Feasibility Analysis of Supercapacitive Vehicle Adoption

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

Gasoline powered automobiles are a significant contributor to the global emissions of greenhouse gases. Consumers and manufacturers have recently increased their interest different kinds of electric vehicles (EVs) powered by batteries, hydrogen fuel cells, and natural gas in response to the looming threat of climate change (US EPA, 2018). One possible but relatively unused alternative electric vehicle power source is the supercapacitor. Supercapacitors are similar to batteries in that they are energy and power storage devices, but they are traditionally used in different applications. Their impressively high charging speed and low capacity compared to lithium ion batteries means that they could offer major gains but carry significant drawbacks for consumers such as reduced environmental impact and changes in driving and refueling behaviors (Jain, Kanungo & Tripathi, 2018).

However, recent developments in supercapacitor technology have resulted in leaps the energy density of previous supercapacitors, bringing them into a range of potential utility (IEEE Spectrum, 2015). In order for supercapacitive electric vehicles (SEVs) to become a common choice for consumers, they must be able to satisfy the transportation needs of drivers and be marketable and desirable to them (BERR, 2008). Depending on the context in which consumers are willing to adopt SEVs, it is possible that public transportation and car ownership could fundamentally change in the future (Zhu et al., 2006). Using a feasibility analysis, it will be determined if supercapacitors are advanced enough for use in SEVs that would satisfy the needs of an appreciable portion of drivers of the 2020s.

Case Context

The technology of focus is on supercapacitive electric vehicles. These vehicles are similar to traditional gasoline-powered automobiles but differ in their fuel and powertrain. Supercapacitors are devices that store energy by holding charge in the form of electrons their surfaces through static electricity (Beguin, Frackowiak, & Lu, 2013). When the electron-rich and electron-poor portions make contact, a current passes between them which can provide power to a motor. Because energy is stored on the surface of supercapacitors, research into improved energy storage focuses not only on their chemical composition but on forming structures with high surface area per unit volume. Since batteries are charged and discharged by applying electricity to a chemical cell and then allowing the reverse reaction to occur, batteries take time on the scale of hours to charge and face heat and efficiency limits (Arambarri et. al., 2019). Supercapacitors can charge much faster on the scale of minutes or seconds because they do not rely on a chemical reaction, and simply need charge to be applied to them to store static electricity. The most prominent limiting factor of supercapacitors is their energy storage, which is at best 131 kWh/kg in experimental settings compared to 200 kWh/kg in traditional lithium ion battery cells in vehicles like Teslas (IEEE Spectrum, 2015). However, this is potentially close enough to capture a significant market segment.

The motor in electric vehicles also differs greatly from the motor in gasoline powered vehicles. While gasoline-powered engines deliver toque to the wheels through the explosion of a gasoline-air mixture, electric vehicle motors are powered by inducing a magnetic field that causes the driveshaft to rotate. This occurs when a current is passed through a circuit creating a magnetic flux that drives the motor (Nerg et. al., 2014). Additionally, gasoline-powered vehicles use transmissions with variable gear ratios to minimize engine speed and workload. However, electric vehicle motors can handle higher rotational speeds thanks to their lack of exothermic combustion. This means that electric vehicles can reach high speeds without a geared transmission, which changes the driving experience and decreases the complexity of the drivetrain.

Infrastructure also plays a key role in EV ownership. These stations are high-voltage power modules that supply 220 or 480V power to batteries, but to harness supercapacitors' full speed, and even higher electrical potential would likely be necessary. The presence and availability of charging stations is closely related to the ease and appeal of owning an EV. While the prevalence of battery-charging infrastructure has increased, it is still limited in many areas. charging stations have only existed in experimental contexts and settings, and so the feasibility of SEV adoption also depends on the feasibility of building adequate charging stations.

STS Framework

All of these factors will play into a feasibility analysis framed around Actor Network Theory (ANT). SEVs represent a new actor in the preexisting network of human and nonhuman actors. One of the defining principles of ANT is that technologies carry the ethics of the engineers that design them (Latour, 1995). The obvious "ethical" difference between SEVs and traditional vehicles is the reduced carbon footprint, but ethics in the context of ANT are not limited to moral issues. Ethics in ANT can be more accurately described as the desired functionality and accessibility of a nonhuman actor. If the ethics prescribed onto a new technology align with those of human actors, then resistance to the new technology is low, and it can feasibly be adopted. The preexisting actor network is comprised of the human drivers and nonhuman vehicles as well as other actors such as vehicle manufacturers. The successful entry of SEVs into the market will depend on resistance from human actors and whether they are satisfied with the abilities of nonhuman actors and the ethics prescribed onto them by the manufacturers that design, produce, and market them.

Drivers ethics will include not only the environmental benefits of electric vehicles but also the refueling requirements, adjustments to driving experience, and performance. If SEVs are to be successfully introduced to the actor network, they must satisfy the driving population’s ethics in these areas. For example, consumers that value the ability to travel long distances without refueling will have an ethical misalignment with SEVs due to their limited range. The other human actors will certainly play a role in adoption too. Manufacturing workers must adjust to making different vehicles, and supercapacitor research will certainly be affected by widespread use.

Finally, the exact nature of initial SEV adoption will depend on which context results in the best ethical alignment in the actor network. It is possible that shorter trips like taxi and bus rides better facilitate the distance limits of SEVs, but it is possible that there are enough vehicle-owning human actors that would adopt SEVs to result in significant market penetration. Both of these cases will be considered.

Research Question

There are technological, social, and political factors impacting the use of electric vehicles (EVs). This thesis addresses the research question: Could SEVs feasibly be adopted by 2020s drivers, and under what circumstances could they effectively enter the market? This question explores the intersection of technological progression and societal ethics that is the basis of ANT.

The research question is answered by four research approaches. First, a quantitative analysis was conducted on the driving capabilities of theoretical SEVs based on supercapacitor technology developed before 2020. This involved research into supercapacitor energy density compared to batteries. By projecting the capabilities of SEVs, the characteristics of the nonhuman actor were established. Second, a profile of drivers and automakers in the early 21st century is established. This includes a quantitative analysis of driving habits based on driving data from surveys or studies such as government reports. It defines the necessary capabilities of a theoretical SEV by determining the needs of the human actors. Additionally, this research provides insight into the perceptions that drivers and manufacturers have of EVs, as well as their perceptions of modifying behaviors to accommodate their use. Doing so informed a stance on whether or not SEVs fill a niche with minimal friction in the actor network. Third, research was conducted to determine a reliable estimate of how long it takes for successful technologies to gain popularity. This research provides a justification for a feasibility judgement in the decade-long window of the 2020s. Fourth, research was performed to examine different potential avenues of SEV adoption, such as public or private transit. Specifically, examples of successful SEV use that have been implemented before 2020 would show promise for success in the 2020s. This could have included a taxi service, a fleet of delivery trucks, or some other commercial or public venture. In summary, my research aimed to inform on the respective needs, capabilities, and ethics of the human and nonhuman actors, their mutual interaction and restrictions, and the settings in which they are conducive to SEV emergence.

Results

Potential market size, consumer opinions, and trends in the automotive manufacturing industry, all suggest that it is infeasible that SEVs will gain significant market share in the 2020s. While current experimental supercapacitor technology approaches the energy and power density of lithium ion batteries used in battery-powered EVs (BEVs), making them sufficient for the needs of an appreciable market, public knowledge and consumer opinion limit the SEV's ability to gain popularity. Additionally, a lack of SEV charging stations and poor investment by manufacturers make the development of useful SEVs unlikely. However, one possible avenue for adoption of SEVs is in public transportation, but this also presents obstacles such as a negative perception of public transit by consumers.

Supercapacitor technology advanced significantly in the 2010s, with certain chemical and structural configurations reaching 10% to 50% the energy density of lithium ion batteries used in BEVs, with comparable or superior power density (IEEE Spectrum, 2018.); Beguin et al., 2013; Jain et al., 2018). Frank Wang, of Nanotune Technologies and a partner at Launch.org, believes that in the 2020s, lithium ion batteries will continue to cost about $200 per kWh due to the high price of lithium, while supercapacitors may fall to as low as $150 per kWh, due to decreasing costs of electrolytes. This means that by the end of the 2020s, supercapacitive vehicles with the same amount of energy as BEVs would be similarly priced. (Wang, 2105.; Zheng et al., 2019). This would happen while supercapacitor energy density approaches and potentially eclipses that of batteries. Using the Tesla Model 3 as a benchmark for range, these experimental supercapacitors with 50% the energy density of batteries could provide a range of about 150 miles if placed in the same vehicle, based on volume and mass limitations (Ali, 2018; Lambert, 2017; Green Car Reports, 2012). These supercapacitors could also be charged on the timescale of stopping to get gas for an internal combustion vehicle (ICV), diminishing the issue of long charging times in BEVs (IEEE Spectrum, 2018). However, it is worth noting that the issue of long charging times is diminishing, with Teslas now charging up to 80% in just 30 minutes at supercharger stations that are widespread across the US, Europe, and other developed nations (Supercharger | Tesla, 2020).

Based on one study of driving habits in the Atlanta, Georgia area, about 20% of drivers could drive an SEV with 150 miles of range on a daily basis, charging only once a day and otherwise not changing their driving and charging habits over the course of a year, and 35% of drivers could get by changing their driving habits two or fewer days annually (Pearre et al., 2011). Additionally, if drivers adjusted behavior daily to charge the vehicle at home *and* another place (shopping or at work) daily, almost 70% of drivers would need to adjust for a third daily charge just twice a year, and 50% of drivers would not need to adjust. This represents a significant market of drivers in metropolitan areas that could theoretically have their needs met by SEVs.

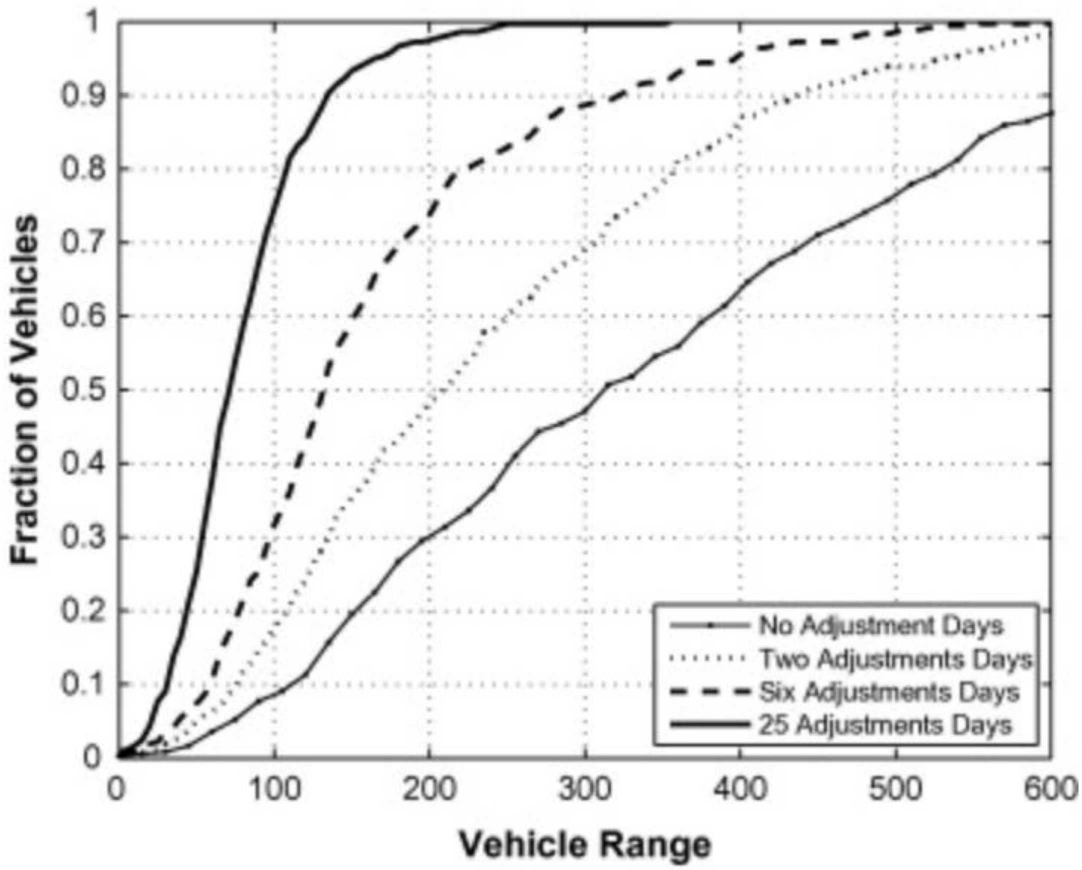

Figure 1. Fraction of vehicles with various daily ranges and necessary adjustment days (Pearre et al., 2011).

Public knowledge and experience are factors that will hinder the proliferation of SEVs. Based on a survey in the US, 47% of drivers only have experience with ICVs (Egbue & Long, 2012). However, 38% have experienced Hybrid Electric Vehicles (HEVs), and 17% have experienced BEVs. This limited exposure to fully electric vehicles will limit the number of people that consider purchasing an SEV. Drivers also tend to see the high initial price of an EV and perceived insufficient financial incentives as deterrents from EV purchase, despite the savings on fueling and maintenance. These savings are actually potentially much higher for SEVs because they can be fully discharged and recharged as much as 10 times more than batteries before they lose appreciable capacity (Jain et al., 2018). Additionally, a perceived lack of charging stations for BEVs is a deterrent from fully electric vehicles, so this issue would hinder the adoption of SEVs (Pearre et al., 2011).

Trends in the automotive industry will also hamper the proliferation of SEVs. Over the 2010s, SUVs gained popularity as sedans lost market share, increasing the size of new potential EVs, thus decreasing their range and hurting the demand for SEV sedans (US EPA, 2016). Additionally, horsepower and fuel efficiency continue to increase across the board in ICVs. This minimizes the comparative environmental benefit of using SEVs and places sporty performance constraints on them. This is a symptom of EV technology making up just 3% of technological investment in automobiles bought in the US in 2016 (US EPA, 2016). However, automakers have been using renewable carbon credits that offset emissions non-compliance that could eventually run low and require more drastic actions than researching more fuel-efficient ICVs, encouraging EV development and sale.

One analogous technology to SEVs is HEVs. They represent a similar technology and embody similar ethics of reduced environmental impact and independence from fossil fuels. However, HEVs are less radical, as they used a gasoline engine and did not require special charging infrastructure. HEVs entered the broad US market in 2000 with the release of the Toyota Prius, which has been the frontrunner in the HEV market every year since then (Alternative Fuels Data Center, 2019). The Prius was announced as a concept in 1997 in Japan and was sold for the following two years in only Japan. HEV sales in the United States rose quickly and reached 351,000 units in 2007, and since then have fluctuated around an average of

363,000 units per year representing 2 to 3 percent of new car sales (U.S. Bureau of Economic Analysis (BEA), 2019). This means that for HEVs, it took 10 years to reach a stable market share in the US that, while small, is appreciable. Additionally, Tesla superchargers were announced in 2012 and have become widespread in 2020, but Tesla still plans to expand their network in the future (Supercharger | Tesla, 2020). Thus, it is reasonable to estimate that a semi-disruptive technology such as HEVs would take about 10 years to reach appreciable market share. Yet, no major auto manufacturer (like Toyota) has announced unveiling SEVs in the future as of April of 2020, and SEVs are a more radical technology than HEVs. In summary, it is doubtful that SEVs would reach a stable market share even if they were announced in late 2020.

The public transportation sector offers some promise for SEV adoption, but not without caveats. In Bulgaria and China, there have been examples of buses being powered by supercapacitors (Chinabuses, 2020).

Figure 2. Supercapacitive HIGER bus used in Bulgaria in 2014 (Image Source: Chinabuses, 2020)

These buses ran limited routes and at speeds of about 30 mph, but because they were able to charge at stops, they could run 24/7. This means that in some contexts, buses and taxis powered by supercapacitors could find a niche that significantly benefits operating entities. Moreover, people using public transportation tend to be more in favor of government action to encourage public transportation use, increasing support for SEVs in this role. However, public transportation users tend to use it out of necessity. They generally have lower income, which motivates them to choose lower-cost public transit options in favor of owning a car (Steg, 2003). Additionally, public transit users perceive personal vehicle ownership as favorable to public transit, though to a lesser degree than car drivers. This is significant, as it shows that even when consumers become accustomed to using public transit, they still desire owning a car. Therefore, the same people that would potentially use public transit SEVs may be willing to choose lower-cost ICVs when they can finally afford one. Some of the most prevalent advantages of personal cars perceived by those surveyed are convenience, independence, flexibility, and freedom, meaning that a successful SEV would likely have to embody these qualities. With cheaper ICVs available, SEVs will likely not be the first car they can purchase to fulfill these ethics. In summary, while SEVs have had success in the public transit sector, their market tends not to prefer them, limiting their potential.

Area of Focus	Feasibility Outlook	Reason(s)
Technological Capabilities	Supercapacitor technology could feasibly be adopted for electric vehicles	• 50% range compared to SEVs • Superior charging time and charge/discharge life • Similar mass density • Similar cost • Increasingly prevalent infrastructure
Market Size	There is a large enough market such that SEVs could feasibly be adopted by drivers, but it is unlikely that this will occur	• Large portion (20%) of drivers able to drive SEVs with no changes to driving habits • Larger portion of drivers who could get by with minimal changes (35-70%) • Consumers' lack of knowledge/experience with EVs • Higher initial purchase price compared to ICVs
Automotive Industry Trends	The automotive industry's actions likely make adoption of SEVs infeasible	• Increased efficiency and sportiness of ICVs • Lack of investment in EV technology
Adoption Timeline	The time it would likely take for SEVs to gain market share likely makes their adoption in the 2020s infeasible	• 10-year timeline for HEV adoption in the US • SEVs are more radical than HEVs
Method of Adoption	The most likely method of adoption for SEVs is through public transit, specifically buses	• Past success of SEV buses • Simplicity of infrastructure implementation for buses • Difficulty marketing to a group that would possibly prefer personal ICVs

Table 1. Summary of Results

Discussion

Clearly there are significant obstacles to surpass for widespread adoption of SEVs in the 2020s, even if experimental technology can be rolled out to consumer cars at a price similar to BEVs. In the context of ANT, there are only some factors that support the feasibility of SEV adoption. While SEVs are capable of satisfying the driving distances of consumers, many obstacles create significant resistance. ANT specifies that accepted technological artifacts are prescribed ethics that align with human actors (Latour, 1995). In the 2020s, human actors will likely not have ethics significantly aligned with those prescribed to SEVs. Car drivers and public transport users alike declare that they see cars as favorable because they embody ethics of convenience, independence, flexibility, and freedom, which clearly shows a disconnect between 2020s drivers and SEVs.

Many consumers lack any knowledge on SEVs, so these human actors will continue on with their understanding of their network with automobiles without even the *opportunity* to change their ethics. The knowledge required to affect the decisions of human actors will likely not be widespread by the end of the 2020s, leaving this disconnect in place. Additionally, the financial incentives that are meant to reduce this dissonance are not perceived as sufficient. Even with up-front costs equal to BEVs, tax breaks, and reduced maintenance costs, human actors will likely be apprehensive to shift away from the lower up-front costs of ICVs due to their frugality and preference for familiarity. Lastly, the lack of charging infrastructure for SEVs means that convenience and freedom are extremely hindered, exacerbating the ethical disconnect. All of these factors in the pool of human actors pose potentially prohibitive resistance to SEV adoption for consumers.

Auto manufacturers and the invested capital in manufacturing is a nonhuman actor, while the labor and management are comprised of human actors. They work to determine the ethics of customers and attempt to prescribe these ethics on their vehicles to increase sales. Based on the past behavior of automakers, specifically the minimal 3% investment in technological development and reliance on carbon credits to buy time to produce efficient ICVs, they have apparently determined that the market would put up too much resistance if they attempted to predominantly produce and market EVs. Therefore, the ethics of automakers and consumers are mutually misaligned with those prescribed on SEVs.

The time it takes for a new technology to enter the actor network is difficult to predict. The adoption of similar technologies is a likely a useful basis for an estimate. SEVs embody similar ethics of reduced environmental impact and independence from fossil fuels. While HEVs are not as radical a new technology as SEVs, their introduction in the 90s did represent a radical step towards electrification of the automobile, at least for the time period. SEVs represent a further and more radical step towards full electrification because it is a complete change in how the car is powered. However, it is not a complete shift to a new mode of transportation, such as from trains to airplanes, so HEVs are the best analogy. Therefore, the 10-year minimum timeline from announcement as a concept will likely hold for SEVs as well, with SEVs likely taking even longer.

Public transportation is likely the best avenue for SEV adoption either in the form of buses or taxis. The proven efficacy in different cases for SEV buses is promising for metropolitan applications where necessary infrastructure would be condensed and recharging could be performed at stops, although taxi stops are more variable than bus stops (Han, 2019; Hao et al., 2020). Their use would increase knowledge of SEVs in the public, and proliferation outwards from cities could assuage concerns of limited infrastructure over time. This would leave cost as a possible concern, but would result in ethics prescribed to SEVs that are more similar to consumer ethics.

There are significant limitations in this research, specifically that research was sourced from throughout the 2010s, so certain statistics may be outdated. Additionally, new supercapacitor technology research has been done leading up to the 2020s with major advances mostly in the 2010s, so breakthroughs could affect price and performance in the 2020s. Finally, this study does not fully evaluate the price of a future SEV, as there are limited sources for estimating such a price and none on the market currently. In the future, I would like to have better information on prices related to supercapacitors and SEVs. This could be obtained through interviews with professionals who have worked for EV manufacturers. Additionally, a survey of college-age students to gauge the opinions of future new car buyers could be useful.

This research is almost completely unrelated to my future field, pharmaceuticals. However, the production of graphene-based supercapacitors will certainly require chemical engineers, and may be a long-term future career path. Even in pharmaceuticals though, this research has taught me about how to evaluate new products and their market potential, which is important in making high-level strategy decisions if I end up in a managerial or executive role.

Conclusion

A time when the environment is an increasingly popular subject of debate, the 2020s is a pivotal decade to explore carbon reduction options. This research explores one option and can be used for comparison to other new automotive technology. To further analyze the future of SEVs, a useful avenue would be their prevalence in HEVs, as these vehicles allow owners to “hedge their bets” on fuel needs, thus posing less of a range risk than the full SEVs this research focuses on. The main conclusion of this analysis is that, based on the ANT framework, it is unlikely that SEVs could be adopted in the 2020s due to a lack of agreement between the ethics prescribed to SEVs those of car drivers and manufacturers. The ethics of the market and manufacturers feed into each other, perpetuating the dominance of ICVs in the actor network. Only through a significant change in ethics, possibly driven by a strong desire to reduce the human carbon footprint from all actors, will SEVs have a real chance of being adopted. Yet, introduction through public transportation is a more promising mode of introduction, although ridership is limited.

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