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Modeling the Market-Driven Composition of the Passenger Vehicle Market during the Transition to Electric Vehicles

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Abstract: The automotive market is currently shifting away from traditional vehicles reliant on internal combustion engines, favoring battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs). The widespread acceptance of these vehicles, especially without government subsidies, hinges on market dynamics, particularly customers opting for vehicles with the lowest overall cost of ownership. This paper aims to model the total cost of ownership for various powertrains, encompassing conventional vehicles, HEVs, PHEVs, and BEVs, focusing on both sedans and sports utility vehicles. The modeling uses vehicle dynamics to approximate the fuel and electricity consumption rates for each powertrain. Following this, the analysis estimates the purchase cost and the lifetime operational cost for each vehicle type, factoring in average daily mileage. As drivers consider vehicle replacements, their choice tends to lean towards the most economical option, especially when performance metrics (e.g., range, acceleration, and payload) are comparable across the choices. The analysis seeks to determine the percentage of drivers likely to choose each vehicle type based on their specific driving habits. Advances in battery technology will reduce the battery weight and cost; further, the cost of electricity will decrease as more renewable energy sources will be integrated into the grid. In turn, the total cost of ownership will decrease for the electrified vehicles. By following battery trends, this study is able to model the makeup of the automotive market over time as it transitions from fossil-fuel based vehicles to fully electric vehicles. The model finds until the cost of batteries and electricity is significantly reduced, the composition of the vehicle market is a mixture of all vehicle types.

Keywords: technology forecasting; batteries; sustainability; electric vehicles; life-cycle cost analysis; drive-cycle models; market models; cost models

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1. Introduction

The automotive industry is currently undergoing a significant shift away from traditional internal combustion engine vehicles, transitioning toward adopting Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), and Plug-in Hybrid Electric Vehicles (PHEVs). The choice of customers to opt for BEVs and HEVs, particularly in the absence of government subsidies, primarily relies on market dynamics, specifically assessing the total cost of ownership. Although BEVs and HEVs boast lower operating costs, they come with higher upfront expenses due to battery costs. However, the operating expenses of BEVs and HEVs are expected to decrease with lighter batteries and the integration of cheaper renewable energy sources into the grid [1]. Nonetheless, the optimal vehicle choice is likely to depend on individual driver behavior, especially their average daily mileage.

This study aims to model the total cost of ownership for conventional vehicles, HEVs, PHEVs, and BEVs, focusing on mid-sized sedans and sports utility vehicles (SUVs) in the United States. As consumer vehicle preferences generally align with the most economical option, particularly when key performance metrics such as range, acceleration, and payload are comparable, this analysis seeks to determine the percentage of drivers likely to opt for each vehicle type based on their individual driving habits. The percentage of drivers will evolve over time as battery technology and the grid will evolve. Therefore, this paper models the composition of the vehicle market during the shift to electrification.

This analysis departs from other studies, which use data from production vehicles for such assessments. Rather, this research draws from fundamental vehicle dynamics, using a notional sedan and SUV to model out the fuel and electricity required for locomotion. In doing so, the study ensures absolute parity between the different vehicle alternatives except their respective powertrains. This methodology offers unique insights into the comparative cost dynamics across these distinct powertrain options.

The paper provides an overview of the American vehicle market, encompassing vehicle market trends, and previous modeling endeavors. It introduces various models, including energy models for different vehicle powertrains, which are used to determine the total ownership cost of each vehicle type. Additionally, the study details a model predicting the market-driven composition of the automotive market in the United States over time. These models are generally simplified correlations that rely on numerous assumptions; regardless, they provide insight into the automotive market trends. Ultimately, the paper concludes by presenting the results of these models, illustrating the diverse makeup of the automotive market in the near future.

2. Materials and Methods

2.1. Background

The current vehicle market in the United States is still dominated by traditional vehicles with internal combustion engines. However, over the past decade, the vehicle market has been experiencing a notable shift towards EVs. This transition is fueled by various factors, including growing environmental consciousness, regulatory pressures to reduce emissions, and advancements in battery technology [2]. Major automakers are ramping up their production and release of EV models to meet the increasing consumer demand [3]. Though EVs are more expensive than conventional vehicles, this cost is partially offset by lower operational costs, as EVs use grid electricity instead of gasoline. To further help with the expenses of EVs, the federal and state governments are offering incentives and subsidies, including tax credits, rebates, and grants that make EVs more financially accessible and attractive to consumers [4].

Another competitor in the vehicle market is the HEV. While the interest in HEVs remained steady, the growth in this market has started to plateau [5]. Hybrid vehicles, blending traditional internal combustion engines with electric propulsion, are often regarded as a steppingstone towards complete electrification. The market is experiencing a shift towards PHEV and EV due to advancements in battery technology and the desire for a fully electric driving experience [6]. However, limitations within the hybrid market primarily arise from their similarity to conventional vehicles. Furthermore, the expected fuel savings over the vehicle's lifetime often do not justify the increased initial cost [7].

Cost and supply chain challenges related to batteries represent a significant hurdle in the widespread adoption of EVs [8]. The cost of manufacturing high-capacity batteries remains relatively high, impacting the overall cost of EVs [9]. Moreover, the supply chain for critical battery materials, such as lithium and cobalt, can be volatile due to geopolitical and economic factors [10]. Addressing these challenges in cost and supply chain management is crucial for accelerating the transition to electric vehicles and expanding their accessibility to a wider consumer base. Continued research, development, and investment in battery technology are essential to overcoming these challenges and making EVs a viable and economical choice for consumers.

2.2. Summary of Models and Other Studies

Several other studies, including Karabasoglu and Michaelek [11], Kawamoto et al. [12], Furch et al. [13], Mustapa et al. [14], Cox et al. [15], Petrauskiene et al. [16], and Hung et al. [17], have conducted similar analyses. These studies primarily focused on comparing the total operating costs of vehicles with internal combustion engines to electrified alternatives, encompassing diverse vehicle applications such as buses, motorcycles, delivery trucks, and passenger vehicles.

Generally, all of these models followed a similar framework to that used in this study, estimating vehicle energy consumption using a drive-cycle methodology and calculating the total cost of ownership. However, it is important to note the total cost of ownership in these analyses is static, relying on values specific to their respective years and may not fully consider cost changes associated with emerging technologies. Nevertheless, they consistently highlight the optimal powertrain choice depends on the application, particularly considering factors like daily mileage and payload capacity.

As Senecal and Leach note in their study on the future vehicle market, they describe the future of vehicles as 'eclectic', indicating a diverse array of vehicle types likely to be available to users [18]. This analysis aims to comprehend these evolving trends by employing a series of predictive models to forecast the market-driven composition of the automotive sector.

2.3. Methodology

Figure 1 outlines the process used in this study, which consists of three models. The first model determines the fuel and electricity consumed per mile for a given vehicle type with a given powertrain. The second model takes this mileage consumption and approximates the total cost of ownership for the vehicle, including 150,000 miles or 12 years of operation. The third model determines the percentage of drivers that are replacing their vehicles with vehicles of a different powertrain. This model assumes the drivers picks the vehicle with the lowest cost of ownership. Through the use of these three models, the changing composition of the vehicle market can be approximated.

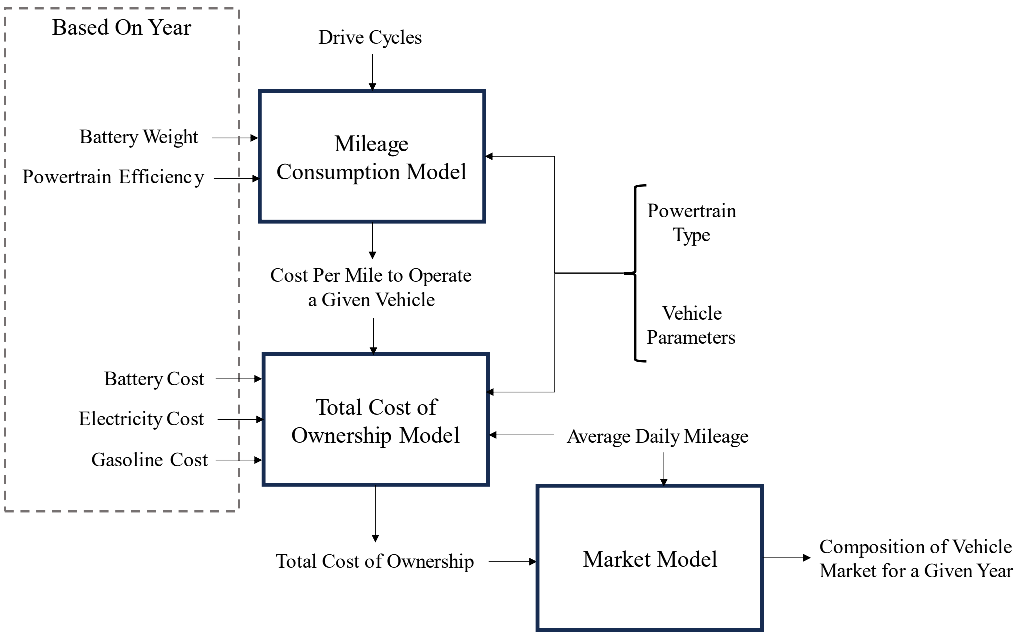


Figure 1. The series of models used in this study. The study used three models that calculated the cost per mile for different powertrains, the total cost of ownership for each type of vehicle, and the makeup of the market based on the overall cost of each vehicle.

These three models, with their underlying calculations and assumptions, are discussed in detail in the following section.

3. Models

3.1. Mileage Consumption Model

The analysis applied a Microsoft Excel-based model to determine the energy consumption for each of the vehicles described in the previous section. The model takes vehicle and powertrain parameters as inputs and calculates the fuel (m_{fuel}) and electricity consumption (c_{elect}) estimations for urban and highway drive cycles [19,20]. The fuel and electricity consumption as a function of distance travelled is approximated as the average of the urban and highway mileages.

The model is deterministic and follows from basic vehicle dynamics [21], calculating the power required to change velocity, overcome air drag, overcome rolling resistance, overcome an incline, and power accessories. As such, the following variables were required to be defined for each vehicle:

- m: mass of vehicle (kg)
- C_d: drag coefficient of vehicle
- A: frontal area of vehicle (m^2)
- f_0, f_s: coefficients of rolling resistance
- η: powertrain efficiency
- P_{peak}: peak power (kW).

The model also required several constants including:

- r: density of air = 1 kg/m^3
- g: gravitational constant = 9.8 m/s^2
- LHV: lower heating value of fuel = 44 MJ/kg.

The model must also define the parameters of the drive cycle, which is broken up into N discrete time steps (Dt) set at 1 s. For each time step (n), the following is defined:

- v_n: instantaneous velocity at a time step n (m/s)
- θ_n: incline of road at time step n (rad).

At each time step, the model then calculates the power required at each time step for acceleration ($P_{accel,n}$), to power accessories ($P_{accessories,n}$), and to overcome grade ($P_{incline,n}$), drag ($P_{drag,n}$), and rolling resistance ($P_{rolling,n}$) using the following equations:

$$P_{accel,n} = \begin{cases} mv_n(v_n - v_{n-1})/\Delta t, & v_n > v_{n-1} \\ 0, & v_n < v_{n-1}\ (no\ electrification) \\ 0.65\ mv_n(v_n - v_{n-1})/\Delta t, & v_n < v_{n-1}\ (w/electrification) \end{cases}$$

$$P_{accessories,n} = 1000\ W$$

$$P_{incline,n} = mg\sin\theta_n\, v_n$$

$$P_{drag,n} = 0.5\ C_d\rho\ v_n^3 A$$

$$P_{rolling,n} = mg\cos\theta_n\left(f_0 + 3.24 f_s\left(\tfrac{v_n}{223}\right)^{2.5}\right)v_n$$

It is important to note for the highway and urban drive-cycles, the road is flat, resulting in $P_{incline,n}$ always being 0.

The equation for $P_{accel,n}$ assumes all power is lost when the traditional vehicle is braking. However, with the HEV, PHEV, or BEV, the engine is able to recapture some of that lost power through regenerative braking. This study uses an efficiency of 65 percent for the regenerative braking process [22].

The associated energy (E_n) required for that time step can then be calculated by summing up the power components and multiplying it by the time step. From there the amount of fuel and electricity required for time step n can be calculated. If the vehicle just uses a standard ICE, the fuel consumption can be calculated as:

$$m_{fuel,n} = E_n/\eta_n/LHV_{fuel}$$

where η_n is the efficiency of the engine which is a function of the engine load (P/P_{peak}). The model uses an efficiency curve shown in Figure 2 for the 2025 engine [23]. The efficiency increases for later years, as engines adapt new technologies to become more efficient in-line with automotive standards [24].

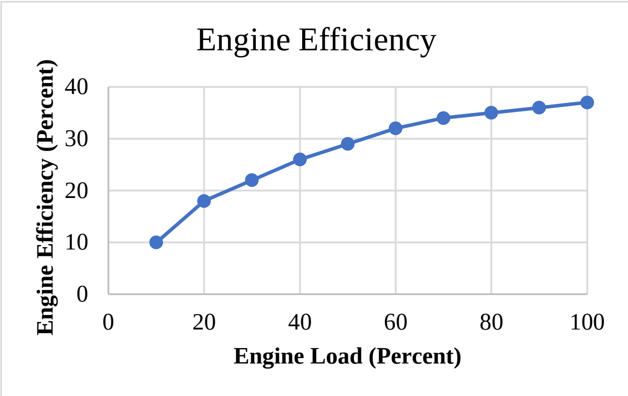


Figure 2. Approximation used for engine efficiency as a function of engine load based on data in [23]. Note this curve is a general curve for a modern turbocharged, direct injection engine.

The model uses a similar approach to determine the amount of energy dissipated from the batteries for the BEV:

$$c_{elect,n} = E_n/\eta$$

The BEV model calculates that state of charge of the battery at each time step. At the start of the drive cycle, the battery is set to being fully charged. As electricity is required at each time step, it is taken out of the battery bank, reducing the state of charge. At any time step, the state charge is not allowed to be less than 10 percent of the overall battery capacity.

For the HEV, the calculation is slightly more complex in that the locomotion can be provided by the engine, the motor, or both. Over a low range of speeds and loads, locomotion is provided by the motors powered by the battery and uses a similar model as that for the BEV. At a mid-range of loads, locomotion is provided by the engine and thus uses the same consumption equations used for the ICE-only vehicle. At high loads, locomotion is provided by both the engine and the motor and thus uses the following equations:

$$c_{elect,n} = P_{max,\ batt}\Delta t/\eta, \qquad m_{fuel,n} = \left(E_n - \eta\ c_{elect,n}\right)/\eta_n/LHV_{fuel}$$

For the HEV, the engine also provides energy to the battery bank to ensure it maintains a consistent level of charge.

The PHEV will use a similar model as the HEV. However, for the PHEV, the battery bank can be substantially depleted since it can be recharged from the grid. When the battery bank drops below this threshold value, the engine recharges the battery to ensure the batteries can run the motors in peak load applications. The engine will not recharge the battery bank completely, allowing it to be recharged from the grid:

$$m_{fuel,n} = c_{elect,n}/\eta_n/LHV_{fuel}$$

The total fuel and/or electricity consumption is then summed over each drive cycle. The consumption rates are then calculated by dividing the fuel and/or electricity consumption by the distance travelled. An average consumption rate is then taken by averaging the rates for the urban and highway drive cycles.

The algorithms used in this study are similar to those used by other drive cycle models including the Future Automotive System Technology (FASTSIM) and Advanced Vehicle Simulator (ADVISOR), both developed by the National Renewable Energy Laboratory [25,26]. While FASTSIM and ADVISOR are used in a number of studies and quite robust, they do not readily allow for the modification of key design parameters needed for this study. In particular, the models are designed and validated for production vehicles; this approach, based on fundamental vehicle dynamics, allows for an understanding of fundamental parameters that play key roles in increasing and decreasing the overall vehicle cost.

3.2. Total Cost of Ownership

The total cost of ownership is made up of the acquisition cost of the vehicle and the operational cost of the vehicle. The operational cost of the vehicle will be based on the fuel and electricity consumption rates calculated in the previous section.

3.2.1. Acquisition Cost

This analysis assumes comparable vehicles, such that the price of the vehicle without the powertrain is consistent across all the vehicle architectures. However, the powertrain will vary significantly across the different architectures.

The model uses the following approximations to capture the powertrain cost:

- engine cost ($): 531 + 15 × P_{engine} (kW) [27]
- transmission cost ($): 12.5 × P_{engine} (kW) [28]
- motor and power electronics Cost ($): 425 + 21.7 × P_{motor} (kW) [27]
- battery cost ($): 160 × $E_{battery}$ (kWh) [29].

While the costs of the other components are not expected to vary significantly with time, the battery cost is expected to decrease significantly with time. A number of different studies have included studies to attempt to forecast the cost change in Li-Ion batteries. One of the most comprehensive studies is by Mauler et al., which predicts the cost per kWh of batteries as shown in Figure 3 [29]. This projection is based on current trends which includes advances in manufacturing, including the development of new infrastructure. It does not account for any changes that can occur from the development of new battery chemistries.

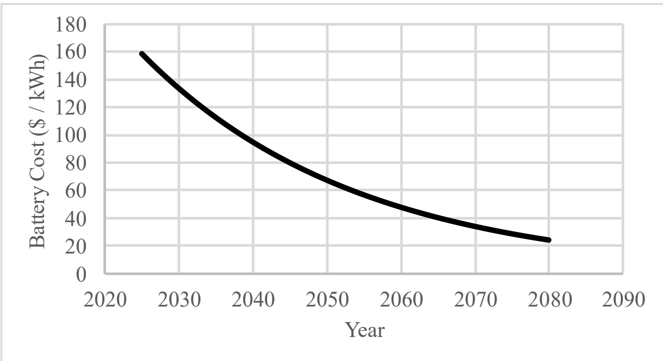


Figure 3. Approximation of battery cost per kWh from 2025 to 2080. The estimation is based on a study performed by Mauler et al. [29].

3.2.2. Operational Cost

The model assumes that the vehicle owner is driving either 150,000 miles or 12 years whichever comes first [30]. Figure 4 breaks up the total drivers in the United States by their average daily mileage based on data from the National Household Travel Survey [31]. Figure 4 shows 59 percent of drivers drive less than 30 miles per day. Meanwhile, six percent of drivers exceed hundred miles per day.

Based on the average daily mileage of a driver, the total vehicle life mileage can be calculated. The total amount of electricity and fuel required to complete this mileage is calculated by dividing the number of miles by the mileage rate calculated in the first model. This quantity is then multiplied by the cost per gallon of gasoline or the cost per kWh of electricity to determine the total operational cost.

While this technique is straightforward for most of the vehicles, the PHEV has the additional complication that the vehicle can be refueled or recharged. The model assumes the vehicle is recharged to capacity nightly and has a range of 30 miles. As the vehicle exceeds 30 miles, the vehicle burns fuel.

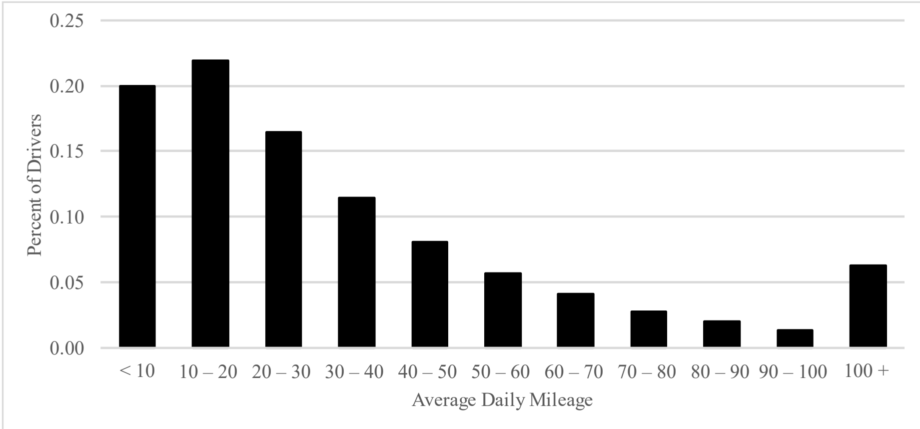
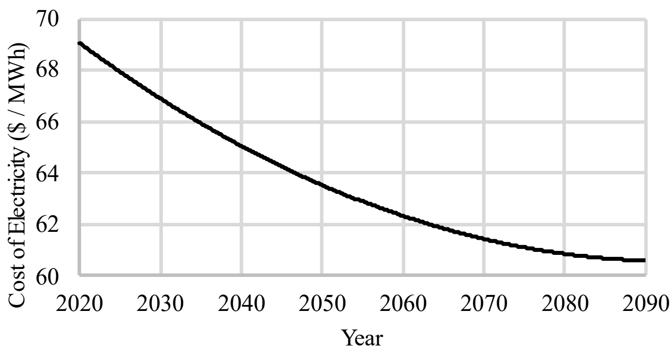


Figure 4. Histogram of the average daily mileage of drivers in the United States based on data from [31].

Similar to batteries, there is significant volatility in the gasoline market, with prices changing significantly based on supply and demand. Further, external factors, including wars, have added further volatility to this market. The general volatility of the market makes it difficult to predict in the future [32]. Further, as electric vehicles fill the market, the demand for gasoline generally decreases, resulting in the cost per gallon to reduce due to market trends. This will be offset by dwindling supplies. As such, this model assumes the cost of gasoline is $3.60 per gallon.

Meanwhile, the cost of electricity in the future is also difficult to predict, due to the complexity of the power-generation sector. This study uses an approximation where the cost for electricity varies based on the generation source. Figure 5 provides the current composition and the associated costs of the grid in the United States [33]. The Environmental Protection Agency (EPA) developed a projection out to 2050 for the composition of the grid with coal and nuclear energy being phased out with an increase in renewables [34]. The EPA trends are extrapolated out to 2080 for this analysis, with the associated cost being approximated, as shown in Figure 5.



Source	Current Cost ($/MWh)	Current Percentage (%)
Coal	110	19
Gas	45	40
Nuclear	72	20
Hydro-Electric	40	7.3
Wind	66	8.4
Solar	45	2.3

Figure 5. Projected cost of electricity from 2020 to 2090 based on estimations by the EPA [33,34].

The operational cost also includes the cost to maintain the vehicle, since every mile driven puts wear on the car. All vehicles require tire changes and general tune-ups related to suspension and handling. Further, vehicles that include an ICE also require frequent oil changes. The BEV powertrain has the fewest moving parts, so it would be expected to have the lowest maintenance cost. Meanwhile, the HEV and PHEV, which have the most components would have the highest maintenance cost.

The model uses the following approximations to capture the maintenance costs:

- vehicle with ICE: 0.055 $/mile [35]
- HEV and PHEV: 0.058 $/mile [35]
- BEV ($/mile): 0.039 $/mile [35]

3.3. Market Model

The market model breaks up the automotive market into car and SUV drivers. It then further breaks up the market by the average daily mileage for the driver. The model then identifies what percentage of drivers are replacing their cars each year based on their average daily mileage. Each vehicle is capped at 150,000 miles or 12 years. For example, for drivers who drive 20 miles per day, they would drive 87,600 miles over the vehicle lifetime of 12 years. As such, 8.3 percent of drivers in this range will switch out their vehicles each year. Meanwhile, a driver who drives 50 miles per day would drive 150,000 miles over 8.2 years. For drivers in this range, 12 percent of drivers will buy a new vehicle annually.

The drivers who are looking at new cars would purchase a new car with the lowest cost of ownership. They will define the cost of ownership based on the current acquisition cost and the cost of ownership based on that year's gasoline and electricity costs.

The model makes the following assumptions:

- all vehicles have no value at the end of their lifetime.
- There are no external incentives (e.g., government subsidies) to decrease the cost of the vehicle.

4. Vehicle Parameters and Energy Consumption

4.1. Vehicle Architectures

This analysis considers the four vehicle architectures shown in Figure 6. The first vehicle is a traditional internal combustion engine (ICE) powered vehicle, which relies on the conversion of liquid hydrocarbon-based fuel to locomotive power. The second vehicle is the battery electric vehicle (BEV) which stores energy in a set of batteries; this energy is then used to provide electricity to a motor to provide locomotion. The batteries for the BEV are recharged from electricity from the grid.

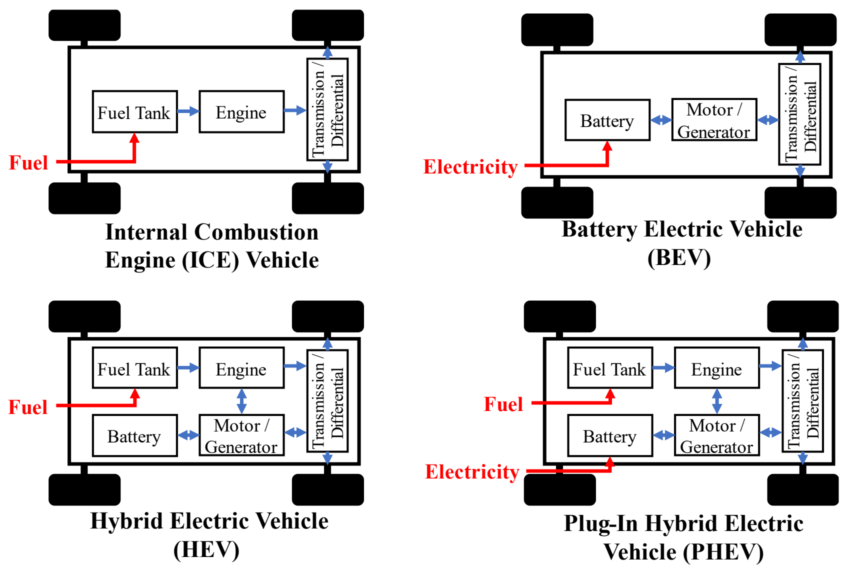


Figure 6. Vehicle architectures considered in this analysis.

The analysis considers two hybrid vehicles that bridge the gap between the ICE-powered vehicle and the BEV. The first is a hybrid electric vehicle (HEV), which can use both an engine powered by liquid hydrocarbons and a motor powered by batteries to drive the engine. For the HEV, the batteries are recharged from the onboard power generation and from regenerative braking. The other vehicle is a plug-in hybrid electric vehicle (PHEV). The PHEV functions similarly to the HEV but has the option of recharging the battery from grid power. Typically, the PHEV has a considerably larger battery pack than the HEV, such that the PHEV can operate as a fully electric vehicle for most common short-duration trips.

4.2. Vehicle Types

4.2.1. Sedan

The analysis considered two different sizes of vehicles for each of the vehicle architectures discussed in the previous section. The first is a standard sedan modelled as a 2022 Toyota Camry which has specifications similar to what are shown for the "Vehicle with ICE" in Table 1 [36].

Table 1. Characteristics for the sedan with the four different powertrains used in this analysis.

	Units	Vehicle with ICE	HEV	PHEV	BEV
Base Weight	kg	1030	1030	1030	1030
Comparable Power Train Design		2022 Toyota Camry	2022 Toyota Camry Hybrid	2019 Chevrolet Volt Plug-In Hybrid	Tesla Model 3 Extended Range
Engine/Transmission					
Power	kW	126	115	79	0
Weight	kg	370	340	260	0
Cost	$	3421	3248	2716	0
Battery					
Capacity	kWh	0	1.82	13.2	154
Weight	kg	0	4.6	33	384
Cost	$	0	290	2112	24,570
Motor/Electronics					
Power	kW	0	29	158	205
Weight	kg	0	210	405	485
Cost	$	0	1046	2853	4884
Total					
Weight	kg	1400	1585	1728	1899
Cost	$	3421	4584	7681	29,460

Table 1 gives the cost and weight parameters for each of the four different vehicle architectures for the sedan. The cars are identical in every aspect aside from the powertrain. The powertrain for the HEV is modeled after the Toyota Camry Hybrid [37]; the PHEV is modeled after the 2019 Chevrolet Volt Plug-In Hybrid [38]; and the powertrain for the BEV is based on the Tesla Model 3 Extended Range [39]. The powertrain sizes were modified to reflect the power and range associated with the 2022 Toyota Camry.

4.2.2. Sports Utility Vehicle

The second vehicle considered in this analysis is a sports utility vehicle (SUV), modelled primarily as the 2023 Ford Explorer [40]. Similar to the sedan, the SUV powertrain specifications were loosely modeled after the 2023 Ford Explorer Hybrid [41], 2023 Mazda CX90 PHEV [42], and 2022 Rivian R1T SUV [43]. The specifications were then modified to match the performance and range associated with the standard 2023 Ford Explorer. The vehicles and their powertrains are described in Table 2. All of the vehicles have approximately 300 kW of power and a range of 300 miles.

Table 2. Characteristics for the SUV with the four different powertrains used in this analysis.

	Units	Vehicle with ICE	HEV	PHEV	BEV
Base Weight	kg	1410	1410	1410	1410
Comparable Power Train Design		2023 Ford Explorer	2023 Ford Explorer Hybrid	2023 Mazda CX90 PHEV	2022 Rivian R1T SUV
Engine/Transmission					
Power	kW	300	260	200	0
Weight	kg	860	750	500	0
Cost	$	8616	7681	3531	0
Battery					
Capacity	kWh	0	2.0	30	180
Weight	kg	0	5	75	450
Cost	$	0	320	4800	28,800
Motor/Electronics					
Power	kW	0	40	100	330
Weight	kg	0	220	400	780
Cost	$	0	1293	2595	8880
Total					
Weight	kg	2270	2385	2385	2640
Cost	$	8616	9294	10,926	36,386

It is worth noting the battery pack for the HEV was only marginally larger for the SUV than it was for the sedan. This is expected given the limited use that the HEV has for the battery pack, with it only being used when idling or to capture lost energy from braking. As such, the battery did not necessarily need to be scaled up significantly for the larger vehicle.

The engine for the PHEV is still capable of providing 200 kW of power; this size is primarily due to the uses of the SUV. When the SUV is being used for everyday commuting, it would seldom need the engine aside from generating electricity to recharge the batteries. However, for certain applications, especially if the vehicle is carrying a heavy load, the engine would provide the additional power. Since the power increase from these loads can be substantial, the engine has to be adequately sized.

5. Baseline Model Results

5.1. Model 1: Fuel and Electricity Consumption

The first model was run for the highway and urban drive cycles. The models assumed the vehicle weights given in the previous section, each carrying an additional payload of 200 kg for the sedan and 300 kg for the SUV. In each case, the vehicle is modeled to be driving over a flat surface.

Table 3 provides the results from the drive-cycle model that estimates the fuel and electricity consumption for each vehicle powertrain for the highway and urban drive cycles. Table 3 also provides the values for the combined fuel and electricity consumption, which is set as the average of the highway and urban drive cycles.

As expected, the HEV has a significant fuel savings when compared to the conventional vehicle for both the sedan and SUV. However, the PHEV provides comparable fuel consumption to the standard vehicle. The benefits from regenerative braking are offset by the increased weight of the vehicles. The main advantage of the PHEV is it has the ability to run in a pure-electric mode. Further, when the PHEV is running in fully electric mode, the electricity consumption is less than that of a fully electric vehicle which is substantially heavier.

Table 3. Fuel and electricity consumption results for the four different vehicle powertrains considered in this analysis for the highway and urban drive cycles.

Powertrain	Units	Sedan			SUV		
		Highway	Urban	Combined	Highway	Urban	Combined
Vehicle with ICE	miles per gallon	32.9	25.3	29.1	23.6	17.4	20.5
HEV	miles per gallon	36.0	32.2	34.1	27.0	23.8	25.4
PHEV (ICE)	miles per gallon	32.4	25.5	29.0	25.5	19.5	22.5
PHEV (Battery)	miles per kWh	3.64	3.16	3.38	2.99	2.48	2.72
Fully Electric	miles per kWh	3.47	2.98	3.21	2.82	2.32	2.54

5.2. Model 2: Total Ownership Cost

Figure 7 displays the acquisition cost and the cost per mile for the sedan for each of the powertrains. The cost per mile includes the cost for fuel and electricity as well as the cost for vehicle maintenance. Figure 8 shows the same diagrams for the SUV. As expected, improvements in technology result in decreases in both the acquisition cost and the cost per mile.

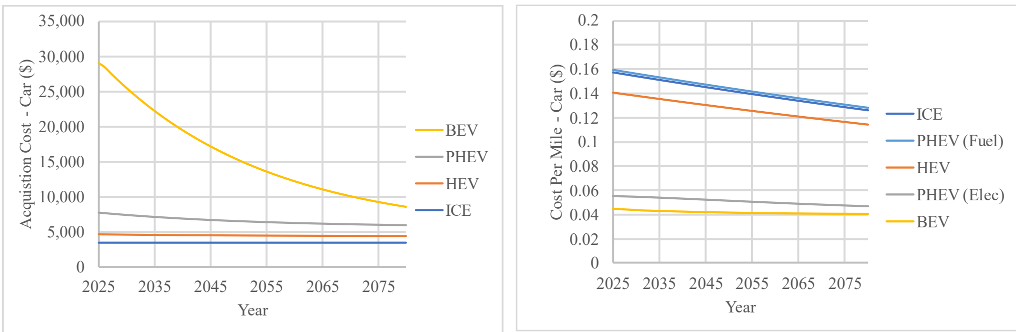


Figure 7. Acquisition cost (**left**) and cost per mile (**right**) for the different vehicle powertrains for the sedan in time based on advances in battery, electronics, and engine technology.

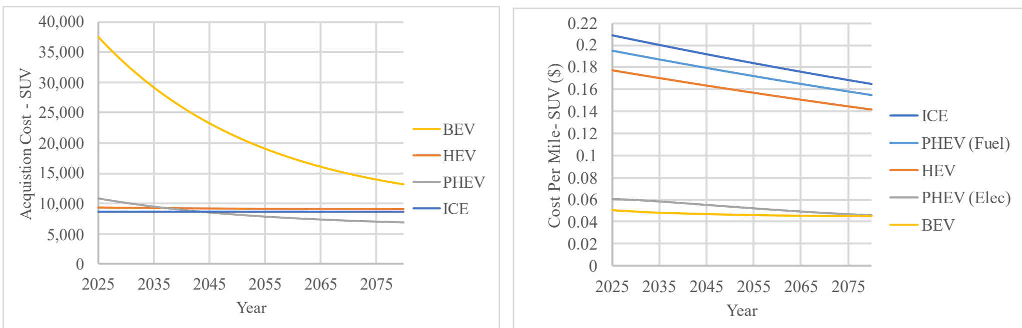


Figure 8. Acquisition cost (**left**) and cost per mile (**right**) for the different vehicle powertrains for the SUV in time based on advances in battery, electronics, and engine technology.

In both vehicles, the most significant cost change is seen in the acquisition cost of the BEV. This is primarily due to the BEV having a large battery bank that is quite expensive at current battery prices. However, the advances in battery technology will drive down this cost. The PHEV also sees a decrease, albeit smaller. Meanwhile, the ICE and the HEV have fairly constant acquisitions costs.

Meanwhile, the ICE-based vehicle and the HEV both have decreasing cost per miles as engine efficiencies increase to meet Corporate Average Fuel Economy (CAFE) requirements [24]. However, since the electric vehicle is already fairly efficient and the cost for electricity is only decreasing slightly (15 percent over 50 years), the cost per mile does not change significantly for the BEV or the PHEV when running on electricity.

It is important to note these costs are just those associated with the powertrain. The total vehicle cost may not stay the same, as other features are added into the vehicle, increasing the total vehicle cost.

5.3. Model 3: Vehicle Share

Figure 9 plots the vehicle shares for the different powertrains for the sedan and the SUV. The model assumes the initial market is at 100 percent ICE-based engines, which is transitioned out if a cheaper alternative is available. Although the current market includes BEVs, HEVs, and PHEVs, these alternatives only make financial sense with government subsidies.

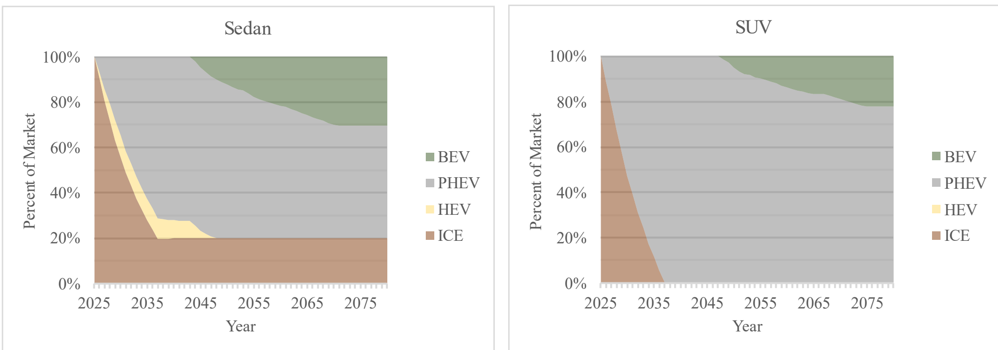


Figure 9. Vehicle market share based purely on the total ownership cost from 2025 to 2080 for the sedan (**left**) and SUV (**right**).

For the sedan, the cheapest alternative is initially the HEV and then the PHEV for the bulk of drivers. However, there are a handful of drivers for whom the cheapest option remains the ICE. These drivers have a low daily mileage, and hence the model predicts they discard their cars prior to 150,000 miles. The lower total mileage in turn gives that the decreased operational cost of the electrified vehicles does not offset the increased acquisition cost. It is interesting to note for the sedan, the BEV only starts to gain a market share in 2045 and only contributes to 30 percent of the market by 2080. This is largely due to the bulk of drivers having a cheaper option with the PHEV due to its considerably smaller battery pack. Drivers who drive less than 30 miles per day are effectively only using electricity for locomotion, resulting in a comparable operational cost. As such, the BEV initially captures the market share for drivers who have a high daily mileage.

The SUV follows a somewhat similar trend. However, for the SUV, the market tended to heavily favor the PHEV to the point where it initially replaced all ICE-based vehicles. The BEV starts competing in 2048 with drivers with large daily mileage, securing approximately 20 percent of the market share by 2080.

6. Analysis

6.1. Effects of Government Subsidies

Figure 10 plots the effect of government subsidies on the vehicle markets for the sedan and the SUV. For this specific case, the BEV has a government subsidy of $7500, equating to the current tax credit offered in the United States [44]. That subsidy results in a substantial increase in the number of BEV vehicles used, allowing them to dominate the entire sedan market by 2068. Additionally, the BEV starts to gain traction in the SUV market by 2030 and secures 80 percent of the SUV market by 2080.

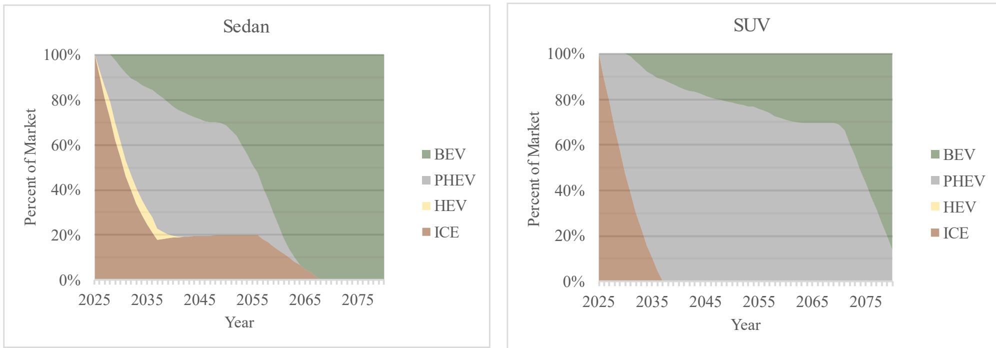


Figure 10. Vehicle market share based purely on the total ownership cost from 2025 to 2080 for the sedan (**left**) and SUV (**right**) with a $7500 government subsidy.

Generally, government subsides result in the widespread acceptance of BEVs to be pushed forward. Figure 11 plots the amount of government subsidies and the anticipated year where all vehicles would be battery-electric. At $10,000 government subsidies, all sedans will be replaced with BEVs by 2060 and all SUVs by 2072. As the amount of subsidies increases, the date for full electrification becomes earlier.

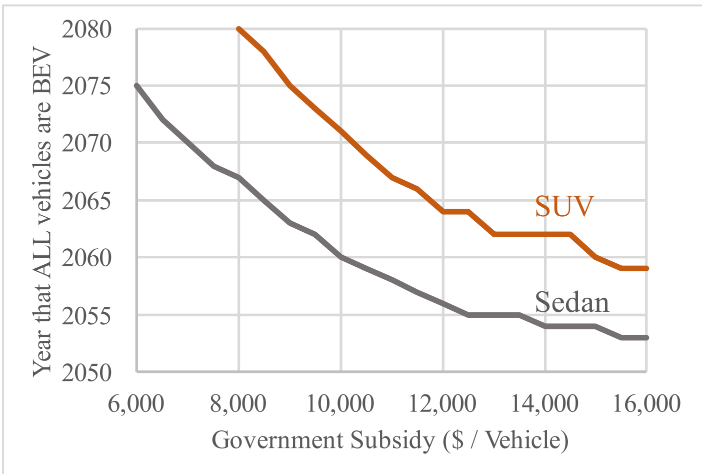


Figure 11. The year when all vehicles will be a BEV as a function of the amount of government subsidies per vehicle.

6.2. Effects of Reducing the Maximum Mileage of BEV

The primary issue with the acceptance of the BEV is the battery pack. For the vehicle to have the same range as an ICE-based vehicle, the battery pack is quite large and expensive. However, if the range could be sacrificed to reduce the cost, more consumers could potentially buy the BEV. The primary demographic holding out against the BEV are those with low daily mileage, who would likely not need a range of 300 miles per charge.

As shown in Figure 12, the model found the cost reduction associated with shrinking the battery pack resulted in increased acceptance of BEVs, assuming the user was okay with the diminished range. Purely based on total operational cost, if the range were decreased to only 100 miles, BEVs would have a market share of 72 percent of sedan drivers and 30 percent of SUV drivers. The challenge is the BEV, even with the smaller battery packs, are competing with the PHEV.

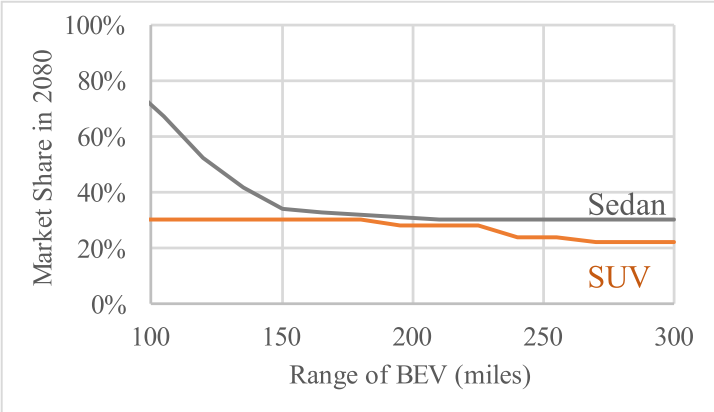


Figure 12. Market share in 2080 for the sedan and SUV based on the total range of the BEV assuming drivers are willing to sacrifice on the vehicle range for a cheaper vehicle.

A similar effect can be realized through investing in battery technology to decrease battery costs more rapidly. In that case, the battery packs will become cheaper, and not necessarily require a reduction in range. However, even with a significant reduction in battery cost, the total market share by 2080 without government subsidies is well below 100 percent for both the sedan and SUV. This is primarily due to the motor assembly being more expensive than a comparable engine setup. As such, drivers who have a low daily mileage would still prefer the ICE-based vehicle.

6.3. *Effects on Increased Taxation on Gasoline*

Many countries tax gasoline much heavier than the United States. As such, the government could potentially levy a tax on gasoline, increasing the cost as an incentive to have drivers switch over to the BEV. Figure 13 plots the BEV market share for the sedan and SUV for 2040, 2060, and 2080 as a function of the taxation rate on gasoline. As expected, the increased taxation of gasoline results in an increase market share for the BEV. However, many drivers would opt for the plug-in hybrid if they had a low daily commute, such they would be operating primarily in an electric mode.

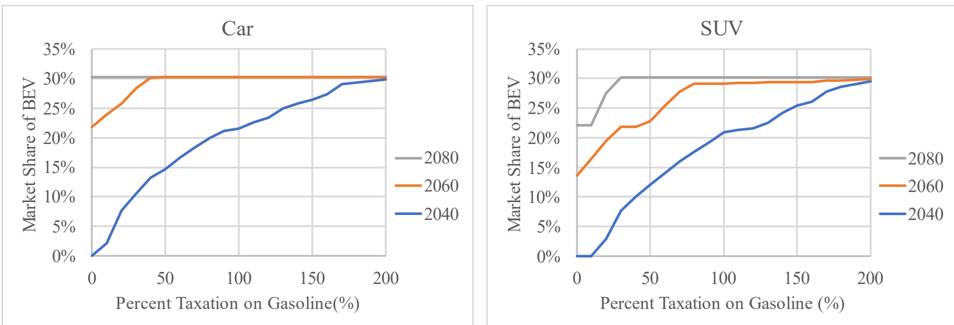


Figure 13. Market share of BEV for sedan (**left**) and SUV (**right**) based on the total ownership cost for 2040, 2060, and 2080 as a function of tax on gasoline.

7. Limitations and Future Work

The models presented in this paper are all fairly simplistic. Indeed, this is intentional to allow for future researchers to reproduce this model and use it to further analyze future automotive trends. Regardless, the simplicity of the models is the largest limitation of this study. Indeed, all of the models in this paper are deterministic and do not account for uncertainty. Future work will modify the operational cost model to be stochastic, introducing variability in the daily distances driven, driving style (highway or urban), and grade of the road. Future models will also attempt to capture the uncertainty in the costs of batteries, gasoline, and electricity.

Meanwhile, the cost models for electricity and fuel did not capture the large variability in the respective marketplaces. In particular, this study assumes the cost of electricity decreases as more renewable energy sources are integrated into the grid and uses the current cost of renewable energies to project the costs. However, there are numerous other factors that will affect the cost. First, non-renewable-based technologies will be necessary for backup and reserve when facing long-term climate uncertainty. Moreover, investment costs of renewable technologies are expected to be internalized in the electricity bids of these technologies for investment recovery, increasing the marginal price of electricity. Additionally, an increased penetration of BEV and PHEVs would also increase the electricity price due to the higher electricity demand. Further, governments may increase taxes for electricity usage to compensate for the lost revenue associated with decreased gasoline sales. Future work will also integrate this variability and uncertainty into the cost models.

Moreover, limitations existed in assessing the ownership costs of each powertrain. The model solely factored in upfront costs and those associated with locomotion. It omitted considerations such as the time value of money and resale value. Incorporating these elements would likely enhance total ownership costs for hybrid vehicles in comparison to BEVs, which possessed higher initial costs and faster depreciation. However, these factors are unlikely to significantly alter the findings presented in this paper.

The market model also had significant simplifications, focusing on consumers only selecting the vehicle with the cheapest overall cost. However, as is visible in today's automotive market, other factors play a role. In particular, individuals are willing to pay extra for the sustainability aspects and other features associated with the BEV. Future work will look at changes in design parameters that will be possible through electrification and factor that into the analysis.

Further, the study did not comprehensively encompass all existing vehicle architectures. For instance, the HEV and PHEV focused on split-power hybrid setups. There is a potential to consider series configurations, which may yield cost and weight benefits. Similarly, the ICE vehicle models solely concentrated on gasoline variants, omitting diesel vehicles. The BEV solely relied on Li-Ion battery packs, disregarding other potential battery chemistries. Future models will aim to encompass these diverse technologies.

8. Conclusions

The transition within the automotive market from conventional vehicles to electrified counterparts, notably BEVs, PHEVs, and HEVs, stands as a pivotal shift driven by a complex interplay of technological advancements, market dynamics, and consumer preferences. This study aimed to analyze and model the total cost of ownership for diverse powertrain options, including conventional, hybrid, plug-in hybrid, and electric vehicles for sedans and sports utility vehicles. It then attempts to capture the market share in the United States of each powertrain architecture based on what vehicle option has the lowest total cost of ownership.

This analysis provided three models. The first model determines the fuel and electricity consumption of each vehicle powertrain for a highway and urban drive cycle. The second model calculates the acquisition cost and the total operational cost of the vehicle over 12 years or 150,000 miles whichever comes first. This model accounts for changes in electricity, fuel, and battery costs in time. The third model takes the total cost of ownership for the vehicle and determines the cheapest overall option for a driver given their average daily drive; it then uses this information to predict the market share of each powertrain.

The overall results of the model indicate the future of vehicles in the United States is more eclectic than electric. For a subset of drivers, those who have low daily mileage, the cheapest overall option is the traditional ICE-powered vehicle. Meanwhile, drivers with a larger daily mileage prefer the BEV. Whereas a large subset of drivers may prefer the PHEV, which avoids a significant battery cost but provides most of the benefits of the BEV.

The analysis also found for the USA to fully transition to the BEV, given current battery cost projections, there would need to be substantial government subsidies. Further, as the amount of subsidies increases, the faster the market transitions to BEVs. Meanwhile, the taxation of gasoline can result in only a small increase in the market share for the BEV. As such, government policies should focus more on promoting BEVs through subsidies than penalizing ICE-based vehicles.

Looking ahead, the model developed in this study serves as a valuable tool for predicting the evolution of the commercial vehicle market as it gradually shifts away from fossil-fuel-based vehicles towards a more electrified future. The models are straightforward and can be reproduced by the academic community to study automotive trends. While simplistic, the analysis provides insight into the importance of decreasing the cost of electric options as well as the large potential for PHEVs for both passenger cars and SUVs. Ultimately, this research underscores the multifaceted nature of the automotive industry's transformation and highlights the need for ongoing analysis and adaptation to navigate this period of significant change effectively. Moreover, the models and the associated results indicate the economic challenges that are associated with the full electrification passenger vehicles.

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