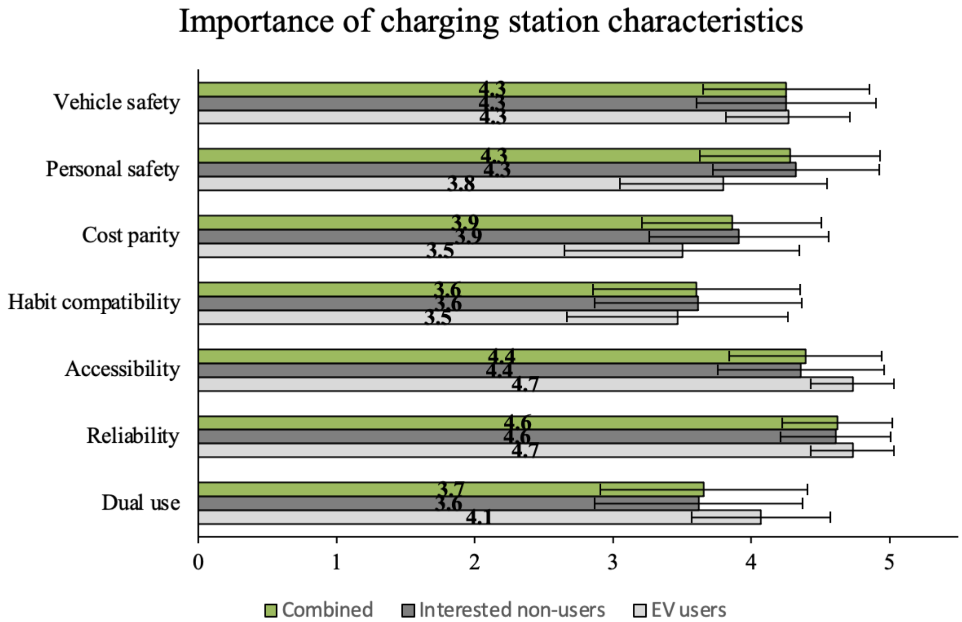


Figure 4.10: Average importance of different characteristics of a charging station between EV users and non-users (min=0, max=5) with 95% CI.

A comparison of age groups (Table 4.3) yielded similar results, with the highest overall value placed on reliability (overall mean=4.6) and accessibility (overall mean=4.4). Reliability did not receive an average mark lower than 4.4 in any age group, with accessibility, personal safety, and vehicle safety all maintaining an average mark at a 4 or above in every age class. Habit compatibility (overall mean=3.6) and dual use (overall mean=3.7) received the least consideration amongst all groups. Age groups over the age of 24 had very similar scoring for each category, with respondents aged 65 and older typically scoring a few decimal points higher than the average except in the case of habit compatibility (mean=3.1), which was ranked 0.5 points below the overall mean of 3.6. Those aged 18-24 (mean=4.3) ranked cost parity relatively high compared to other groups (overall mean=3.9) and accessibility (mean=4.0) relatively low (overall mean=4.4).

Table 4.3: Average importance of different characteristics of a charging station by age class (min=0, max=5) with 95% CI.

Characteristic	**Overall average**	**18-24**	**25-44**	**45-64**	**65 and older**
Dual use	3.7 ± 0.75	3.7 ± 0.85	3.6 ± 0.75	3.7 ± 0.75	3.8 ± 0.75
Reliability	4.6 ± 0.50	4.5 ± 0.75	4.6 ± 0.50	4.6 ± 0.55	4.9 ± 0.15
Accessibility	4.4 ± 0.55	4.0 ± 0.75	4.4 ± 0.55	4.4 ± 0.60	4.8 ± 0.20
Habit compatibility	3.6 ± 0.75	3.5 ± 1.00	3.8 ± 0.70	3.5 ± 0.80	3.1 ± 0.85
Cost parity	3.9 ± 0.65	4.3 ± 0.50	3.8 ± 0.50	3.8 ± 0.80	4.0 ± 0.65
Personal safety	4.3 ± 0.65	4.0 ± 0.80	4.2 ± 0.65	4.3 ± 0.65	4.8 ± 0.25
Vehicle safety	4.3 ± 0.60	4.2 ± 0.85	4.2 ± 0.60	4.3 ± 0.65	4.6 ± 0.35

Finally, the willingness of drivers to accept drawbacks in the charging process was determined through the final Likert question of the survey. The willingness to accept waiting times, vacate a parking spot, and make detours were considered (Figure 4.11). A comparison between EV users and interested non-users showed that current users are much more willing to accept the three drawbacks, scoring higher in all categories compared to non-users. Significant differences were found for waiting times, with EV users (mean=3.2) scoring 1.1 points higher on average than non-users (mean=2.1), and for detours, with EV users (mean=3.6) again scoring 1.1 points higher on average than non-users (mean=2.5). Both groups were the most willing to vacate a parking spot upon completion of charging.

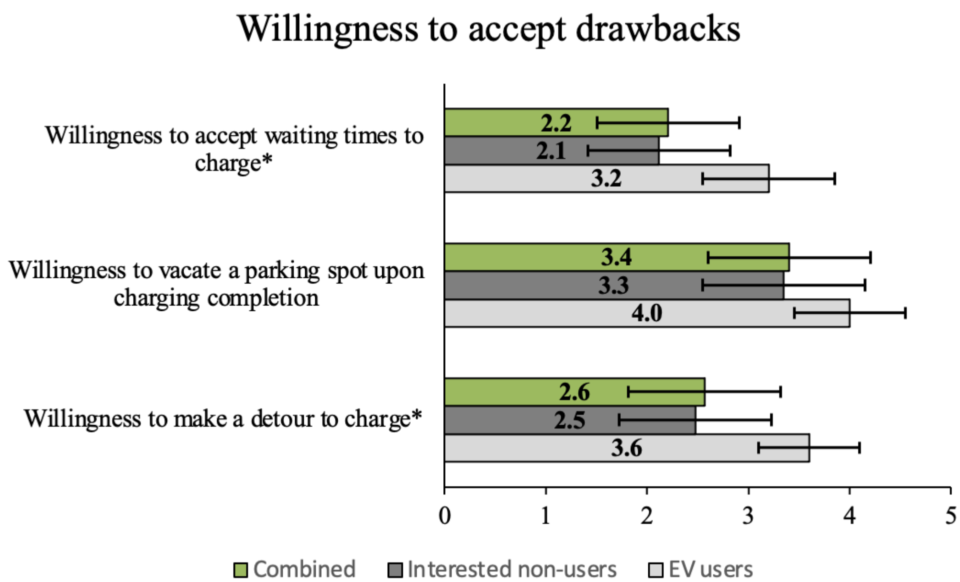


Figure 4.11: Average willingness to accept drawbacks in the charging process between EV users and non-users (min=0, max=5) with 95% CI. Categories with an asterisk indicate a significant difference between groups.

A comparison of willingness across age groups saw a few interesting trends (Table 4.4. Participants aged 18-24 were much more willing to accept all three drawbacks compared to the rest of the groups, scoring above the overall mean in all three categories. On the other hand, respondents aged 65 and older consistently expressed the lowest willingness, scoring below the overall mean in all three categories.

Table 4.4: Average willingness to accept drawbacks to charging by age class (min=0, max=5) with 95% CI.

Category	**Overall average**	**18-24**	**25-44**	**45-64**	**65 and older**
Making a detour	2.6 ± 0.75	2.8 ± 0.85	2.6 ± 0.65	2.5 ± 0.80	2.3 ± 0.90
Vacating a parking spot	3.4 ± 0.80	3.6 ± 0.85	3.3 ± 0.75	3.5 ± 0.75	3.5 ± 0.95
Accepting waiting times	2.2 ± 0.70	2.5 ± 0.70	2.2 ± 0.70	2.3 ± 0.75	1.7 ± 0.70

4.2.5 Insights used in the model

While a large volume of data was obtained from the survey responses, only a subset will actually be utilised in the agent-based model. Table 4.5 summarises which values will be considered within the model and the role they will play. A full discussion of the results from the driver survey and their implications for stakeholders will be presented in Section 5.

Table 4.5: Summary of values from driver survey used in the agent-based model.

Parameter	Purpose	Value within model
Type of residential charging available	Input	68% of residents with L2 and 32% with L1
Recreational destinations	Input	Top 10 local trailheads used for hikes
Charging station location	Scenario	Running different availabilities of workplace charging
Accepting drawbacks	Input	Low waiting time threshold (15 min)
Cold weather performance	Scenario	Winter scenarios with static SOC drop
Residential charging	Validation	Validate high residential charging proportion (85%)

4.3 Modelling results

For each of the scenarios considered, the model was run three times to obtain reliable results and account for slight variations in agent characterisations due to random assignment of certain variables, which was discussed in the methodology.

In the simulations that were run, a set of parameters were tracked with each passing time-step which characterised the particular scenario. These were:

- Demand by charger type (residential, L2 public, L3 public)
- Demand by charger
- Queue of charging stations

The charging demand for a particular station, zip code, or charging speed was converted from a percentage SOC value, as was the unit in the model, to a kW value using the following formula:

$$(charging\_demand) = (num\_EVs\_charging) * (charger\_speed) * (battery\_capacity)/100 \tag{4.1}$$

The equation counts the number of residents charging at a certain time instance at each charging port and finds the demand through multiplication by the particular charging speed of the station. The aforementioned demand parameters of demand by charger type and zip code are then generated through aggregation of the demand calculation either based on area or location. The following subsections describe the results of each modelled scenario through the demand and queue parameters for both weekend and weekday simulations. The number of agents which get stranded, and those agents who did not make it back to their home before the end of the simulation are also tracked between scenarios.

4.3.1 2021 scenarios

The baseline simulations for 2021 had two main goals: understand the differences between summer and winter EV demand and visualise charging station utilisation in the current state of EV penetration and public infrastructure availability. This is presented as the baseline weekday and weekend scenarios. Secondly, the goal was to consider the influence of adding a fast-charging station along the travel corridor at Bird Creek, which was proposed by Tesla in discussions with Alaskan researchers. If the station had immediate benefits to the system, the Bird Creek station would maintain its presence in the model for further simulations.

2021 baseline

The 2021 baseline scenario considers the current population of electric vehicles (225) and the 11 charging stations currently installed or planning to be installed with the VW grant money. The summer and winter EV loads for the weekday scenario are depicted in Figure 4.12, while Figure 4.13 shows the weekend scenario.

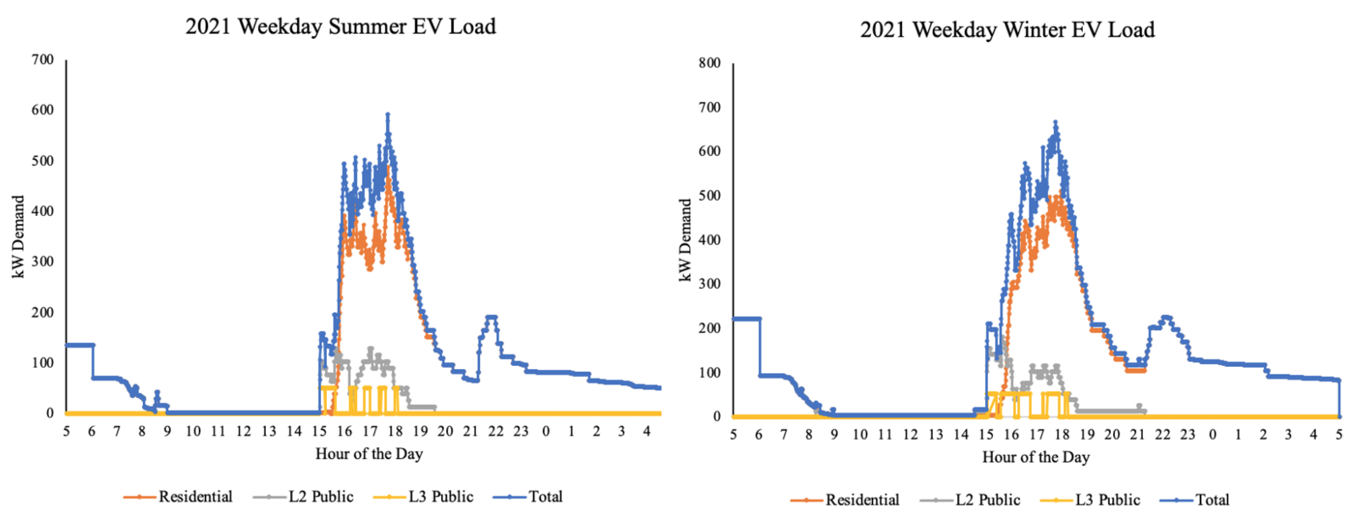


Figure 4.12: Summer and winter load profiles for the 2021 baseline weekday scenario.

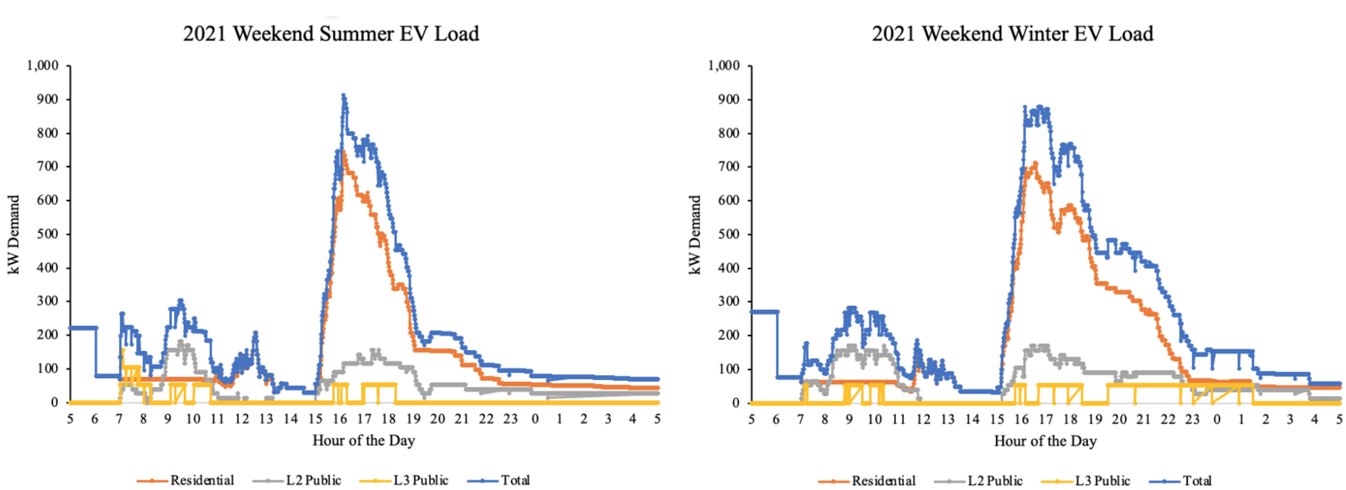


Figure 4.13: Summer and winter load profiles for the 2021 baseline weekend scenario.

While the shape of the load profiles is very similar in both the summer and winter scenarios, it can be seen that there is a slight increase in magnitude of the load peaks during winter as a result of the additional energy loss of vehicles when idle. The initial charging which occurs at the onset on the weekday is due to individuals with level 1 charging at home beginning with a lower SOC than 100%. In the weekday, the morning load drops to zero by about 9 am from individuals leaving home or reaching full charge, and picks up again at around 3 pm beginning with agents with kids returning home from school, followed by the the rest of the agents returning from work, the nearest commercial area, or potentially a hike if they are unemployed.

Peak load occurs between 5-6 pm and has a magnitude of 593 kW and 668 kW in the summer and winter, respectively. The peak load drops off rapidly as vehicles reach full charge. A slight secondary rise in demand is seen at 8 pm from individuals arriving later because of charging, mainly from those arriving from hiking locations, which are farther away. The demand never reaches zero, stagnating at around 100 kW from agents slowly charging with level 1 residential infrastructure. The utilisation of public charging infrastructure is minimal in the baseline, with approximately 86% of charging occurring at home in both summer and winter, which verifies the responses given by stakeholders during the interviews and is almost identical to the 85% cited by EV drivers in the survey. The energy consumed in the summer and winter scenarios totals 2.7 MWh and 3.5 MWh of electricity, respectively, of which 48% (1.3 MWh) and 42% (1.5 MWh) is consumed between 4 pm and 6 pm, respectively. The total energy demand of all public chargers in the summer and winter scenarios is equal to 375 kWh and 485 kWh, respectively, which is less than 50 kWh per charger, on average. In both scenarios, not a single vehicle got stranded and everybody made it home by the conclusion of the simulation. As a result of the minimal utilisation of public chargers on the weekday, scenarios which consider improving mobility and queuing will focus on the weekend loads, which are described below.

The 2021 weekend load profile follows a similar pattern to the weekday baseline, with the summer and winter profiles showing very slight differences in peak magnitudes. The main difference between weekday and weekend lies in the increased load experienced in the morning due to charging requirements by residents to reach further hiking destinations and agents who quickly return home from the nearest commercial area and must charge again. This results in a load of 100-300 kW of both public and residential origin which oscillates slightly between the hours of 9 am and 2 pm.

Peak load is once again achieved between 5-6 p.m., however reaching a magnitude of approximately 900 kW,and persisting for a longer duration than in the baseline. In the summer, the peak energy demand between 4-6 pm of 1.95 MWh constitutes 41% of the total daily demand (4.76 MWh), while the winter peak consumption of 2.2 MWh comprises 37% of the total (5.95 MWh). The most significant difference between the summer and winter weekend simulations is the fact that in the summer, nobody gets stranded and only 2 residents were unable to reach their residence as they were still charging. Meanwhile, in the winter, 2 residents get stranded and 20 are unable to reach their residence due to a few vehicles charging and a majority still queuing at a charging station.

To visualise the utilisation of the existing charging network, queue lengths of each of the initial 11 charging stations is plotted as a function of time. This is presented in Figure 4.14 for the summer and weekend simulations.

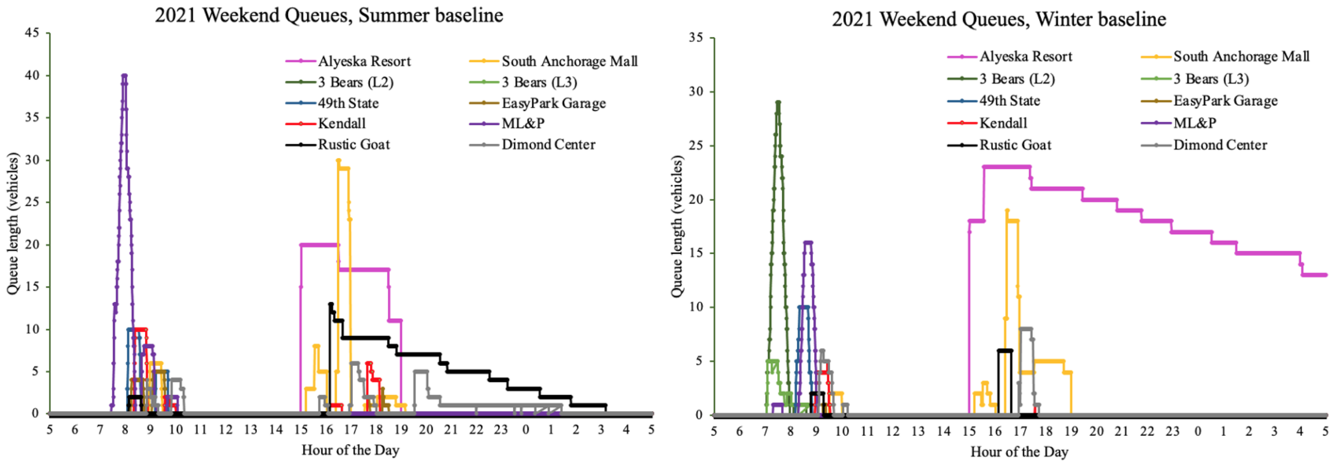


Figure 4.14: Summer and winter charger queues for the 2021 baseline weekend scenario.

The weekend queuing identifies weak points within the public charging network of the MoA. When compared, the profiles of the queues and total EV load match temporally, with queues rising during times of demand. The morning rise in queues is a result of vehicles requiring a top up on their charge to reach their hiking destination and return home. However, as a function of the range anxiety factor, although vehicles charge enough in the morning to meet their exact needs, they still would like to charge in the evening prior to driving home not to return on a completely empty battery.

The chargers which have significant queues during the evening demand are those located south of the Anchorage Bowl, corresponding to individuals which choose to hike in the Girdwood/Portage/Whittier areas. In both the summer and winter evenings, the nearest charger is Alyeska Resort as it encounters the first wave of agents which have completed their hike (it is the first station with nonzero queue). In the summer scenario, the queue reaches a maximum of 20 vehicles, while in the winter, it reaches 23. As a result of the idle drop in state of charge while vehicles are parked at the trailheads, much more agents in the winter simulation are unable to reach the next nearest station from Alyeska Resort, and must queue there until their turn is reached. Meanwhile, in the summer scenario, vehicles are able to reach the Anchorage Bowl, with queues first appearing at the South Anchorage mall and then diverting to other stations. A significant queue forms at Rustic Goat, reaching a peak of 13 vehicles which are unable to reach the next station. For Rustic Goat (summer) and Alyeska Resort (winter), both of which have two level 2 chargers on site, vehicles are removed from the queue at a rate of approximately one vehicle per hour, with Rustic Goat relieving its queue at 3 am. Alyeska Resort, however, still contains 13 vehicles in its queue at the end of the simulation. As the winter simulation has more severe impacts on queuing and strains the existing infrastructure more, the scenarios considering improvements to the network will focus on the winter as that will inherently have a similar but elevated positive impact in the summer.

2021 weekend interventions

As weekday demand was shown to be met primarily through residential charging, the intervention simulations were only run for the weekend scenario, specifically during winter. The primary goal of the Bird Creek intervention was to determine the effectiveness of an additional station on the travel corridor to alleviating the queue length at the Alyeska Resort station and allowing all residents to return home before the simulation completed. The Bird Creek station was located at the nearest street patch to the Bird Ridge hiking location within the model and was equipped with two level 3 (50 kW) charging stations. A second intervention was modelled which proposed an additional level 2 charger placed at Alyeska Resort in combination with Bird Creek. Both interventions are presented in Figure 4.15.

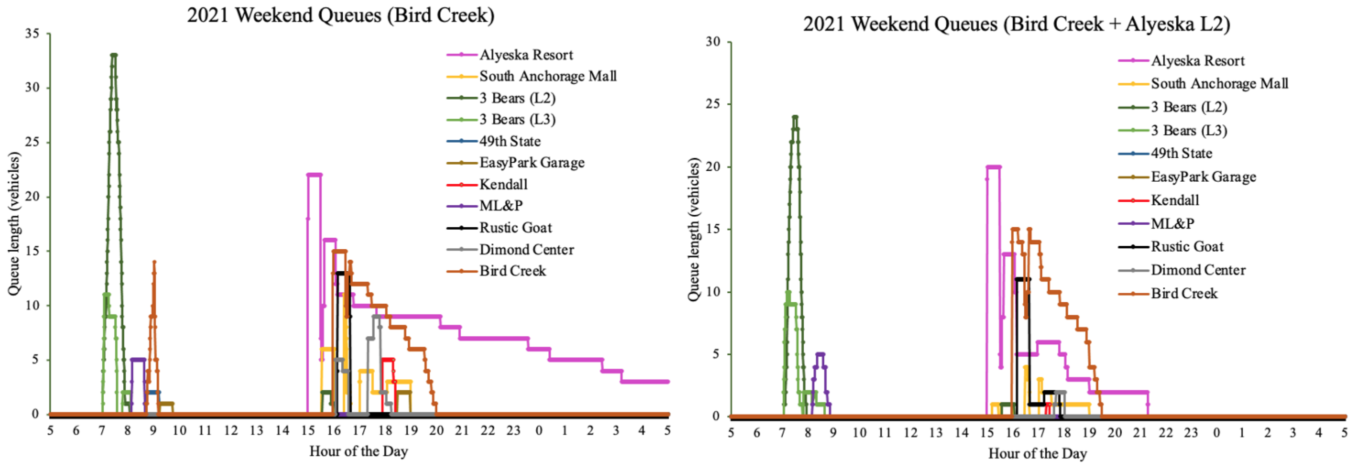


Figure 4.15: Winter queue length of the baseline chargers in the 2021 Bird Creek and Bird Creek + Alyeska L2 scenarios.

The results of the Bird Creek simulation indicate that the closest charger to most individuals hiking near the Girdwood area is still the Alyeska Resort charger as the queue for that station begins earlier, reaching a peak at 22 vehicles. However, upon reaching their waiting time there is a significant number of vehicles which have enough charge to reach the Bird Creek charging station. This can be seen with the immediate spike in queue length at the Bird Creek charger at approximately 4 pm, which rises to 15 vehicles, with a identical drop in queue length at Alyeska Resort. Although both Bird Creek and Alyeska Resort have 2 charging ports, the superior charging speed at Bird Creek allows for an average vehicle turnover rate of 16 minutes, which meant that the entirety of the 15-vehicle queue was attended to before 9 pm. At the Alyeska resort, 13 vehicles could not reach the next station due to low charge, with only 3 vehicles still queuing at the end of the simulation. In total, 5 agents did not make it home by the completion of the simulation. While this is already a significant improvement from the baseline, it was decided that the additional intervention of adding another charging port at Alyeska Resort be modelled. This was run to see if a fairly simple improvement could result in all residents returning home before the end of the simulation.

A significant improvement is visualised in the Bird Creek + Alyeska L2 simulation. A similar procedure to the Bird Creek scenario occurs, with 22 vehicles initially entering the queue of Alyeska Resort. After the completion of the first waiting period, 16 vehicles are able to move to Bird Creek. A second wave of hikers again increases the Alyeska Resort queue to 14, but 8 leave for Bird Creek, with the rest having too low of a state of charge to leave. The additional charger at Alyeska Resort allows the 6 vehicle queue to be tended to before 10 pm., with all vehicles waiting at Bird Creek having charged and left before 9 pm. All agents in this simulation made it home before the 5 am completion time.

4.3.2 2025 scenarios

The simulations for 2025 had three main goals:

1. Analyse the impact of maintaining the current EV-charging station ratio by adding more chargers in commercial areas. The goal is to assess the grid impact of extending the existing commercial charging infrastructure.
2. Assess how the 2021 weekend interventions handle the additional EV load.
3. Evaluate the influence of workplace charging on reducing evening peak load.

In the 2021 picture, there were 225 electric vehicles in an environment of 11 charging stations, corresponding to an EV: charging station ratio of approximately 20:1. To maintain this ratio, the 2025 scenario required an additional 17 stations to be erected in commercial areas to compensate for the 230 new agents. All stations were assumed to have one available charging port and were spawned in random commercial areas. For each of the simulations with additional commercial chargers, the stations were spawned once and maintained for all remaining simulations to produce consistent results. These simulations are described in the subsection titled "2025 baseline". For the 2025 scenarios, the number of commuters from the MatSu Borough was increased to 110 agents using half of the annual EV growth rate of the MoA as a result of the MatSu Borough having a lower population size and a less sophisticated public charging infrastructure. The full calculation is described in Appendix C. For the weekend simulations, the interventions from 2021, which were the erection of the Bird Creek station and addition of a L2 port at Alyeska Resort, were kept to assess their effectiveness at higher EV penetrations.

2025 baseline

The 2025 baseline scenarios consider the impact of additional commercial chargers on the weekday load as well as the queuing lengths of the baseline chargers during the weekend. The results of the weekday simulations are visualised in Figure 4.16.

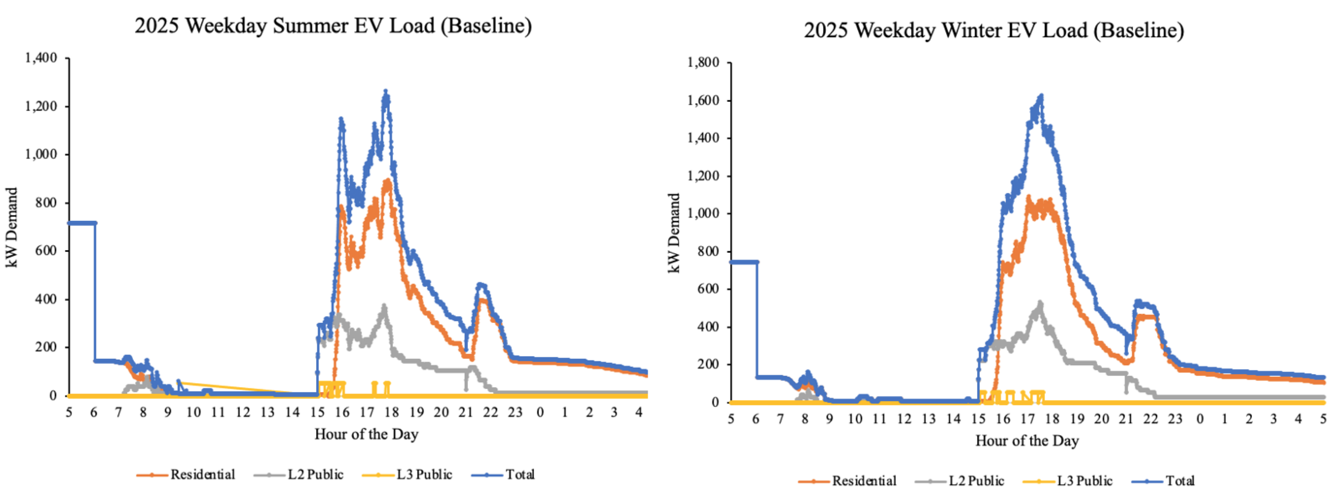


Figure 4.16: Summer and winter EV load from 2025 weekday baseline scenario.

The load profiles are very similar in shape to the 2021 baseline, with demand and energy consumption being elevated at each non-zero time step because of the increased number of EVs. In the summer simulation, peak demand reaches 1.3 MW, with total peak energy consumption totalling 2.7 MWh. Compared with the 2021 summer weekday, this is an increase of 120% and 110%, respectively. The additional charging which occurs in commercial areas plays no small part, accounting for 26% (690 kWh) of the peak demand compared to 16% seen in 2021. The total energy demand of EVs during a 2025 summer weekday is 6.5 MWh, a steep rise of 141% compared to 2021.

A similar but more magnified picture is observed for the winter-time simulation. Peak demand reaches 1.6 MW with total peak consumption equalling 3.7 MWh, of which 28% (1.0 MWh) is a function of commercial charging. These values are, respectively, 140% and 153% of the 2021 winter weekday. The total energy demand of EVs during a 2025 winter weekday is 8.1 MWh, which is almost triple the total 2021 demand of 3.5 MWh.

The weekday scenarios make it clear that commercial area chargers provide an additional charging location for residents, however this charging mostly occurs at peak times, which is detrimental to the stability of the electrical grid. The next step is to understand the impacts of additional urban public infrastructure on waiting times. The 2025 summer and winter weekend simulations are shown in Figure 4.17.

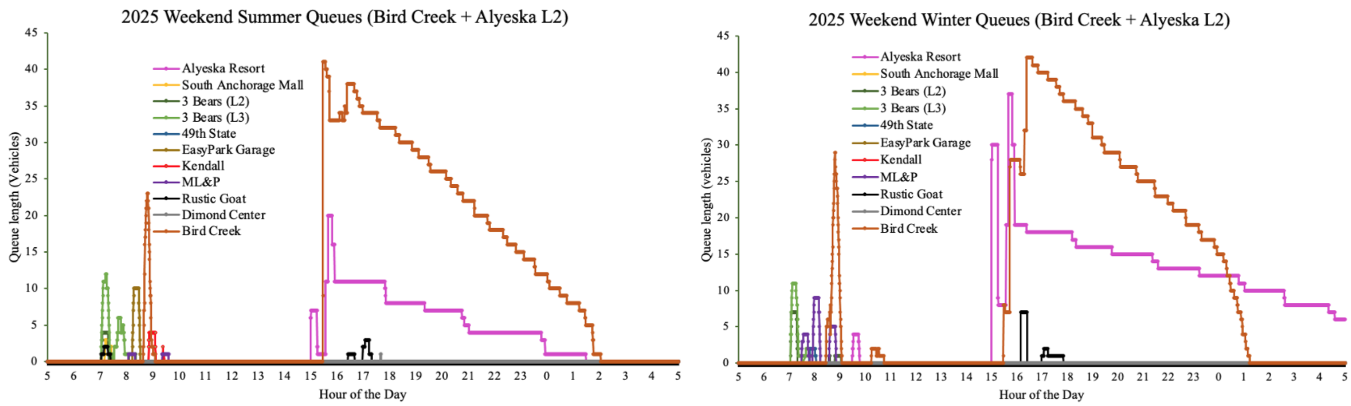


Figure 4.17: Summer and winter EV load from 2025 weekend baseline scenario.

The greatest impact of the additional stations lies in the reduction of the queues of stations located in the Anchorage Bowl. The only 2021 station with which a queue forms in the evening is Rustic Goat, as residents hiking near the Anchorage Bowl have a larger selection of stations to chose from. However, those agents choosing to hike to the south of the MoA near Girdwood still see very long queues. In the summer simulation, the queue at Alyeska Resort peaks at 20 vehicles, with a total of 11 which cannot reach Bird Creek and must queue. Meanwhile, the Bird Creek queue reaches a maximum of 40 vehicles, all of which are able to charge before the simulation ends. Although the summer scenario sees all queues reduced before the end of the simulation, there are still vehicles which must wait until 2 am to charge, which is unreasonable to expect.

As a result of the idle drop in state of charge, the winter scenario is more extreme. Approximately 20 agents are stuck at Alyeska Resort, with 11 remaining in the queue at the end of the simulation. The Bird Creek charger sees a similar profile to the summer, with a maximum of 40 vehicles all which are able to charge before 2 am. It is clear from the baseline simulations that extending the existing commercial infrastructure reduces utilisation of the existing charging stations with no positive repercussions on mobility. In addition, the new charging stations have an inconsistent level of utilisation, with certain chargers seeing little to no usage while others experiencing a high volume of drivers (Figure 4.18). Furthermore, there is little difference observed between the weekday and weekend simulations. This indicates that additional commercial chargers act as more of a convenience for agents rather than a necessity, showing little impact on enhancing mobility, and generally do not improve the existing network of chargers. As a result, subsequent simulations focus on the impact of adding workplace chargers to limit the strain on the electrical grid through reduction of peak load.

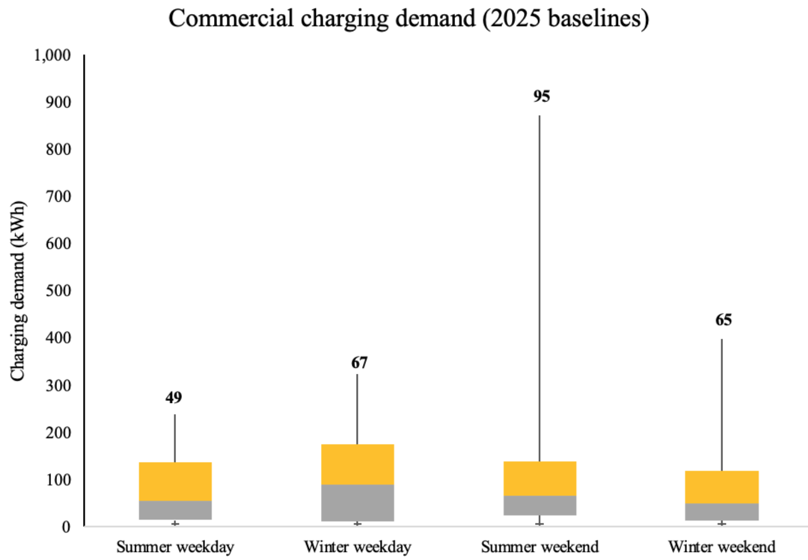


Figure 4.18: Box plots of additional commercial charger utilisation in the 2025 baseline scenarios. Data labels correspond to the average energy demand per charging station.

2025 weekday with workplaces

Additional weekday scenarios were run which considered percentages of workers which had access to workplace charging. Three simulations were run with a 5%, 10%, and 25% workplace charging penetration to determine the impacts on peak load. The penetration values were based on the number of workers with non-commercial workplaces. These simulation runs did not contain the additional commercial chargers which were generated for the 2025 baseline scenarios. The impacts of access to workplace charging was analysed for both winter and summer weekdays; as a result of loss of charge while parked, the reductions in peak demand are not as significant in the winter as in the summer. This is best visualised in Figure 4.19, which compares the EV load profile of a summer and winter weekday at 25% workplace charging penetration.

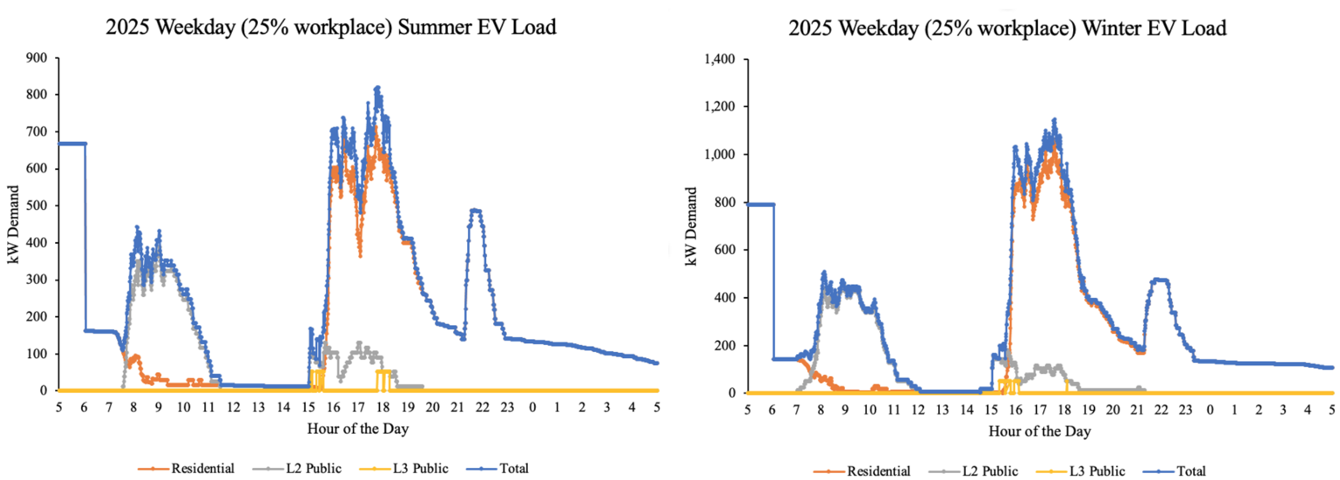


Figure 4.19: Summer and winter EV load profile for the 25% workplace scenario.

The additional workplace charging load can be seen as an rise in demand between the hours of 7 am to 12 pm, reaching a maximum of approximately 500 kW and totalling 900 kWh of energy demand in both the winter and summer simulations. Once all vehicles complete charging, the demand drops back to zero until the agents return home or use a public charger. The difference in the seasons lies in the magnitude of the evening peak. In the summer, the peak demand in the evening reaches close to 800 kW, while in the winter, the demand exceeds 1.1 MW. This is a result of the drop in state-of-charge of vehicles upon completion of charging in their workplace. It is assumed that agents unplug their vehicle upon reaching 100% charge, and thus as their vehicle remains parked after charging, it loses charge until they depart the workplace. Hence, the peak load is less significantly reduced.

Figures 4.20 and 4.21 visualise the peak power demand and the total peak energy demand for the different scenarios run for both summer and winter weekday. The summer-time scenarios see the greatest benefit from the addition of workplace chargers. With just 5% availability, both the peak power demand and total peak kWh reduce by approximately 17.5%. With a 25% penetration, the overall reduction in peak power demand is 35%, with a 29% reduction in peak kWh consumed. Meanwhile, the winter-time scenarios see a reduced benefit as the workplace charging proportion increases. A significant improvement is seen between the baseline and 5% scenario, with the peak demand reducing by 12% and total peak kWh consumed dropping by 18%. However, the continued improvements with 10% and 25% penetration are limited, with the 25% scenario seeing an improvement of 14% and 19.5% in peak demand and total peak kWh, respectively, compared to the baseline.

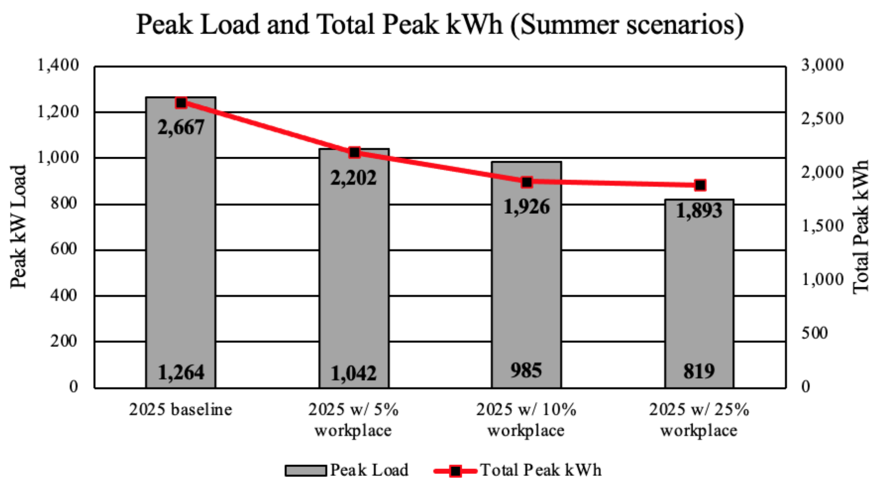


Figure 4.20: Peak demand and total peak kWh for summer weekday scenarios.

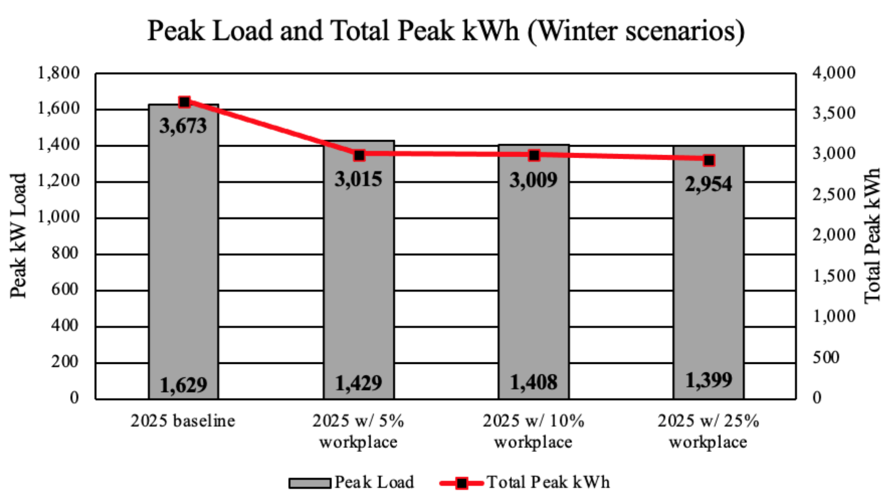


Figure 4.21: Peak demand and total peak kWh for winter weekday scenarios.

5 Discussion

5.1 Anchorage driver survey

The goal of the driver survey was to get an understanding of the travel behaviour and charging preferences of MoA residents, as well as the motivations behind purchasing/choosing not to purchase an electric vehicle. The results can serve as a guideline for future EV policy and education and provide a baseline for focused investment in charging stations. In this section, the responses provided by residents will be compared with the concerns and opportunities raised by the stakeholders to determine the level of cohesion and note any potential gaps that may exist between public and private players and the end user.

5.1.1 Motivations on EVs

Although few people who owned EVs participated in the survey (n=19, 9% of total), their responses were still valuable in understanding the differences in behaviour and preference with non-users. With regards to motivation for EV purchase, the highest ranked response was, surprisingly, the driving experience (overall mean=4.1/5). This result confirms the responses given by stakeholders, who believe public awareness of EV driving to be a major barrier to further adoption. The second motivation was access to residential charging (overall mean=3.8/5), which has a combined effect of convenience and reduction in fuel costs. With the costs to install a level 2 charging port being relatively insignificant compared to the cost of purchasing an EV, it is likely that the utility incentives for residents to upgrade residential chargers to level 2 will continue to see success as EV growth progresses in the MoA. This is seen currently in that 67% of respondents with EVs have access to level 2 charging at home. Tax incentives were given the lowest ranking (overall mean=2.1/5) out of all options, and with carbon emissions ranking third highest (overall mean=3.6/5), it is likely the case that existing EV drivers value a reduction in their carbon footprint more than saving money on a new vehicle.

On the other hand, residents who had not yet purchased an EV ranked all of the provided categories highly when asked about their reasons for abstaining. The overall average for all categories was a 3.5/5 or above, with a high number of additional responses provided to cite concerns not listed. A lack of public charging infrastructure (overall mean=4.2/5) was the highest ranking concern, which supports the current undertakings of utilities and state agencies. With the state government using federal funding (from the VW settlement) to subsidise capital costs of installing fast-charging stations and the utilities proposing a separate rate structure to reduce the demand charge, a clear urgency is being placed on the primary concern of the end user. The second biggest concern is cold weather performance, which is being addressed by researchers currently planning to undertake a study on EV performance in the northern community of Fairbanks. The supplementary responses provided indicate additional areas where attention is necessary. Concerns regarding a lack of servicing expertise in Alaska and the emissions surrounding battery manufacturing were raised, which indicates a need for further education on life cycle emissions and potential investment into local technical knowledge. It was interesting to observe that all facets of the life cycle of an electric vehicle are considered by residents in their decision-making.

5.1.2 Travel habits and destinations

The second section of the survey was aimed at determining popular destinations for MoA residents, which could help guide future investment into charging stations. It also provided the basis for the hiking locations considered in the ABM and validated a simulation assessing additions to the existing infrastructure.

The results showed that the popularity of a recreational area (in terms of mentions) was not necessarily correlated with the frequency of travel there. Certain areas, such as Turnagain Pass or Hatcher Pass, are popular for a low proportion of individuals, but hold a high proportion of total travel days. Considering the location of these areas, which can be far from the main distribution network, promoting electric mobility for such recreation may be difficult. While providing access to destination charging at these sites may not be feasible, since these areas are still located along main travel corridor, travel to these areas needs to be considered when determining proper charging station placement and modelling utilisation. Additionally, as most recreational destinations are relatively close to the MoA, while destination charging may be unfeasible, a few strategically-placed stations along the main travel network with a high number of charging ports may sufficiently cover such a travel demand.

Popularity of town destinations, however, was more correlated with frequency of travel. In the majority of cases, the more a particular destination was mentioned, the higher its proportion of total travel days was. Additionally, while a total of 13 destinations were mentioned, four destinations accounted for 70% of mentions and 75% of total travel days. These locations were Girdwood/Alyeska, Seward, Homer, and Kenai, all of which lie south of the MoA. Furthermore, Seward and Homer are both end-of-the-road destinations of their respective highways. As such, while its important to promote travel **to** these locations through the installation of charging stations along the corridor, an additional consideration should be the importance of placing public infrastructure **within** these destinations. Further research could determine the length of time travellers spend at their destinations, which, considering the distances shown in Figure 4.8, is likely longer than a day. Hence, getting to the destination may only be the first barrier to overcome, with additional investment necessary for infrastructure at the destination itself. This will likely require a multi-stakeholder solution as federal grant money cannot be guaranteed to cover costs, and although level 2 chargers are much more manageable in terms of upfront cost, proper planning will be necessary to maximise investment value.

5.1.3 Requirements for the charging process

The final section of the survey asked about respondent preferences about charging station location, characteristics, and willingness to accept drawbacks in the charging process. With regard to charging station characteristics and location, all options received significant consideration. For location, the lowest average score was a 3.5/5 given to commercial areas; for characteristics, the lowest overall score was a 3.6/5 given to habit compatibility. The high consideration for all locations is likely a result of a general lack of infrastructure availability, as only 9 stations currently exist within the MoA. An interesting dichotomy was seen in the rating given to fuelling stations, which non-users (mean=4.2/5) ranked 0.8 points higher than current EV users (mean=3.4/5). As fuelling stations do not typically provide parallel activities to pass the time, this is consistent with the rank given to the importance of dual use, which EV users (mean=4.1/5) ranked higher than non-users (mean=3.6/5). However, fuelling station are an important location to promote long-distance mobility, as they are the only consistent service provided over long stretches of road on the travel corridor. Accessibility and reliability of stations were the highest priority characteristics for both EV users and non-users, which mirrors the end user concerns regarding range anxiety and cold weather performance. With limited funding available for charging station installation, if only the bare minimum infrastructure is provided to meet mobility needs, the consistent operation of those stations will determine end user confidence in using EVs for long-distance travel. This is especially true for winter-time travel. However, providing the bare minimum infrastructure may not be sufficient to promote EV adoption as the overall willingness to accept drawbacks is very low. Although EV drivers ranked all categories higher than than non-users, both groups ranked waiting times as the lowest category (overall mean=2.2/5). The willingness to vacate a parking spot upon charging had the highest rank (overall mean=3.4/5) for both groups. This is good news for workplace charging installations, which, as a result of the long periods spent in the workplace, may find sufficiency in investing in infrastructure to only partially meet employee capacity.

The insights provided in the driver survey should serve merely as a baseline of understanding end user preferences with regards to electric vehicles and the public charging infrastructure. Further research is necessary to better understand driver needs to maximise the potential for limited investment power within Alaska in the coming years.

5.2 Agent-based model

The initial simulations considered the current state of electric vehicles and charging infrastructure in the municipality of Anchorage, modelling a typical weekday and weekday in both the summer and winter. The goal of these scenarios was to understand the use case of EVs for all local travel needs and assess the limitations of the existing infrastructure to meet those needs. Interventions were then considered to improve local driver mobility and improve the breadth of activities which EVs could cover. Finally, simulations were run which considered the future of EVs in the MoA and interventions to reduce their impact on the electricity grid.

5.2.1 2021 baseline picture

The baseline simulations indicated that weekday driving needs of residents within the municipality can be met with the existing infrastructure. 86% of the charging demand came from residential charging, which validates the value of 85% provided in the driver survey. For most residents, destinations did not require long drives. With the longest trip of the day being to the workplace, which had a mean distance of 6.5 miles, charging infrastructure was utilised minimally. Public charging utilisation was restricted to commuters from outside the MoA and unemployed individuals who chose to go on a hike. Total winter EV demand was 30% higher and the peak demand was 13% higher than the summer from additional energy losses to maintain battery temperature. While increased EV consumption did not result in a disruption in daily schedules nor in an increased utilisation of public infrastructure, it is still an important consideration for the utility which operates the electrical network. In the case of the 2021 weekday, the winter demand stayed below 700 kW, which from a systems perspective is insignificant, especially when spread out over the entire Anchorage area.

The most interesting results came when modelling the weekend. During the weekend, all residents had a high likelihood of choosing to go on a hike, with commuters and residents having an 80% and 60% chance, respectively. The popularity of the Girdwood/Alyeska area for recreational activity was represented by commuters having a 40% chance to choose that specific area as the destination. It became clear that the southern portion of the MoA was very limited in its ability to cater to a significant population of EV drivers. As seen from the map of hiking locations in the methodology, the area south of the Anchorage Bowl contains 5 of the 10 most popular hiking destinations, however currently only has one charging station, located at the Alyeska Resort. Agents prepared for their journey by requiring twice the necessary charge to reach their hiking trailhead in consideration for the lack of destination infrastructure. This led to a well-distributed morning charging load from commuters, as most residents had reached a full charge at home before embarking. Even with this consideration, the range anxiety factor still forced a certain portion of drivers to search for stations after completing the hike.

In the summer simulation, long queues were seen in the Anchorage Bowl, as drivers had enough state of charge to not get stuck in the Girdwood area, which resulted in queues at Rustic Goat and South Anchorage mall. While it was the case that all vehicles returned home before the end of the simulation, there were vehicles waiting to charge until 2 am, which indicates that at the current state of the infrastructure, it is likely that drivers would not choose to use their EVs for recreational purposes at a significant distance from their home. This validates the responses from EV drivers in the survey, who showed nearly identical travel frequencies for recreation as non-EV drivers, but quantified only 60% of their recreational travel needs being met by the EV.

The winter-time simulation is much more dramatic; approximately 25 vehicles were unable to reach the Anchorage Bowl, and were forced to queue at the Alyeska Resort station. This simulation further supports the assertion that the current public infrastructure network cannot support recreational travel, especially in the wintertime. However, it additionally provides insight on where infrastructure investment should be channelled if such mobility is to be enabled in the future. Specifically, it points to the need for additional charging stations to be placed for travellers moving along the southern travel corridor between Girdwood and the Anchorage Bowl.

5.2.2 2021 interventions

Improvements to the charging infrastructure network were modelled only for the winter weekend as the restrictions to mobility were more severe than in the summer. The interventions proposed were a combination of two considerations. The first intervention was the addition of a new charging station placed between Girdwood and Anchorage near the Bird Ridge trailhead, approximately at the halfway point between the two locations.

The modelling of this station has direct implications for future investment, as Tesla, in conversation with researchers, mentioned Bird Creek specifically as a potential site location for a new installation. The addition of the Bird Creek station significantly reduced the queue length of Alyeska Resort, with more than half of the individuals initially stopping at the station having enough charge to reach the newly-added station. As a result of the faster charging speeds, even a queue of 15 vehicles was able to be reduced in a matter of hours, with all individuals who remained at Bird Creek leaving for their home before 9 pm. However, although the queue at Alyeska Resort was diminished, it was still long enough for a few individuals to be left stranded there at the end of the simulation. Hence, the second intervention was employed, which was adding another level 2 charger at the Alyeska Resort site. In this scenario, all vehicles completed charging by 10 pm and made it home before the end of the simulation.

As only a combination of interventions proved to significantly improve the waiting times of drivers, it can be concluded that investment into charging infrastructure cannot be one-dimensional. Additional fast chargers on the network most certainly improve mobility and the feasibility of using an electric vehicle for recreational purposes. Unfortunately, they cannot be the only solution as empowering mobility does not imply comfort or real-world usability. While the existing infrastructure, especially with the addition of Bird Creek, certainly improve the feasibility of an individual driving their EV to a hike, the long queues at charging sites would certainly inhibit widespread adoption of EVs. Residents are much more likely to continue using their ICE vehicles if it better aligns with their normal schedules. This is especially true considering the lack of willingness to accept drawbacks indicated by participants of the driver survey.

On the other hand, these results also show that the addition of 3 new charging ports in strategic locations had a positive impact on mobility even during winter conditions with reduced battery life and more difficult driving conditions. From the perspective of policy, this shows that with limited investment power, impactful action can still be taken to progress the electrification of transport. The solution presented in this report is meant to provide a framework with which to consider future investment, and allows for discussions to begin between stakeholders interested in promoting EV adoption.

5.2.3 2025 baseline picture

One of the goals of the 2025 scenarios was to consider the impacts of continuing the existing trend of placing charging stations in commercial areas. 17 new stations were erected to maintain the same EV: charging station ratio that exists in 2021. The analysis indicates that peak demand and total energy consumption more than doubles in all scenarios modelled as a result of the additional EVs on the road and the additional public demand from agents charging when visiting commercial areas. While the increased consumption certainly has positive implications for utility profits, and produces a lower energy cost for consumers within the MoA, the exacerbation of peak load has negative consequences for grid stability. Although the capacity of the network is not a topic of this study, the 2025 baseline results point to the potential need to mitigate peak EV demand in the MoA in the future.

The 2025 weekend scenarios were run to determine potential benefits of additional public chargers in urban areas to promote mobility for recreational purposes, as well as assess the effectiveness of the 2021 interventions with a higher EV penetration. While the additional chargers provided relief to the initial infrastructure for residents hiking near the Anchorage Bowl, no effect was had on agents which chose to hike near Girdwood. It was interesting, however, to see that an EV population that was approximately double that of 2021 was able to be serviced within the time frame of the simulation for the summer scenario. Although it took until 2 am for all vehicles to be removed from the queues, the fact that none of the vehicles got stranded shows that investment in a station at Bird Creek and an additional charger at Alyeska can be impactful now and into the future. Unfortunately, the success was limited; the winter weekend scenario showed that the additional energy consumption of vehicles forced more vehicles to queue at Alyeska Resort than could be serviced within the time frame of the simulation. More than 10 vehicles remained in the queue at Alyeska Resort, which indicates that additional investment in infrastructure is required in and around the Girdwood area to allow simultaneous charging access to more vehicles. On the other hand, with twice as many vehicles on the road, less agents remained queued at the end of the simulation than with the initial charging network in the 2021 baseline scenarios. This further supports the effectiveness of the interventions in improving the ability of the network to meet driver needs into the future.

An analysis of the charging demand experienced by the new chargers in all scenarios indicated very little difference in the spread between weekday and weekend. While there are certainly outliers, with some chargers seeing excessively high demand and others seeing basically none, the overall low utilisation indicates that charging events at these new chargers is likely out of convenience and not necessity. From the limited positive impact seen by introducing new commercial chargers, the high regard for workplace chargers shown by survey results, and the lack of willingness by the utility to currently invest in high-cost smart technologies, it was determined that interventional 2025 scenarios would consist of assessing the specific impact of workplace charging on peak load.

5.2.4 2025 workplace scenarios

Workplace charging was implemented as giving access to charging to a proportion of the working population not employed in commercial areas, as those in commercial areas already had access to nearby public chargers. An analysis was run with 5%, 10%, and 25% penetration of workplace charging to assess the impact on peak load for a summer and winter weekday.

In both summer and winter, a 5% penetration of workplace chargers saw immediate impacts on peak energy demand. In the summer, both the peak load and the total peak kWh were reduced by 17%; in the winter, peak load was reduced by 12% and peak kWh by 16%. However, while increased workplace penetration in the summer resulted in further reductions in the peak demand, the same was not seen for the winter. A 25% penetration of workplace charging in the summer amounted to a 35% overall reduction in peak power from the baseline and a 29% drop in total peak energy consumption. In the winter, reductions stayed stagnant at 10% and 25% penetration, with relative improvements between the different penetration levels being less than 2%. This is consistent with the behaviour of agents, who, in the model, would begin charging upon reaching their workplace and stop when their state-of-charge reached 100%. This behaviour in the winter-time scenario led to a subtle drop in state-of-charge which later required most agents to still charge upon returning home. This is evident in the fact that total peak kWh consumed between the 5%, 10%, and 25% scenarios being maintained at approximately 3 MWh.

The results from the workplace simulations indicate that while reductions in peak load are achievable through injection of workplace charging availability in the summer, it has limited impacts in the winter. This was mainly a result of agents behaviour, who would unplug their vehicle upon reaching 100%. While this behaviour is unrealistic from the perspective of a driver, who would likely prefer to keep their vehicle charged for the entirety of their time it work, it is realistic from a infrastructure point of view. A simplification was applied to the model which allocated individuals, and not workplaces, to have available charging at work, as the number of patches designated as workplaces was limited. As a result, all agents with access to workplace charging did not need to share the charging port with others. In a realistic scenario, there would likely be limited availability of charging ports shared between a group of drivers. As such, the results are still realistic from a real-world behavioural perspective, as drivers would likely be forced to unplug after reaching full charge to allow others to utilise the port.

The workplace simulations also show that seasonal differences in EV energy use is a critical consideration when determining the impact of workplace charging on the electricity network. While in the summer, increased penetration of workplace charging certainly extends the usability of the existing grid network, the winter-time simulations show that under certain charging behaviours, the positive impacts of early charging do not result in reductions in peak demand. As individual charging behaviour is a stochastic variable that cannot be systematically controlled, the network operator has two potential investment pathways for mitigation. The first is network upgrades, which fortify the existing electrical infrastructure but cannot foresee the implications of ever-increasing demand. The second is smart charging technology, which has a high upfront cost, but adds network flexibility and maintains the integrity of existing infrastructure. Additionally, time-of-use rates could be employed which financially incentivise EV drivers to charge at later hours. If the future of EVs in Alaska is an inevitability, as is the opinion of Alaskan researchers, then utilities have important decisions to make regarding the future of their electrical grid and how it will cope with the increased demand from new electric vehicles entering the landscape.

6 Concluding Remarks

This section concludes the report, first by providing a summary of the preceding chapters and answering the questions posed in the introduction. Secondly, the limitations of the methodology are examined and suggestions are given for future work. Thirdly, key recommendations stemming from the results of this work are extracted and conferred.

6.1 Summary

Chapter 2: Literature Review

Chapter 2 examined the state-of-the-art literature with regards to transport electrification through the lens of consumer preferences and public fast charging deployment. The main findings of the literature is summarised as follows:

- The importance of the driving experience in consumer decision-making regarding EV adoption cannot be understated. While subsidies to reduce purchase price and policy to promote secondary benefits are important, a robust charging infrastructure, especially fast-charging infrastructure, is essential to promote the transition to electrified transport.
- Significant barriers to fast-charging infrastructure are high upfront cost, inconsiderate rate structures, which are exacerbated by low initial utilisation. Additionally, negative grid impacts must be considered before installation can occurs, the solutions for which are also costly and may not be feasible to implement. As a result, outside of a few use cases, fast-charging infrastructure appears to be economically inviable.
- Modelling of fast-charging infrastructure requirements is still in the early days of implementation, and the initial assumptions play a big role in determining the infrastructure requirements for a particular area. Agent-based modelling appears to be the best option for understanding the interactions within an EV system, however limitations exist in current implementation.

From the summary of the literature, research gaps were identified where further research is needed. These were:

- A lack of diverse EV use cases, which limits the existing findings regarding transport electrification for communities which do not fit the mold of a highly-populated urban area.
- A lack of consideration for end user travel behaviour and characteristics in the implementation of agent-based models to analyse EV systems.
- Limited business models for fast-charging infrastructure which does not consider stakeholder interactions and indirect revenue sources.
- Dynamic rate structures as a potential solution to mitigate high operational costs of fast-charging stations has been minimally studied.

The literature review concludes with a characterisation of the case study of the municipality of Anchorage, Alaska. The general structure of the methodology is outlined, and the basic modelling framework is described. Certain aspects of the agent-based model from Pedro, Hardy, and van Dam [81], which had similar goals to the current study, were used as an example.

Chapter 3: Methodology

Chapter 3 meticulously describes the components of the methodology, which include stakeholder interviews, a survey of drivers, and an agent-based model. The design of the interviews and driver survey are discussed, however a majority of the focus is placed on the initialisation of the agent-based model, whose major components include:

- The model environment: real-world sources are utilised to render a realistic layout of the MoA, with representative residential and workplace areas, charging infrastructure network, and hiking locations.
- Agents representing residents: Population distribution and socio-demographic data gathered from the U.S. Census and local Alaskan databases are used to accurately portray the resident population of the MoA.
- Scheduling: weekday and weekend schedules are developed for agents based primarily on the 2002 Anchorage travel survey.
- Charging behaviour: the logic for how an agent searches for a charging station was developed in consideration for the existing local charging infrastructure network.

The model was designed in collaboration with Alaskan researchers, and certain inputs along with the non-baseline scenarios were conceived from the insights obtained from the stakeholder interviews and the driver survey.

Chapter 4 and 5: Results, Analysis and Discussion

Chapter 4 described the results obtained from the interviews, survey, and agent-based model, the implications of which were discussed in Chapter 5. A brief summary of the insights gathered regarding the initial research questions presented in the introduction is given below:

What are the significant barriers to EV adoption and the expansion of public charging (with a focus on fast-charging) infrastructure in Alaska, as perceived by major stakeholders?

The major barriers to EV adoption are the lack of public charging infrastructure, a minimal selection of vehicles for Alaskan use cases, and poor perception of EV use in Alaska, especially in the cold winter months. The major hurdle facing fast-charging infrastructure expansion was identified as a lack of a business case on both the capital and operational fronts. However, this issue is not unique to Alaska, and an important local barrier cited is political and regulatory uncertainty regarding climate and the energy future of Alaska, which deters industry interest in electric mobility and meaningful conversation regarding investment in charging infrastructure.

What is the travel behaviour of MoA residents, what are their concerns regarding electric mobility, and what are their requirements for charging?

Current EV owners were most motivated by the convenience of home charging and the driving experience when making their EV purchase, with the environmental impacts playing a secondary role. On the other hand, interested non-users considered a lack of public charging infrastructure and cold weather performance to be the main determinants of not purchasing an EV. However, a lack of servicing expertise and concerns regarding battery end-of-life were also cited. For both groups, it appears that monetary considerations did not play a major role in decision-making, which provides insights on future policy. With regards to travel behaviour, EV users and non-users showed similar characteristics, with almost no difference in recreational travel and slightly more commuting to work by non-users. The major travel destinations of respondents was also characterised, with the most popular locations being nearby recreational areas. As it pertains to charging requirements, workplace charging was the most sought after location, followed closely be leisure centres and fuelling stations. However, all locations received high consideration which is reasonable considering the very limited existing charging network. Accessibility and reliability were the most valuable characteristics of a charging station to all respondents, with cost parity being one of the lowest considerations. In general, current EV users had a higher willingness to accept drawbacks to charging in all categories than non-users. Both groups gave a relatively high willingness to vacate parking spots and a low willingness to accept waiting times to charge.

What are the limitations of the existing public charging network and what interventions can improve them?

While weekday travel schedules required little use of the public charging network, with 86% of agent charging needs met by residential infrastructure, simulating EV use for weekend recreational travel identified gaps in the charging infrastructure south of urban Anchorage, in the Girdwood area. The Alyeska Resort charger was the only charging location within significant distance, with 23 agents having to queue at this location in the winter, unable to reach the next nearest station. This resulted in agents who had to wait hours before charging, and some which did not make it home by the end of the simulation. The issue was alleviated with a combination of adding a fast-charging station near the Bird Ridge hiking location in between urban Anchorage and Girdwood, as well as supplementing the Alyeska Resort station with an extra level 2 charger. In the intervention scenarios, all agents were able to charge before 10 pm and return home before the end of the simulation. This infrastructure was even able to support the demand of an increased EV fleet, meeting a majority of the needs of the projected 2025 fleet of electric vehicles. All vehicles were able to charge in the summer, although 11 vehicles remained in the queue of Alyeska Resort in the winter. This showed that strategic charging placement has benefits even for future penetrations of EVs, although additional investment is certainly required to fully meet the needs of additional drivers.

Are there simple strategies to mitigate negative grid impacts of future EV loads?

5%, 10%, and 25% workplace charging penetration were considered as potential solutions to reduce the evening peak load during the weekday. The implications are high during the summer, with consistent reductions in peak load as the penetration of workplace charging increases. At 5% penetration, peak kW demand is reduced by 17% from the baseline, and at 25% penetration sees a reduction of 35%. Unfortunately, the same effectiveness is not seen in the winter. While a 5% penetration sees the peak demand drop by 12% and peak kWh consumption drop by 18%, additional workplace charging availability has almost no successive impact, with less than 2% additional reduction in both peak power demand and peak kWh consumed between 5% and 25% workplace charging penetration.

6.2 Future work

While the methodology employed within the framework of this research paper has been apt at gathering certain insights, there are limitations to its application. This section will discuss improvements which could be made to future iterations of the methodology to address these limitations.

With regards to the stakeholder analysis, a straightforward improvement would be to expand the number of stakeholders interviewed and consider additional players within the EV landscape. Interviewees which were approached but did not respond included: Alaskan correspondents from a private EV manufacturer and a VW grant recipient for charging station installation. The stakeholders approached were mainly operating within the MoA as that was the chosen case study for the project. However, gathering supplementary expertise from outside the case study, especially from Juneau, which has a more developed EV infrastructure, would have certainly enhanced the analysis and provided a more complete picture of the EV and charging infrastructure landscape within Alaska.

In terms of the driver survey, a significant limitation was the low number of responses from EV drivers. Although heavily advertised to on social media and through the Alaska EV Working Group, only 20 total responses were gathered from this subgroup. Future work could certainly benefit from increased input from existing drivers, potentially with some comparative questions between their travel behaviour with an ICE vehicle and an EV. As for the general questions, future iterations of the survey should consider more probing inquiries into charging preferences, specifically regarding the speed of charging available, charging behaviours, and end user opinions on policy.

The model developed for this case study made certain strides to provide a more realistic simulation of EV drivers with consideration for seasonal differences in temperature and local recreational habits. However, there are limitations and simplifications within the model which can be improved upon in future iterations.

Future work within this agent-based system can more accurately assess EV impacts on the grid system by integrating network data into the model, such as feeder limits and substation capacity, which was unavailable for this study. Furthermore, as the survey did not provide an accurate sample of the population, workplaces were assigned randomly to agents as a simplification; subsequent analyses can utilise traffic flow data to better represent residential travel. This can also be achieved through an additional survey iterations to reach a higher proportion of the population.

Similarly, the scope of travel in this analysis was restricted to destinations within the MoA, although most of the popular destinations cited in the survey were external. The model environment, in future work, can be expanded to include the full breadth of destinations available to this particular population of drivers. A simulation which considers all major travel destinations will have a better view of the limitations of the planned charging network, with important implications for the chargers expected to be installed in 2022. Additional fleets can also be considered, such as the taxi fleet, public buses, and government vehicles.

Finally, although this model analysed the utilisation of existing and potential future charging stations within the MoA, time constraints and lack of data precluded an analysis of the economics of charging stations. Further work can expand on the conclusions reached in this report by performing an economic analysis to determine the necessary fee charged to the consumer which would create profitability for site hosts under different EV penetrations. This is especially prudent considering the potential new rate structure these stations would be operating under if the RCA gives a positive ruling on the rate design modification. Such an analysis can provide key evidence to spur interest from local site hosts and investment from major stakeholders.

6.3 Final recommendations

From the discussions with stakeholders and results provided through the driver survey and agent-based model, a set of recommendations is conceived within 3 major topics which were identified. These recommendations can help guide future decision-making in electric mobility in Alaska, with specific implications for the Municipality of Anchorage. While certain ideas can only be implemented by specific stakeholders, the majority of the insights presented attempt to be general in their application, and can prove useful for any stakeholder within the EV system in the MoA.

6.3.1 Promoting cohesion and understanding

- Continue to develop communication with regulators and policy-makers to clarify the challenges and benefits of transport electrification. Push for policy to align the goals of different stakeholders on this issue by quantifying large-scale value of EVs from the perspective of climate, energy, and grid services.
- It is clear from the driver survey that the list of concerns of end users regarding electric vehicles is high. A continued emphasis on educational programs such as the "Ride and Drive" event held in August 2021 will continue to reduce uncertainties about EVs.

6.3.2 Consideration for preferences and behaviour

- Understand that high expectations from drivers for charging and low willingness to accept drawbacks likely means the bare minimum infrastructure will not be enough to convince drivers outside of early adopters to electrify. Similar to energy generation in rural communities, charging infrastructure planning will require consideration for redundancy.
- Consider opportunities to improve the existing charging network as a way to minimise investment in new infrastructure. Can additional charging ports be added to overutilised stations? Can a service be provided in areas with high utilisation and low capacity, similar to a valet, which can charge electric vehicle parked for long periods?
- As the EV market in Alaska is rapidly evolving, plan infrastructure investment for current and future consumer types. While this may not enhance the existing economic outlook, it will certainly have financial and societal benefits in the future.

6.3.3 Planning for impacts

- Place an emphasis to improve local expertise on EV maintenance and operation. This will enhance the perceived reliability and ease of owning an electric vehicle, and enhance fundamental EV knowledge within the community.
- Understand the benefits and potential risks of EVs as a flexible source of power and energy. Plan ahead to prepare the electrical grid for such a load and leverage opportunities such as smart charging and vehicle-to-grid energy storage to maximise the positive impacts of EVs.
- Consider the end-of-life of EVs, specifically with regards to recycling and reusing secondhand batteries. While this is certainly a distant concern, it may have significant benefits for rural communities looking for relatively cheap storage options to mitigate the intermittency of renewable generation.

Appendices

A Stakeholder Interview Questions

Charging station installer

1. Is your enterprise focused exclusively on DCFC installations or are you interested in level 2 infrastructure as well?
2. What is the process of installing a fast-charging station? What are important differences between an installation in an urban area vs. on the travel corridor?
3. Do you have any comments about the proposed rate structure design currently on the RCA docket?
4. What are the benefits/drawbacks of utility participation in charging station installation?
5. How are the costs of DCFC changing with time?
6. What are policy mechanisms that could incentivise expansion of public charging infrastructure or EV adoption directly?
7. Are there any topics worth mentioning that I did not ask about?

Utility representative

1. What is the role of a utility in the transition to a decarbonised future?
2. How important is decarbonising transport to reach climate goals?
3. What are the major barriers to widespread adoption of EVs in Alaska?
4. How does Alaska's harsh climate impact EV adoption and further expansion of charging infrastructure?
5. What is your opinion on the proposed rate structure design currently on the RCA docket?
6. What are additional barriers to charging infrastructure expansion (besides demand charge)?
7. With a high penetration of EVs, does it make sense for utilities to invest in public infrastructure?
8. What policy mechanisms could influence EV adoption and expansion of infrastructure?

State agency representative

1. How important is decarbonising transport to reach climate goals?
2. What are the major barriers to EV adoption in Alaska?
3. Is part of the barrier of range anxiety a lack of education/awareness on EVs from consumers?
4. Are there other policy mechanisms outside of rate structure modification which could spur EV adoption?
5. What was the interest level for the VW grant funding for site hosts?
6. Do you see any issues with putting higher power chargers (¿50 kW) on the road system?
7. What role should a utility play in the expansion of public charging infrastructure?

8. Can state funds be provided to utilities directly for installations?
9. Has any investment modelling been done with regards to public charging infrastructure needs?
10. Do you participate in public education with regards to EVs?

Researchers

1. What role does transport electrification have in meeting climate goals?
2. What are the major barriers to EV adoption in Alaska?
3. Do you think that the energy mix is a barrier to further EV adoption (from the perspective of the consumer)?
4. What are the barriers to expanding public charging infrastructure in Alaska?
5. How effective will the new rate structure be in expanding interest in becoming site hosts for charging stations?
6. How do you view the role of a utility in transport electrification and expansion of public charging infrastructure?
7. Where should investment be directed for public charging infrastructure?

State government representative

1. What do you see as the biggest energy issues facing Alaska currently?
2. How ubiquitous are climate considerations for members of the state energy committee?
3. Alaska is in an interesting dilemma where the state government is extremely reliant on revenue from fossil fuel extraction and still harbor a high quantity of fossil fuel resources; however, we are seeking the impacts of climate change at an accelerated rate to the rest of the U.S. How do you reconcile putting the state government on solid financial footing with the need to transition away from fossil fuels?
4. What role does transport electrification have in meeting climate goals?
5. What are the major barriers to EV adoption in Alaska?
6. What do you view as the role of government in spurring EV adoption and the expansion of public charging infrastructure?
7. Do you see state government investment into transport electrification as a possibility considering its current fiscal situation?
8. What do you see as the role of a utility in transport electrification and expansion of public charging infrastructure?

B Driver Survey

Table B1: Comparison of residential zip codes proportions between MoA driver survey and U.S. census data.

Zipcode	Sample survey data	U.S. Census Data
99501	4.4%	5.7%
99502	6.8%	8.6%
99503	6.3%	4.4%
99504	8.7%	14.4%
99505	0%	2.1%
99506	15.5%	2.3%
99507	8.7%	12.7%
99508	0.5%	12.5%
99511	0.5%	0%
99513	0%	0%
99515	10.2%	7.8%
99516	11.2%	7.1%
99517	11.2%	5.4%
99518	4.4%	3.7%
99840	0%	0.1%
99567	0.5%	3.0%
99577	7.8%	9.7%
99587	3.9%	0.6%

Survey questions

Personal information

1. What is your age bracket?
   - ☐ 18-24
   - ☐ 25-44
   - ☐ 45-64
   - ☐ 65 and older
2. What is your gender?
   - ☐ Male
   - ☐ Female
   - ☐ Non-binary/third gender
   - ☐ Prefer not to say
3. What is your highest level of education?
   - ☐ High school diploma
   - ☐ Undergraduate degree
   - ☐ Master's degree
   - ☐ PhD
   - Other
4. What is your 5-digit residential zip code?
5. What is your 5-digit workplace zip code?
6. Do you currently own an EV?
   - ☐ Yes
   - ☐ No

EV preference (Current owners) This section is only for those respondents who answered "Yes" to currently owning an EV

1. What importance did you place on the following considerations when making your electric vehicle purchase? Importance is ranked on a scale from 0 to 5, with 0 indicating no importance and 5 indicating utmost importance.
   - ☐ Air quality concerns
   - ☐ Carbon emissions
   - ☐ Lower maintenance costs
   - ☐ The driving experience (responsiveness, silence, etc)
   - ☐ Tax incentives
   - ☐ Convenience of home charging

- ☐ Other (please specify)

2. Do you keep your EV in a garage or is it parked outside?
   - ☐ Garage
   - ☐ Outside
   - ☐ Depends on the season
   - ☐ Other (please specify)
3. What sort of charging infrastructure is available at your residence?
   - ☐ Level 1 (standard outlet)
   - ☐ Level 2 (240 V)
   - ☐ None
   - ☐ Other (please specify)
4. Use the sliders (0-100) to identify the utilisation of your EV.
   - ☐ Percentage of charging needs met by residential charging
   - ☐ Percentage of daily travel needs met by EV
   - ☐ Percentage of leisurely travel needs met by EV
5. What is the longest trip you have taken in your EV and where did you go?

EV interest (non-EV users) This section is only for those respondents who answered "No" to currently owning an EV.

1. Do you have any interest in electric mobility or purchasing an electric vehicle for yourself (at some point)?
   - ☐ Yes
   - ☐ No

If you answered "No" to the above question, you are redirected to "Travel behaviour". If you answered "Yes", you are given the additional question below.

1. What importance did you place on the following considerations when deciding to abstain from an electric vehicle purchase? Importance is ranked on a scale from 0 to 5, with 0 indicating no importance and 5 indicating utmost importance.
   - ☐ High upfront cost
   - ☐ Lack of public charging infrastructure
   - ☐ Fear of running out of charge
   - ☐ Cold weather performance
   - ☐ Other (please specify)

Travel behaviour

1. Approximately how many days per week do you commute to your workplace in your personal vehicle? Summer is considered May - Sept and Winter is considered Oct - Apr.

☐ Summer

☐ Winter

2. Approximately how many days per week do you commute on the highway for recreation in your personal vehicle? Summer is considered May - Sept and Winter is considered Oct - Apr.

   ☐ Summer

   ☐ Winter

3. List your top 5 recreational destinations to drive to and how frequently you visit them. Any time frame is acceptable; i.e. # of times per week, month, year are all valid.

Charging preferences

1. Identify the importance, in your opinion, of having public charging infrastructure in these locations. Importance is ranked on a scale from 0 to 5, with 0 indicating no importance and 5 indicating utmost importance.

   ☐ Fuelling stations

   ☐ Workplaces

   ☐ Shopping centres

   ☐ Leisure centres (hotels, recreational areas, etc)

   ☐ Educational institutions

   ☐ Other (please specify)

2. Identify the importance, in your opinion, of the characteristics of a charging station, which are described below the question. Importance is ranked on a scale from 0 to 5, with 0 indicating no importance and 5 indicating utmost importance.

   ☐ Dual use

   ☐ Reliability

   ☐ Accessibility

   ☐ Habit compatibility

   ☐ Cost parity

   ☐ Personal safety

   ☐ Vehicle safety

   ☐ Other (please specify)

3. Identify your willingness to accept drawbacks and interruptions to travel for charging purposes. Willingness is ranked on a scale from 0 to 5, with 0 indicating unwilling and 5 indicating very willing.

   ☐ Willingness to make a detour to charge

   ☐ Willingness to vacate a parking spot upon completion of charging

   ☐ Willingness to accept waiting times to charge

C Agent-Based Model

Scheduling data

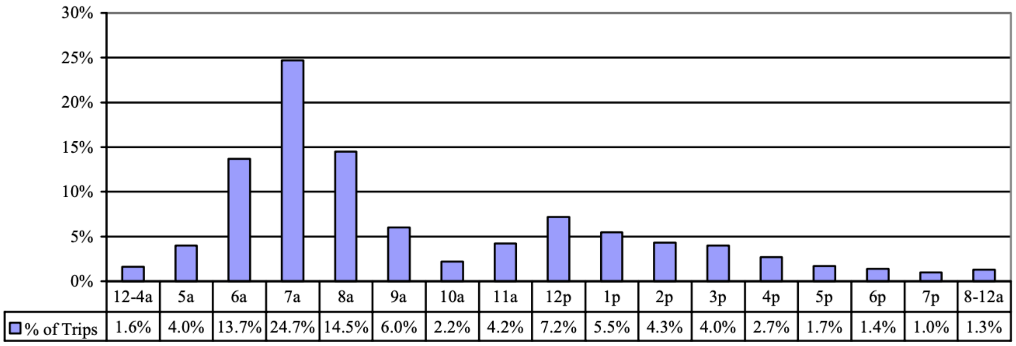


Figure C1: Distribution of departure hours for trips to work in the MoA, 2002 Anchorage Household Travel Survey [116].

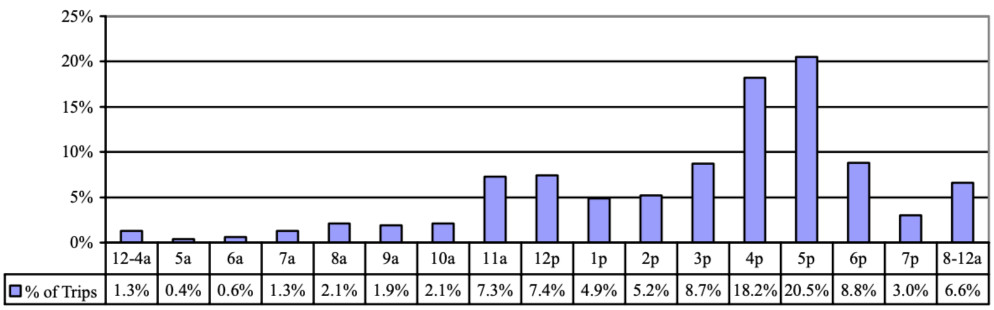


Figure C2: Distribution of departure hours for trips from work in the MoA, 2002 Anchorage Household Travel Survey [116].

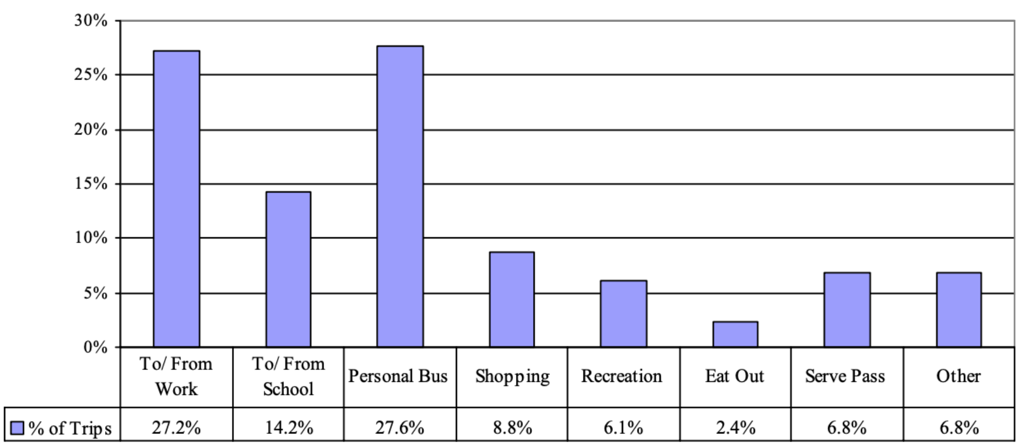
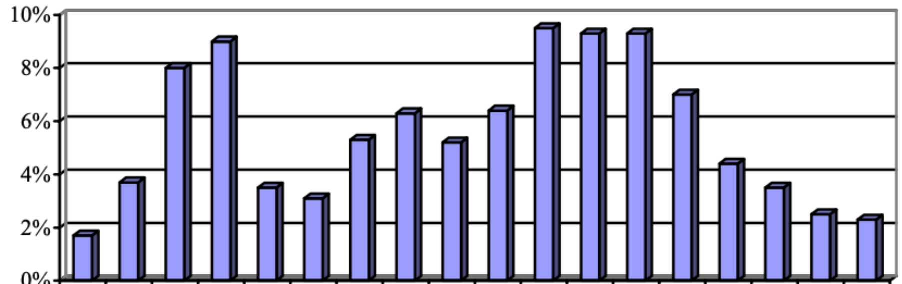


Figure C3: Distribution of residents in the MoA, 2002 Anchorage Household Travel Survey [116].



	12-5a	6a	7a	8a	9a	10a	11a	12p	1p	2p	3p	4p	5p	6p	7p	8p	9p	10-12a
% of Trips	1.7	3.7	8.0	9.0	3.5	3.1	5.3	6.3	5.2	6.4	9.5	9.3	9.3	7.0	4.4	3.5	2.5	2.3

Figure C4: Distribution of departure hours for all trips by residents in the MoA, 2002 Anchorage Household Travel Survey [116].

Agent characterisation

Label	Households with one or more people under 18 years	Households with one or more people 60 years and over	Householder living alone	65 years and over
Anchorage	0.34	0.304	0.263	0.071
99501	0.212	0.342	0.458	0.159
99502	0.392	0.227	0.22	0.042
99503	0.202	0.278	0.401	0.08
99504	0.318	0.341	0.234	0.079
99505	0.903	0.011	0.057	0
99506	0.478	0.015	0.166	0.007
99507	0.336	0.281	0.258	0.059
99508	0.341	0.316	0.273	0.092
99513	-	-	-	-
99515	0.387	0.34	0.212	0.06
99516	0.377	0.407	0.158	0.051
99517	0.247	0.366	0.342	0.095
99518	0.3	0.294	0.373	0.08
99540	0.154	0.348	0.527	0.114
99567	0.396	0.377	0.176	0.06
99577	0.423	0.262	0.183	0.03
99587	0.248	0.186	0.39	0.075

Figure C5: Household data of MoA residents from 2019 ACS Community Survey estimates [115].

Job type	Number of employees	Include?	Why?			
Total Nonfarm	140400	No	total value of all workers			
Goods Producing	11600	No	category unknown			
Service-Providing	128800	No	total value of all categories below			
Mining and Logging	2000	No	non-local workplace			
Oil and Gas	1800	No	non-local workplace	**city centres**	67500	0.64
Construction	7600	Yes		**industrial**	9600	0.09
Manufacturing	2000	Yes		**commercial**	19600	0.19
Trade/Transportation/Utilities	30200	Yes		**schools**	8100	0.08
Wholesale Trade	4600	No	subcategory of "trade"	**total**	104800	
Retail Trade	15000	No	subcategory of "trade"			
Trans/Warehouse/Utilities	10600	No	subcategory of "trade"			
Information	3000	Yes				
Financial Activities	6800	Yes				
Professional and Business Svcs	16600	Yes				
Educational and Health Services	26200	Yes				
Health Care	20900	No	category unknown			
Leisure and Hospitality	14300	Yes				
Accommodation	2500	No	subcategory of "leisure"			
Food Svcs and Drinking Places	10500	No	subcategory of "leisure"			
Other Services	4900	No	subcategory of "leisure"			
Government	26800	Yes				
Federal Government	8500	No	subcategory of "gov't"			
State Government	9200	No	subcategory of "gov't"			
State Education	1500	Yes				
Local Government	9100	No	subcategory of "gov't"			
Local Education	6600	Yes				

Figure C6: 2021 workforce data taken from MoA Department of Labor Statistics [114]. The small table on the right represents the final percentage allocation of workers to the different land use areas within the agent model.

Calculation of EV parameters

The calculation of the drop in state-of-charge was based on the physical distance between patches within the agent-based model. In QGIS, there is a measuring tool which allows calculation between any two points.

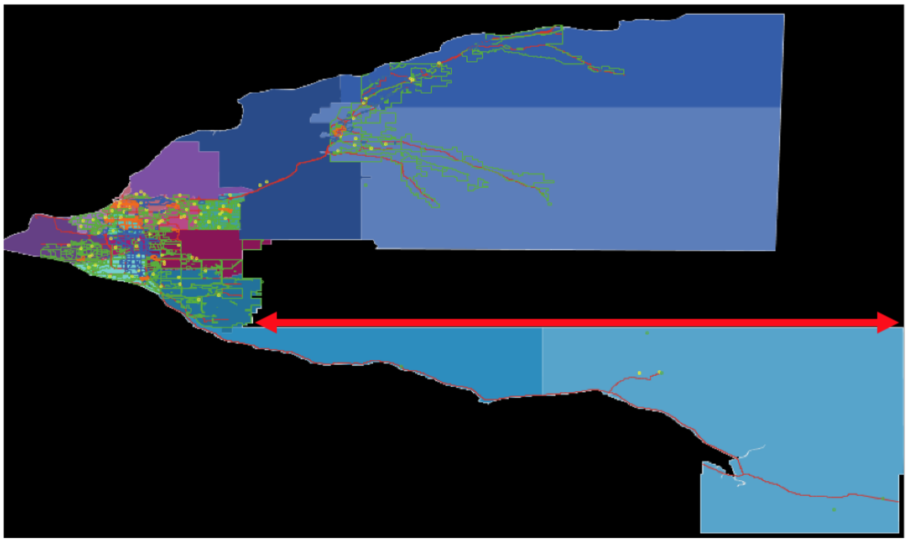


Figure C7: Representation of the MoA, with the red arrow indicating the section used to calculate the distance.

The distance shown by the red arrows in the figure was calculated to be approximately **57 km** in QGIS; in NetLogo this length was covered by **117 patches**. As a result, the average distance between patches is:

$$patch\ distance = \frac{QGIS\ distance}{number\ of\ patches} = \frac{57km}{117\ patches} = \frac{450\ metres}{patch} = \frac{0.27\ miles}{patch} \tag{C.1}$$

Based on the calculated distance, a constant speed of **30 mph** was chosen for all agents within the model as this results in a simple time passage of **half a minute** between ticks. This is given by:

$$time\ per\ tick = \frac{patch\ distance}{average\ speed} = \frac{0.27\ miles}{30\ mph} = approx.\ \frac{0.5\ minutes}{tick} \tag{C.2}$$

Hence, during each tick an agent will travel **0.27 miles in 0.5 minutes**. From these calculations the state-of-charge parameters can be ascertained.

The Chevy Bolt, which is the chosen vehicle within the model, has a rated battery capacity of **60 kWh**. However, as it is common for Alaskans to purchase used vehicles, the capacity must be reduced. Using an average annual degradation of 2.3% per year, the actual battery capacity for vehicles within the model is **54 kWh**, or **6,480 kW-half-minutes**, which is the individual unit of time within the model.

Independently collected data provided by the ACEP researchers indicates that at the minimum historical average temperature of -15 deg. C in the Anchorage area, battery consumption during driving is **0.5 kWh per mile**. Additionally, power consumption when idle to maintain battery temperature is **0.32 kWh per hour**. Considering a battery capacity of 54 kWh and converting the distances into patch distances yields:

$$\frac{0.5\ kWh}{mile} * \frac{0.27\ mile}{patch} = \frac{0.14\ kWh}{patch} = \frac{0.25\%}{patch}\ loss\ of\ SOC\ when\ driving \tag{C.3}$$

$$\frac{0.23\ kWh}{hour} * \frac{120\ half\_minutes}{hour} * \frac{1\ tick}{1\ half\_minute} = \frac{0.005\%}{tick}\ loss\ of\ SOC\ when\ idle \tag{C.4}$$

A similar calculation is employed when determining the percentage increase in state-of-charging during charging events. The results are summarised in the table below, and are the raw increases in charge before consideration for the idle power requirements:

Table C1: Percentage increase in state-of-charge of vehicles within the agent-based model as a function of charging speed.

Parameter	**Speed**	**Percentage SOC increase**
Charging speed L1	1.5 kW	0.02%
Charging speed L2	12 kW	0.2%
Charging speed L3	50 kW	0.8%

When determining the number of commuters from the Matanuska-Susitna Borough (MSB) in 2025, the following calculation was employed:

If we assume that EVs in MSB will grow linearly with time, and proportional to the growth currently seen in the MoA, then:

$$\frac{EVs\ in\ MSB}{EVs\ in\ MoA} = \frac{70}{225} \approx 30\% \tag{C.5}$$

As the current EV population of the MSB is 30% of the population in MoA, we should expect an annual growth that is 30% of the growth expected in the MoA.

$$EV\ growth\ MoA \approx \frac{60}{year} \Rightarrow EV\ growth\ MSB \approx \frac{60 * 0.3}{year} \approx \frac{20}{year} \tag{C.6}$$

However, because the MoA has more available public charging infrastructure, the annual EV growth was reduced by a factor of 2.

$$EV\ growth\ MSC \approx \frac{20 * 0.5}{year} = \frac{10}{year} \Rightarrow 2025\ EV\ population\ MSB = 70 + (10 * 4) = 110 \tag{C.7}$$

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