Adoption of green fleets: An economic and environmental life cycle assessment of light duty electric vehicle fleets

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Abstract:

This study assesses regional characteristics of fleet vehicles within New England calculating total cost of ownership (TCO) and greenhouse gas (GHG). Inventory for battery electric vehicles (BEV), extended mileage battery electric vehicles (BEV+), plug in hybrid electric vehicles (PHEV), hybrid electric vehicles (HEV) and internal combustion vehicles (ICV) light duty fleet vehicles is based on New Hampshire Department of Environmental Services (NHDES) fleet characteristics. This analysis was conducted using empirical data from the State of New Hampshire and University of New Hampshire fleets, ISO-New England (ISO-NE) grid data, and peer reviewed literature to capture the impacts of regional driving characteristics, energy grid, and climate. With 2019 gasoline and electricity prices, results show the HEV has the lowest lifetime TCO, $2,709.88 less than the second lowest vehicle. The PHEV is shown to cost $1,082.86 dollars less than the ICV while the BEVs total costs are $233.65 greater. All vehicle technologies show major reductions in fuel and operations and maintenance (O&M) costs compared to the ICV, specifically under the high mileage of State of New Hampshire fleet vehicles. The BEV shows the largest GHG abatement potential by emitting .17kg/mile CO_2^e, representing a 54% decrease below the ICV. This study indicates both PHEVs and BEVs are cost competitive with ICVs while providing substantial GHG emission abatement while the HEV is determined to have the lowest TCO amongst all vehicles along with 33% GHG abatement.

Introduction:

Anthropogenic global climate change is a great risk to human health and the environment. These realities have brought about changes in many aspects of the transportation sector, which accounts for approximately 28% of total greenhouse gas (GHG) emissions within the United States (United States Environmental Protection Agency, 2019). In New England, the proportion of emissions from the transportation sector is greater due to interstate passenger vehicle transportation networks for work, tourism, and daily life (Gobin et al., 2018). The proportion of GHG emissions from the transportation sector are higher than the national average in all six New England states, with values ranging between Rhode Island's 36% to Maine's 53% (NHDES, 2018; State of Vermont, 2019; State of Massachusetts, 2019; Maine Department of Environmental Protection, 2018; Connecticut Department of Environmental and Environmental Protection, 2017; Rhode Island Department of Environmental Management, 2017). A switch to electrified transportation vehicles could have potentially large impacts on reducing GHG emissions across the nation, and specifically in New England.

Of the national transportation sector's GHG emissions, 62% are from light duty vehicles (Jenn, Azevedo, & Michalek, 2016). These high emission rates have led to the growth of the alternative fuel vehicle (AFV) industry. AFVs provide potential reduction in GHG emissions and can decrease dependence on foreign oil. Implementation of low carbon AFV transportation fleets is an attractive investment for government agencies, municipalities, and businesses looking to reduce their carbon footprints and promote themselves as a green operation (Sengupta & Cohan, 2017). Of the AFVs studies across the literature, battery electric vehicles (BEVs) present the highest potential for GHG reduction and fuel cost savings. These GHG emission reductions are directly related to the fuel mix generating the electricity, since carbon neutral electrical sources such as renewables, hydro, and nuclear drastically reduce life cycle emissions when compared to electricity generated from a coal powered grid (Longo, Yaïci, & Zaninelli, 2016). A surge in electric vehicle (EV) ownership paired with carbon neutral electrical generation sources could lead to greatly reduced transportation sector emissions.

This belief that EV adoption is a fix for many environmental problems such as transportation sector CO_2 emission and dependence on fossil fuels has been a major factor in their global rise in popularity (Rezvani, Jansson, & Bodin, 2015). In addition to the belief they are more environmentally friendly, consumers are told EVs have economic advantages over internal combustion vehicle (ICVs) due to reduced fuel and operations and maintenance (O&M) costs across the vehicles lifetime (Kleiner & Friedrich, 2017). These potential benefits of EVs have led to increased interest in electrified fleets. The presence of electric vehicle service equipment (EVSE), or charging infrastructure, at a workplace increases the likelihood employees will purchase an EV. Thus, governments and private business can lead by example through publicly operated electric fleets to help increase EV visibility and awareness (Gobin et al., 2018).

Globally, EVs have shown major growth as an industry with sales doubling from 2012 to 2017 (Breetz & Salon, 2018). Within the U.S. EV sales experienced a 72% increase from 2015 to 2017 (Dumortier et al., 2018). Despite the potential economic and environmental benefits, the market share of electric vehicles is still small at 4.5 percent in 2018 (CAM, 2019). While EVs are projected to be a fast-growing industry, their slow adoption is due to perceived disadvantages including the large investment premium for vehicles and charging infrastructure. Continued technological advancement have lead consumers to believe they will receive a better quality good in the future for the same high investment price (Carley, Krause, Lane, & Graham, 2016).

The economics of EVs, including high initial investment and low operating costs over time, have led researchers to assess various vehicle types using total cost of ownership (TCO) and life cycle cost analysis (LCCA) frameworks. In 2001, Delucchi & Lipman performed a life cycle analysis comparing light duty passenger BEVs and ICVs. Their analysis found battery costs were the largest contributor to BEV purchasing price. To make BEVs cost competitive, lithium ion (Li-ion) battery costs would have to be greatly reduced to $100 kWh. In their analysis published in 2011, Sui & Wang used a life cycle cost framework to assess how battery electric buses, passenger auto's, and mini cars compared to applicable ICVs. The results showed the BEVs were generally more costly. However, under high fuel price and fuel shortage scenarios, the BEVs were determined to be more competitive. This line of research was continued in 2018, when Weldon, Morrissey, & Mahony, 2018 compared small, medium, and large BEVs, along with electric vans, to comparative ICVs. The authors found BEVs are more competitive when usage is high, there are incentives in place, and when the vehicles are larger. Specifically, electric vans have high potential to be cost competitive with ICVs. The authors concluded that, despite range anxiety shown by BEV operators, BEVs should be promoted to high mileage users.

In addition to analyzing BEVs, hybrid vehicle technologies like hybrid electric (HEV) and plug in hybrid electric (PHEV) vehicles have been discussed in the literature. Propfe et al., 2012 compared HEV and PHEV technologies to ICV and BEVs using a LCCA framework. They made the argument hybrid vehicles present large improvements over ICVs, such as decreased operations and fuel costs and reduced GHG emissions, without the high costs of BEVs. They conclude that, in the long run, PHEV technologies will become the preferred choice for many car buyers due to their low operating cost and unlimited driving range. Similarly, Lin et al., 2013 compared HEV compact, mid-sized, and SUV vehicles to similar ICVs. Their results showed that in high driving scenarios, HEVs reduced energy use by 35-45%, and that HEVs would be less costly under high fuel scenarios. In 2015, Wu, Inderbitzin, & Bening assessed both battery electric and hybrid vehicle technologies by comparing BEVs, PHEVs, HEVs, and ICVs for the model year 2014, as well as attempting to forecast future vehicles' costs in 2020 and 2025. Their results showed ICVs to be the least costly in 2014, with ICVs and HEVs being the least costly in 2020-2025. Both PHEVs and BEVs were shown to be significantly more expensive in the early years, with cost differences diminishing in later years. The authors also discuss the effect miles driven has on a vehicle's total costs, pointing out that high mileage scenarios will favor EVs because of their lower operating costs.

In 2017, Sengupta & Cohan built on previous literature by bringing an LCCA study to the fleet setting and incorporating an assessment of GHG emissions. By assessing battery electric and hybrid technologies they determined both HEVs and ICVs were the most cost competitive, with BEVs costs between 32-50% greater than the HEV. Additionally, all vehicle types showed major greenhouse gas reductions over the ICV. The inclusion of EVSE, estimated at $11,000 per EV, greatly influenced economic results in favor of the traditional HEV and ICV technologies. The inclusion of GHG emissions was an important addition, as business and governments operating EV fleets often are incentivized to reduced emissions as well as consider economic costs. In their 2018 study, Breetz & Salon compared life cycle costs of BEVs, HEVs, and ICVs across the U.S. using regional driving characteristics of 14 American cities. The results indicated regional characteristics have great impacts on BEV total costs as fuel economy and driving range can be greatly affected by winter driving conditions as energy is needed for cabin heat and the battery has reduced discharge efficiency. The authors found EVs low operating costs seldom make up for their high purchasing prices, and government incentives or low rate/ free charging is needed for them to be less costly than competing technologies. While their analysis was focused on private vehicle ownership, thus incorporating a short 4-year lifespan, the authors provide important insight into the influence regional characteristics can have on the life cycle costs of EVs.

Much like assessing economic costs, environmental output including GHG inventories should be approached using a life cycle analysis (LCA) methodology. In their 2013 study, Cai, Wang, Elgowainy, & Han assessed both GHG and criteria air pollutant (CAP) emissions from BEV and ICV technologies, with a specific focus on upstream emissions from the electrical generation sources. Using U.S., Northeast, and California average grid mixes, as well as 100% natural gas, the authors showed changes in electrical energy sources have great impacts on emissions. The results indicate BEVs reduce GHG emissions by between 68% using California grid and 34% using U.S. average grid data, thus highlighting the importance of energy sources and distinct regional characteristics which influence BEV emissions. These findings were supported by research from Archsmith, Kendall, & Rapson who determined spatial attributes are important in determining the potential advantages of BEVs, as in some areas GHG emissions are significantly reduced and in others emission increase compared to ICVs. The effect of extreme temperatures, which can reduce BEV energy efficiency, was also included in this analysis. The authors determined regions with coal heavy grid and cold winter temperatures, such as the Dakoda's, could potentially lead to negative emissions abatement if BEVs are substituted for ICVs.

Research in 2016 by (Holland, Mansur, Muller, & Yates, 2016) assessed emissions of GHGs and CAPs for BEV and ICV technologies, with their findings highlighting the spatial factors which influence the impacts of vehicle emissions. ICV emissions occur at the vehicle tailpipe, leading associated externalities to be seen locally 81% of the time. In contrast, BEV emissions are seen at the electrical generation source which is not necessarily in the same place the vehicle is being driven. The location, along with the height of smokestacks associated with powerplant emissions, lead the environmental and health effects of regional pollutants (CAPs) to be drastically different between the two vehicle technologies, and the associated economic damage functions will differ greatly. However, as GHGs are global pollutants, spatial factors do not impact the effects of these emissions. Thus, making the comparison of GHG emissions between vehicle technologies simpler than CAPs.

In 2018, Laberteaux & Hamza assessed both BEV, PHEV, HEV, and ICVs based on driving patterns to see how operational usage affects emission for each technology. Each vehicle was assessed under city and non-city driving scenarios. Both HEVs and BEVs were shown to have little effect resulting from driving conditions, with HEVs emitting between 200-250g carbon dioxide equivalent (CO^2_e) per mile while BEVs emitted around 100g CO^2_e/mile under both scenarios. Inversely, ICVs ranged from 280-350g CO^2_e/mile in non-city to 350-550g CO^2_e/mile in the city while PHEVs were 100g CO^2_e/mile in the city and 200g CO^2_e/mile in non-city. This research clearly identifies operational range and driving patterns as major variables to be considered when assessing emissions of vehicle technologies.

While previous literature focused on emissions associated with a vehicles operation phase, such as the influence of electric grid for BEVs and tailpipe emissions for ICVs, Qiao, Zhao, Liu, Jiang, & Hao (2017) assessed emission from each vehicle technologies production phase. Using a cradle to gate approach, the authors determined GHG emission in BEV production are 50% greater than that of the ICV, at a roughly 5 tons of CO^2_e increase. The large increase in BEV embedded emissions are due to the production of the Li-ion battery, which is much more energy intensive than the production of lead acid batteries used in ICVs. The impacts of battery production were included by (Elgowainy et al., 2018) who estimated vehicle emissions in 2015 as well as future emissions in 2025-2030, while also calculating the cost per mile driven. HEV, PHEV, and BEV from 2015 were estimated to emit between 300-350g CO^2_e/mile while the ICV emitted 450g CO^2_e/mile. In the future, AFVs are expected to emit 250g CO^2_e/mile while ICVs will emit around 350g CO^2_e/mile. On the economic side, BEVs were shown to have a \$0.32/mile greater cost than the ICV. By 2025, this difference is projected to shrink to \$0.08/mile with the ICV remaining a cheaper option.

Both economic and environmental life cycle analysis have highlighted to importance of regional characteristics when assessing the impacts of EVs. The decarbonization of the transportation sector has been a topic of great regional interest across New England in recent years, with specific focus being paid to the adoption of EVs. In 2018, a group of northeastern states, including all six in New England, came together to present a unified goal to grow the region into one of the world's leading EV markets, outlined in the publication *Northeast Corridor Regional Strategy for Electric Vehicle Charging Infrastructure*. These goals will be met chiefly by the implementation of an EVSE network available continuously across the region, funded through environmental mitigation funds from the Volkswagen lawsuit (Gobin et al., 2018). The Transportation Climate Initiative (TCI), a regional climate policy introduced in 2019, is another example of regional collaboration drawing interest in EVs. The TCI does not directly promote the adoption of EVs, but rather limits the volumes of gasoline sold in the marketplace through a cap and invest program. A subsequent increase in gasoline prices, between \$0.05/mile and \$0.17/mile, may lead to increased interest in EVs from public and private sectors. Additionally, revenue from TCI may be re-invested in EV rebates, EVSE network development, and other public EV projects (Transportation Climate Initiative, 2020).

While there is a clear recognition of potential EV benefits across the northeastern U.S. through the generation of regional policy, local interest in EV fleets has been growing, specifically in New Hampshire. State institutions such as the New Hampshire Department of Environmental Services and University of New Hampshire, both data contributors to this study, have successfully begun the implementation of both PHEV and BEV fleets. In a response to regional momentum and as a result of the success of local EV fleets, the New Hampshire state Senate proposed House Bill 275 in early 2019. This legislation would have required all State light duty passenger auto fleet vehicles purchased or leased to be zero-emission starting in 2021, with light, medium, heavy-duty trucks and vans phasing into the program over the next 20 years. This legislation was eventually vetoed by the governor in June 2019, citing an increase in economic costs derived from comparing the purchasing price of EVs to comparable ICVs (State of New Hampshire, 2019).

What the State of New Hampshire did not consider, and the literature highlights, is the need to assess EV technologies in a life cycle framework. Differences in cost structures where high initial investments are offset by reduced operations costs across the vehicle’s lifespan have been identified. Additionally, previous economic assessments highlight the importance of regional characteristics in terms of climate considerations, expected fleet operational range, and driving characteristics. There is a well-established research base, but for regions such as New England, there is still nuance as to how the climate affects BEV operation and how the energy grid influences emissions. Based on regional uncertainty regarding the impacts driving patterns have on BEVs, fleet managers and policy makers across the region remain uncertain about the feasibility of such investments, which serves as a potential barrier to their adoption.

The failing of House Bill 275 highlights the need for a study assessing electric and traditional vehicles within a life cycle cost framework in New England (State of New Hampshire, 2019). This study is an attempt to fill this void and provide an applied analysis of how electric vehicles compare to traditional vehicle technologies within a fleet setting. Empirical data from the State of New Hampshire and University of New Hampshire fleets, along with peer reviewed literature, will help to incorporate regional and fleet operational characteristics to ensure results are applicable to New England fleet managers. Along with the economic analysis, an in-depth GHG inventory will be conducted to capture vehicle emissions given regional electric grid data, battery production, and fuel efficiency. The results of this study will allow fleet managers and policy creators to make informed decisions on the economic costs associated with EV fleet adoption and understand the environmental effects of different vehicle technologies. In additional to filling the need for specific regional analysis on EVs, this study will also advance the knowledge base on economic costs of EVs in the fleet setting. Fleet vehicles must be considered under extended mileages and longer lifespans than private vehicles. These characteristics have seldom been considered in the literature, and the use of empirical data on fuel and maintenance costs makes this study unique to date.

Methods:

Economic Life Cycle Cost Analysis:

To calculate total cost of ownership (TCO) this study will utilize the life cycle cost analysis (LCCA) methodology. Life cycle cost is an economic method of evaluation that accounts for owning, operating, maintaining, and disposing of an asset (Ellis, 2007). By considering the entire lifespan of a project, decision makers can assess costs beyond high initial investment. LCCA is used when assessing purchasing decisions where high investment costs are traded for lower occurring costing in the future (Akhlaghi, 1987), as is seen with electric vehicles (EVs) when compared to traditional internal combustion vehicles (ICVs). LCCA accounts for costs relating to an asset from purchasing through disposal and is concerned with optimizing its value by accounting for costs through its operational life. Maximizing the trade-off between these costs will lead to the minimum life cycle cost of the asset. Life cycle costing encourages long term thinking as opposed to attempting to minimize upfront expenditures when purchasing a product (Woodward, 1997). The LCCA formula is described by (Akhlaghi, 1987) as seen below:

LCCA = Investment + PV (operations and maintenance) + PV (energy) + PV (disposal) – PV (salvage)

The calculation of LCCA includes costs from investment, maintenance and operations (O&M), energy inputs, and costs occurring at the end of an asset’s operation life either through a disposal fee or salvage value (Akhlaghi, 1987). Initial ***investment*** can be represented through purchasing price of an asset, acquisition and finance costs, or installation costs. ***Operations and maintenance (O&M)*** include labor, materials, and direct/indirect expenditures as well as fuel inputs. ***Disposal*** accounts for the costs incurred at the end of a projects working life, including demolition, scrapping, or selling of the asset (Woodward, 1997).

LCCA is a useful tool for assessing vehicle investment because of their extended time horizons, as well as the stark differences in costs occurring at different life stages between vehicle technologies. This is the case with EVs, where the investment premiums are high while operations costs are significantly lower than alternative vehicles.

What should be highlighted is the need for separation between vehicle life cycle costs and the costs of electric vehicle service equipment (EVSE). In the majority of previous LCCA and TCO studies represented in the literature, charging infrastructure is not included in the calculation of vehicle life cycle costs, including studies by (Breetz & Salon, 2018; Weldon et al., 2018; Wu et al., 2015). This is because these two costs represent two distinct systems. EVSE costs must be considered; however, their useful lives will long outlast those of the EVs, and they will be available to subsequent EV generations. If EVSE costs were included in vehicle life cycle cost calculation, the results would be skewed in the favor of traditional vehicle technologies which don't require this infrastructure. This separation is not unlike the relationship between traditional vehicle technologies as petroleum infrastructure used for fueling. At this time, the State of New Hampshire operates numerous re-fueling stations across the state for use by petroleum powered fleet vehicles, and the subsequent investment and upkeep costs are not represented in traditional vehicle LCCA.

However, it is clear the EVSE infrastructure is still an important cost which can act a barrier to entry for EV fleets. For this reason, a discussion of EVSE costs is presented within the Operational Consecrations section. EVSE must be accounted for when assessing the feasibility of electrified fleets, but their costs should be separated from the quantification of a vehicle's life cycle costs. The data necessary for calculating the LCCA of light duty vehicles in this study are outlined in Table 1.

Table 1: Vehicle Data Required for LCCA

Analysis Requirement	**Data**
Investment Cost	Vehicle purchase/ lease price (Included are any federal, state, or local tax incentives or subsidies)
Operations and Maintenance Costs	Repair and reoccurring maintenance costs for vehicles (ex. oil change, tires, brake, battery replacement, etc.)
Energy inputs	Total cost of fuel and water input; -BEVs: cost per charge -PHEVs/HEVs/ICVs: total cost per gallon
Salvage value	Projected resale value or disposal cost at end of vehicles life cycle (value or cost is left over when vehicle is decommissioned)

Costs or benefits of a project occurring at different points in time cannot be compared without allowing for the opportunity value of time (U.S. Department of Transportation, 2002). These expenses occurring at different points in a vehicle's operational life must be discounted into their present value as of the base date of project operation before they can be used in LCCA estimates. Investors generally prefer dollars received/saved in the present verses the future. Money loses purchasing power over time, and money saved today can be reinvested leading to additional returns (Akhlaghi, 1987). To account for this, values are levelized to the present though discounting. Discounting is the process of converting cost and benefits across time into one point (Jawad & Ozbay, 2006). A discount rate is used which makes the investor indifferent between cash flows received at different time periods, thus accounting for the time value of money. A project's costs can't be summed across its lifespan as money at different times has different values, thus discounting into the PV must be used to allow for a meaningful LCCA (Akhlaghi, 1987). In the LCCA equation above this is shown by (PV) which represents the discounting of these costs into the comparable value at the time of purchase.

$$NPV = \sum \frac{F_t}{(1+d)^t}$$

The formula for calculating net present value (NPV) is shown above. F_t is representative of the future value of a project in year t. This future value is divided by $(1+d)^t$, where d is the discount rate and t is the year.

The discount rate selected is extremely influential on results, specifically when considering climate related projects with long time horizons (Nordhaus, 2007). The overall net present value of a project depends on the level at which the discount rate is set. A higher discount rate indicates a greater time preference for immediate costs and benefits and a lower value placed on future benefits and costs. Inversely, a lower interest rate indicates high value placed on future benefits (Moretti et al., 2017). Selection of an appropriate discount rate is a crucial decision in life cycle analysis. There is a wide range of discount used across the literature from 3% to 20%+. The appropriate discount rate will vary on a project to project basis (Woodward, 1997). In this analysis the U.S. Department of Energy Federal Energy Management Program's (FEMP) 2019-2020 discount rate of 3% will be used. This discount rate selection of 3% is not outside the range of values considered by in previous LCCA studies. This analysis argues that investment in BEVs should be considered in the same way as any renewable energy or energy efficiency investment, and therefore the FEMP discount rate is most appropriate. To determine if the chosen discount rate has a major influence on the results, a sensitivity analysis using 0% though 7% discount rates was performed and discussed later in this analysis.

Table 2: Study Vehicle Use Projection

Average Miles Per Year	Year of Operation	Total Lifetime Miles
12931.03	11.6	150,000

Data used as an input into this analysis for plug-in hybrid (PHEV), hybrid electric (HEV), and internal combustion (ICV) vehicles were obtained from the State of New Hampshire Government fleets. The final life cycle cost value for each vehicle type is extrapolated based on the New Hampshire Department of Environmental Services (NHDES) fleet, a state agency within the New Hampshire Government. The NHDES fleet contains 34 compact light duty vehicles which drove over 300,000 miles in 2017. From 2009-2016 the average lifespan of compact fleet vehicles retired by the NHDES is 11.6 years. These vehicles drove between 80,000 and 250,000 lifetime miles, averaging over 150,000 miles per vehicle. With historic vehicle usage as a guide, Table 2 outlines the projected usage of vehicles in this analysis.

The NHDES fleet has traditionally consisted of ICVs and HEVs. Since the year 2000, the state has purchased several different makes and models, the most frequent ICV model being the Ford Focus while the most frequent HEV model has been the Toyota Prius. As these two models were the most common within the NHDES fleet, they were selected as the “traditional” vehicle make and model for this analysis.

The intention of this analysis is to compare these traditional ICV and HEV vehicles to modern plug in electric vehicle technologies. The transition from traditional vehicles to EVs has already begun within the State of New Hampshire fleets. In 2017 and 2018, three PHEV Toyota Prius Prime’s began operation within the State fleet, with data being collected and used in this analysis. These data were used to assess the Toyota Prius Prime’s fuel efficiency in the temperate climate conditions of the northeastern U.S. The associated maintenance data were not detailed enough for use in this analysis, thus maintenance costs for HEVs were assumed to be the same as the PHEV. In reality, this is most likely a conservative estimate as previous studies have indicated PHEV maintenance costs are anywhere from 1% to 40% reduced in comparison to HEVs (Propfe et al., 2012; Sengupta & Cohan, 2017).

The final vehicle technology assessed is BEVs. There are currently no BEVs in operation within any State of the New Hampshire fleets. However, BEVs have been successfully integrated into the University of New Hampshire (UNH) fleet since 2017. The similarity to the Ford Focus and Toyota Prius models in operational ability, economic price point, and successful integration into the UNH fleet made the Nissan Leaf a logical choice for the BEV model selected for this analysis. Data collected by UNH were used to assess maintenance costs, just as data from the State of New Hampshire were utilized for ICV and HEV vehicle. However, UNH was unable to collect data on fuel efficiency and electric costs. To make up for this, as well as to account for climate effects of BEV and PHEV performance, a 93% energy efficiency assumption was used. This assumption came from work by (Taggart, 2017) who assessed climate effects on BEV performance across the U.S., and found BEVs in New York state operated at the 93% efficiency level. Given New York State's similar climate to New England, this assumption should hold for vehicles operating across the region. Both BEVs and PHEVs driving range and energy efficiency can be negatively affected by both extreme cold and warm climate conditions (Dost, Spichartz, & Sourkounis, 2015). Cabin climate controls such as heating or air conditioning, as well as changes in performance based on battery chemistry, are the main reasons for reduced EV performance in extreme climates (Li, Stanula, Egede, Kara, & Herrmann, 2016). Just as climate conditions and driver characteristics are considered for EVs, historic energy efficiency from State of New Hampshire vehicles can be used to assess how ICVs and HEVs operate in comparison to EPA mpg estimates. The projected fuel efficiency of each vehicle type is shown in Table 3.

This analysis is not only an attempt to understand past costs of operating these vehicles, but an attempt to project future prices to allow for comparison of traditional vehicles to evolving electric vehicle technologies. To most accurately project into the future, costs must be discounted into the present value, and changes in fuel costs and inflation should be considered. Maintenance, fuel costs, and salvage values for each vehicle were subject to a compounding 2% inflation rate assessed yearly (Moretti et al., 2017; OECD, 2020). These values were then discounted into the present value using the 3% discount rate discussed above.

The purchasing price is the largest single investment made when considering fleet vehicles. The primary dates used in this analysis contained purchasing prices for the fleet vehicles currently on the road, but as this analysis is attempting to quantify new vehicle models, the industry reported purchasing prices of the 2019 models were considered for all vehicles, with the exception of the Ford Focus which used the 2018 purchasing price (2018 was the last year the ICV Ford Focus was sold in the U.S.). As the purchasing price is assumed to be paid in total at the time of purchase, this investment cost is not discounted.

Energy and O&M costs for ICV, HEV, and PHEV vehicle types were calculated using data collected by NHDES while the BEV costs were taken from the University of New Hampshire. All records were extremely detailed, allowing for a yearly breakdown of each individual vehicle's purchasing, maintenance, and operations costs as well as miles driven on a yearly basis. These data allowed for each of the "traditional" vehicles' total maintenance and fuel costs to be compiled though 2017. As the vehicles were not all purchased in the same year, or driven the same total miles, the total maintenance and fuel cost values were converted into cost per mile value. Theses cost per mile value were then easily extrapolated to the lifetime vehicle characteristics for this study outlined in Table 2.

As of 2019 Nissan offered two Leaf models, the standard Leaf and the Leaf Plus (BEV+). The difference between these two models is the size of the Lithium Ion battery, which is 40 kWh in the Leaf and 62 kWh in the Leaf Plus. The larger battery for the Leaf Plus allows for greater driving range, but also increases the vehicles purchasing price. Though UNH only operates base Nissan Leaf models, the effect of climate on fuel efficacy as well as the maintenance costs are assumed to the same for both Leaf models included in this analysis.

The final cost needed to assess LCCA is the salvage value. In the case of these vehicles, salvage value is typically a positive return which comes from the vehicle's resale value. Data used in this analysis were unable to quantify vehicle resale value. Therefore, the resale value was calculated using Kelly Blue Book's (KBB) resale value calculator (Kelly Blue Book, 2019). The KBB value of each vehicle's 5-year-old model was taken in August 2019 and discounted by 5% annually until the 12th year. This value was then discounted into the present value using the 3% discount rate to reach the final salvage value estimate. The Toyota Prius Prime's first model year was 2014, meaning it had not been on the road for 5 years at the time of this analysis. To calculate its resale value the percentage of resale to purchasing price of the HEV Toyota Prius was assumed. This ratio multiplied by the Prime's purchasing price was used as the salvage value for the Prius Prime.

By combining the costs of investment, maintenance, energy, and salvage value LCCA of each vehicle can be calculated. After the lifecycle costs of each vehicle type are calculated, the total costs of investment over the lifespan of the project are compared. In this case, the life cycle costs of each vehicle type (BEV, BEV+, PHEV, HEV, ICV) are compared and investment is selected. The LCCA approach enables the total cost comparison of competing design alternatives for implementation in a transportation project (U.S. Department of Transportation, 2002).

Table 3: Study Vehicle Specifications

Vehicle	Type	MPG/Range	Li-Ion battery
2018 Ford Focus[1]	ICV	38.42 mpg	-
2019 Toyota Prius[2]	HEV	56.56 mpg	-
2019 Toyota Prius Prime[2,3]	PHEV	83.48 mpg	8.8 kWh
2019 Nissan Leaf[3]	BEV	139.5 range	40 kWh
2019 Nissan Leaf Plus[3]	BEV+	210.18 range	62 kWh

[1] 2018 final model year ICV Ford Focus was sold in U.S.
[2] ICV/ HEV mpg based on EPA mpg data and NHDES past vehicle performance
[3] BEV/ PHEV assumed 93% energy efficiency due to temperate climate (Taggart, 2018)

LCCA is highly dependent on assumptions made during calculation which can lead to potential uncertainty. These assumptions can be improved by collecting historical data, though there is always an element of uncertainty in the analysis (Woodward, 1997). To assess this potential uncertainty a sensitivity analysis was performed and covered in the discussion section. This sensitivity analysis allows for a more accurate understanding of the dimensions of a qualitative asset (Wu et al., 2015). In this analysis potential changes to each cost perimeter are analyzed to determine how price changes in each area could potentially change to overall economic total cost of ownership for each vehicle type.

Life Cycle Analysis Greenhouse Gas Inventory

In addition to calculating the economic costs this study aims to quantify the greenhouse gas (GHG) outputs of these light duty vehicle technologies. To quantify these impacts in the most comprehensive way possible a life cycle assessment (LCA) for each technology was conducted. An LCA is a "cradle to grave" approach which assesses environmental impacts of products, processes, or service systems from raw material extraction through production, use, and disposal. LCA promotes a more holistic assessment of environmental impacts across a wide range of systems (Sousa, 2002).

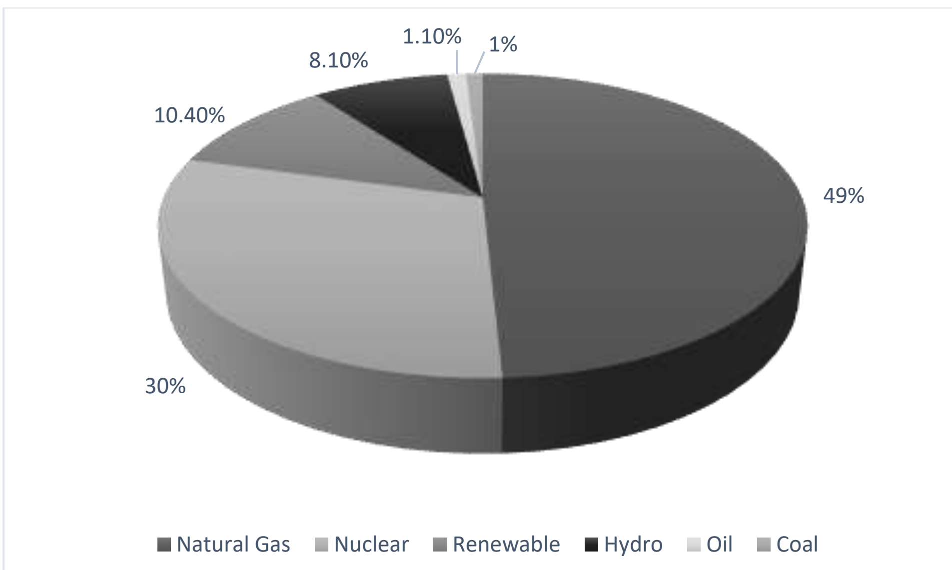
Light duty vehicles have many environmental impacts which could be assessed with an LCA approach including air pollution, waste disposal, land use and ecological damage, and many more. This analysis is focused on air emissions, specifically GHG emissions across a vehicle's operational life as well as those relating to the life cycle of the energy inputs. GHG emissions were chosen because of available data, the potential for quantification, and ease of comparison to similar studies. The impacts of GHG emissions on global climate change and the subsequent importance of GHG reduction technologies to fleet managers, government agencies, and consumers in general give the quantification of these emissions on a regional basis great value.

A complete LCA GHG inventory for passenger vehicles is done by accounting for emissions across both the vehicle and fuel cycles. The vehicle cycle includes material extraction, vehicle production, operation, and disposal while the fuel cycle accounts for upstream emissions from extraction, processing, and transportation of fuel (M. Q. Wang, 1999). For traditional light duty vehicles, the vehicle cycle is the largest emitter of GHGs. Emissions from vehicle operations make up the largest potion, followed by upstream fuel cycle emissions, while production and disposal are the smallest. In contrast, BEVs are often referred to as "zero emissions vehicles" as they have zero emissions during their use phase (Holland et al., 2016). There are of course emissions relating to other areas of a BEVs life cycle such as the fuel cycle and vehicle production and disposal (Elgowainy et al., 2018). For BEVs the fuel cycle not only includes upstream effects, but also "Extended Tailpipe" emissions from the production of electricity used to power the vehicle. A life cycle analysis of BEVs should also incorporate Li-ion battery production (M. Q. Wang, 1999). The second EV technology, PHEVs, can be seen as a blend between traditional and BEVs technologies as they can run solely on electricity (chard depleting mode) and similar to a gas powered HEV (charge sustaining mode). Once the Li-ion battery is depleted the vehicle switches from charge depleting to charge sustaining mode (ANL, 2016; M. Wang et al., 2018; M. Q. Wang, 1999)

Environmental impacts assessed through an LCA framework previously published in the literature used the Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model (GREET) from the Argonne National Laboratory as a tool to quantify vehicle related emissions (Sengupta & Cohan, 2017; Windecker & Ruder, 2013). In this analysis, the GREET model is used to generate comprehensive estimates of each light duty vehicle considered. The GREET model uses data from open literature, simulations from ASPEN Plus, EPA specifications for mobile emissions sources, EIA annual energy outlook projections, and EPA eGrid for electric systems. Results are displayed in 100-year greenhouse gas potential (GHG-100) or carbon dioxide equivalent (CO_2^e). GHG-100 allows for the comparison of GHG impacts of different gasses over a 100-year timespan, specifically 1 ton of CO_2 compared with 1 ton of another greenhouse gas. The major greenhouse gases emitted through light duty vehicle use are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). To calculate each gas's warming potential, it is assigned a value relative to the potency of $CO_{2.}$ This value multiplied by the volume of gas emitted indicates the GHG-100 and CO_2^e values (U.S. EPA, 2019). By converting different GHGs into GHG-100 and CO_2^e, the GREET model can be used to both inventory emissions as well as assess impacts in terms of warming potential. Using GREET, the most comprehensive emissions estimates are calculated by inputting different energy efficiency and range data for vehicle types as well manipulating grid inputs (ANL, 2016; M. Wang et al., 2018; M. Q. Wang, 1999).

Region specific electrical inputs have a direct influence on the use phase emissions for electric vehicles, specifically BEVs. As this analysis is intended to assess vehicle impacts within New England, region specific electrical inputs must be used. To meet this goal the analysis is run using ISO- New England (ISO-NE) grid data. The generation sources and percentages of total generation capacity per energy source is seen in Figure 1. Natural gas and nuclear account for the largest percentage of electrical production with 49% and 30% capacity respectively. They are followed by renewables and hydro power which together account for 18.5% of generation. Finally, coal and oil account for a meager 2.1% of electrical generation in New England (ISO-New England, 2018). New England's less carbon intensive grid in comparison to other regions within the U.S. leads to a favorable outlook for EV carbon reductions (Archsmith et al., 2015). These ISO-NE grid characteristics were input into the GREET model to allow for the most accurate use phase BEV and PHEV emissions estimates.

Figure 1: ISO-NE Grid Generation



Use phase emissions are not only a result of the energy inputs discussed above, but also the efficiency of the vehicle resulting from climate conditions. In this analysis an EV energy efficiency assumption of 93% as well as historic fuel efficiency from traditional vehicles operated by the State of New Hampshire were input into the GREET model to represent the effects of regional climate characteristics.

Additionally, lithium ion (Li-Ion) battery production was input into the GREET model for all EV technologies. Analysis by (Kim et al., 2016) showed carbon emissions of 140 kg CO_2 equivalent per kilowatt hour (kWh) of battery strength during production. In this analysis, the per kWh carbon equivalent was multiplied by the battery size and added to use phase emissions to more accurately estimate Li-ion batteries carbon emissions. Using these energy efficiency estimates, projected operations, ISO- New England grid data, and embedded GHG emissions from battery production, life cycle GHG emissions were estimated based on 2019 vehicle models using the GREET software.

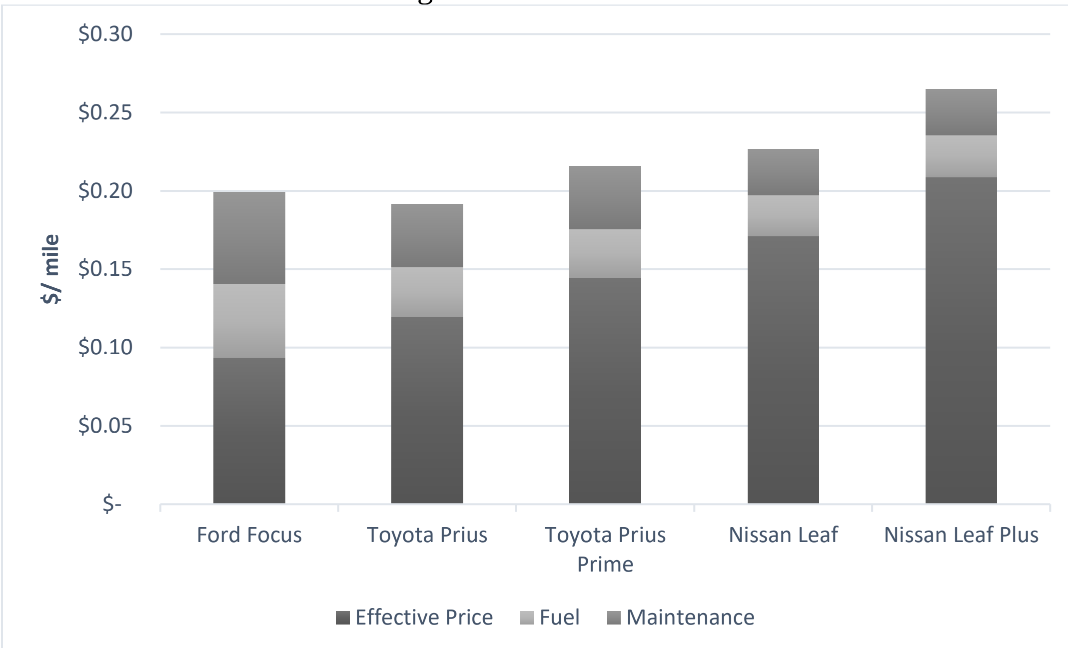
Results

Table 4: Total Cost of Ownership in Present Value

Vehicle	Purchasing Price	Fuel	Maintenance	Salvage	Total
Ford Focus	$17,950.00	$10,168.06	$13,243.40	$3,884.60	**$37,476.86**
Toyota Prius	$23,770.00	$6,906.94	$8,828.93	$5,821.76	**$33,684.12**
Toyota Prius Prime	$28,300.00	$6,196.31	$8,828.93	$6,931.25	**$36,394.00**
Nissan Leaf	$29,999.00	$6,144.60	$5,885.96	$4,319.05	**$37,710.50**
Nissan Leaf Plus	$36,555.00	$6,321.33	$5,885.96	$5,264.52	**$43,497.76**

The total cost of ownership (TCO) for each vehicle over 11.6 years and 150,000 miles is shown in Table 4, along with its purchasing price, fuel inputs, maintenance costs, and salvage value. Column six displays the TCO calculated using the LCCA formula described in the methods section. The Toyota Prius (HEV) is projected to have the lowest total cost of ownership at $33,684.12, nearly $3,000 lower than any other vehicle in this analysis. The vehicle with the second lowest total cost of ownership is the Toyota Prius Prime (PHEV) at $36,394.00. This is followed by the Ford Focus (ICV) and the Nissan Leaf (BEV) with total costs of ownership which are nearly identical at $37,467.86 and $37,710.50 respectively. The fifth vehicle, the Nissan Leaf Plus (BEV+), projects to be the most expensive at $43,497.76

Figure 2: Cost Per Mile



The MSRP for each vehicle is shown in column two, with the traditional fleet vehicle technologies being the least expensive to purchase. The electric vehicles (EVs), whose purchasing price increases with greater pure electric driving range, have the highest upfront costs. These MSRP values range from the Ford Focus at $17,950.00 to the Nissan Leaf Plus at $36,555.00. Column three shows the present value of fuel inputs with gas prices ranging from $2.73/gallon to $3.30/gallon and electric prices from $0.15/ kWh to $0.18/ kWh. As suggested by previous studies, traditional vehicle technologies have the highest projected fuel costs. The Ford Focus at $10,168.06 is the highest in this analysis, over $3,000 more than the Toyota Prius at $6,906.94. The three EV technologies are expected to have the lowest life cycle fuel costs with the Nissan Leaf Plus at $6,321.33, the Prius Prime at $6,196.31, and the base Nissan Leaf at $6,144.60.

Also represented in Table 4 are the operations and maintenance (O&M) costs, whose results are in line with previous studies, suggesting EVs provide substantial O&M reductions when compared to ICVs. The Ford Focus has the highest projected O&M costs at $13,243.40, less costly are the Toyota Prius models at $8,828.93, and least expensive are the Nissan Leaf models at $5,885.96. The final input into the LCCA formula is salvage value, which is represented in column five. This value is highest with the hybrid vehicles at $6,931.25 for the Prius Prime and $5,821.76 for the Prius. The two Nissan Leaf Models are expected to have the next highest salvage value with $5,264.52 and $4,319.05. These are followed by the Ford Focus which has the lowest expected salvage value of $3,884.60.

Total costs on a per mile basis are seen in Figure 2. The five vehicle types are shown on the X axis along with cost categories while the Y axis indicates the total cost per mile driven. These per-mile results show a Toyota Prius operating under New Hampshire Department of Environmental Services (NHDES) driving conditions is expected to cost $0.22/mile, followed by the Prius Prime at $0.24/mile, the Ford Focus and Nissan Leaf at $0.25/mile, and the Nissan Leaf Plus at $0.29/mile. It is clear the effective price (shown in blue) is the largest contributor to a vehicles total cost of ownership. Effective price is calculated by subtracting the eventual salvage value from a vehicle purchasing price. Figure 2 indicates effective prices are greater for EVs due to the high initial investment. For example, the effective price of the base Nissan Leaf is $25,679.95. Compare that to the Ford Focus at $14,065.40; the effective price difference is $11,614.55. However, in the case of both the base Nissan Leaf and Toyota Prius Prime the substantial difference in effective price is mitigated by the reduced life cycle fuel and O&M costs. These results indicate EVs are more cost competitive than purchasing price would indicate as the total cost of ownership for the Toyota Prius Prime is below, while the base Nissan Leaf is nearly identical, to the Ford Focus.

Figure 3: Life Cycle GHG Emissions by Category

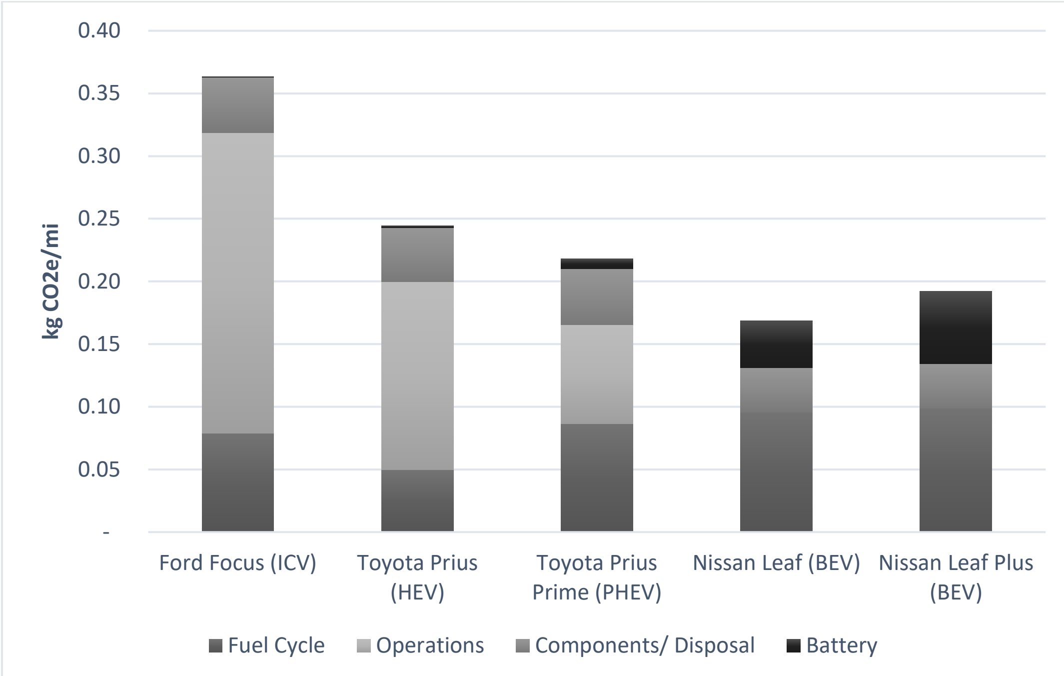


Figure 3 shows the life cycle carbon dioxide equivalent (CO_2^e) emission per mile driven for each vehicle over the projected vehicle lifespan. Vehicle types are shown on the X axis while kilogram per mile (kg/mi) of CO_2^e emissions are represented on the Y axis. The traditional light duty fleet vehicles have the highest projected GHG emissions per mile driven. The Ford Focus is projected to have the highest per mile emissions at .36 kg/mile followed by the Toyota Prius at .24 kg/mile. Traditional vehicles have substantial emissions from the operations phase, which accounts for 66% of Ford Focus emissions (.24 kg/mi) and 62% of Toyota Prius emissions (.15 kg/mi). However, they have comparatively lower fuel cycle emissions of .08 kg/mile (Focus) and .05 kg/mile (Prius) when compared to EV's. For these traditional vehicles fuel cycle emissions are associated with oil extraction, refinement, and transportation (M. Q. Wang, 1999). The expected emissions from fluids, components, assembly, and disposal for all five vehicles are identical at .04 kg/mile.

The BEV models are the two lowest emitters with the Nissan Leaf projected to emit .17 kg/mile and Nissan Leaf Plus .19 kg/mile. Both BEV's are expected to have large fuel cycle emissions, which are generated during electricity production and are sometimes referred to as "extended tailpipe" emissions. For both the Nissan Leaf and Nissan Leaf Plus these emissions are projected to be .10 kg/mile. Differences between the two are seen though embedded carbon emission from lithium ion (Li-ion) battery production. Given the Nissan Leaf Plus's 62 kWh Li-ion battery compared to the Nissan Leaf's 40 kWh battery, the expected emission for the Nissan Leaf Plus is .06 kg/mile compared to .04 kg/mile for the base Nissan Leaf model. The fifth vehicle, the Toyota Prius Prime, is projected to emit .22 kg/mile CO_2^e with the greatest volume coming from the fuel cycle (.09 kg/mile) and operations (.08 kg/mile). The Toyota Prius Prime has an 8.8 kWh battery which accounts of .01 kg/mile of CO_2^e.

Table 5: Life Cycle CO_2^e Emissions

Vehicle	kg/mi	Per Vehicle Ton	Fleet Ton[1]	Percentage Reduction ICV
Ford Focus	0.36	54.50	1,852.88	——
Toyota Prius	0.24	36.68	1,246.96	33%
Toyota Prius Prime	0.22	32.74	1,113.26	40%
Nissan Leaf	0.17	25.28	859.41	54%
Nissan Leaf Plus	0.19	28.83	980.37	47%

1. Based on NHDES 34 light duty vehicles in 2017

Total life cycle GHG emissions are outlined in Table 5. Total kg/mile of CO_2^e, total metric tons emitted, and percent emissions reduction in comparison to ICV are presented. Operating under NHDES fleet characteristics, the Nissan Leaf has the lowest total lifetime CO_2^e emissions at 25.28 metric tons, which is a 54% reduction in comparison to the highest emitter, the Ford Focus. The Nissan Leaf Plus (47%), Toyota Prius Prime (40%), and Toyota Prius (33%) also showed large potential lifetime CO_2^e emissions reductions compared to the Ford Focus. Also shown in this table are projected fleet wide emissions for each vehicle type. Given NHDES's 34 vehicle fleet, the difference between a Ford Focus fleet (1,852.88 metric tons CO_2^e) and a Nissan Leaf fleet (859.41 metric tons CO_2^e) is 993.47 metric tons of CO_2^e.

Table 6: Final Results

Vehicle	Total Cost	Cost Per Mile	Lifetime Tons CO2e	Percentage Reduction ICV
Ford Focus	$37,476.86	$0.25	54.50	——
Toyota Prius	$33,684.12	$0.22	36.68	33%
Toyota Prius Prime	$36,394.00	$0.24	32.74	40%
Nissan Leaf	$37,710.50	$0.25	25.28	54%
Nissan Leaf Plus	$43,497.76	$0.29	28.83	47%

Table 6 presents the take-home results of both TCO and GHG emissions inventory for each vehicle type operating under NHDES fleet characteristics. This table of basic results allows for the comparison of both economic and environmental life cycle models simultaneously providing a holistic view of the costs for each vehicle type. The Toyota Prius has the lowest total costs at $0.22/mile while providing a 33% reduction in GHG emissions compared to the Ford Focus. The Toyota Prius Prime and Nissan Leaf have similar total costs as the Ford Focus at $0.24/mile and $0.25/mile, while providing substantial emissions reductions of 40% (Prius Prime) and 54% (Nissan Leaf). Finally, the extended range Nissan Leaf Plus has total costs of $0.29/mile while reducing emissions by 47%.

Discussion

These results indicate electric vehicle (EV) technologies are cost competitive with internal combustion vehicles (ICV) within New England given climate consideration and New Hampshire Department of Environmental Services (NHDES) fleet characteristics. The cost competitiveness of these technologies is due to decreased life cycle fuel and operations and maintenance (O&M) costs. The Nissan Leaf (BEV) and Toyota Prius Prime (PHEV) displays a nearly $4,000 reduction in fuel costs when compared to the Ford Focus (ICV). These fuel cost reductions come despite historic NHDES data indicating ICVs operating above industry reported fuel efficiency and the inclusion of a 93% energy efficiency assumption for all EVs representing the effects of the temperate New England climate.

The EVs in this analysis showed major reduction in O&M costs when compared to the ICV. The Prius Prime is expected to cost $4,400 less in maintenance while the Nissan Leaf models have an expected savings of $7,300. These major cost savings are due to less complicated drivetrain and transmission systems resulting from no internal combustion engine (Propfe et al., 2012). The maintenance reductions of 33% for hybrids and 56% for BEVs seen in this analysis are on the higher end of results published in previous literature. This may be due to the extended timeframe of this analysis of 11.6 years and 150,000 miles driven per vehicle. When compared to ICVs, alternative vehicle technologies show reduced O&M costs due to lower or no use of internal combustion engine, reduced wear and tear to the break system, less complicated or no exhaust system, and reduced fluid input (ex. oil changes)(Kleiner & Friedrich, 2017). These age-related costs are not captured in total cost of ownership studies with timeframes of 5-8 years, which are typically seen in the literature. It's worth noting that while BEVs and PHEVs may have reduced annual operations and less maintenance costs as they age, the potential replacement of the lithium ion (Li-ion) battery could greatly increase an EVs total maintenance and subsequently its overall cost. Battery health, expected lifespan, and replacement are discussed in the sensitively analysis below.

In addition to being cost competitive, all three EVs provide substantial CO_2^e emissions reductions. Given regional energy mix and New England climate considerations BEVs release less greenhouse gases (GHGs) than traditional light duty vehicles, even when embedded carbon from Li-Ion battery production is accounted for. The emissions associated with ICV and HEV operations stages represent the highest values in the study. The Ford Focus operation phase emissions of 0.24 kg/mile alone are greater than the total emissions for the Prius Prime, Nissan Leaf, and Nissan Leaf Plus. Both Nissan Leaf models' "extended tailpipe" emissions from energy production are .10 kg/mile, which is less than half the Ford Focus operation emissions. This indicates emissions generated for electricity production to run a BEVs are less than tailpipe emissions of an ICV, despite the energy grid not being carbon neutral.

The inclusion of emissions from Li-Ion battery production make this analysis more representative BEV life cycle emissions than simply accounting for energy production. Three vehicle types, the Nissan Leaf, Leaf Plus, and Prius Prime have Li-Ion battery packs. The resulting emissions estimates of .06 kg/mile (Leaf Plus), .04 kg/mile (Leaf), .01 kg/mile (Prius Prime) are substantial. Li-Ion battery production typically occurs in areas with energy grids heavy in fossil fuels, specifically with coal and natural gas. As a result, approximately half the GHG emissions associated with Li-Ion battery production come from the use of these utilities. Emissions associated with intercontinental transportation of battery packs should also be considered, as they represent between 1% and 3% of total emissions (Kim et al., 2016). Battery recycling programs may represent a potential avenue to reduce Li-Ion battery life cycle emissions. Recycling programs have been shown to potentially reduce up to 35% of energy use and GHG emissions from battery production, accounting for about 4.1 tons of CO_2^e reduction per vehicle (Qiao, Zhao, & Liu, 2019).

When comparing traditional vehicle technologies, hybrid electric vehicles (HEV) shows clear benefits over the ICV both economically and environmentally. Much like the EV technologies, the Toyota Prius (HEV) shows fuel and maintenance cost reductions over its lifetime in comparison to the ICV. This, along with a lower purchasing price and competitive resale value, make the HEV the least costly vehicle in the analysis with total costs savings of $3,792.14 over the ICV. The HEV offers environmental improvements with a 33% emissions reduction, which translates to a nearly 18-ton reduction in CO_2^e emissions over each vehicle's operational life. As HEVs don't require additional infrastructure investment and planning, these befits can be achieved while maintaining a "business as usual" approach to fleet design.

Sensitivity Analysis

This sensitivity analysis highlights areas of uncertainty and examines how manipulating assumptions can influence each vehicle total cost of ownership and GHG emissions. Variables discussed are the discount rate, effective price, fuel costs, energy efficiency, battery replacement, miles driven, and electric generation source. This knowledge leads to a better understanding of the variables which influence a vehicles total cost of ownership, helping fleet managers, policy makers, and investors make informed decisions about EV fleets.

Discount Rate

Manipulating the discount rate can potentially influence the economic outcome of this analysis without altering any of the data used to generate results. In their study (Breetz & Salon, 2018) used a range between 5%-8%, and calculated the final results using a 7% discount rate. (Elgowainy et al., 2018) calculated results using 3%, 5%, and 7% discount rates, choosing a final of 5% (Wu, Inderbitzin, & Bening, 2015), (Sengupta & Cohan, 2017), and (Lin et al., 2013), used a 4%, 5%, and 8% discount rate respectively. In addition, these studies conducted a sensitivity analysis using 0% and 10% discount rates, which determined the choice of discount rate did not dramatically change results. In (Wu et al., 2015), the relative importance of each parameter within their analysis was assessed. Their results indicated the discount rate was not one of the 10 parameters with the highest impact on the results. These previous studies outline a range of acceptable discount rates between 3% and 10%.

Figure 4: Cost Per Mile by Discount Rate

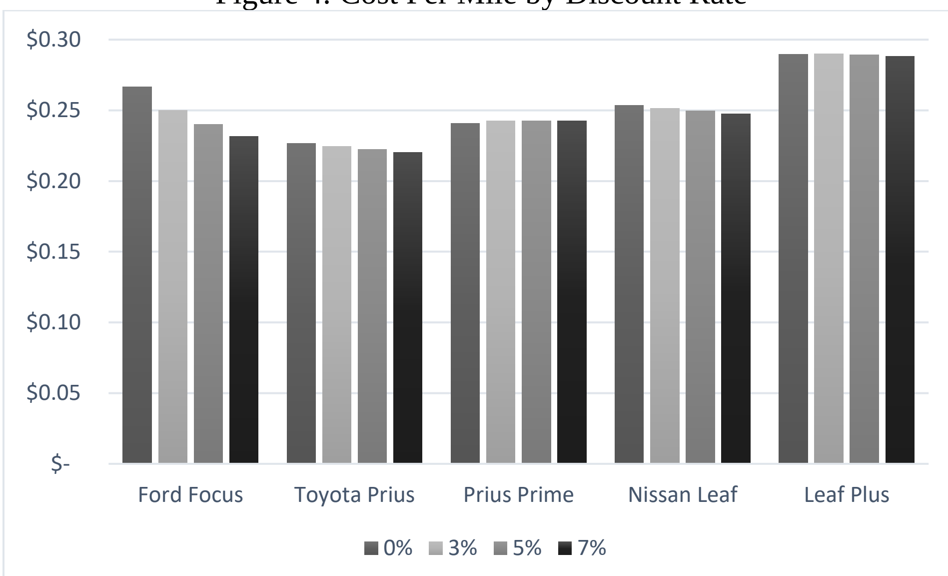


Figure 4 outlines the total cost per mile for each vehicle type under four different discount rates ranging from 0%-7%. Included in this graph is 3% which is the primary rate used to produce results discussed throughout this analysis. This graph is intended to show how changing the discount rate, effectively changing the time value of money, can influence the cost comparisons between each vehicle type. The results show vehicle technologies are not affected by changing discount rate to the same degree. The Nissan Leaf Plus (BEV+) total costs are essentially unaffected per mile staying of $0.29 at each discount rate, with total costs falling $245 between 3%-7%. The Nissan Leaf (BEV) and Toyota Prius (HEV) are both influenced in similar ways with modest $560 and $670 decreases in total cost between 3%-7%. The Prius Prime (PHEV) shows the least effect on total costs when changing discount rates as the total cost of ownership increase by $27 between 3%-7%. The vehicle which is most influenced by changing discount rates is the Ford Focus whose costs per mile fall from $0.25 to $0.23 between 3%-7%, resulting in a $2,750 decrease in total cost of ownership.

These results indicate the Nissan Leaf, Nissan Leaf Plus, Toyota Prius Prime, and to a lesser extend the Toyota Prius, costs are front loaded. As the discount rate increases, the value of costs and benefits in the later years of operation are reduced. This leads the total cost of ownership for EVs models to be marginally affected as the bulk of their total costs come during vehicle purchase. In comparison, the costs associated with the Ford Focus grow larger over time with increased operation, maintenance, and fuel costs. With higher discount rates these costs occurring later in the vehicles life are reduced, hence leading to larger changes in total cost of ownership compared to the other vehicles in this study. It's worth noting that, at a 0% discount rate (there is no discounting into the present value), the Ford Focus is the fourth most expensive vehicle in the analysis with total costs nearly $2,000 greater than the base Nissan Leaf. Overall, this analysis indicates that fleet managers looking for quick return on investments and economic benefits early in the vehicle's operational life, the ICV will be an attractive investment. Inversely, managers with long time horizons and those who value reoccurring cost savings over time will be drawn to electric vehicles.

Effective Price

Table 7: Effective Price

Vehicle	Purchasing Price	Salvage Value	Effective Price
Ford Focus	$17,950.00	$3,884.60	$14,065.40
Toyota Prius	$23,770.00	$5,821.76	$17,948.24
Toyota Prius Prime	$28,300.00	$6,931.25	$21,368.75
Nissan Leaf	$29,999.00	$4,319.05	$25,679.95
Nissan Leaf Plus	$36,555.00	$5,264.52	$31,290.48

Effective price is the largest contributor to overall total cost of ownership for each vehicle type, with substantial differences between ICV and EVs. For EVs, effective price increases along with the range of pure electric driving. A reduction in effective price for EV's could lead them to be more economically efficient than ICVs. The first avenue to reduce effective price is a reduction in the vehicles purchasing price. This can be accomplished through several federal and state level incentives on the purchase of different alternative fuel vehicle (AFV) technologies. These incentives have effects on the electric vehicle market as shown by (Tal & Nicholas, 2016) who determined 30% of plug in vehicle sales were attributed to incentives, with the percentage rising to 49% for Nissan Leafs.

The values for both federal and state incentives are laid out in Table 8. Electric and plug-in hybrid vehicles purchased after 2010 are eligible for a federal tax rebate. As of January 22nd, 2020, the Nissan Leaf, Nissan Leaf Plus, and Toyota Prius Prime are still eligible for original full incentives of $7,500 (BEVs) and $4,502 (PHEVs). On the state level, four of the six New England states offer some form of AFV incentive to promote industry growth. Under the CHEAPER program, Connecticut offers up to $500 for PHEVs, $500 for BEVs with range under 200 miles, and $1,500 for BEVs with range over 200 miles. The Efficiency Maine program offers rebates of $1,000 for PHEVs to $2,000 for BEVs. Massachusetts offers rebates for electric vehicles though the MORE-EV program, with BEVs eligible for $1,500. The state of Vermont offers incentives for private vehicle purchases to households with $96,122 of income or less (U.S. Department of Energy, 2010; State of Maine, 2019; Connecticut Department of Energy and Environmental Protection, 2020; State of Massachusetts, 2020; Drive Electric Vermont, 2020). The states of New Hampshire and Rhode Island do not have EV incentive or rebate programs at the time of this papers writing.

Table 8: Electric Vehicle Incentives

Vehicle	Federal	Connecticut (<$42,000)	[1]Maine	Massachusetts (<$50,001)	New Hampshire	Rhode Island	[2]Vermont (<$40,000)
Toyota Prius Prime	$4,502	$500	$1,000	______	______	_____	$1,500
Nissan Leaf	$7,500	$500	$2,000	$1,500	______	_____	$2,500
Nissan Leaf Plus	$7,500	$1,500	$2,000	$1,500	______	_____	$2,500

[1]Rebate shown for individual, business, or organization in Maine
[2]Incentive for private use only. Residents with $96,122 or less

The inclusion of any combination of these incentives will drastically reduce the total cost of ownership for the EVs when compared to ICVs. For example, the inclusion of solely the federal incentive reduces the total cost of ownership for the Nissan Leaf to $30,210.50 or $0.20 per mile which makes the Nissan Leaf the lowest total cost vehicle in the analysis, while the Nissan Leaf Plus total cost of ownership would be less than the Ford Focus. This is also true for the Toyota Prius Prime, which when the federal incentive is accounted for becomes more cost effective than both the Toyota Prius and Ford Focus. Adding any additional state savings to the federal incentives will only further the economic advantages displayed by all three electric vehicles. Fleet managers should check with both federal and state governments to determine which incentives their business/ organization qualifies for. The incentives identified in Table 9 outline general rebates, status as a government agency, private business, non-profit, or resident will alter availability. If fleet managers can successfully apply for federal or state funding, then EVs become significantly more cost effective than ICVs.

Also considered when assessing effective price is a vehicle's salvage value. In this analysis the salvage value is represented by each vehicle's resale value. This value was calculated using a five-year resale value from Kelly Blue Book with an annual 5% discount every year thereafter across the vehicle's operational life. This approach reflects the current resale value market for 2014 model year vehicles, shown in Table 9.

Table 9: Resale Value

Vehicle	Five-year resale value (%)
Ford Focus	44%
Toyota Prius	50%
Prius Prime	50%
Nissan Leaf	29%
Leaf Plus	29%

This approach captures the current rate of depreciation for each vehicle type, clearly favoring hybrid and ICV technologies. As seen in table 9, both the Prius and Prius Prime are expected to retain 50% of their value after five years on the road. This value is higher than the Ford Focus, which is still competitive with 44% retention value. In comparison, both Nissan Leaf models currently have a slim 29% retention value. This is not only a much smaller percentage, but when considering the larger initial purchasing price this small retention value becomes a large detriment when comparing total cost of ownership to hybrid and ICVs.

Compact BEVs, such as the Nissan Leaf, are among the vehicles which depreciate most in the first years of ownership. This high level of depreciation is due to BEV resale markets not being well established due to market size, technological advances, and reductions in battery cost in recent years (Lévay, Drossinos, & Thiel, 2017). However, this effect is not seen across all BEVs.

Luxury BEVs have been shown to retain value at a higher rate than the less expensive compact BEVs. In a 2015 study, the Tesla model S retained 83.1% of its value after one year, a greater percentage than the average for luxury ICVs between 62%-70%. In comparison, the Leaf retained only 43.5% of its initial value after one year, which according to this analysis, is less than the retention value of all three hybrid and ICVs after five years. The Leaf's resale value is hampered by high upfront costs, limited driving range, low gas prices, and competition with a wide range relatively high quality light duty economy vehicles (Vehicle & Report, 2015). Worth noting is that Nissan Leaf's first model year was 2010 and coincided with the beginning of the $7,500 federal tax incentives introduced that same year. By reducing a new Leaf's purchasing price, these incentives drive down the resale value of older models. This may not always be the case, as it's possible new BEV adopters will look to purchase less costly used vehicles once the federal incentives expire, leading to a stronger resale market and reduced depreciation (Breetz & Salon, 2018). While the depreciation of ICVs is well documented and understood, BEVs are a new technology whose depreciation is a relatively new concept (Weldon et al., 2018).

It's worth asking whether this trend will continue as over the projected lifetime of the vehicles in this analysis as many of the factors contributing to the Leaf's low retention value may be negated. As both the new and used market for BEVs mature, they will become more competitive and accepted by consumers while an expected increase in public charging infrastructure will help reduce consumers' range anxiety (Caperello & Kurani, 2012; Gnann et al., 2018). The 2019 model year Leafs are comparatively higher quality vehicles than those from 2014 as they boast increased driving range and improved features which should lead to a higher retention value. With this logic in mind it may be appropriate to forecast a residual value which is even for all vehicles. Table 10 displays each vehicle's scrap value if the five-year retention was equal to the

Ford Focus at 44% across all technologies. In this scenario the Leaf Plus, due to its large purchasing price, becomes the vehicle with the largest scrap value by a large margin. This has a positive effect on both BEV models total cost of ownership compared to the ICV. The Nissan Leaf’s cost drops to $0.24/mile with a total cost of ownership nearly $2,000 lower than the Ford Focus.

Table 10: Salvage Value

	Baseline		44% Retention		Scrap Value	
Vehicle	Scrap Value	Per Mile	Scrap Value	Per Mile	Scrap Value	Per Mile
Ford Focus	$3,884.60	$0.25	$3,884.60	$0.25	$269.25	$0.27
Toyota Prius	$5,821.76	$0.22	$5,144.12	$0.23	$356.55	$0.26
Prius Prime	$6,931.25	$0.24	$6,124.47	$0.25	$424.50	$0.29
Nissan Leaf	$4,319.05	$0.25	$6,490.21	$0.24	$449.85	$0.28
Leaf Plus	$5,264.52	$0.29	$7,910.95	$0.27	$548.33	$0.32

Also shown in Table 10 is a third scenario where vehicles are driven until they are no longer road worthy and are left with a true “scrap value” of the remaining raw materials. This scenario would most likely occur with vehicles driving outside the 150,000-range specified in this analysis. These scrap values were based on previous research by (Raustad, 2017), who determined a vehicle scrap value is 1.5% of its initial purchasing price. These values range from $269.25 to $548.33, with larger values associated with higher priced vehicles, although all values are so small that they have negligible effects on total cost of ownership. In the scrap value scenario, the Toyota Prius remains the vehicle with lowest costs at $0.26/mile, while the base Nissan Leaf and Prius Prime have total costs of ownership of $487.50 and $1,808.54 greater than the Ford Focus respectively.

Not accounted for are the potential economic benefits of battery second use (B2U) programs. B2U has been identified as a possible area of future revenue for EV manufacturers, which could reduce overall vehicle costs. Under these programs, retired EV Li-ion batteries are implemented into smart grid technologies with less demanding energy usages, such as grid storage. B2U drastically lengthens Li-ion battery service life, leading to improved resource management and delayed recycling for 10-20 years (Reinhardt, Christodoulou, Gassó-Domingo, & Amante García, 2019; Xiong, Ji, & Ma, 2020).

The effective price is a large determinant of the total cost of ownership for light duty fleet vehicles which skews in favor of traditional fleet vehicles due to high purchasing price and low value retention of BEVs. However, there are several federal and state level incentives available which can drastically reduce the effective price of BEVs making them far more economically efficient. The potential maturity of the BEV resale market may also help to normalize value retention, which would lead to additional savings for BEVs in comparison to ICVs.

Fuel Costs

Fuel inputs are an important factor in a vehicle's life cycle costs which can vary greatly based on its technology. Potential fuel savings are among the attributes which attracts private and public investment in EV's (Lebeau, van Mierlo, Lebeau, Mairesse, & Macharis, 2012; Tchetchik, Zvi, Kaplan, & Blass, 2020). To better understand how variations in fuel prices influence total costs of both EV and traditional vehicle technologies, several fuel scenarios were considered and presented in this section. These scenarios are not an attempt to estimate the future prices of either gasoline or electricity in New England, but rather a way to show the potential variability of fuel inputs within this model.

Gasoline prices have proven to be volatile due to fossil fuel shortages, budget changes, and global disturbances (Weldon et al., 2018). Evidence of this can be seen through the EIA's *Weekly New England (PADD A) Regular All Formulations Retail Gasoline Prices* graph, which shows in the past decade the price of gasoline has ranged from below $2.00/gallon in 2016 to above $4.00/

gallon in 2011(EIA, 2020). Based on these past market trends, it should be expected that gasoline prices will fluctuate greatly around the values projected in this analysis. Electricity prices have historically been less variable. Data from the EIA on the *Average Retail Price of Electricity* from 1960-2011 show nominal commercial electric rates have steadily increased at .16 cents/year. With inflation accounted for, the Real electric rate has remained relatively steady from 8.7 cents in 2000 to 9.1 cents in 2011 (EIA, 2012). These data support the conclusion that electric prices are less volatile than gasoline prices, and a steady increase in electric rates should be expected through the timespan of this analysis.

To account for potential fluctuations in key fuel prices previous studies have integrated high and low fuel scenarios into their sensitivity analyses. In a study by (Breetz & Salon, 2018) both residential and free electric rates were quantified as an input for BEVs, along with gasoline price scenarios equal to the study start data, prices rising $0.25/year, and “spike” prices starting a $4.00 and ending at $5.00. Given the short five-year ownership period assumed in the study, these fuel scenarios resulted in minor total cost of ownership variations. In another study, (Sengupta & Cohan, 2017) incorporated a blanket +/-50% fuel price scenario for both electric and gasoline, which resulted in the variation in all vehicle technologies total cost of ownership in comparison to the ICV.

In this analysis the same approach as (Sengupta & Cohan, 2017) is used to represent high and low fuel scenarios by quantifying +/- 50% change in both electric and gasoline prices. These high and low fuel scenarios are respective to each fuel source’s 2019 value, along with a BEVs with zero electric scenario which is also considered. This high and low fuel scenario was chosen as it closely represents historic gasoline price fluctuations within New England, the more variable fuel source in this study. Zero electric was included to account for BEV fleets with access to non-grid renewable energy fuel sources such as solar PV. While these energy sources require upfront investment, the marginal production of electricity comes with little to no costs. BEV fleets paired with distributed renewable energy have the potential to cover necessary fuel needs with no additional costs to the facility (Breetz & Salon, 2018).

Table 11: Alternative Fuel Scenarios

	Baseline	Fuel (-50%)	Fuel (+50%)	Zero Electric
Ford Focus	$37,476.86	-$2,952.17	$1,457.04	———
Toyota Prius	$33,684.12	-$2,005.35	$989.74	———
Prius Prime	$36,394.00	-$1,828.66	$840.17	-$1,516.67
Nissan Leaf	$37,710.50	-$1,904.06	$687.09	-$6,144.60
Leaf Plus	$43,497.76	-$1,958.83	$706.85	-$6,321.33

Gasoline - 2019: $2.73/gal - in 2030: base scenario($3.30/gal) high scenario ($4.10/gal), low scenario ($1.37/gal)
Electric - 2019: $0.15/kWh - in 2030: base scenario ($0.18/kWh) high scenario ($0.22/kWh), low scenario ($0.07/kWh)

Table 11 presents the change in total cost of ownership resulting from each of the four fuel scenarios. Traditional vehicles show varying effects of changing gasoline prices, with the Ford Focus (ICV) being impacted approximately 33% greater than the Toyota Prius (HEV). Under a low fuel scenario, the Focus total costs drop by $2,952.17 while the Prius drops $2,005.35. In the high fuel scenario, the Focus shows a $1,457.04 increase while the Prius increase $989.74. BEVs project to have less fluctuation in total costs under high and low fuel scenarios. When commercial electric prices are low, both the Nissan Leaf (BEV) and Nissan Leaf Plus (BEV+) are expected to have an approximate $1,900.00 decrease in total costs. If fuel prices increase 50%, total cost will jump to $687.09 and $706.85 respectively. If electric prices are zero, each BEV total cost of ownership will drop by over $6,000 dollars. The fifth vehicle is the Toyota Prius Prime (PHEV), an EV which is fueled by both gasoline and electricity. Under the low fuel scenario, with both gasoline and electric prices dropping by 50%, the Prius Prime shows a $1,828.66 decrease in total cost compared to an increase in costs of $840.17 under the high fuel scenario. If electricity is assumed to be zero, the total cost will drop by $1,516.67.

Figure 5: BEV compared to ICV, HEV, PHEV under Fuel Scenarios

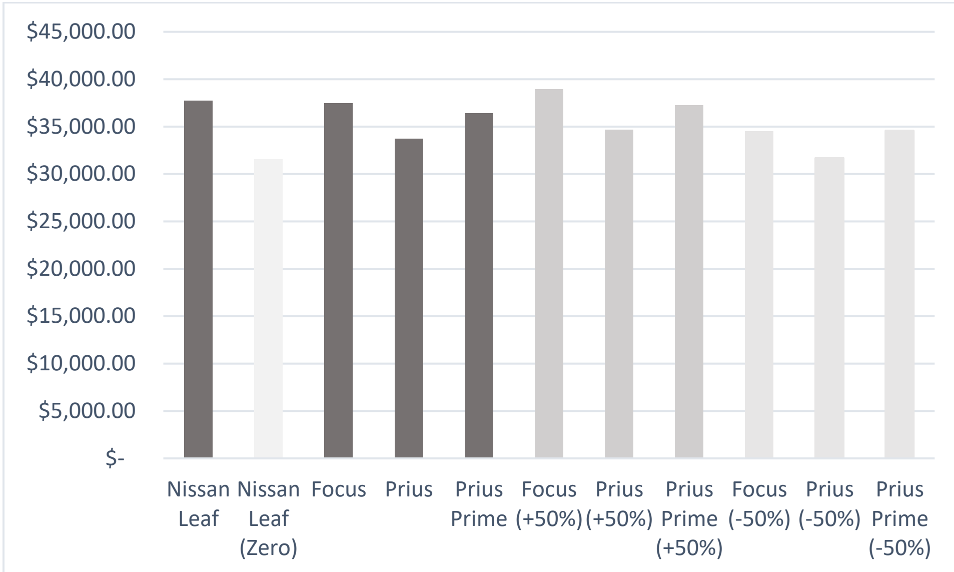


Figure 5 displays the total cost of ownership differences between the Ford Focus, Toyota Prius, and Toyota Prius Prime under high and low fuel scenarios compared to the base Nissan Leaf and the Nissan Leaf with zero electric. The vehicle name and fuel scenario are shown in the X axis, while the total costs are shown in the Y axis. Each scenario is represented by a different color, with the base scenarios in dark grey, zero electric is white, high fuel (+50%) in grey, and low fuel (-50%) in light grey. The results show that in the low fuel scenario the three vehicles which rely on gasoline have lower projected total costs than the base Nissan Leaf. Under the high scenario the Ford Focus total cost raises over $1,000, the Prius Prime is reduced by $500, and the Prius is still over $3,000 less expensive than the base Nissan Leaf. Finally, the base Nissan Leaf with zero electric has a lower cost of ownership than any of the gasoline powered vehicles, even under the low-price scenario.

The high/low scenario electric rate results shown in table 13 indicate the potential advantages time of use (TOU) and variable peak pricing (VPP) policies can have on EV fuel costs. TOU rates are implemented by a utility to encourage “off peak” electrical use during times of low electrical demand. These policies lead to increased grid efficiency, reduced rates, and reduced grid level emissions as base load plants tend to provide less expensive energy than peaking plants, which meet short term energy spikes (Dobrow & Lingara, 1988). Within New England, base load plants are less carbon intense than peaking plants (ISO-NE, 2019). TOU pricing provides an opportunity for EV operators to take advantage of cheaper off-peak rates, specifically if an overnight charging strategy coinciding with off peak hours is implemented. Some utilities, such as Californian's Pacific Gas and Electric (PG&E), have implemented Electric Vehicle Rate Plans which encourage off peak EV charging. In areas with TOU rates EV charging patterns have responded, greatly increasing grid level electric use during off peak hours while not exasperating current peak loads (Kim, 2019). PG&E's TOU plan electric rates vary by as much as $0.40/ kWh between peak and off-peak hours. These large price swings can add variability to EV fuel costs, and when off-peak charging is implemented, potentially bring costs closer to the low fuel scenario seen in table 13.

The high and low fuel scenario indicate fluctuations in fuel prices have are larger impact on ICVs compared to other vehicle technologies. The three EVs have a total cost of ownership range of approximately $2,500 between high and low fuel scenarios. This range jumps to approximately $3,000 for the HEV, and $4,500 for the ICV. Given historic gasoline price fluctuations and their reduced fuel efficiency, the ICV is the technology most susceptible to changes fuel prices. For EVs, these potential fuel fluctuations will likely only be met if TOU rates are incorporated broadly across New England and if they are adopted, fleet managers can easily take advantage of them by incorporating an overnight charging strategy. Additionally, facilities with distributed renewable energy source on site have the potential to greatly reduce fleet vehicle costs by investing in BEV technologies.

Energy Efficiency

Table 12: Effects of Energy Efficiency Assumptions

	Actual MPG/Range	EPA MPG/Range	TCO Difference
Ford Focus	38.42	34	-$1,321.85
Toyota Prius	56.56	56	-$69.07
Prius Prime	83.48	133	$3,259.04
Nissan Leaf	139.5	150	$430.12
Leaf Plus	210.18	226	$442.49

To more accurately predict fleet vehicle output within New England, historic operations data and energy efficiency assumptions were incorporated into this analysis. As discussed in the methods section, historic State of New Hampshire fleet data was used to formulate the output of Ford Focus, Toyota Prius, and Prius Prime vehicles. The proportion of highway driving for these State of New Hampshire vehicles has historically had a positive affected on both ICV and HEV fuel efficiency, causing the miles per gallon projections to increase beyond EPA estimates. When extrapolating these results to other fleets, differences in driving patterns should be considered. Fleets with less highway and more city driving or increased idling may reduce the fuel efficiency of ICVs and HEVs below the level shown in this analysis. The electric vehicles were subject to an energy efficiency assumption of 93% which is used to represent the effects New England's climate has on vehicle efficiency. This assumption is an average across an entire year. As seen in analysis done by (Yuksel & Michalek, 2015) BEV energy efficiency may drop as low as 71% on extremely hot days (105+ F) and 64% on extremely cold days (-15 F). There's a clear effect on BEVs from both extremely cold and extremely hot temperatures, both of which are seen annually across New England.

Table 12 outlines the effect of these assumptions on each vehicle's overall energy efficiency as well as the total cost of ownership differences which result from these changes. The traditional ICV and HEV technologies show an overall increase in energy efficiency. The Ford Focus jumps from an EPA mile per gallon (MPG) of 34 to 38.42 while the Toyota Prius increases by .56 from an EPA fuel efficiency of 56 mpg. For BEVs, the energy efficiency assumption limits their overall operational range. Without considering the effects of climate, the Nissan Leaf projects to have a 150-mile range with the Nissan Leaf Plus range expected to be 226 miles. However, with the efficiency assumption included this range drops to 139.5 miles and 210.18 miles respectively.

To assess how these changes impact economic costs, total cost of ownership was calculated using only EPA MPG and electric driving range while holding all other costs equal. The total cost of ownership differences between the two energy efficiencies is shown in Table 14, column four. The traditional vehicles show a negative value, indicating the increase in fuel efficiency from historic State of New Hampshire fleet operation drops total cost of ownership by $1,321.85 and $69.07 for the Ford Focus and Toyota Prius. Unlike the traditional fleet vehicles, the change in fuel efficiency negatively effects the BEVs overall costs. The Nissan Leaf and Nissan Leaf Plus's loss in fuel efficiency due to New England climate corresponds to an increase in total cost of ownership of $430.12 and $442.49. Overall, efficiency resulting from fleet operational characteristics and climate have a minimal effect on BEV total cost of ownership, resulting in cost changes in the hundreds of dollars over the vehicles lifetime. The resulting changes are relatively minor when considered within the totality of costs over a vehicle's lifespan.

Two vehicle technologies, the ICV and PHEV, show major cost variations between reported and EPA fuel efficiencies. The Ford Focus ICVs historic fuel efficiency resulting from extensive highway driving, reduces its overall TCO by $1,300 over the vehicle's lifespan. This result further indicates ICVs are a sensitive technology to fuel prices and vehicle driving characterizes. Fleet managers and policy makes should take this into account when assessing costs of ICV fleets operating in city driving scenarios as their fuel, and subsequent total costs, will most likely be greater than those seen in this analysis.

While the traditional and BEV technologies show minor differences between actual field reported and EPA fuel efficiency, the remaining EV, the Toyota Prius Prime (PHEV) does not follow this trend. Historic State of New Hampshire Prius Prime's have reported 83 mpg efficiency, which is significantly lower than EPA 133 mpge (miles per gallon equivalent). This indicates State PHEVs are not being operated at maximum fuel efficiency. EPA fuel efficiency for a PHEV is calculated by comparing the amount of kWh energy needed to travel 100 miles in electric mode compared to the amount of kWh energy in one gallon of gasoline. According to the EPA, one gallon of gasoline is equal to 33.7 kWh of electricity. As the Prius Prime can travel 100 miles on 25 kWh of electricity, showing roughly 33% energy efficiency increase over gasoline, the resulting energy efficiency is 133 mpge (Edmonds, 2013). If EPA mpge rating were applied to the Toyota Prius Prime in this analysis, the resulting TCO would drop $3,259.04. This substantial drop in price would be by far the largest among the vehicles in this analysis.

However, An EPA mpge rating describes a vehicle *under maximum efficiency*, which in the case of the case Prius Prime is when it's operating under pure electric driving mode. Given the Prius Primes 25-mile pure electric range, along with the extensive highway and long-distance trips undertaken by the NHDES fleet, it isn't reasonable to assume this fleet would operate PHEVs under maximum efficiency. The reported 83 miles per gallon fuel efficiency is likely a reflection of the fleet's operational characteristics. These findings indicate PHEVs would be maximized in lower mileage and city driving scenarios, and there is potential for fleet managers across New England to increase fuel savings for EVs when fleets are designed to maximize each vehicle technology.

Battery Replacement

It is difficult to estimate how Li-ion batteries will degrade over time as the amount of energy stored in a battery will change as cells age, resulting in large estimation errors. Factors which lead to these errors include temperature, state of charge, charge/discharge current, and general charging methods. More frequent vehicle charging could lead to decreased battery life. This indicates range anxiety induced charging and vehicle to grid (V2G) energy transfer may lead to additional battery degradation that hasn't been accounted for in the literature. The interaction of these physical and use factors lead to a very complex system, which makes modeling Li-ion battery aging extremely difficult to project (Barré, Suard, Gérard, Montaru, & Riu, 2014; Han, Ouyang, Lu, & Li, 2014).

Li-ion batteries degrade in 2 ways, calendric aging (independent of use) and cyclic aging (from battery use). Cyclic aging only applies during EV use and charging while calendric aging is influenced by the batteries state of charge and temperature. By assessing charging patterns and temperature, (Barré et al., 2014) determined battery life can be forecasted between 8.5 and 25 years under optimal charging scenarios. Optimal charging techniques include charging as late as possible and only to the point which meets needs of the next trip, thus reducing battery state of charge. Typical "as fast as possible" charging strategies are the most convenient yet lead to degraded battery and reduced useful life. These strategies emphasize vehicle charging when not in use and maximizing the batteries state of charge. Despite the increased planning required, EV fleet operators should employ an "as late as possible" charging strategy where EVs are often charged to less than 100% capacity to minimize state of charge. There are drawbacks to a full as late as possible charging strategy, including reduced flexibility, difficulty accommodating unplanned trips, and issues arising with inaccurate range predictions. Given these restrictions this type of charging strategy is hard to implement, specifically in fleet settings such as those of the

New Hampshire Department of Environmental Services (NHDES) (Barré et al., 2014). Given adoption of a limited as late as possible charging strategy along with New England's cool temperatures, Li-ion batteries should not need replacement within the vehicle lifespan outlined in this analysis.

However, given the number of factors which impact battery life and the uncertainly in degradation rates, it is worth considering how possible battery replacement in the later years of an EVs operational life will impacts its total cost of ownership. Potential battery replacement can have large impacts on an EVs total cost of ownership as the Li-ion battery costs constitute a large portion of an EVs initial purchasing price (Weldon et al., 2018). The expected lifetime of a Li-ion battery varies across the literature. On the lower end of expected battery life is (Archsmith et al., 2015) who projected and 85,000km (aprox. 53,000 miles) operational life. Analysis by (Breetz & Salon, 2018) spreads battery replacement costs of $3,000 for BEVs and $1,500 for PHEVs across operation years 6-10. (Weldon et al., 2018) projected battery replacement after a vehicle undergoes 3,000 charging cycles or in the 10th year of operation with costs between €100- €300 kWh. Additionally, (Sui & Wang, 2011) projected Li-ion battery replacement would come at 150,000 miles. This wide range of projected LI-ion battery life supports (Han et al., 2014) writing about difficulty projecting battery degradation over time. It's worth noting that vehicle models in the year following those used in this analysis have expanded Li-ion battery warranties. The 2020 Nissan Leaf models come with an 8 year/ 100,000-mile Li-ion battery warranty (Nissan, 2020) while the 2020 Prius Prime's have a 10-year 150,000-mile hybrid battery warranty (Toyota, 2020). For fleet managers considering an investment in EVs at the time of this study' writing, manufacturer warranties will cover the majority of the vehicles operation life and protects against premature battery degradation.

The cost of Li-ion battery replacement varies across vehicle makes and models based on the size of the battery pack and vehicle type. These costs vary greatly due to age of the technology, battery size and shape, and the packaging used (U.S. Department of Energy, 2016). Li-ion battery costs have declined 8% annually, from $1,000 to $300 per kWh in 2014. To continue this level of annual decline, cost reductions will likely come in the form of economies of scale rather than Li-ion chemistry advancements as this technology has been used heavily since the 1990s (Nykvist & Nilsson, 2015). Typically, an EV's Li-Ion battery must cost $150 per kWh to be cost combative with an ICV. Battery packs accounted for approximately 25% of costs in 2014 Nissan Leaf (Nykvist & Nilsson, 2015). With this percentage as a guide, the 2019 Nissan Leaf's battery should cost roughly $187 per kWh. These costs are expected to decline annually as the market for EVs continues to grow. Looking forward, costs of Li-ion battery packs is expected to reach the $100 kWh threshold between 2020-2030 (Berckmans et al., 2017;U.S. Department of Energy, 2016).

Table 13: Projected Battery Replacement Costs

	[1]Replacement Cost	O&M	Total	per mile
Ford Focus	_____	$13,243.40	$37,476.79	$0.25
Toyota Prius	_____	$8,828.93	$33,684.08	$0.22
[2]Prius Prime	$880.00	$9,708.93	$37,274.00	$0.26
[2]Nissan Leaf	$4,000.00	$9,885.96	$41,710.47	$0.28
[2]Leaf Plus	$6,200.00	$12,085.96	$49,697.73	$0.33

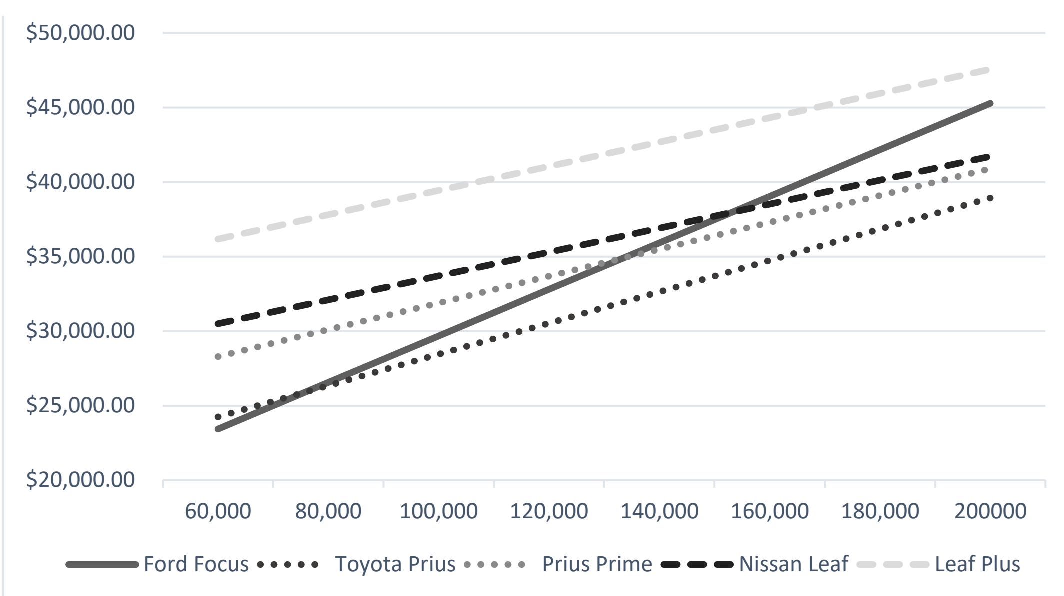
[1] *Battery replacement costs estimated using $100 kWh * battery size*
[2] *Li-ion battery size: Prius Prime 8.8 kWh, Nissan Leaf 40 kWh, Nissan Leaf Plus 62 kWh*

Table 13 gives the projected battery replacement costs for vehicles included in this analysis based on an expected $100 kWh future Li-ion battery price. These replacement costs range from $880 dollars for the Toyota Prius Prime, $4,000 for the Nissan Leaf, and $6,200 for the Nissan Leaf Plus. These additional costs have large effects on an EVs total costs, specifically for the two BEVs. A battery replacement during the operational life of the Prius Prime would cause the total cost of ownership to rise \$0.01/mile, for the Nissan Leaf \$0.03/mile, and the Leaf Plus \$0.04/mile. Battery replacement would eat into the significant operations and maintenance costs advantages shown by the three EVs over traditional vehicle technologies, although even under a battery replacement scenario the Ford Focus still has the highest expected O&M costs of any vehicle in this analysis. Under the battery replacement scenario, the Toyota Prius (HEV) would continue to have the lowest cost of ownership. The lowest cost EV would be the Prius Prime, with total costs \$200 less than the Ford Focus. The two Nissan Leaf BEVs, requiring the largest investment in battery replacement, would have total costs of ownership \$4,200 and \$12,200 greater than the Focus.

While the results presented in this analysis assumes no Li-ion battery replacement will be necessary for electric fleet vehicles, assessing the potential costs of battery replacement is a useful exercise for fleet managers. The degradation of Li-ion batteries in electric vehicles is not understood as well as the degradation of traditional ICVs, leading to potential uncertainty. This scenario indicates that battery replacement is a major cost, specifically for long range BEVs with larger Li-Ion battery packs. Under the battery replacement scenario, EVs major O&M cost advantages over ICVs is mitigated, leading BEVs to have substantially larger total costs of ownership across their operational lives. Not quantified in this scenario is the possibility that replacement of a Li-ion battery could lead to a vehicle's operation life extending beyond 150,000 miles, and therefore reducing cost per mile beyond the results outlined above.

Miles Driven

Figure 6: The Effect of Miles Driven on Total Cost of Ownership



Perhaps the most influential variable in calculating the TCO and life cycle greenhouse gas emissions for any vehicle is the total miles driven. This is particularly true when comparing EVs, with lower operations and fuel costs, to traditional vehicle technologies (Breetz & Salon, 2018;Sengupta & Cohan, 2017). These findings are supported by the results of this analysis which documents the large O&M and fuel cost reductions as well as the high investment costs of EVs. These high upfront costs can deter investment in EVs, but given the lower costs over time, logic indicates the longer an EV is driven the closer total costs will become. This will eventually lead to the EV being more cost competitive than traditional vehicle technologies.

Figure 6 outlines the effect of miles driven on TCO as all five vehicles are represented allowing for comparison of total costs based across fleet miles projections. This figure reinforces the notion that traditional vehicle technologies, specifically ICVs, are the most cost effective at lower mileages. The Ford Focus (ICV) is the vehicle with the lowest total cost of ownership until mile 76,000, when the second traditional technology, the Toyota Prius (HEV), becomes the least costly. The Toyota Prius remains the least costly vehicle up to and beyond 200,000 miles. The lowest cost EV, the Toyota Prius Prime (PHEV), reaches even total cost with the Ford Focus at 133,500 miles while the Nissan Leaf (BEV) reaches equality with the Ford Focus at 153,000 miles. Finally, the Nissan Leaf Plus (BEV+) reaches equality with the Ford Focus up to 230,500 miles, which based on previous literature, is beyond the expected lifespan of this vehicle's Li-ion battery and is likely past the point of scrap value.

Table 14: Total Cost of Ownership under Mileage Scenarios

	Low (46,780)		Medium (103,866)		High (150,000)	
	Total Cost	Per Mile	Total Cost	Per Mile	Total Cost	Per Mile
Ford Focus	$21,304.02	$0.46	$30,276.49	$0.29	$37,476.79	$0.25
Toyota Prius	$22,813.64	$0.49	$28,844.43	$0.28	$33,684.08	$0.22
Prius Prime	$27,098.29	$0.58	$32,239.34	$0.31	$36,394.00	$0.24
Nissan Leaf	$29,399.69	$0.63	$34,010.42	$0.33	$37,710.47	$0.25
Leaf Plus	$35,064.87	$0.76	$39,743.32	$0.38	$43,497.73	$0.29

Table 14 outlines the comparison of total costs under three specific mileage scenarios. The three scenarios are Low (46,780), Medium (103,866), and High (150,000). Each of these scenarios are extrapolated form the data used as an input into this analysis. The Low scenario is based on the University of New Hampshire fleet, whose vehicles average 3,998 miles driven per year. If an 11.6-year lifespan is assumed, each vehicle is expected to operate 46,780 miles. Similarly, the Medium scenario is calculated based on the average miles driven by the NHDES fleet in 2017, which was 8,954. Across 11.6 years, the total mileage driven would be 103,866. Finally, the high mileage scenario is based on the historic operation of the NHDES fleet where vehicles operate 12,931 miles annually. The high mileage scenario was used to produce results discussed throughout this analysis.

These three mileage scenarios further emphasize that in order to show economic benefits EVs should be incorporated into high mileage fleets. As mentioned in the Results section, if vehicles drive 150,000 miles the Toyota Prius Prime has a total cost of ownership which is lower than that of the Ford Focus, while the base Nissan Leaf's total costs are roughly equal to this ICV. As the total operational mileage goes down, the EVs become more costly. This is seen under the medium mileage scenario, where the Prius Prime and Nissan Leaf's cost per mile rise $0.02/mile and $0.04/mile in comparison to the Ford Focus. The low mileage scenario indicates a further difference in costs between the traditional and EV technologies as the Nissan Leaf's total costs are $8,065.22 while the Prius Prime's are $5,794.27 greater than the Ford Focus. These raised costs represent a 29% and 38% increase over the ICV.

Table 15: CO_2^e Emissions Under Mileage Scenarios

	Low (46,780)		Medium (103,866.4)		High Mileage (150,000)	
	Ton	% Reduction	Ton	% Reduction	Ton	% Reduction
Ford Focus	20.74	——	39.41	——	54.50	——
Toyota Prius	15.32	26%	27.14	31%	36.68	33%
Prius Prime	14.92	28%	24.78	37%	32.75	40%
Nissan Leaf	15.17	27%	20.76	47%	25.28	54%
Leaf Plus	18.41	11%	24.18	39%	28.84	47%

Table 15 shows the CO^2_e emissions for each vehicle type based on the three mileage scenarios discussed above. When assessing GHG emissions, EVs have high embedded carbon from battery production (Kim et al., 2016). These embedded carbon emissions act similarly to high initial investment costs when calculating total cost of ownership, in that the longer an EV is operational the greater the CO^2_e emissions reductions compared to an ICV (Laberteaux & Hamza, 2018). This is seen across the three vehicle mileage scenarios as the percentage of emissions reductions grows for every vehicle as their mileage increase. The effects of embedded carbon are most notable with the Nissan Leaf Plus, whose 62 kWh Li-ion battery is responsible for 8.66 tons of CO^2_e emissions. Due to this embedded carbon, in the Low mileage scenario the Nissan Leaf Plus only reduces life cycle emissions by 11%. However, in the high mileage scenario, the Leaf Plus reduced emissions by 47% due to large reductions during the vehicle's operation. Embedded carbon similarly reduces environmental benefits for the base Nissan Leaf and Prius Prime in Low mileage fleets where emissions are only reduced by 27% and 28% respectively.

It's worth noting the Prius Prime has the lowest GHG emissions under the low driving scenario due to having the smallest Li-ion battery among EVs in this analysis. These GHG advantages can potentially be further improved under certain scenarios if daily operations can be met using only the charge depleting (CD) (fully electric) mode. If the Toyota Prius Prime uses only the full electric mode, the tons of emissions under the low mileage scenario would drop to just under 12 metric tons, a roughly 44% reduction compared to the Ford Focus. In addition to emissions reductions driving solely in fully electric mode can provide economic benefits. Under this scenario, the Toyota Prius Primes Fuel costs, and subsequently it's TCO, falls by $470 dollars. This modest drop does not bring the Prius Prime to the same level of costs as the two traditional vehicle technologies, but it does further reduce its total costs below the two full electric Nissan Leaf models.

The comparison of EVs and traditional vehicles under the low mileage scenario may be conservative when quantifying their potential environmental and economic benefits. As seen in the Energy Efficiency section, historic NHDES driving characteristics, extensive highway driving, lead vehicles to operate above EPA fuel efficiency, resulting in a $1,300 dollar decrease in TCO. ICVs operating in city driving scenarios may see the opposite effects. (Laberteaux & Hamza, 2018) writes that ICVs operate less efficiently in scenarios with constant stops, starts, and frequent idling and in these scenarios EVs provide substantial emissions reductions. This research indicates real vehicle costs and emissions may not be as linear as the results of this analysis indicate. The benefits of EVs in Low mileage scenarios are likely greater than indicated in the above results.

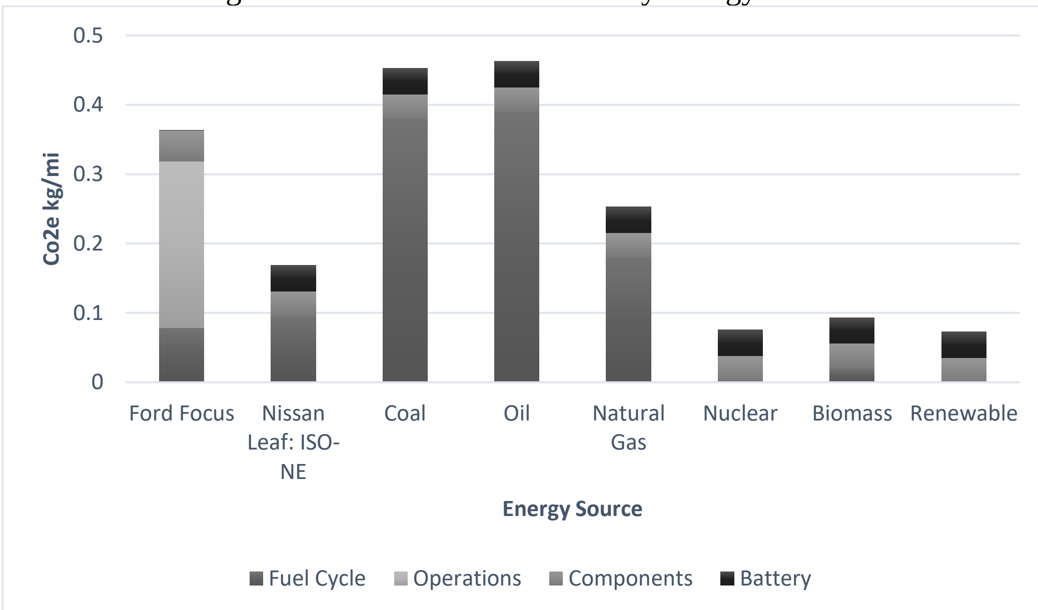
The lifetime miles driven has major implications on which vehicle technology is both economically and environmentally preferred. At extended mileages, full electric BEVs can be economically viable, and in some cases, have lower life cycle costs than competing technologies as well as allowing for maximum reduction in CO^2_e emissions. Under medium mileages, EVs become slightly more costly compared to ICVs, while maintaining large carbon reductions. Under these conditions, the procurement of Federal and State incentives becomes important to reduce BEV and PHEV costs to the level of and below traditional vehicle technologies. In low mileage fleets, the high upfront costs of EVs are noticeable, and heavily influence total cost of ownership above those of ICVs.

This does not imply EVs should be ignored in short range fleets, despite higher costs. Again, the procurement of Federal and State incentives can equalize costs between electric and traditional vehicles. Additionally, fleets like the University of New Hampshire's (UNH), which primarily drive 25-30 miles per day, can invest in PHEV's with all electric modes covering these distances. This will lead to additional cost savings compared to BEVs due to reduced purchasing price and higher salvage value. A smaller Li-ion battery would reduce GHG emissions above what the BEV provides over the ICV. Depending on fleet needs, managers may consider additional PHEVs not discussed in this analysis. PHEVs with extended full electric range beyond the Prius Prime's 25-mile charge depleting mode may be optimal, such as the Chevy Volt with 50-mile full electric range (Chevrolet, 2019). Finally, investment in pre-owned BEVs can be a cost-effective approach for fleets operating at low mileages. Pre-owned BEVs, with smaller battery packs and potentially reduced Li-ion battery performance will have reduced range compared with a new BEV. However, under low mileage scenarios these drawbacks may be inconsequential. When purchasing used BEVs, fleet managers can take advantage of their heavily deflated value retention to buy a vehicle which meets their fleet's needs without the high initial investment. And unlike pre-owned ICVs, fleet managers would still greatly reduce fleetwide CO^2_e emissions.

The final suggestion on improving BEV fleets' economic feasibility is directed at vehicle manufacturers. As BEV fleets become more popular, it may be prudent for manufactures to offer "fleet models", where managers can order specific battery packs depending on fleet needs. This way, extremely high mileage fleets can order large battery packs while low range fleets can obtain BEVs with the smallest packs possible, thus reducing overall costs and maximizing environmental benefits. As Federal and State incentives phase out and the BEV resale market stabilizes, the ability to custom order battery packs may become vital in allowing for the adoption of BEV fleets.

Electric Source

Figure 7: Nissan Leaf Emissions by Energy Source



As the fuel cycle accounts for half of the projected Nissan Leaf emissions, it's clear the electrical generation source has an extremely large impact on BEV life cycle emissions. Figure 7 shows projected Nissan Leaf life cycle emissions under 6 fuel sources along with the Ford Focus and ISO-NE grid as a reference. These six energy sources are coal, oil, natural gas, nuclear, biomass, and renewables, which represent the most common fuel sources for electric generation within New England. Electricity generated from both coal and oil has the highest associated GHG emissions at .38 kg/mile and .39 kg/mile respectively. This is significantly higher than ISO-NE's .1 kg/mile, biomass .02 kg/mile, nuclear .002 kg/mile, and the zero associated emissions with renewable sources (wind, hydro, and solar). While there are no direct air emissions from energy generation for nuclear power, upstream impacts must be assessed. Emissions are associated with uranium mining, diesel fuel for transportation, electricity used for uranium enrichment, as well as management of spent fuel (M. Q. Wang, 1999). Therefore, the results indicate minor emissions for BEVs operating on nuclear power. The GREET model assumes renewable energy resources have no emissions during energy production. A study by (Nugent & Sovacool, 2014) showed minor GHG emissions related to renewable energy generation ranging from 10-50g CO_2^e per kWh of energy production. These emissions are associated with mineral extraction, asset manufacturing, and disposal. The study found similar results for nuclear power, which was responsible for 66g CO_2^e per kWh embedded GHG emissions. It is safe to say both nuclear and renewables emit small volumes of GHGs over their life cycles, but these emissions are minor compared to fossil fuel energy sources.

The three fossil fuel energy sources of coal, oil, and natural gas have emissions higher than the current ISO-NE grid mix. A Nissan Leaf connected solely to a coal and oil grid will emit a larger amount of GHGs during the fuel cycle than a Ford Focus across its entire life cycle. Thus, the energy generation source should be accounted for when assessing the environmental benefits of vehicle electrification. Given the grid energy mix of 48% carbon neutral and only 2% coal/ oil, BEV's connected to the ISO-NE grid emit far less GHGs than ICVs. Additionally, BEVs connected to the ISO-NE grid will have less GHG emissions compared to the same vehicle operating in other regions of the country with more fossil fuel heavy grids. As seen in Figure 7, in a different study area with a grid predominantly coal and oil powered the benefits of forgone GHG emissions will be non-existent, leading to potentially increased GHG emissions for BEVs in comparison to ICVs. These results support previous research by (Archsmith et al., 2015) who analyzed EVs connected to the coal intense grid of the Midwest states Minnesota, Wisconsin, the Dakotas, outlining various scenarios where their GHG emissions would be greater than an equivalent ICV.

The substantial CO_2^e emissions reductions shown by carbon neutral energy sources over both fossil fuel and the ISO-NE grid indicate there is potential to further reduce BEV GHG emissions going forward. It should be mentioned that the ISO-NE generation mix is expected to continue to decarbonize over the coming years due to the maturity of state Renewable Energy Portfolios. By 2030, renewable energy generation will increase in each New England state to between 25% (New Hampshire) to 71% (Vermont) of total generation capacity (ISO-NE, 2020). This continued decarbonization of the ISO-NE grid will lead to a steadily reduction in annual GHG emissions for grid connected BEVs within New England. To maximize the benefits of an electrified transportation network, grid developers should focus on reducing the share of natural gas and eliminate coal and oil from the generation mix. A shift away from fossil fuel towards renewable energy sources such as wind, hydro, and solar will substantially reduce the emissions associated with grid connected BEVs. Additionally, fleet managers who wish to reduce the emissions associated with their BEVs could look to installing distributed renewable energy capacity, such as solar PV, at their facility. By "disconnecting" from the grid, BEVs have the potential to drastically reduce emissions to below .1 kg/mile.

Social Cost of GHG Emissions

Table 16: Potential Economic Cost of Carbon Emissions

Carbon Price	[1]GHG Abatement	RGGI	California	EU ETS	Social Cost of Carbon	Federal Incentive
Abatement Value	29.22	$165.09	$522.15	$678.77	$1,344.10	$7,500.00

[1] Difference in CO2e emissions between Nissan Leaf and Ford Focus

In this analysis greenhouse gas (GHG) emissions associated with differing vehicle technologies are referred to as an environmental cost, and largely considered separately than traditional market economic costs. However, GHG emissions are a classic example of an externality leading to a market failure (Gillingham & Stock, 2018), causing policy makers globally to internalize the externalities associated with carbon emissions in several ways, most commonly in the form of subsidies, Pigouvian taxes, and the market allocation of carbon allowances (Holland, Mansur, Muller, & Yates, 2016; Schmalensee & Stavins, 2017). Currently, New England automotive users, including fleet managers, don't pay an economic cost for their vehicle emissions. However, this may soon change with the potential adoption of the Transportation Climate Initiative, a cap and trade program with a market for regional transportation sector carbon emissions (TCI, 2019).

To quantify the potential economic costs of GHG emissions, table 16 outlines the implied costs of the differing carbon emissions between the Nissan Leaf and Ford Focus, totaling 29.22 tons of CO_2^e. These economic costs come from cap and trade allowance prices, the U.S. EPA social cost of carbon (SC-CO_2), and the U.S. federal incentives on BEVs. The three carbon allowance prices come from the Regional Greenhouse Gas Initiative (RGGI), California Cap and Trade Program, and European Union Emissions Trading Scheme (EU ETS). All three programs directly place a price on one ton of carbon emissions, with most recent allowances priced at $5.65 (RGGI), $17.87 (California), and $23.23 (EU ETS) (Bayer & Aklin, 2020; RGGI, 2020; Carbon Pulse, 2020; California Air Resources Board, 2020). Based off these global carbon allowance prices, the costs of the Ford Focus carbon emissions above that of the Nissan Leaf is between $165.09 and $678.77.

In addition to carbon allowances, the U.S. federal government has implied the economic cost of GHG emissions through historic climate policy in the form of federal incentive on the purchase BEVs and the U.S. EPA's SC-CO_2. The SC-CO_2 is the dollar value of long-term impacts of one ton of CO_2 emissions including economic and human health considerations (EPA, 2017). Another way to frame the SC-CO_2 is the margin effect of on additional ton of CO_2 emitted or the net present value of the incremental damage due to a small increase in CO_2 emissions (Tol, 2011). Using the EPA projected SC-CO_2 in 2025 of $46/ton, the implied difference in carbon emissions costs between the Nissan Leaf and Ford Focus is $1,344.10. Finally, the federal BEV incentive implies the value of carbon offsets between the two vehicle technologies at $7,500.

All five policies indicate the carbon abatement shown by the Nissan Leaf can be valued between $165 and $7,500. While this range is quite large it is clear the carbon offsets of BEVs, while not accounted for in their TCO, should be valued positively. When direct or implied carbon prices are included in the TCO calculation, the Ford Focus' total costs rise above those of the Nissan Leaf under four of five policies. This indicates not only that society is better off when a BEV is substituted for an ICV, but future compliance costs associated with a transportation sector carbon policy, such as the Transportation Climate Initiative, may lead BEVs to be more economically efficient than ICVs.

Average vs Marginal Emissions

The calculation of emissions from EVs can be complicated as they typically rely on a complex electric grid for their fuel. The electric grid is not static, with generation sources varying on a daily and seasonal basis (Laberteaux & Hamza, 2018;ISO New England, 2019). This complexity and regional specificity lead researchers to use two approaches, grid average and marginal emissions, to calculate an EVs environmental output. This analysis uses the average grid generation mix approach, because when calculating future emissions, it is assumed the energy grid will grow to incorporate the EV within the regional demand. EVs will no longer be "adding to the margins" of the electric grid (Archsmith et al., 2015). Using an average may cause less carbon intense energy grids, such as ISO-NE, look cleaner in the short term (Archsmith et al., 2015).

When using a marginal emissions approach, researchers calculate vehicle emissions based on the energy source needed to meet the additional demand placed on the grid by a charging EV. This energy source, which would not be utilized without the demand added by the EV, is considered marginal. As marginal electricity generation sources vary by location, time of day, and time of year, the resulting emissions from an EV will change based on these variables. Ignoring seasonality could potentially lead to incorrect conclusions on not just the magnitude but the sign of GHG benefits (Archsmith et al., 2015). A marginal emissions technique was used by both (Archsmith et al., 2015) and (Holland et al., 2016) to forecast environmental outcomes of wide spread EV adoption. Both determined regional differences have great effects on EVs, and simply substituting BEVs for ICV does not guarantee environmental benefits as the fuel source and performance under real-world conditions determine life cycle GHG emissions. When average and marginal emission approaches were compared, (Archsmith et al., 2015) came to the same conclusions, though marginal emission results were more extreme.

The ISO-NE marginal generation source is dependent on the seasonal variations such as fuel availability, fuel price, consumption at the time of generation, and reliability. These factors influence the grid differently across seasons, as well as varying daily, thus influencing the marginal energy source. The dynamic nature of the ISO-NE grid leads marginal generation source to differ across time (ISO New England, 2019). In the most recent Electric Generator Air Emissions report aggregating grid data from 2017, ISO-NE found natural gas was the primary marginal fuel source 65% percent of the time across the grid. Additional marginal sources included renewables and hydro (21%), pumped storage (12%), coal (2%), and oil (1%). When assessing only sources emitting air pollutants, natural gas was the marginal fuel source 95% of the time (ISO New England, 2019).

For fleet vehicles the optimal charging strategy involves plugging in vehicles overnight while not in use. When assessing emissions through a marginal approach an overnight charging strategy highlights the importance of the grid's baseload electrical generation sources. Baseload power is the minimum amount of electricity required over a given period (EIA, 2020). In New England grid demand is lowest from 12am to 7am, indicating generation sources supplying the grid during these times can be considered base lead generation (ISO-New England, 2020). Historic base load generation sources include nuclear, coal, and renewable generation, while natural gas an oil is utilized as marginal generation to balance electrical supply and demand (ISO-NE, 2019). In recent decades coal has been largely phased out of the ISO-NE grid, leaving nuclear and renewables, such as wind and hydro, as the primary overnight baseload power capacity. As these sources are carbon neutral, it is likely an overnight fleet charging strategy will lead to reduced GHG emissions in comparison to peak load charging. Overnight charging strategies may not lead to reduced emissions in all regions as coal is still a primary base load power source in other geographic areas.

It appears a marginal generation approach to calculation GHG emissions would lead to higher estimated emission rates for EVs connected to the ISO-NE grid. As seen in Figure 6 the highest marginal fuel source, natural gas, leads to greater emissions per mile than the ISO-NE average. Coal and oil generation sources are higher in a marginal emissions scenario (3%) than in an average (2%) while renewables jump 3% from average to marginal. Using a marginal approach to determine GHG emissions associated with EV electrical generation would give a more nuanced understanding of environmental output. However, additional data would be needed such as a detailed record of EV charging including season, time of day, and amount of energy consumed. Regional spatial data and detailed ISO-NE grid data would also be necessary. This level of detail is beyond the scope of this study. Calculating the environmental impact of EV charging using a marginal generation approach constitutes a potentially valuable area of future research for comparison against the average grid approach used in this analysis.

Regional Air Pollutants

Table 17: [1]Criteria Air Pollutant Emissions

	Ford Focus	Toyota Prius	Toyota Prius Prime	Nissan Leaf	Nissan Leaf Plus
VOC	0.85	0.50	0.42	0.32	0.32
CO	5.33	5.32	2.95	0.25	0.25
NOx	0.39	0.31	0.25	0.14	0.14
PM10	0.04	0.04	0.05	0.05	0.05
PM2.5	0.03	0.02	0.03	0.03	0.03
SOx	0.25	0.31	0.37	0.39	0.39

[1]*Values in g/mile*

Vehicle electrification can not only reduce global GHG emissions, but also lead to improved local air quality (Elgowainy et al., 2018). Throughout this analysis the focus on environmental output has been placed on calculation of greenhouse gases (GHG), a global air pollutant which has been converted into carbon dioxide equivalents (CO_2^e). However, GHG emissions are not the only class of air pollutant emitted by motor vehicles. As defined by the National Ambient Air Quality Standards (NAAQS) in the Clean Air Act of 1970 criteria air pollutants, a group of regional air pollutants including volatile organic compounds (VOCs), carbon monoxide (CO), nitrous oxides (NO_x), particulate matter (PM), and sulfur dioxides (SO_x), emitted by motor vehicles and are responsible for various health effects, environmental damage, and formation of ground level ozone (EPA, 2017).

Criteria pollutant emissions calculated using an average grid approach are represented in Table 17. VOC emissions are highest with traditional petroleum vehicles with the Ford Focus at 0.85 g/mi, the Prius at 0.50 g/mi, and Prius Prime at 0.42 g/mile, while the BEV models emit 0.32 g/mile. CO emissions are noticeably greater with traditional vehicle technologies as the Ford Focus emits 5.33 g/mile and Toyota Prius emits 5.32 g/m, while the EVs are responsible for 2.95

g/mile (Prius Prime), 0.25 g/mile (Nissan Leaf/ Nissan Leaf Plus). The same trend holds for NOx emissions with petroleum fueled Focus (0.39 g/mi), Prius (0.31 g/mi), and Prius Prime (0.25 g/mi) being the largest emitters. Both PM pollutants show minor emissions increases with BEVs responsible for an additional 0.01 g/mile while SO_x are highest with BEVs at 0.39 g/mi, a 0.14 g/mile increases compared to the ICV. These results show an overall reduction in VOC, CO, and NOx emissions for BEVs, while SO_x and PM emissions are greater.

These results are in line with (Cai et al., 2013), who assessed criteria pollutant output for BEV technologies in comparison to comparable ICVs. Their analysis found BEVs connected to the northeast electric grid would have 100% chance of reducing VOC and CO emissions and 99% chance of NOx emissions reductions. However, PM and SO_x emissions are far less likely to be reduced at 12% and 8% respectively. As with GHG emissions, a marginal generation approach to emissions calculations can be helpful given the spatial characteristics associated with the health and environmental effects of criteria pollutants (Elgowainy et al., 2018). There is significant physical difference between emissions of EVs and ICVs. Many transportation studies focus on CO_2 emissions are their impacts are global, meaning the geographic area where the generation source is located has no bearing on impacts. However, for local pollutants, driving EVs and ICVs in the same place leads to different damages, as the EV tailpipe is potentially located in a separate geographic area (Holland et al., 2016). In fact, 90% of environmental externalities from driving a BEV are exported across state lines while ICVs only export 19%. This is due not only to the variation in geographic location where emissions occur, but also due to smokestack height which release pollutants much higher in the atmosphere than a vehicle’s tailpipe. In most states EVs reduce overall impacts from criteria pollutants. However, this tradeoff may make society worse off as the exported pollution is of a greater magnitude (Holland et al., 2016).

Operational Considerations

Electric Vehicle Service Equipment (EVSE)

Widespread implementation of electric vehicle service equipment (EVSE), or charging infrastructure, is vital to the adoption of public and private electric vehicles (EVs) (Hafez & Bhattacharya, 2017;Madina, Zamora, & Zabala, 2016). A reliable, economically efficient, charging network is one of the key components needed to transition fleets from traditional to electric vehicles (National Renewable Energy Laboratory, 2012; U.S. Department of Energy, 2013). To meet current and future demand provided by ever increasing EV adoption, the *Northeast Corridor Regional Strategy for Electric Vehicle Charging Infrastructure 2018-2021* study was conducted, including input from each New England state (Gobin et al., 2018). This study outlines a regional plant on how light duty EV adoption can be encouraged through integrated charging infrastructure between all states to not only improve access but increase viability of EV chaining infrastructure. This will be accomplished through a network of roadside direct current (DC) fast charging units, as well as promotion of home and work charging available to all drivers regardless of payment network (Gobin et al., 2018). The implementation of this network design has already begun in New Hampshire, with the allocation of 4.6 million dollars in Volkswagen settlement money for the development of DC fast charging infrastructure along state highways (New Hampshire, 2020).

Despite the potential for dramatic increases in available road charging, fleet managers should look to invest in single or multiple location charging networks for sole use by fleet vehicles for reliability, increased access, and ease of payment (U.S. Department of Energy, 2015). EVSE come in three stages Level I, Level II, and DC fast charging, all three with distinct advantages for EV fleets. Each level generally differs on price point, strength of charge, and time necessary to fuel a vehicle. The costs of installing EVSE vary widely depending on location, EVSE features, available electrical capacity, and labor costs. This variability makes is difficult to predict total costs as a fleets technologic makeup must also be considered (U.S. Department of Energy, 2015).

Table 18: Electric Vehicle Service Equipment (EVSE)

EVSE Level	Cost[1]	Leaf 80% Charge Time[1]	Leaf Plus 80% Charge Time[1]
Level I[1]	$500-$850	24 hours	37 hours
Level II	$3,000	5 hours	7 hours
DC Fast Charging	$30,000+	40 minutes	60 minutes

[1]. Costs and Level I charge times from (Howell, et al. 2017)

Table 18 shows the price range and potential charging time at each EVSE level from empty to 80%. DC fast charging is typically displayed at 80% charge because the final 20% often takes a long time (DERİCİOĞLU et al., 2018). Level I charging utilizes 120V (volt) outlets, and can be implemented through plugging an EV into a wall outlet with a portable chord or installation of a wall mounting. These units have the longest charge times with Nissan Leaf and Leaf Plus charging times of 30+ and 50+ hours needed to reach 80% battery state of charge. Level II is the second most powerful charging infrastructure with a range between 208 – 240 volts. This increased power results in faster charging times of 8-11.5 hours for Nissan Leaf and Leaf Plus models to reach 80% state of charge. Finally, DC fast charging are the most expensive and powerful EVSE using 480 volts with charge times reduced to 40 – 60 minutes to reach 80% state of charge (Rahman, Vasant, Singh, Abdullah-Al-Wadud, & Adnan, 2016) (D. Howell, S. Boyd, B. Cunningham, S. Gillard, 2017;DERİCİOĞLU et al., 2018;Nissan, 2020).

In general, the price of EVSE increases along with the level of power utilized, as shown in Table 18. Level I EVSE are the least costly charging option with upfront costs between $500-$850. These low costs are due to ease of installation as most EVs come with a Level I charging chord which can be plugged into wall outlets. Additionally, easy to install wall mountings can be used for parking or outdoor charging areas (U.S. Department of Energy, 2015). There are significant variation for Level II costs, with (U.S. Department of Energy, 2015) reporting roughly 70% falling below $4,000. These cost variations are due to differences in site preparation and labor costs as opposed to the EVSE itself. On average, fleet managers should expect Level II chargers to cost around $3,000 (Rahman et al., 2016). The most expense EVSE are DC fast charging units with a wide range of potential costs. Much like Level II, DC fast charger costs can be reduced by selecting optimal sites which decreased labor and construction costs. Specifically, sites with existing electric service (and thus avoiding an expensive upgrade to accommodate 480 volt charger) and areas where construction, such as trenching, are minimized will help keep installation expenses low (U.S. Department of Energy, 2015). The expected price of a DC charger is $30,000 or more (Rahman et al., 2016).

These site preparation and labor costs which add variation to the price of DC fast charging infrastructure must also be considered with both Level I and Level II units. These costs are largely separate from the number of units being installed and are determined by the extent of necessary site construction (U.S. Department of Energy, 2015). While this may be a disadvantage for small fleets or facilities looking to install a small number of public charging stations, for larger fleets such as the NHDES this opens the door to potential economies of scale. Whether a facility is installing few or many EVSE, the costs of removing and replacing parking lots, upgrading electrical infrastructure, and labor must be paid. Once they are accounted for, increasing the number of charging units will marginally increases total costs, leading to costs per unit for large fleets to decrease. This not only implies that larger fleets will pay less on average for EVSE, but also that facilities should consider future infrastructure needs during the planning process. Installing EVSE for future fleet needs, or at least prepping the site for future expansion, will lead to maximum cost savings (U.S. Department of Energy, 2015). Additionally, facilities planning to offer EVSE for employee and public vehicles could combine infrastructure installation with that of their fleet to reduce overall costs. Along with initial investment EVSE have varying operation and maintenance (O&M) costs depending on the volume of electricity used, software packages, and general maintenance. Electricity cost constitute the largest portion of O&M, and will vary based on frequency of use, vehicle type, and rate structure (Kettles, Raustad, & Dunn, 2017). Facilities should monitor potential changes in facility peak electrical demand charges which may accompany the installation of level 2 and DC charging stations. In certain areas of the country, peak pricing can increase electrical bill beyond a facilities normal rate. These effects can be mitigated by employing off peak charging strategies or coordinated charging rotations during peak times. These peak load mitigation strategies can be helped by the adoption of smart charging infrastructure which can set charging times for off peak hours. If the goal is to minimize EVSE costs, fleet managers should invest in units with minimum features necessary and consider wall mounted and duel port charging stations which may reduce per unit installation costs (U.S. Department of Energy, 2015).

When assessing fleet charging specifically it's important to consider factors such as EV battery size and necessary charging speed. In general, fleet EVSE need less advanced charging infrastructure than public EVSE as payment tracking and access issues do not exist, thus lowering overall costs (U.S. Department of Energy, 2015). Fleet charging is typically a mix of Level I and Level II EVSE. In these circumstances, Level II EVSE should be utilized as the primary charging infrastructure. Since EVs are typically located on site for 9+ hours, Level II infrastructure can typically meet each vehicles charging needs (Chandra Mouli, Bauer, & Zeman, 2016). Level II infrastructure can utilize overnight charging where vehicles are idle, as well as potentially reducing electric costs in areas with time of use rates (Kettles et al., 2017). Level I EVSE should be employed to supplement Level II through opportunity charging due to reduced cost of installation as well as the extended time it takes to fully charge a BEV. DC fast chargers are typically not necessary for fleets that operate out of one single location due to the amount of vehicle idle time. DC chargers can be utilized as on-road charging for fleet vehicles which travel outside their electric range. Due to fast charging times this infrastructure can be utilized in a similar way as gas stations for traditional fleet vehicles (Chandra Mouli et al., 2016; U.S. Department of Energy, 2015). To reduce overall costs, selection and design of EVSE for electric fleets should be directly representative of fleet vehicle makeup and operational requirements.

An area of potential cost reduction is the implementation of smart charging infrastructure and vehicle to grid (V2G) technologies. Smart charging network can minimize EVSE O&M, extend its lifespan, and reduce overall fuel costs (Hafez & Bhattacharya, 2017) and allows for the implementation of V2G techniques enabling the electric grid to use EV batteries for energy storage. V2G has the potential to limit GHG emissions and reduce cost of electrical supply in the long run (Rahman et al., 2016;Mortaz & Valenzuela, 2018). V2G is a promising field of research, however it has not been implemented in a widespread manner because of financial limitation. This approach can maximize the benefits of both EV fleets and renewable energy technologies by growing both industries, improving renewable energy viability, and reducing costs (Rahman et al., 2016)

While this analysis does not include the cost of EVSE as a variable in the calculation of a vehicles total cost of ownership, these costs nevertheless must be considered when designing an EV fleet. EVSE costs vary greatly based on site location, labor costs, and expected use. In a fleet setting Level I and Level II charging infrastructure should be utilized whenever possible because of the large increase in costs associated with DC fast chargers. The choice of EVSE equipment should be directly related to the battery size and operational range of the EV fleet. Short range fleets consisting of small lithium ion (Li-ion) batteries can reduce costs by investing in less expensive Level I and Level II chargers, while long range fleets should focus on Level II on site with the potential to deploy a network of DC fast chargers outside the initial EV electrical driving range. As technology and industry understanding improves, the implementation of smart charging and V2G approaches may work to reduce overall EV costs and GHG emissions and enhance reliability of unions between EVs and distributed renewable energy sources.

NHDES Fleet Design

As discussed throughout this analysis the results for each vehicle technology are modeled after historic New Hampshire Department of Environmental Services (NHDES) fleet operational data. The NHDES is located in the city of Concord, the state capital of New Hampshire. NHDES fleet vehicles make frequent trips to nearby New Hampshire population centers such as Manchester and Nashua which total between 40- and 70-miles round trip. These trips can easily be covered by a fleet of 40 kWh Nissan Leaf vehicles with an EPA estimated 150-mile range. However, fleet vehicles must also make occasion trips to more distant areas of the state, and as these visits occur both during the hottest and coldest times of the year, the operational capacity of BEVs to make these trips must be considered.

Table 19: New Hampshire Population Centers

[1]Municipality	[2]Distance
Manchester	37.8
Concord	4
Laconia	24.8
Conway	155.4
Keene	109.6
Berlin	228
Lebanon	121.8
Derry	29.8
Dover	73
Claremont	106.4

[1]Largest city in each New Hampshire County
[2]Distances from 29 Hazen Drive to town/city hall

Table 20: BEV Efficiency

	Efficiency	Range	Percent Cities
Nissan Leaf	100%	150	80%
	93%	139.5	80%
	71%	106.5	60%
	64%	96	50%
Nissan Leaf Plus	100%	226	90%
	93%	210.18	90%
	71%	160.46	90%
	64%	144.64	80%

1. Vehicle efficiency: EPA, Taggard 2017, Yuksel & Michalek 2015

While data on individual NHDES fleet vehicle trips were not available for this analysis, it's important to consider the potential destinations of these vehicles. Table 19 displays the largest city in each New Hampshire county, and the round-trip distance of the most direct route from the NHDES campus at 29 Hazen Drive, Concord to that municipality's city or town hall. While this is not an exhaustive list of potential fleet vehicle destinations, it is meant to represent the wide potential operation range of this fleet. If the NHDES intends to switch its fleet to exclusively BEVs, they must ensure all fleet needs would be met.

In table 20 the potential driving range of both the Nissan Leaf (BEV) and Nissan Leaf Plus (BEV+) under EPA estimated range, regional average (93%), extremely hot (71%), and extremely cold weather (64%) scenarios are outlined (Taggart, 2017; Yuksel & Michalek, 2015). The expected range under each scenario is show in column three, with the Nissan Leaf ranging from 96 to 150 miles per change and the Nissan Leaf Plus ranging from 145 to 226 miles per charge. Column four displays the percentage of the largest cities per county which lie within the vehicles range. The results show the majority of potential fleetwide range could be met with base Nissan Leaf under the regional average energy efficiency of 93%. However, under extreme weather scenarios, this percentage drops to 50-60%, indicating a fleet of solely Nissan Leaf's would likely not fill the entirety of NHDES fleet needs. For the extended range Nissan Leaf Plus the effects of extreme weather are much less at 80-90%. Together, these results indicate that a fleet designed of both BEV and BEV+ technologies could potentially fill between 80-90% of NHDES needs.

However, it is clear a portion of NHDES fleet operations would not be covered by BEV technologies under one charge. The remainder of uncovered trips could be accounted for in two ways, by designing a network of offsite electric vehicle service equipment (EVSE) or incorporating hybrid vehicle technologies into the fleet design. Each approach comes with potential tradeoffs. A network of roadside EVSE equipment would likely need to incorporate DC fast charging infrastructure, which could potentially drive up costs drastically with a price of over $30,000 per unit. However, this approach would lead to maximum fleet GHG abatement and provide flexibility for unforeseen changes in driving distance. An investment in hybrid technologies such as PHEVs and HEVs would lead to reduced costs but continue the states' reliance on petroleum and lead to an upkeep of both EVSE and gasoline infrastructure needed to serve their fleet. It should also be noted that in addition to light duty vehicles the NHDES operates a number of SUV, light and heavy-duty trucks, and vans within their fleet. At this time these classes of EV are not on the market. However, research by (Weldon et al., 2018) outlining the potential economic advantages of larger class EVs, indicating in the future there may be the possibility of 100% electrified fleets across all vehicle sizes.

Table 21: NHDES Fleet Design

Design	Fleet Cost	EVSE	Fleet+EVSE/Vehicle	Abatement
2017 NHDES	$1,232,493	$0	$36,250	___
HEV	-$87,233	$0	-$2,566	25%
PHEV	$4,903	$17,000	$161	33%
60/40 BEV HEV	-$6,705	$60,000	-$138.39	38%
60/40 BEV PHEV	$31,233	$67,000	$984	42%
60/40 BEV BEV+	$130,686	$102,000	$3,944	45%

Table 21 outlines six potential NHDES fleet designs which could fill the operational needs discussed above. The first option is to keep fleet makeup the same as in 2017, by incorporating 11 compact HEVs and 23 compact ICVs. Over the 11.6-year lifespan of each vehicle the state would spend $1,232,493 on vehicles and none on EVSE. Between fleet and EVSE costs, the NHDES would spend an average of $36,250 per vehicle while emitting 1,656.98 tons of $CO^2{}_e$. Using 2017 NHDES fleet makeup as a control, four alterative fleet designs can be compared 100% HEV, 100% PHEV, 60/40% BEV/HEV, 60/40% BEV/PHEV, and 60/40% BEV/BEV+.

The first potential design incorporates 100% HEVs. Given HEVs have the lowest total cost of ownership (TCO) and require no EVSE investment, total fleetwide costs would be reduced by $87,233 with an average costs savings of $2,566 per vehicle and total GHG emissions reductions of 25%. Another alternative is 100% PHEVs which would correspond with a $4,903 increase in total vehicle costs along with a $17,000 EVSE investment. This EVSE cost assumes 34 level I chargers costing $500 per unit, which would be sufficient to meet overnight charging needs. If a 30-year EVSE lifetime is assumed, the fleetwide cost comes is $567 per year. When fleet and EVSE costs are combined the average increase in vehicle price is $161 over 11.6 years with GHG abatement of 33%.

The final three alternative fleet designs are a mixture of vehicle technologies, all with 60% BEVs and 40% an alternate vehicle technology. A fleet consisting of BEV and HEV technologies would provide 38% abatement while reducing total fleet vehicle costs by $6,705, or $138.39 per vehicle. A BEV/PHEV fleet would increase vehicle costs by $31,233 along with a $67,000 investment in necessary level I and level II EVSE for PHEVs and BEVs respectively. The average increase in costs per vehicle would be $984 with GHG abatement jumping to 42%. The final fleet design of exclusively BEV and BEV+ technologies would increase vehicle costs by $130,686 along with a $102,000 investment in corresponding level II EVSE. This would bring the average cost per vehicle to $3,944 over the control while GHG abatement would be maximized at 45%.

If the NHDES is looking to reduce overall costs investment in HEV technologies is clearly the most economically efficient approach. These cost savings are achieved while reducing emissions by one quarter and continuing a business as usual approach, where the necessary petroleum infrastructure is already in place. This indicates NHDES should not consider compact ICVs going forward as their potential benefits are maximized by HEVs. A fleet design incorporating both BEV and HEV technologies would also save money in the long term, while achieving 38% GHG abatement.

The three EV fleet designs should be implemented if GHG abatement is the primary goal in fleet design. Abatement potential ranges from 33-45% but comes with drastically different costs. To maximize abatement, a fleet of BEV and BEV+ technologies could be implemented. However, an increase of nearly $4,000 per vehicle would be substantial. Additionally, this design would necessitate a number of road DC charging stations which would further increase prices. These economic costs, specifically the high initial investment in vehicles and infrastructure, make this fleet difficult to implement.

While a fleet of PHEVs would have virtually no increase in costs, GHG abatement would not reach over the 40% threshold, which is only possible with the incorporation of BEVs. In fact, this design would be more costly and have less total GHG abatement than a BEV/HEV fleet mix, and therefore is not the most attractive option. Finally, the BEV/PHEV fleet would provide similar abatement potential to the BEV/BEV+, while increasing costs by a manageable sum under $1,000 per vehicle when compared to NHDES 2017 design. This mixture of minor cost increases with enhanced GHG abatement make this design an attractive option.

In the view of this analysis a fleet design consisting of BEV and either PHEV or HEV technologies should be incorporated. If HEVs are incorporated, total costs will be reduced below that of the control. This will make partial fleet electrification easy to justify, an important consideration when dealing with frugal state governments. The second option is to incorporate PHEVs. This design will come with a slight increase in costs but will further reduce GHG emissions. Additionally, the expansive EVSE investment will allow for easier future transitions to 100% BEV fleets when longer range less expensive BEV+ vehicle hit the market. Both approaches can be cost effective and greatly reduce GHG emissions beyond what is seen in today’s fleet.

Due to technological limitations such as electric driving range the operational needs of a fleet must be carefully considered before adopting BEVs. To maximize their benefits and ensure reliability any agency or business, including the NHDES, should have a detailed understanding of the distances and number of trips taken by their fleet. Future analysis is needed beyond the simple calculation presented in table 18 and table 19 above to identify NHDES’s exact fleet optional patterns. Once this information is collected and analyzed, the appropriate mix of EV technologies and EVSE can be implemented to fill fleet needs, manage economic costs, and maximize GHG abatement.

House Bill 275

Table 22: House Bill 275

Vehicle Type/Class	Quantity	Average ICV Contract Price	NH Estimated Implementation Cost	LCCA estimate
Passenger Auto	760	$17,149	$4,300,969	$81,252
Extra Heavy-Duty Truck	95	$125,000	$3,918,750	$74,032
Heavy Duty Truck	322	$85,000	$9,032,100	$170,631
Light Duty Truck 1	634	$25,999	$5,439,511	$102,761
Light Duty Truck 2	393	$26,702	$3,462,982	$65,421
Medium Duty Truck	173	$33,510	$1,913,086	$36,141
Van/Bus	19	$26,319	$165,020	$3,118
Total			$28,232,418	$533,357

State of New Hampshire House Bill 275 was introduced in 2019 and outlined a proposal to switch all State of New Hampshire Fleet vehicles to EVs by 2040, starting with compact cars in 2021 and phasing in light and heavy-duty trucks and vans over the remaining 20 years. The methodology used by the State for cost calculation is shown in table 22. To calculate potential economic costs, the Nissan Leaf was compared to the lowest cost ICV on the market between 2016-2019 and determined to have a 33% increase in average purchasing price. This percentage was used to calculate total State of New Hampshire fleet costs by multiplying 33% by the 2019 average State contract price for each vehicle class, then multiplying by the total quantity of vehicles. These values were then summed across each class for a total cost estimate of $28,232,418.

The state's approach hinges on the assumption that BEV technologies are more costly than ICVs based on their purchasing price. As discussed throughout this analysis, when a life cycle cost analysis (LCCA) approach is implemented, the true total cost differences between the two technologies are minimal. This analysis indicates a more accurate ratio of price increase for BEV technologies is .6% rather than the 33% used by the State. If the .6% ratio were implemented, the fleetwide total cost estimate would be closer to $530,000.

The discussion on House Bill 275 is included not to proclaim a 100% BEV fleet would cost the State of New Hampshire $530,000 to implement, but rather to highlight the power of using an LCCA approach. While this analysis argues the State should have used an LCCA approach, a more nuanced methodology to estimating costs of transitioning the entire State fleet to BEVs would be needed. Most notably the potential differences in cost ratios between vehicle classes and the implementation of necessary infrastructure networks were not addressed in this calculation. Despite these uncertainties, it's clear an LCCA approach will give policy makers a more accurate depiction of total costs than traditional purchasing price driven comparisons.

Conclusion

With many public and private fleets across New England are considering fleet electrification as a possible method to carbon reduction, fleet managers must have a thorough understanding of both economic costs and environmental outputs of this transition. This study assesses the total cost of ownership (TCO) and life cycle greenhouse gas (GHG) emissions of three electric vehicle (EV) technologies battery electric (BEV), battery electric extended mileage (BEV+), and plug in hybrid electric vehicles (PHEV) compared to traditional hybrid electric (HEV) and internal combustion vehicle (ICV) technologies. Drawing on historic operations data from State of New Hampshire and University of New Hampshire fleets and peer review literature, the impacts of regional climate and driving characteristics on vehicle energy efficiency are captured while ISO-NE grid data is incorporated to more accurately reflect regional GHG emissions. The TCO approach was used to account for lower fuel and operations costs for EVs compared to ICVs over their lifespans. Within a fleet setting, where vehicles drive high mileages over many years, these reductions can make EVs particularly attractive. This study shows that both BEV and PHEV vehicles operating over 150,000 lifetime miles have total costs of ownership which are comparable to that of the ICV, with the PHEV approximately $1,100 less and the BEV $250 greater. The traditional HEV is shown to have to lowest total cost of ownership across all vehicle technologies at $2,700 less than the vehicle with the second lowest costs, the PHEV. All EV technologies showed major reductions in both fuel and operations & maintenance (O&M) costs compared to the ICV.

It is important to consider several factors outside miles driven when assessing TCO. The effective price is the largest expenditure for all vehicle technologies, which is shown to increase along with a vehicle's total electric range. If fleet managers can secure a federal or state level incentive to reduce the purchasing price, EVs total costs can be reduced far below that of the

ICV. Additionally, the maturity of the pre-owned BEV market leading to vehicle salvage value retention similar to traditional vehicle technologies could lead BEV TCO to fall below the ICV. The effects of historic vehicle operations and climate considerations have inverse effects on vehicle technologies, reducing the fuel costs and GHG emissions of traditional vehicles while increasing those of EVs. Due to fuel efficiency changes resulting from operational characteristics and variable petroleum prices, future ICV fuel costs are difficult to predict, and could potentially increase greatly. Conversely, electrical prices have historically risen steadily and, along with minimal cost increases resulting from loss of BEV efficiency from climate variables, lead BEV fuel costs to be more easily forecast. Additionally, while this study assumes no battery replacement, if Li-ion battery replacement were necessary there would be significant a increase in O&M costs for EVs, specifically BEVs with larger kWh battery size.

EVs are often referred to as zero emission vehicles, which leads to potentially overstated emissions abatement when EVs are compared to traditional vehicle technologies. This analysis clearly shows the BEV has the largest emissions abatement of 54% compared to the ICV. Other technologies such as BEV+ (47%), PHEV (40%), and HEV (33%) all showed major emissions reductions. The majority of BEV and BEV+ emissions came in the form embedded carbon from battery production and “extended tailpipe” emissions due to fuel cycle electrical production. Due to ISO-NE’s natural gas and nuclear heavy grid, these emissions are less than areas with grids heavy in coal and oil. As New England States progress towards Renewable Energy Portfolio standards these fuel cycle emissions should continue to decline. Due to the small amount of GHG emissions from renewable energy sources, fleet managers should consider investing in distributed renewable energy capacity on site to pair with BEV technologies for the largest possible GHG abatement.

Operational consideration for BEV fleets should be accounted for, such as the cost of electric vehicle service equipment (EVSE) and driving range. Most fleet charging needs can be met with Level II EVSE, with prices around $3,000 per unit. While detailed analysis of trips made by NHDES fleet vehicles was beyond the scope of this analysis, a brief assessment of distances to each New Hampshire county shows most of the state's population centers lie within operational range of BEVs. A substation of BEVs for ICVs can lead to large GHG abatement with minimal increase in overall costs. However, this simple substitution is not feasible for the NHDES fleet without the implementation of a costly network of road EVSE infrastructure given the limited range of BEV technologies. Given this barrier, NHDES should consider a fleet makeup of both BEV and PHEV technologies which would maximize GHG abetment while total costs similar to those of ICVs. This dynamic fleet could eventually transition into a solely BEV fleet in the future once technology advances to the point where longer range BEVs get to market or a network of road charging infrastructure is implemented which NHDES can take advantage of.

Overall, this study shows that EV technologies can be cost competitive with ICVs within New England under high mileage scenarios, while providing substantial emissions reductions. Fleets looking to minimize costs should consider HEV fleets which are shown to have the lowest TCO and would not require additional infrastructure development while those looking to maximize GHG abatement should consider BEVs. While BEV fleets are cost competitive and are shown to reduce emissions, there is no one size fits all approach to their implementation. Fleet operational needs must be considered, leading to the potential implementation of a dynamic fleet consisting of multiple vehicle technologies and levels of EVSE.

Areas of future research should include an assessment of ICV fuel efficiency under local driving/ high idling scenarios such as those on a campus or city as compared to both BEVs and PHEVs, the economic costs and operational feasibility of BEV fleets paired with solar PV in New England, how battery second use programs can be implemented to utilize retired Li-ion batteries, and the optimal design and economic costs of a network of EVSE for State of New Hampshire fleet vehicles including those of the NHDES. Additionally, a detailed marginal emission based GHG and criteria air pollutant (CAP) study of an existing BEV fleet should be conducted to provide more accurate short-term emissions values and assess the impacts of regional air pollutants within New England.

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