Driving the Future of Long-Haul Trucking: Realizing the Potential of Battery Electric Vehicles through an Analysis of Financial and Environmental Impacts

by

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Submitted to the MIT Sloan School of Management and
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Abstract

This thesis examines the transition to battery electric vehicles (BEVs) for long-haul trucking, using system dynamics modeling, financial impact modeling, and environmental impact modeling, and looks across a broad range of possible future scenarios that could impact the viability of BEV use in long-haul trucks. System dynamics modeling, with causal loops, is used to identify key factors influencing adoption rates. Results show that battery capabilities, the total cost of ownership, and feedback loops are critical considerations in increasing BEV adoption. Environmental impact analysis demonstrates that transitioning to BEVs can lead to significant and immediate reductions in emissions. If the transition occurs now, with current development, there would be an immediate 37% reduction in GHG emissions and an 85% reduction in all direct emissions from air pollutants, not including SO2 emissions. If the medium or aggressive development scenarios outlined in this paper occur, there would be a 60% reduction in GHG emissions and a 90% reduction in all direct emissions from air pollutants, not including SO2 emissions.

These reductions could be vital in addressing emissions in this sector and helping curb climate change. Payload impact analysis demonstrates that the additional battery weight in a BEV long-haul truck would not be an issue for 93% of long-haul trucks. Financial impact analysis indicates that if charging capabilities increase to 500kW or above, BEVs are a better investment across all economic scenarios over the years of ownership, driven by lower operating costs. If no further development in charging capability occurs, the economic benefits of transitioning are subject to market conditions. Regardless of charging station capability development, if the price of diesel fuel remains above US$3.65 per gallon, BEVs are the preferred investment. Additionally, comprehensive net present value (NPV) analysis is used to demonstrate whether BEV long-haul trucks are a good investment for both the trucking industry and partner companies depending on various economic and development speed scenarios.

In current economic scenarios with no further development, BEV long-haul trucks are a good investment for both the trucking industry and partner companies, with net financial gains of $59K with a payback period of 5 years or $77K with a payback period of 4 years respectively. It is also significant to note that these calculations use transportation end consumer electricity prices and do not include subsidies or incentives. By sourcing energy differently and utilizing renewable energy sources, companies can substantially decrease operating costs, making the transition to BEVs even more financially viable than presented. With subsidies and incentives in place, the case for BEV long-haul trucks is further strengthened. The thesis also includes a specific analysis of the Tesla semi-truck with a fuel economy of 19.8MPGe. This Tesla semi-truck analysis revealed that regardless of charger development, the Tesla semi-truck would be a better investment than an ICE long-haul truck for both the trucking industry and partner companies.

Additionally, the analysis in this thesis suggests that there are significant benefits to increasing charging capabilities to 500kW, which would reduce charging downtime from 4 hours to approximately 2 to 2.5 hours per full charge. Even with the significant downtime, such an increase in charging capabilities would make the BEV long-haul truck the better investment in all feasible projected economic scenarios. The thesis concludes that the case for BEV long-haul trucks is clear, and there is significant potential to accelerate and capitalize on the transition to BEVs in the long-haul trucking industry.

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Acknowledgments

"Climate Change is the defining issue of our time and we are at a defining moment."[38] This quote, coming from the United Nations, stresses the importance of focusing on climate change and creating actionable steps to reduce emissions. Climate change is the most pressing issue of our time and it requires immediate action. To effectively address climate change, we must transition to a decarbonized economy. This means taking actionable steps as a society to reduce greenhouse gas emissions and transition to clean renewable energy sources. This transition will not be easy and it will require change. As the great conservationist President Theodore Roosevelt said "Nothing in the world is worth having or worth doing unless it means effort, pain, difficulty".[44] This process will require the support and involvement of industry, academia, and government to identify and implement effective solutions. The collaboration of these groups is vital to ensure that we, as a society, transition to a decarbonized economy.

This work is dedicated to future generations who will hopefully benefit from the research being done at MIT and the crucial collaboration being facilitated at the MIT Climate and Sustainability Consortium. The impact of climate change becomes more pressing with each passing day, and the efforts of these dedicated individuals are crucial in shaping our future.

I am deeply grateful to the individuals who have supported me throughout this process. My parents, Robin and Cameron Chehrazi, and partner, Zach Mayes, who have provided encouragement throughout my time at MIT. My advisors, Charlie Fine and David Hardt, who have provided invaluable guidance and mentorship. Florian Allroggen, who has provided invaluable contributions to my research. His insights and industry expertise were key in helping me understand the nuances of the consortium, sustainability, and my topic.

Finally, I want to thank the MIT Climate and Sustainability Consortium and Leaders of Global Operations (LGO) program office for giving me the opportunity to be a part of this important work and providing me with the resources and support I needed to do this research. The LGO programs' commitment to supporting students, coupled with the MCSC's inspiring perspective on sustainability and the environment has had an impact on the way I view the world. I am grateful for the opportunity to contribute to their work and the program.

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Chapter 1

Introduction

As the impacts of climate change become more pressing, it is essential to understand the extent to which different industries contribute to global greenhouse gas emissions and to identify practical ways to reduce these emissions. This is the goal of the MIT Climate and Sustainability Consortium (MCSC). MCSC is a partnership between MIT academia and different industries focused on creating realistic solutions to reduce emissions. Their mission is focused on "working together to vastly accelerate the implementation of large-scale, real-world solutions, across sectors, to help meet global climate and sustainability challenges."[16] MCSC is "helping to lay the groundwork for one critical aspect of MIT's continued and intensified commitment to climate: helping large companies usher in, adapt to, and prosper in a decarbonized world."[16] The MCSC uses a standard approach to evaluate and address their impact areas. They "strategize: linking stated company goals to value chains, enhance synergy, and find blind spots; implement: define, design, and pilot cross-industry technology, process, and organizational change; and educate: embed sustainability practice throughout workforce and university education." [17] The MCSC utilizes this approach in multiple impact areas, like Tough Transportation Modes, Value Chain Resilience, and Circularity. The Tough Transportation Modes impact area specifically focuses on industries within the transportation sector that are difficult to decarbonize, such as aviation, maritime, and trucking. It is critical to focus on these industries because the transportation sector is a major contributor to global greenhouse gas emissions.

Due to the expected increase in demand for long-haul trucking, the MCSC believes it is essential to examine alternative technologies that can lower the environmental impact of this industry. This thesis specifically investigates the feasibility of electrification as a potential solution for long-haul trucking. The electrification of long-haul trucking is an increasingly popular topic as technology advances and the need to reduce emissions becomes more urgent. The use of electric long-haul trucks would significantly reduce greenhouse gas emissions. However, the adoption of electric vehicles in the long-haul trucking industry has been slow due to concerns about upfront costs, limited charging availability, and range limitations. This thesis will evaluate the potential costs and benefits of transitioning to an electric fleet for companies utilizing long-haul trucking. By analyzing industry norms and comparing the Total Cost of Ownership (TCO) for electric and diesel long-haul trucks, valuable insights will be provided for decision-makers at companies that are considering electrifying their fleets. This research also aims to contribute to a better understanding of the feasibility and potential benefits of electrifying long-haul trucking more broadly.

1.1 The Transportation Industry

The transportation sector is a vital component of the economy. It enables the movement of people and goods both within and between countries. The transportation industry is a significant contributor to the United States' economic growth, with various modes of transportation being utilized, including road, rail, air, and water. [28] Road transportation is the most widely used mode, with approximately 60% of the market share in the main transportation and logistics sectors. Within this sector, the trucking industry plays a crucial role, accounting for 35% of the market share. While road transportation dominates, other modes also play a significant role, including ground transportation with 26% of the market share, water transportation with 17%, air transportation with 14%, and rail transportation with 4%.[7] It is evident that the transportation industry in the United States is crucial for supporting the country's economy and facilitating the movement of people and goods.

1.1.1 Statistics on the Industry

Transportation plays a significant role in the U.S. economy, as it contributed 8% of the U.S. Gross Domestic Product (U.S. GDP) in 2020, as seen in figure 1-1. This makes transportation the fourth largest contributor to the U.S. GDP.[22]

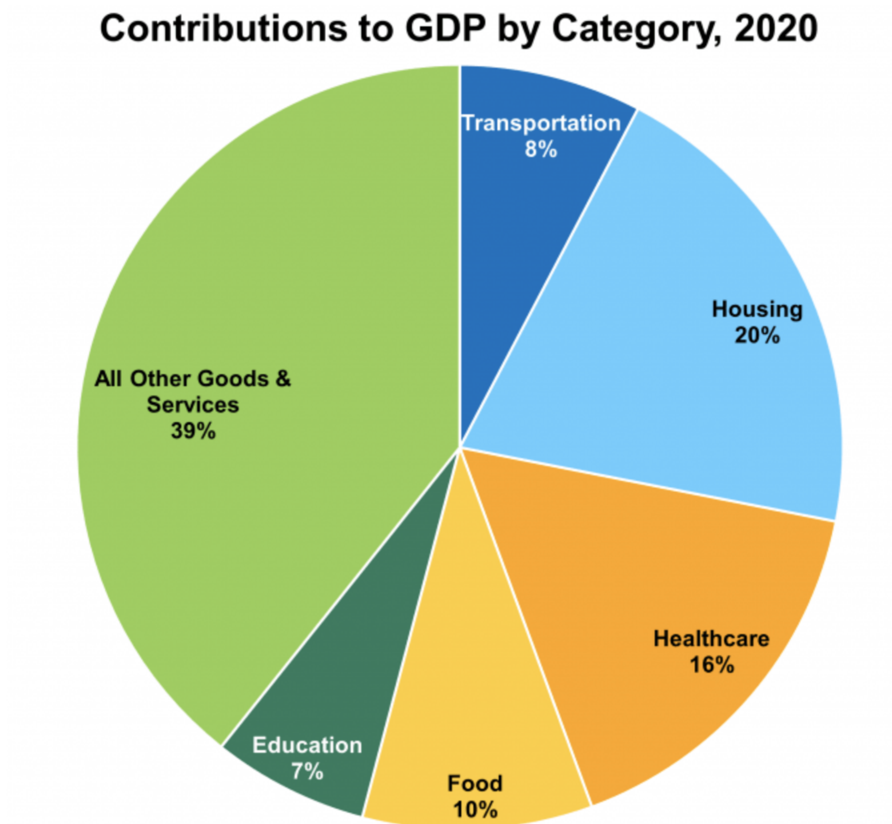


Figure 1-1: U.S. Gross Domestic Product Industry Breakdown 2020 [22]

In 2021, 14.9 million people, or 10.2% of the U.S. labor force, worked in the transportation and warehousing sector and related industries, such as automotive manufacturing. This represents an increase of 3.9% from the previous year.[49] This highlights the importance of transportation in the U.S. economy and the significant number of jobs it creates.

1.1.2 Emissions Contribution

The transportation sector is a significant contributor to U.S. Greenhouse Gas (GHG) emissions. According to the Inventory of U.S. Greenhouse Gas Emissions and Sinks

1990–2020, transportation accounted for the largest portion, 27%, of total U.S. GHG emissions in 2020, as seen in figure 1-2. This includes emissions from various modes of transportation, such as cars, trucks, commercial aircraft, and railroads.[53]

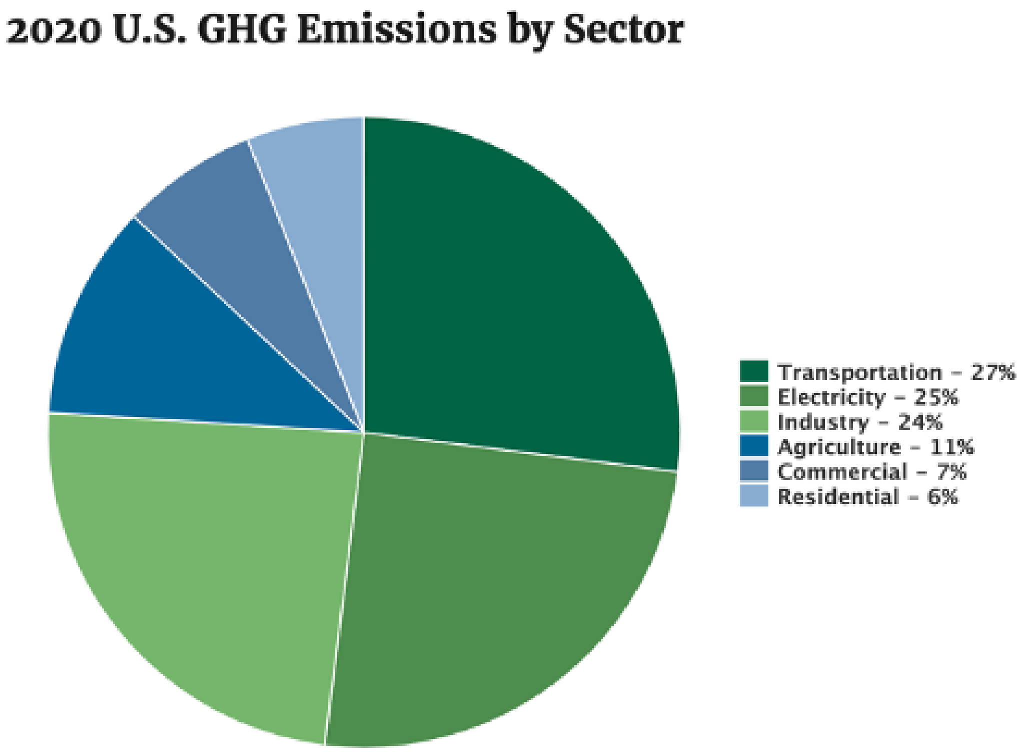


Figure 1-2: 2020 U.S. GHG Emissions by Sector [53]

These findings highlight the need to address GHG emissions in the transportation sector to mitigate the negative environmental impact. Within the 27% of U.S. GHG emissions attributed to transportation, light-duty vehicles make up the largest portion at 57%. Medium and heavy-duty trucks make up 26%, aircraft make up 8%, rail makes up 2%, ships and boats make up 2%, and the remaining 5% is attributed to an "other" category, as seen in figure 1-3.[53]

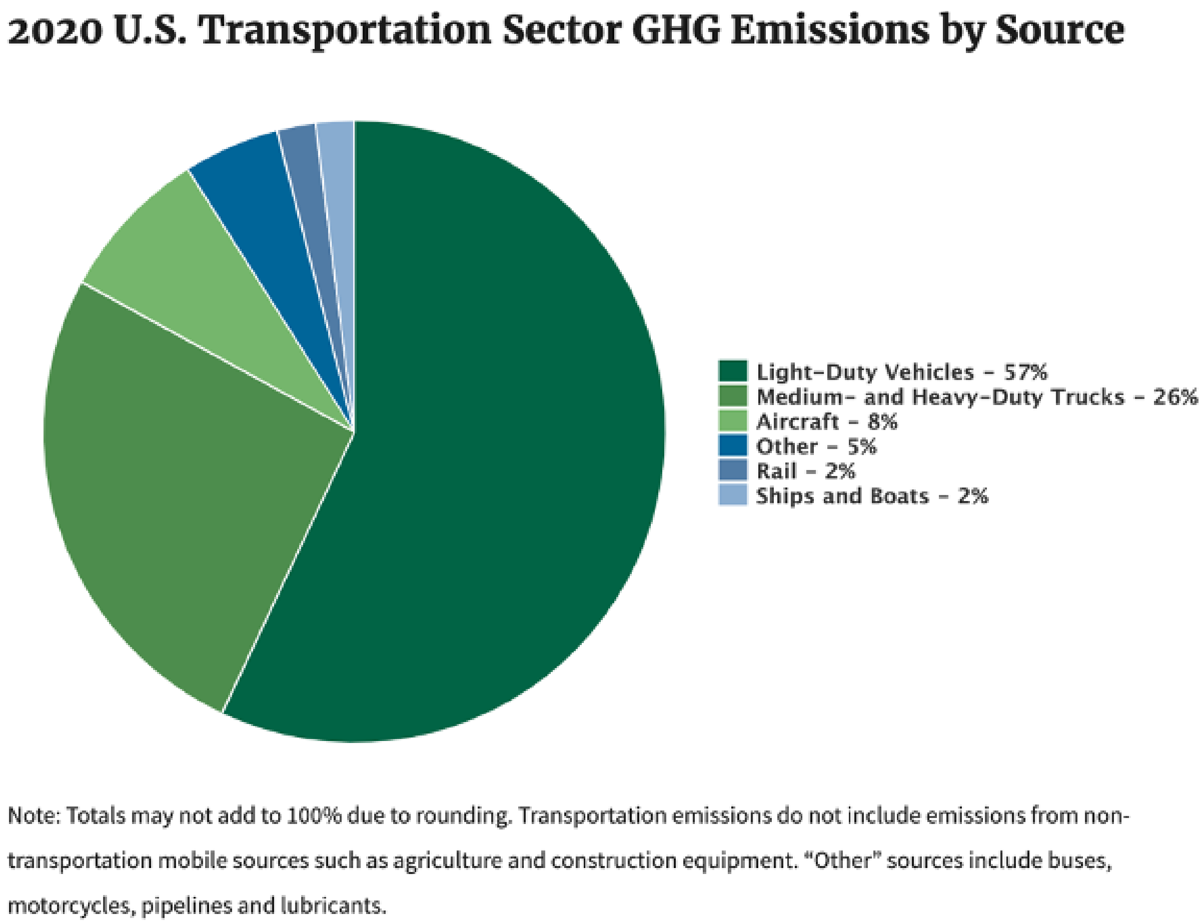


Figure 1-3: 2020 U.S. Transportation Sector GHG Emissions by Source[53]

The 26% attributed to medium and heavy-duty trucks is significant, as it accounts for approximately 6% to 7% of total U.S. GHG emissions.[53] This highlights the need to address emissions from these vehicles to reduce the overall environmental impact.

1.2 The Trucking Industry

The United States has different types of commercial trucks that are used for carrying freight. These trucks are classified based on their size and the number of axles. The Federal Motor Carrier Safety Administration (FMCSA) "defines commercial vehicles designed to carry freight as trucks with a weight of 10,001 pounds or more."[25] The Federal Highway Administration (FHWA) also has a classification system for commercial trucks based on their size and the number of axles. There are three main types of commercial trucks in the U.S.: single-unit trucks, combination trucks, and longer combination vehicles (LCVs). Single-unit trucks, or straight trucks, have permanently attached power units and vehicle chassis. They are often used for retail delivery, construction, utilities, and services. Combination trucks, also called 18-wheelers, have "two variations in the power units or tractors: day cabs and sleeper cabs. Day cab tractors have a shorter wheelbase and are for pickup and delivery or other short-haul operations. Sleeper cabs integrate a living area or a sleeping berth into the tractor. Sleeper cabs have an extended wheelbase, often 25 feet or more. Sleeper cabs are typically used for over-the-road or long-haul operations... The typical cargo-carrying unit of a tractor-semitrailer combination can vary in length from 40 feet to 53 feet... Combination trucks accounted for 61% of all commercial vehicle miles traveled in the United States in 2012, including LCVs." LCVs are a tiny portion of combination trucks because they can only be used in certain states and are allowed to be over 80,000 pounds.[25]

1.2.1 Statistics on the Industry

The trucking industry is an integral part of the U.S. economy, as it plays a vital role in transporting a wide range of goods. According to statistics from 2021, trucks moved approximately 72.5% of America's freight by weight, with the industry generating $875.5 billion in revenue.[8] This indicates the significant impact of the trucking industry on the overall U.S. economy. The truck driving industry is also a large employment sector in the U.S., with 3.6 million people employed as professional drivers and 7.95 million working in the transportation field in some capacity. This accounts for 5.8% of the overall U.S. workforce.[8] In addition to the large number of truck drivers in the U.S., there are also a significant number of trucking carriers operating in the country. There are approximately 1.9 million trucking carriers in the U.S., with 996,894 for-hire carriers and 813,440 private carriers.[37] These carriers are responsible for transporting goods across the country, with trucks accounting for 71.6% or $10.4 trillion of the $14.5 trillion value of all goods shipped in the United States in 2017.[12] The vast majority of trucking carriers in the U.S. operate with fewer than 20 trucks, with 97.4% operating with fewer than 20 trucks and 91.5% operating with six or fewer trucks.[37] This indicates that the trucking industry in the U.S. is primarily made up of small and medium-sized companies.

1.2.2 Industry Challenges

The trucking industry faces several challenges, including a shortage of drivers, rising costs, and regulatory pressures. One cost concern for trucking companies is the price of diesel fuel, which represents a significant portion of their operating expenses. The industry is also a major contributor to greenhouse gas emissions and air pollution, with diesel trucks responsible for a substantial amount of these emissions. To address the shortage of drivers, one projection suggests that "the industry will need to hire around 1.1 million new drivers over the next decade, or an average of 110,000 drivers per year".[18] However, other analysts believe that autonomous driving technology will eventually reduce the need for drivers.[47] In addition to these challenges, the trucking industry is highly competitive, with low barriers to entry and many companies, totaling approximately 1.9 million.[37] This competition means that trucking companies must work to attract customers and drivers to fulfill their commitments and succeed in the industry.

1.3 Long-Haul Trucking

Long-haul trucking is a significant subset of the trucking industry in the United States. It refers to the transportation of goods over long distances. A long-haul carrier is defined as a carrier that serves destinations more than 300 miles from its origin. [27]. Within the trucking industry, long-haul trucking is typically performed by heavy trucks and tractor-trailers. Within this category is a subset of vehicles that are called Class 8 vehicles, as seen in figure 1-4.[15]

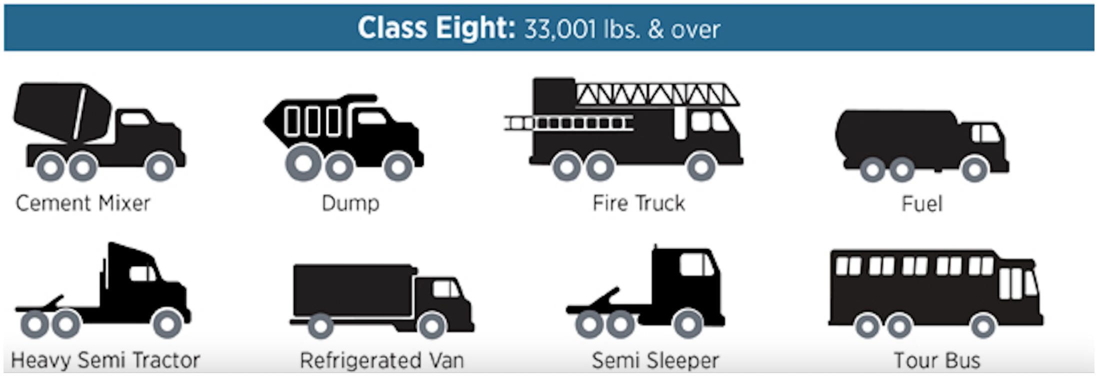


Figure 1-4: Class Eight Long-Haul Truck Classification [15]

Class 8 vehicles have a gross vehicle weight rating (GVWR) exceeding 33,000 lbs.[15] These vehicles, which include tractor-trailer tractors, single-unit dump trucks, and non-commercial chassis fire trucks, typically have three or more axles. The Class 8 vehicles that are the focus of this analysis are the heavy semi-tractor and the semi-sleeper. This is a common subset known for the typical 5-axle tractor-trailer combination, also known as a "semi" or "18-wheeler".[56] In 2019, approximately 58% of the 3.6 million truckers employed as professional drivers in the U.S. drove heavy trucks and tractor-trailers.[31]

1.3.1 Statistics on the Industry

As of 2021, there were 4.06 million Class 8 trucks operating in the United States used for business purposes. This number represents an increase of 2.3% from 2020.[8] It is essential to note that this excludes government and farm business purposes. The average annual distance traveled by Class 8 long-haul trucks is 62,750 miles [13], and these vehicles are typically semi-tractors or semi-sleepers.

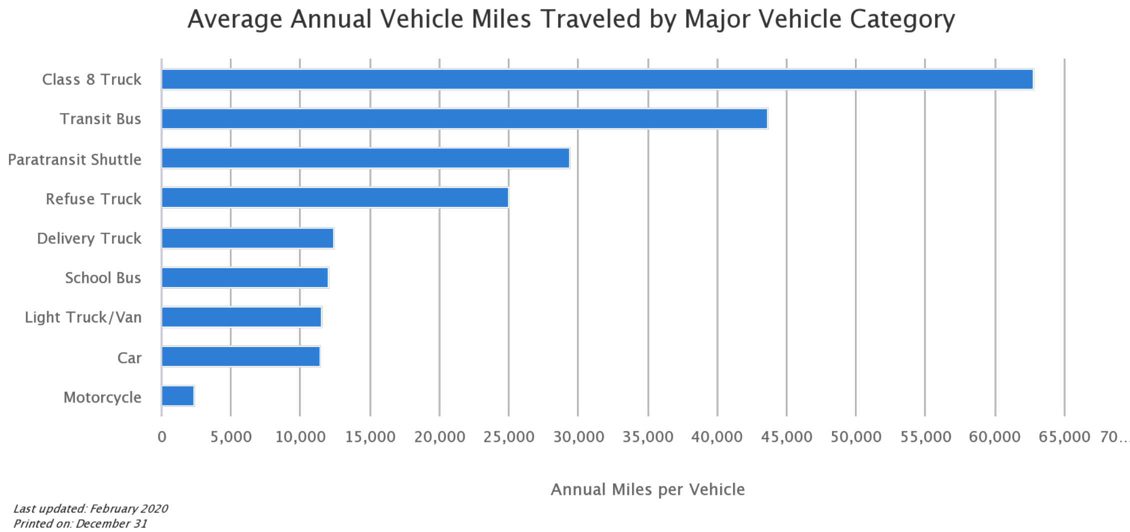


Figure 1-5: Average Annual Vehicle Miles Traveled [13]

Class 8 trucks play a crucial role in the U.S. trucking industry, as they transport a significant portion of the country's goods over long distances.

1.3.2 Emissions Contribution

The majority of medium and heavy trucks and buses on the road in the United States are diesel vehicles, making up about 90% of this type of vehicle as seen in figure 1-6.[14]

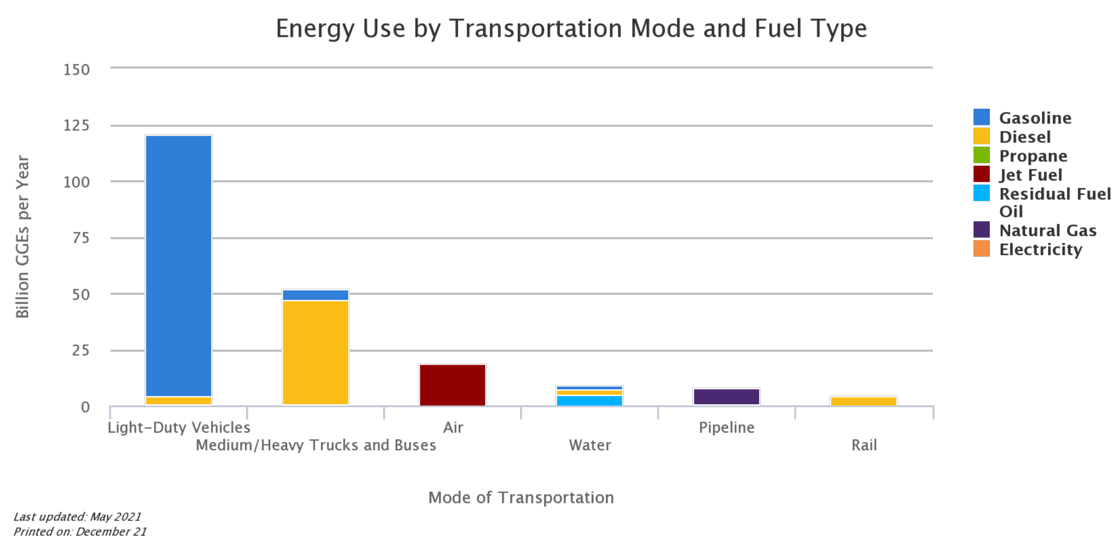


Figure 1-6: Energy Use by Transportation Mode and Fuel Type [14]

Despite comprising only 1% of on-road vehicles, heavy-duty trucks are responsible for a significant portion of on-road energy consumption, greenhouse gas emissions, and NOx emissions. Specifically, "heavy-duty trucks account for 28% of on-road vehicle energy consumption, 27% of on-road greenhouse gas emissions, and 47% of on-road vehicle NOx emissions." [11] The use of diesel fuel in heavy-duty trucks has contributed significantly to these emissions, highlighting the need for efforts to reduce the environmental impact of this type of vehicle.

1.4 Thesis Overview

Given the need to reduce carbon emissions and given the heavy use of carbon-based fuels by the trucking industry, the electrification of long-haul trucking to reduce operating costs and address environmental concerns is of great interest. Electric trucks have the potential to reduce carbon emissions significantly, and several companies and organizations are working to develop and deploy these and accompanying technologies.

However, perceptions about the challenges and barriers to adopting electric trucks, such as the high upfront cost and limited availability of charging infrastructure, have slowed the adoption of this technology. Despite these challenges, electrification is a promising option for long-haul trucking.

This thesis evaluates the feasibility of electrification as an alternative to diesel for long-haul trucking. It examines electrification's costs, benefits, limitations, and environmental impacts to assess if and where electrification would be a suitable alternative for the long-haul trucking industry. This analysis aims to understand where electrification can be a cost-effective and environmentally-friendly option for long-haul trucking and whether it is a viable alternative to economically reduce carbon emissions in this sector.

Chapter 2

Key Benefits of Adoption

The electrification of long-haul trucking offers several key benefits. As previously stated, heavy-duty trucks, which make up only 1% of on-road vehicles, contribute significantly to on-road energy consumption, greenhouse gas emissions, and NOx emissions. The electrification of long-haul trucking can substantially and cost-effectively reduce these emissions. In addition to reducing emissions and lowering operating costs, electrification has a lower barrier to integration than other alternative fuel sources and can increase national energy security.

2.1 Emissions Reductions

Adopting electric long-haul trucks would significantly reduce emissions within this tough-to-decarbonize transportation sector. As mentioned in Chapter 1, currently, "heavy-duty trucks account for 28% of on-road vehicle energy consumption, 27% of on-road greenhouse gas emissions, and 47% of on-road vehicle NOx emissions." [11] By transitioning to electric drivetrains, these emissions can be significantly reduced, as electric trucks produce no tailpipe emissions. This means that the transition would reduce GHG emissions and direct emissions from harmful air pollutants such as NOx, which can negatively impact public health.

Some critics may argue that the emissions produced by BEVs are not significantly reduced due to the carbon intensity of the electricity used to power them. However, it is essential to consider that the carbon intensity of the electricity used to power BEVs is generally lower than the emissions produced by other alternative fuels in consideration, such as hydrogen. In the United States, renewable energy accounts for "19.8% of total utility-scale electricity generation" [2]. At the same time, "only 0.1% of hydrogen is currently produced from renewable electricity, according to a 2021 analysis from Fitch Ratings".[23] The vast majority of hydrogen is produced from carbon-intensive steam methane reforming, making it a less environmentally-friendly alternative to electric drivetrains.[23] This highlights the critical role electric long-haul trucks can play in reducing global emissions and protecting public health.

2.2 Lower Operating Costs

Electric vehicles not only have a significant impact on emissions reductions but also on operating costs. The adoption of electric vehicles can significantly reduce operating costs, making them a feasible option for companies as the transition will not negatively impact their bottom line.

One of the main reasons for the lower operating costs of electric vehicles is their increased fuel economy and lower energy pricing compared to that of diesel vehicles and other alternative fuel options. Electricity costs are significantly cheaper than diesel, and the fuel economy of an electric vehicle is currently double that of a diesel vehicle. The energy efficiency of available batteries continues to improve with technological development, and as prices for batteries continue to drop, this will further reduce the cost of electric vehicles and overall operating costs. In addition, maintenance costs for electric drivetrains are significantly lower as their systems are less complex.

Compared to other alternative fuels, electric vehicles still have lower operating costs. For example, green hydrogen fuel cell electric vehicles (FCEVs) are less energy efficient than electric vehicles, requiring twice as much electricity to power them.[50] This is because hydrogen production is inefficient, with "significant energy loss in the process of electrolyzing water to make hydrogen, chilling and transporting that hydrogen, and then converting the fuel back into electricity."[23] It is estimated that hydrogen vehicles have an overall efficiency rate of about 30% efficient.[55] In comparison, electric vehicles "convert over 77% of the electrical energy from the grid to power at the wheels."[21] The low efficiency of alternative fuels, like hydrogen fuel, means that these fuels will likely continue to be more expensive than battery electric vehicles(BEVs).[23]

2.3 Ease of Integration

In addition to the environmental and economic benefits of electric long-haul trucks, the widespread existing and growing infrastructure for charging electric vehicles makes them easier to adopt compared to other alternative fuel trucks that may require specialized fueling infrastructure, such as hydrogen. Although the existing charging infrastructure needs to be expanded and updated to accommodate the needs of long-haul trucking, it offers more significant potential than the infrastructure required for other alternative fuels like hydrogen. "Integrating hydrogen into the system is a “complex endeavour”, says the IEA, involving long-term policy signals, support for demand creation, promotion of innovation and standardisation" [23] Some critics have argued that the electrical grid may not be able to support the power demands required for the electrification of long-haul trucks. However, this concern can be addressed through energy storage mechanisms such as stationary onsite storage and microgrids, which can help balance electricity demand and ensure a reliable power supply. In contrast, alternative fuels like hydrogen are difficult to transport due to their corrosive and flammable nature, and there is little existing infrastructure to support their adoption. This makes the transition to alternative fuels like hydrogen more challenging compared to the adoption of electric drivetrains, which can utilize existing infrastructure and energy storage mechanisms.

2.4 Energy Security

Electrifying long-haul trucking also has the benefit of reduced dependence on a single fuel source and increased energy security. "By one measure, energy security is the ability of households and businesses to accommodate disruptions of supply in energy markets. The United States is more secure with regard to a particular energy source if a disruption in the supply of that source creates only limited additional costs for consumers."[48] Currently, "the U.S. vehicle fleet is almost completely dependent on petroleum."[1] Currently, "most of the diesel fuel consumed in the U.S. is produced in U.S. oil refineries"[5]. This single fuel source dependence can make the transportation industry vulnerable due to the lack of flexibility in fuel choice. "If petroleum supply declines unexpectedly, as a result of refinery problems or lagging imports, diesel inventories (stocks) may decline rapidly."[1] "Volatility is also greater for transportation fuels because very few oil-producing countries have spare production capacity they can use when supply disruptions occur".[48] The lack of production capacity and the fact that the "world market dictates the price of oil" means that "increased domestic production would probably not dampen price changes resulting from disruptions."[48] Therefore, a reduction in the use of oil is necessary to increase U.S. energy security. This is because "reducing the amount of oil used could reduce the cost of disruptions to U.S. consumers [and businesses]."[48] The electrification of long-haul trucking is a solution to this. It would increase energy security as "electricity production relies on several fuels, making the sector more secure because it can adjust to a disruption in the supply of any one energy source."[48] For example, electricity can be generated from domestic sources, including renewable energy sources like solar and wind. The adoption of electric vehicles can ensure the energy mix for transportation is diversified and reduce the reliance on a single fuel source. As a result, the electrification of long-haul trucking can help to increase energy security and reduce the potential for dependence on other countries.

2.5 Key Takeaways

The adoption of electric long-haul trucks can significantly reduce emissions and operating costs. Electric trucks produce no tailpipe emissions, which can help to reduce greenhouse gas emissions and direct emissions from air pollutants harmful to public health. They also have lower operating costs due to their increased fuel economy and lower energy pricing, as well as lower maintenance costs due to their design. In comparison to other alternative fuels, electric vehicles have the advantage of being more energy efficient and being able to utilize existing infrastructure. In addition, the electrification of long-haul trucking can also reduce risk in the transportation sector and increase energy security by diversifying the energy mix used in the U.S., reducing reliance on a single source of fuel. These key benefits demonstrate why electrification could be an essential and feasible step in addressing climate change and improving sustainability.

Chapter 3

Key Hurdles to Adoption

Although there are clear benefits to electrifying long-haul trucks, key hurdles must be addressed. The hurdles include upfront cost, battery weight, range limitations, and charging infrastructure. Most of these are perceived hurdles that have already been or can be addressed. The key hurdles were used to shape the approach to evaluating the adoption of electric vehicles for long-haul trucking. This section briefly describes the hurdles, which will also be addressed in detail in later chapters.

3.1 Main Hurdles

3.1.1 Upfront Cost

The upfront cost of an electric long-haul truck is higher than that of an equivalent-capacity diesel truck, due to the cost of the battery, a crucial component. For example, the Tesla Semi has an MSRP of $180,000, while the average MSRP of an equivalent ICE truck is $135,000, as seen in Chapter 5.1.1 Table 5.2. Some may perceive that this upfront cost difference is a barrier that would deter companies from considering transitioning to BEVs. However, it is essential to consider that electric trucks have significantly lower operating costs due to their lower energy pricing and higher fuel efficiency, which (for most reasonable scenarios, as shown later in this thesis) more than offsets the higher upfront cost over time.

3.1.2 Battery Weight

The weight of the batteries used in electric long-haul trucks is a significant factor because that weight can potentially impact the vehicle's payload capacity. The added weight of the BEV can reduce its carrying capacity, compared to using a diesel alternative. This has been perceived as a hurdle for the adoption of electric trucks; however, as battery weights have decreased from improvements in power density, and as shifts in payload shipping trends have occurred, this hurdle is not a major issue for the majority of long-haul trips. Further justification for this assertion can be found in Chapter 5.1.1, which discusses payload analysis and assumptions in more detail.

3.1.3 Range Limitations

Electric long-haul trucks currently have a limited driving range compared to diesel trucks, which is perceived as a challenge for long-haul routes. "Vehicle range is often cited as the greatest barrier for battery electric trucks, but daily range requirements vary, and many trucks in the United States are not driven over long distances."[10] "VIUS data show that just ~10% of heavy-duty trucks require an operating range of 500 miles or more, whereas ~70% operate within 100 miles."[10] Regardless, this issue is being addressed with the development of longer-range electric trucks to curb range anxiety and the significant expansion of charging infrastructure.

3.1.4 Charging Infrastructure

There are several perceived hurdles regarding charging infrastructure for electric long-haul trucks. The most significant of these are limited availability of charging stations, the capability of the electrical grid, and charging time. Although the charging infrastructure in the U.S. has expanded, there is still limited charging infrastructure available for electric long-haul trucks, especially in rural areas. The charging infrastructure must be further developed for the transition to electric long-haul trucks to be practical. In addition to infrastructure needs, charging times should be reduced to increase operational efficiency and minimize downtime. Charging time is a significant hurdle due to the effect on operating costs of charging downtime. The analysis of different development speed types in Chapter 6 found that to prepare for all potential economic scenarios, there must be development in increased charging station power output from 350kW. As the adoption of electric long-haul trucks increases, the charging infrastructure will likely expand to meet the demand, and charging times will likely become more similar to refueling times. Additionally, there has been concern that the electrical grid may not be able to support the power demands required for the electrification of long-haul trucks. However, as previously discussed, this concern could be addressed through energy storage mechanisms such as stationary onsite storage and microgrids, which can help balance electricity demand and ensure a reliable power supply.

It is important to recognize that this analysis focused solely on the charging time and cost of constructing and implementing charging infrastructure for each electric vehicle purchased. The electrical grid and a more in-depth analysis of charging infrastructure were beyond the scope of this study. This decision was made to provide a more targeted and specific examination of the costs associated with charging infrastructure. While the electrical grid and its relationship to charging infrastructure are essential factors to consider, analyzing these elements was beyond the scope of this particular analysis.

3.2 Resistance to Change and Key Takeaways

Among some in the industry, there is significant resistance to adopting electric long-haul trucks due to concerns about outdated technology limit perceptions, such as battery weight, and the unfamiliarity of electric drivetrains compared to diesel drivetrains. This unfamiliarity has created doubt around the technology, leading to a lack of acceptance for the transition to electric trucks. For example, there are currently fewer options on the market than diesel trucks, which is often cited as a limitation; however, as adoption increases, market scale and availability will improve. As the technology is adopted, upfront cost and range will become less significant hurdles, and charging infrastructure will increase with demand. The industry's resistance to change will also decrease as they become more accustomed to the technology. This feedback loop is clearly shown in the system dynamics causal loop model presented in Figure 4-1 in Chapter 4. Based on this analysis, electrification presents the best opportunity for decarbonizing this sector, and the perceived hurdles should not prevent this technology from being pursued.

Chapter 4

System Dynamics Causal Loop Model

System Dynamics is a methodology "to understand how system structures cause system behavior and system events." [30] Often, a system dynamics causal loop model is used to represent a system and demonstrate how the different parts of the system interact. These relationships are defined to better understand the behavior between parts of the system, the system as a whole, and how the system will respond to changes.

4.1 Modeling

A high-level system dynamics model was created to understand the factors driving the adoption of electrification in the long-haul class 8 trucking space, as seen in figure 4-1. To create the model, the following steps were taken:

First, the system and its boundaries were defined, and the key components, such as TCO (Total Cost of Ownership), were identified. Next, the relationships between these components were represented, including feedback loops showing how the elements influence each other. Feedback loops and their signs are of particular importance. They can be either positive or negative, with positive loops indicating that the components act in the same way when a change is made and negative loops suggesting that they function in opposite directions.

This system dynamics model provides valuable insights into the complex relationships that influence the adoption of electric vehicles in the long-haul trucking industry. Its high-level approach illustrates the challenges of investing in this space, the behavior of the system, and the key variables that can be used to influence the adoption rate. Overall, this model is a valuable tool for understanding the factors driving electrification adoption in the long-haul trucking industry.

4.1.1 System Dynamics Model

Variables

The variables that define the system dynamics model are as follows:

1. Adoption
2. Industry Learnings
3. Available Technology
4. Battery Capabilities
5. Total Cost of Ownership
6. Capital Investment
7. Energy Infrastructure Density Demand
8. Energy Infrastructure Density
9. Infrastructure Investment
10. Policy (Subsidies)

It is worth noting that the battery capabilities of electric vehicles in the long-haul trucking industry include factors such as weight, range, and power density. The total cost of ownership (TCO) is a comprehensive cost analysis considering all of the variables shown in Chapter 5.1.1.

The model is defined using these variables, as seen in Figure 4-1.

The Model

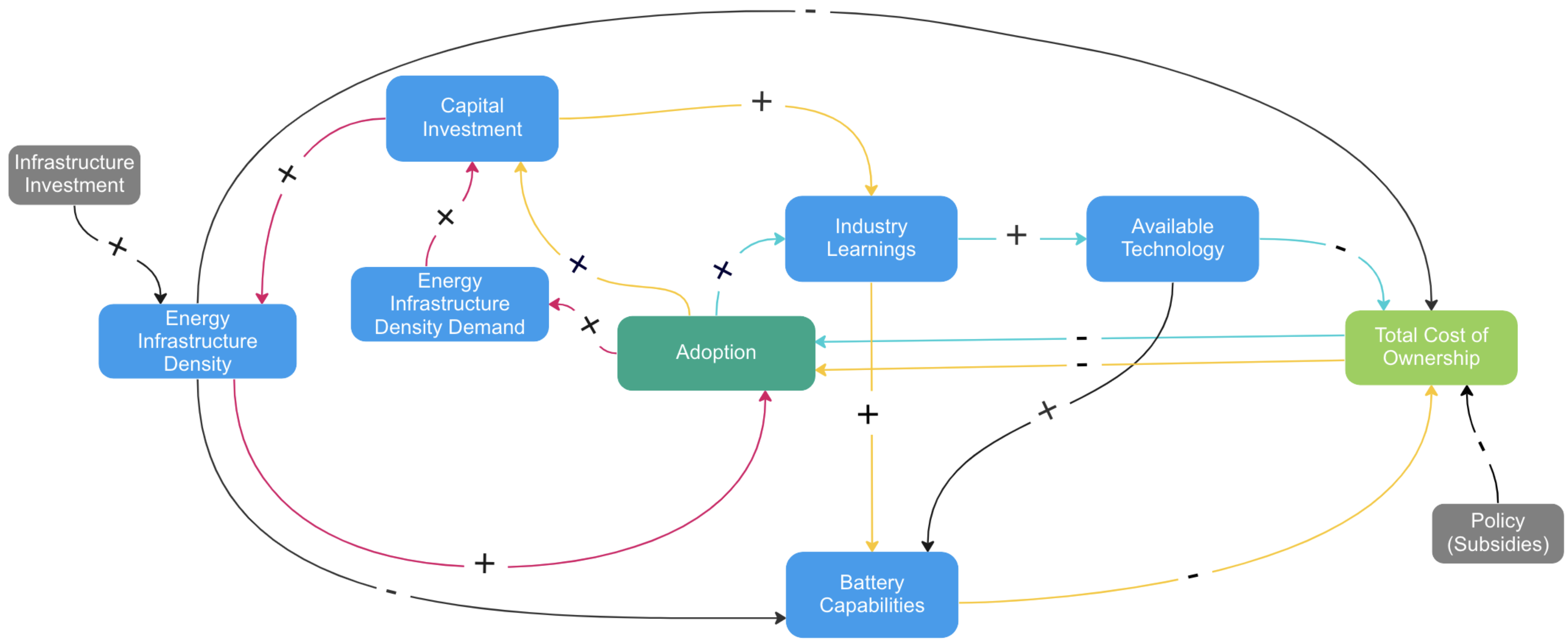


Figure 4-1: System Dynamics Model for the Adoption of Electrification in Long-Haul Trucking Class 8 Vehicles

Each colored arrow (pink, yellow, turquoise) is a specific feedback loop. Relationships external to feedback loops have black arrows. The plus sign (+) indicates a proportionately influenced relationship, whereas a negative sign (-) indicates an inversely influenced relationship. The dark green box is the core variable, adoption. The light green box highlights the total cost of ownership, a crucial driver of adoption. The grey boxes indicate triggers. The blue boxes are the remaining key factors to adoption.

4.2 Model Description and Analysis

The system dynamics model, shown in Figure 4-1, outlines the relationships between the variables discussed in Chapter 4.1.1. These relationships describe the system and identify the model's feedback loops, leverage points, and triggers.

4.2.1 System Description

The adoption rate of BEV long-haul class 8 trucks is the focus of this system dynamics model. The variables that directly influence this adoption rate are the total cost of ownership and energy infrastructure density. The adoption rate is inversely influenced by total cost of ownership changes, while energy infrastructure density changes proportionately influence the adoption rate. The total cost of ownership is influenced inversely by changes in energy infrastructure density, available technology, and battery capabilities. While energy infrastructure density is proportionately influenced by changes in capital investment which are driven by proportional changes in energy infrastructure density demand.

Changes in the adoption rate of BEVs for long-haul trucking, resulting from changes in the total cost of ownership or the density of energy infrastructure or both, will proportionately affect the demand for energy infrastructure, capital investment, and industry learnings. These influences form the three main feedback loops within the system dynamics model.

4.2.2 Feedback Loops

Understanding the feedback loops in a system dynamics model is critical to understanding the system. These loops predict how the system will respond to different changes.

The three main feedback loops are defined as:

1. Industry Learnings Loop

2. Battery Capabilities Loop

3. Energy Infrastructure Demand Loop

Industry Learning Loop

The industry learning loop is illustrated using blue arrows in Figure 4-1. This relationship shows that an increase in the adoption rate of BEVs for long-haul trucking will lead to an increase in industry learning. As industry learning increases, more and better technology will become available due to increased knowledge informing research and development. This, in turn, will reduce the total cost of ownership, which will further increase the adoption rate. This creates a reinforcing loop in which each factor amplifies the other, leading to exponential growth in the adoption rate of BEVs. It is important to note that this reinforcing loop could possibly flow in a negative direction, whereby lower investment leads to slower learning and lower technology improvements thereby reducing investment incentives. However, momentum at the present time seems to be flowing in the positive direction.

Battery Capabilities Loop

The battery capabilities loop is illustrated using yellow arrows in Figure 4-1. This relationship shows that an increase in the adoption rate of BEVs for long-haul trucking will increase capital investment. As capital investment increases, there will be more industry learning. As industry learnings increase, increased knowledge informing research and development will increase battery capabilities. This, in turn, will reduce the total cost of ownership, which will further increase the adoption rate. This creates a reinforcing loop in which each factor amplifies the other, leading to continual growth in the adoption rate of BEVs. It is important to note that this reinforcing loop might also flow in the opposite direction, thereby damping the adoption rate.

Energy Infrastructure Demand Loop

The energy infrastructure demand loop is defined using pink arrows in Figure 4-1. This relationship shows that an increase in the adoption rate of BEVs for long-haul trucking will increase energy infrastructure density demand. As energy infrastructure density demand increases, there will be more capital investment for energy infrastructure. This, in turn, will increase the building of energy infrastructure and its density, further increasing the adoption rate. This creates a reinforcing loop in which each factor amplifies the other, leading to exponential growth in the adoption rate of BEVs. It is important to note that this reinforcing loop might also flow in the opposite direction, thereby damping the adoption rate.

4.2.3 Leverage Points

Within a system, leverage points are places where, if small changes occur, those changes can have a significant impact on the system as a whole. These points can be used to influence significant changes to the system's behavior. For this model, the leverage points are the places where changes can be made that result in adoption speeding up or slowing down. The critical leverage points in this system dynamics model for the adoption of electrification in long-haul trucking class 8 vehicles are battery capabilities and energy infrastructure density. These leverage points were identified because a change in these variables drives a change in the system's overall behavior, i.e. a change in the adoption of BEVs. Therefore, the adoption of BEVs for use in long-haul trucking depends on the rate of improvement in battery capabilities and the density of energy infrastructure. If the density of energy infrastructure increases, there is less need for improvement in battery capabilities, as there will be more charging stations and denser networks available. These denser networks will also enable better route optimization. Conversely, if battery capabilities improve, the density of energy infrastructure becomes less critical. Based on the analysis performed, it is believed that battery capabilities are the most significant leverage point. As battery capabilities improve, companies will rely less on external factors like energy infrastructure density, and the total cost of ownership will be reduced due to increased range capabilities and decreased vehicle weight.

4.2.4 Triggers

The triggers in a system dynamics model are actions that initiate a change in the system. In the analyzed system dynamics model, the triggers are depicted using grey boxes in Figure 4-1. These triggers are related to monetary policy, including infrastructure investment and subsidies associated with the cost of ownership, i.e., vehicle or operations. Increasing these triggers is expected to increase the adoption rate of BEVs for long-haul trucking. These triggers are considered external to the system.

4.3 Key Takeaways

The system dynamics model shows that several key factors need to be considered to increase the adoption rate of BEVs for long-haul trucking. These include the battery capabilities of the vehicles, the total cost of ownership, and the leveraging of feedback loops. First, the battery capabilities of the vehicles must be sufficient for operations. Second, the total cost of ownership is a crucial driver of adoption. Third, the reinforcing nature of the feedback loops explains why companies may have been hesitant to invest in the transition to BEVs. However, these loops can be leveraged to positively influence the adoption rate by increasing investment in the space. This will improve the available technology and reduce the total cost of ownership, incentivizing more companies to adopt BEVs. Companies can take advantage of these reinforcing loops to their benefit by being the first movers in this space. Using these critical insights, it is possible to accelerate and capitalize on the transition to BEVs in the long-haul trucking industry.

Chapter 5

Financial and Environmental Impact Modeling

Models were created to understand the cost and environmental impact of transitioning from an internal combustion engine (ICE) long-haul Class 8 truck to a battery electric vehicle (BEV) long-haul Class 8 truck. Total cost of ownership (TCO) and net present value (NPV) models were used to analyze the transition cost. The TCO model compared each truck's nominal cost per mile within different economic scenarios and development speeds. The NPV model considered the profitability of transitioning to the BEV alternative over a standard ownership period of 7 years. For each model created, a sensitivity analysis was performed on statistically significant variables.

This TCO model calculates the total cost of acquiring and using a BEV long-haul Class 8 truck over its lifetime. It considers upfront costs, such as the purchase price, and ongoing costs, such as maintenance. With this model, businesses can identify the most cost-effective option in different economic and development scenarios and understand whether transitioning to a BEV long-haul Class 8 truck is feasible and cost-effective.

To effectively assess the environmental impacts of BEV and ICE long-haul Class 8 trucks, it is necessary to consider not only greenhouse gas emissions (GHGs) but also direct emissions from air pollutants such as Nitrogen oxides (NOx), Sulfur dioxide (SO2), Particulate matter 10 micrometers in diameter or less (PM10), Particulate matter 2.5 micrometers in diameter or less (PM2.5), and Volatile organic compounds (VOC). By utilizing all of these pollutants in the Well-to-Wheel (WTW) emissions models developed, the completed lifecycle emissions for the procurement of both types of vehicles could be analyzed, including emissions from charging and upstream processes in addition to those generated during operation. This approach allows for a comparison of the environmental impacts of using a BEV long-haul Class 8 truck versus an ICE long-haul Class 8 truck.

The model's foundation is built on the Fleet Procurement Analysis Tool initially developed by The Camdus Group, Inc. and continued by Atlas Public Policy [42]. This tool generates both financial and environmental impact models using predefined inputs. A high-level model overview can be seen in figure 5-1 below.

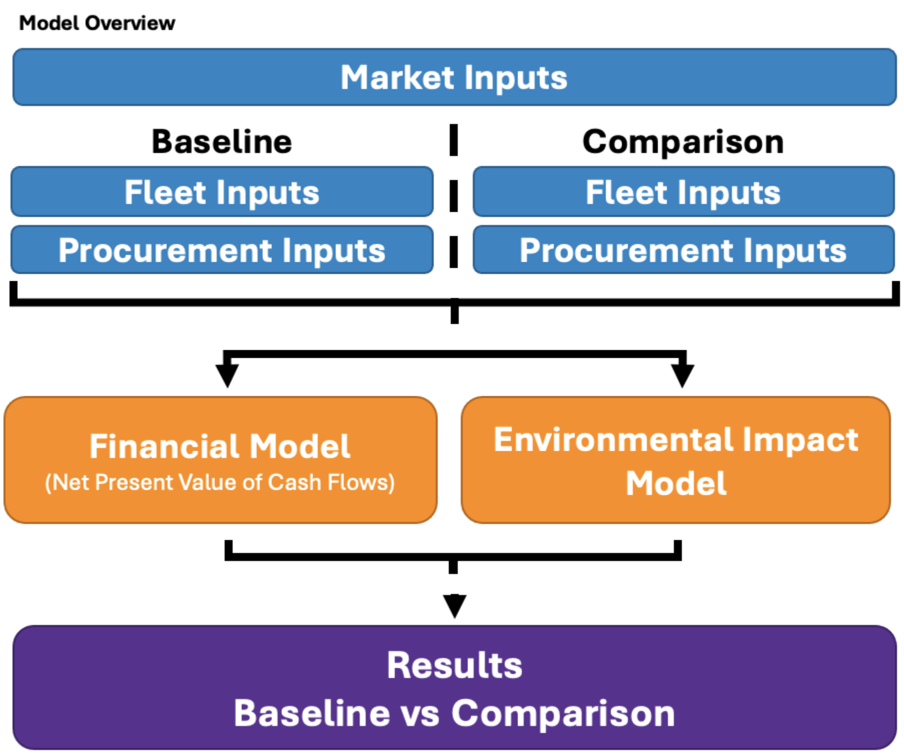


Figure 5-1: Fleet Procurement Analysis Tool Model Overview [42]

Significant modifications were made to the data and user inputs to ensure that the TCO and emissions models accurately reflected the conditions and assumptions required for this comprehensive analysis.

5.1 Model Design

The model is based on four input types: market conditions, vehicle conditions, vehicle procurement conditions, and EV charging infrastructure use and installation conditions. These inputs were used to create financial and environmental impact models. The inputs are based on a combination of economic and development scenarios seen in Chapter 5.2, as well as the various industry assumptions and metrics outlined in Chapter 5.1.1. It should be noted that all of the models discussed in this analysis are specific to the United States market and the emission for the average United States grid energy mixture. Utilizing the average U.S. grid impacts the assumptions for diesel costs, electricity costs, and electrical grid emissions.

Examples of the financial models, cash flows, and financial model summary (both total cost and nominal cost per mile) can be found in figures A-2, A-4, and A-3 in Appendix A. The emissions modeling method can be found in Chapter 5.2.4 below.

5.1.1 Model Inputs and Assumptions

Market Inputs

The market inputs enable the model to be customized to the economic scenarios required for analysis.

The market inputs evaluated are:

1. Diesel Price ($/Gallon)
2. Transportation Industry End Consumer Electricity Cost ($/kWh)
3. Public Charging Price ($/kWh)
4. General Inflation Rate (Excluding Fuel) (%/Year)
5. Energy Inflation Rate (%/Year)
6. Cost of Downtime from Public Charging ($/Hour)

The diesel price, electricity cost, public charging price, and general inflation rate all changed based on the economic scenario evaluated. The economic scenarios evaluated are based on Energy Information Administration (EIA) projections and discussed in more detail in Chapter 5.2 on Model Parameters. [4] The electricity price used in this analysis is the end consumer price for the transportation industry, which is a pessimistic view of energy sourcing, as the analysis assumes that companies will simply consume energy as an end consumer, without considering where the energy is sourced from.

To effectively estimate the impact of public charging on the cost of operating long-haul class 8 trucks, it is necessary to make an assumption about the public charging price. The public charging price in this model is determined based on the electricity costs specific to the given economic scenario. The public charging price is calculated by multiplying the current electricity cost by 2.35. This factor is derived from the ratio between the conservative estimate of current public charging pricing provided by the National Renewable Energy Laboratory (NREL)[33] and current electricity costs from the EIA. This approach determines the appropriate public charging price in different economic scenarios.

The cost of downtime from public charging is called "dwell time". Dwell time is the length of downtime when a truck and its driver are not moving products while on duty. "This includes time loading and unloading equipment, as well as time spent refueling, which is currently considered on-duty time."[29] When comparing ICE and BEV vehicles, the difference in refueling time is particularly significant. This is because it has implications for the efficiency and practicality of each type of vehicle in different scenarios. "Carriers (trucking service firms) typically have detention rates of \$50–\$100/h for dwell time costs imposed on them, which accounts for unproductive driver labor hours (approximately \$30–\$40/h)(ATRI 2020) and other indirect logistics costs associated with waiting(Federal Motor Carrier Safety Administration 2018; Load Delivered 2017; OOIDA 2011; Truck Drivers Salary 2017; Transport Topics 2021). For this analysis, a \$75/h cost was assumed for dwell time associated with refueling/recharging of vehicles. The cost of vehicle dwelling during loading/unloading was not included, as this cost is assumed to be the same across powertrains."[29]

Vehicle Inputs

The vehicle inputs enable the model to be customized to the specific vehicle requirements and costs needed for analysis. A summary of these inputs can be found in Appendix A-1.

The long-haul Class 8 truck inputs evaluated are:

1. Average Fuel Economy Diesel (MPG)
2. Average Fuel Economy Electric (MPGe)
3. Annual Vehicle Mileage (VMT/Year)
4. Expected Years of Ownership (Years)
5. Cost to Insure ($/Year)
6. Maintenance and Repair Cost ($/Mile)
7. Recurring Taxes and Fees ($/Year)

"MPGe is an acronym for "Miles Per Gallon equivalent". MPG stands for "Miles Per Gallon" and tells you how far a particular vehicle can travel using one gallon of gasoline. MPGe similarly tells you how many miles an electric vehicle can travel using the electric equivalent of one gallon of gasoline."[9]

To effectively estimate the fuel consumption of long-haul class 8 trucks, it was necessary to assume the driving mixture they would be doing. It was assumed that the trucks would spend 55% of their driving time in city areas. This assumption was based on the Environmental Protection Agency's (EPA) method for calculating fuel economy.[54] As a result, an average between the fuel economy ratings for city and highway driving was taken and used as the MPG or MPGe input in the analysis. This approximation provided a more realistic representation of the vehicles' fuel consumption in today's driving environment.

The Annual Vehicle Mileage per year used was 62,750 miles. This is based on the industry average from the AFDC discussed in Chapter1.3.1 in Figure1-5.[13]

The expected use of the vehicle, or years of ownership, was determined based on the MCSC's partnerships with various companies. According to survey data, a single vehicle's average expected ownership period was seven years.

The model takes into account not only the vehicle specifications but also customized estimates of the associated costs of ownership, including insurance, maintenance and repair costs, and recurring taxes and fees. These costs are included to ensure that a comprehensive analysis of the total cost of the vehicle is provided.

The cost of insurance and the recurring taxes and fees were set per Atlas Public Policy. The cost of insuring each vehicle per year is set at $10,000. The recurring taxes and fees per year include annual taxes or other recurring fees for vehicle ownership. These were set to the standard provided by Atlas Public Policy. [42]

Maintenance and repair costs are based on the years the vehicle has been operating and its drivetrain (BEV or ICE). For the first five years, these costs are set to a standard cost per mile, increasing to a different standard cost per mile after five years. These maintenance and repair cost estimates come from the 2019 Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) Tool created by Argonne National Laboratory that analyzes medium- and heavy-duty vehicles in the US market.[32] The specific maintenance and repair costs used for this analysis are found in Table 5.1 below.

Table 5.1: Maintenance and Repair Costs by Drivetrain[32]

Drivetrain Type	**Cost for Year 1-5 ($/mile)**	**Cost for Year 6+ ($/mile)**
ICE	$0.20	$0.26
BEV	$0.17	$0.22

It is important to note that the minor difference in maintenance and repair cost between a BEV and ICE vehicle presented in these estimates is seen as highly conservative because BEVs have "fewer fluids, such as engine oil, that require regular maintenance. Brake wear is significantly reduced due to regenerative braking[, and there] are far fewer moving parts"[20] relative to a conventional engine.

Vehicle Procurement Inputs

The vehicle procurement inputs enable the model to be customized to the specific details and terms of the procurement process. A summary of these inputs can be found in Appendix A-1.

The vehicle procurement inputs evaluated are:

1. Number of Vehicles to Procure (#)
2. Ownership Structure
3. Initial Tax, Title, and Registration Cost ($/Vehicle)
4. Discount Rate for NPV Calculations (%)
5. MSRP ($/Vehicle)

To make a fair, one-to-one comparison, the model compares only one vehicle procurement of each type (BEV and ICE). It also assumes that the vehicles were purchased in cash outright and that no federal or state incentives (tax or non-tax) or tax credits were used to reduce the cost of the vehicles. An initial tax, title, and registration cost of $1,000 was set for all vehicles evaluated. The model assumes that BEV and ICE vehicles will depreciate at the same rate. In the first year of ownership, the value of the vehicle is assumed to depreciate by 23%, which includes a 15% annual depreciation rate and an additional 8% depreciation after the initial purchase. After the first year, the value of the vehicle is assumed to continue depreciating by 15% per year. Two different discount rates were used in the net present value (NPV) calculations for the purchase of the vehicle and other associated costs. One is that of the trucking industry, which is 10.3%. This rate represents the time value of the money used for the investment based on the weighted average cost of capital (WACC) for the trucking industry as of January 2023, as determined by Professor Aswath Damodaran of NYU Stern School of Business.[19]. The other is the average WACC for the partner companies deciding whether to make this transition and trying to understand the profitability if they invested in BEV long-haul vehicles internally. The average WACC for this scenario is 7.61%. Using the industry-specific WACCs as the discount rate for NPV analysis helps give a more accurate prediction of the profitability of the investment within that industry. This is because the industry-specific WACC reflects the specific financial characteristics of the industry in which the investment is being made. Using these WACCs, a more realistic assessment can be made of the profitability of investing in electric long-haul trucks compared to using a generic discount rate.

The manufacturer's suggested retail price (MSRP) is the market price per vehicle purchased. For ICE vehicles, the MSRP is set to $135,000. This was calculated based on the median price for 2021 Class 8 long-haul trucks seen in Table 5.2.

Table 5.2: MSRP for 2021 Class 8 Long-Haul ICE Truck Offerings

Vehicle Year, Name, Make, & Model	**MSRP ($)**
2021 International LoneStar Day Cab ICE	$135,000
2021 International LoneStar Sleeper ICE	$160,000
2021 Mack Anthem 64T ICE	$125,000
2021 Mack Granite ICE	$90,000
2021 Mack Pinnacle ICE	$90,000
2021 Peterbilt 567 ICE	$130,000
2021 Volvo VNL Truck ICE	$165,000
2021 Volvo VNR Truck ICE	$145,000
2021 Volvo VNX Truck ICE	$150,000
Median	**$135,000**

The MSRP for BEV vehicles is set to $198,000. This was based on the MSRP of a Tesla Semi, $180,000, with a 10% operational capacity adjustment. This operational capacity adjustment reflects potential inefficiencies, like greater downtime due to longer refueling cycles, that may arise during the transition to using BEVs that could require a more extensive fleet to carry out the same operations. This adjustment was agreed upon by the companies partnered with the MCSC and is included in the model as a conservative measure.

EV Infrastructure Inputs

The EV infrastructure inputs ensure the EV charging infrastructure use and costs are integrated into the procurement cost of the vehicle. This enables the model to account for vehicle charging and infrastructure requirements and associated costs. A summary of these inputs can be found in Appendix A-1.

The EV infrastructure inputs evaluated are:

1. Number of EV Charging Stations Needed (#)
2. Ownership Structure
3. Charging Equipment Cost ($/Station)
4. Construction & Equipment Installation Cost ($/Station)
5. Maintenance Cost ($/Station/Year)
6. Depot/Home Charging Time (%)
7. Public Charging Time (%)
8. Maximum Power Output for Public Charging Only (kW)

The model requires the purchase and installation of an EV charging station for each vehicle purchased. This adds the additional costs for charging equipment, construction and equipment installation, and maintenance to procuring a single BEV truck. The model takes a highly conservative approach by assuming that a charging station must be installed for every BEV vehicle purchased. It also assumes that the cost of the purchase and installation related to the charging stations were paid in cash outright and that no federal or state incentives (tax or non-tax) or tax credits were used to reduce the cost. To address the highly conservative nature of this approach, in the

NPV analysis, two scenarios were created. One in which the one-to-one ratio exists and one where every four vehicles use one charging station.

For each charging station, the construction and equipment installation cost is set to $20,000 with a charging equipment cost of $3,800. The annual maintenance cost for station upkeep is assumed to be 3% of the total cost of the charging station, which is $23,800. This results in an additional $114 in annual maintenance cost per charging station. These charging station costs are based on the Electrification Assessment of Public Vehicles in Washington[41] and are specific to DC Fast Charging Stations. These calculations did not consider costs related to electric utility upgrades and grid interconnection.

The model assumes that 80% of charging for BEV trucks will be done at charging stations owned by the company operating the vehicles (either at a depot or for home charging), while 20% of charging will be done at public charging stations. This specific 80:20 ratio was requested by the companies partnered with the MCSC.

The maximum power for public charging adjusts based on the development speed scenarios evaluated. The development speed scenarios evaluated are based on industry projections and discussed in more detail in Chapter 5.2 on Model Parameters.

It is important to note that this model is built on the assumption that the grid will support the increased demand for electricity caused by the new and upgraded charging infrastructure and provide stable electricity for operations. This assumption is based on the potential for implementing various strategies to optimize energy usage and the existence of technologies like microgrids that can store excess energy.

Payload Analysis and Assumption

A concern often raised when evaluating the potential of BEV vehicles for long-haul trucking is the weight of BEV vehicles compared to their diesel counterparts. This is an important issue to consider, as an increase in weight could cause the vehicle, with its typical load, to surpass the federal regulation that states that its maximum gross vehicle weight can only be up to 80,000 pounds on interstate highways.[25] If the weight were to surpass the maximum gross vehicle weight, it would limit the payload capacity, impacting businesses that transport large loads.

However, upon assessment, this concern is outdated in most cases due to the weight reduction "from elimination of engine, cooling system, transmission and accessories"[40] and technological advancements of the battery energy density that significantly reduced battery weight.[24]

Based on the information detailed below, the payload capacity for an ICE long-haul truck is up to 63,000 pounds because the weight of a typical class 8 truck tractor is about 17,000 pounds. [35]

	Pounds	Share of total
Wheels and tires	1,700	10%
Chassis/frame	2,040	12%
Drivetrain and suspension	2,890	17%
Misc. accessories/systems	3,060	18%
Truck body structure	3,230	19%
Powertrain	4,080	24%
Total	17,000	100%

Figure 5-2: Class 8 Truck Weight By Component [35]

Figure 5-2 highlights that "the powertrain is nearly a quarter of the weight (24%), while the truck body structure is 19%."[35] This weight distribution is significant because the engine, cooling system, transmission, and accessories account for 24% of the weight of a diesel tractor, which would be nearly eliminated with the use of a battery pack.[40] This is because the "electric drive train is substantially lighter relative to a diesel drive train, which offsets a significant amount of battery pack weight."[40] When analyzed, the Lawrence Berkeley National Laboratory found that "the weight difference between and battery electric and diesel trucks is small (resulting in a potential payload loss of about 5%) and is likely to fall lower as light-weighting techniques are employed."[40]

Regardless of the vehicle component weight distribution changes, industry analysis "indicates that most operations are volume, route or time-constrained, not weight constrained." [40][35]. This is shown clearly through the payload analyses performed by the NACFE and Oak Ridge National Laboratory (ORNL). The NACFE found that "the average truck payload is less than 45,000 pounds (70% of the maximum payload capacity)."[40][26]. Analysis of U.S. weigh-in-motion data collected by ORNL also reveals that approximately 93% of current long-haul heavy-duty trucks weigh under 73,000 pounds and have average payloads of 56,000 pounds or less, as shown in Figure 5-3.

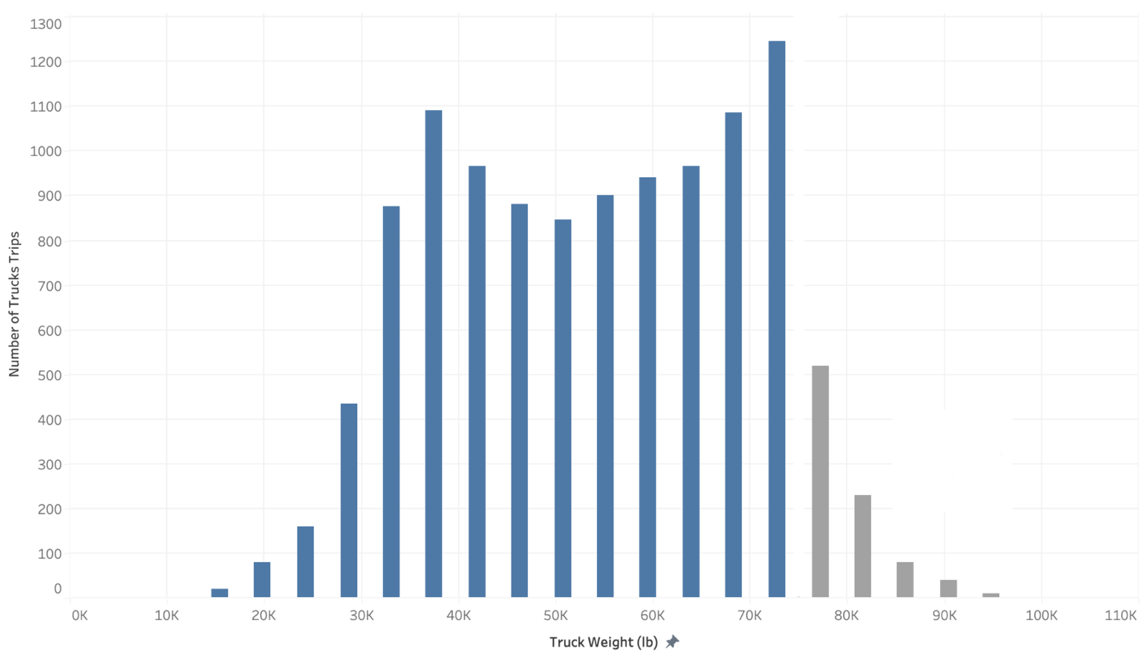


Figure 5-3: Class 8 Truck Weight per Trip [35]

The analysis of Figure 5-3 indicates that 93% of long-haul vehicles, seen in blue, still have at least 11%, or 7,000 pounds, of their payload weight capacity available. Of the 7% of trips that exceed 73,000 pounds, seen in grey, 40% are already above the 80,000-pound federal regulation limit. This means that only 4.7% of all long-haul truck trips currently within federal regulation could potentially be impacted by transitioning to BEV alternatives. On average, these trucks have a payload weight that is at 95% capacity, around 60,200 pounds. Even though this 4.7% are outliers, to incentivize the transition to BEV vehicles, "there is currently a nationwide 2,000-pound exemption for electric trucks (towards 80,000 pounds, the maximum roadway gross vehicle weight for conventional trucks in the United States, although several state exceptions exist)."

[40] [35] If payload weight capacity is a legitimate concern, this regulation could help offset the impact of the transition. If the 2,000-pound exemption is not enough to offset the payload weight impact for the companies that operate within the 4.7% of long-haul truck trips, these companies will not be well suited for transitioning to BEVs. An example of such a company would be a concrete company because they frequently reach the maximum payload weight capacity due to the material they transport.

These results suggest that payload capacity concerns should not be a significant factor in the decision to transition to BEVs for most long-haul trucks. Therefore, the model did not include payload capacity concerns as a constraint.

5.2 Model Parameters

5.2.1 Scenario Development

Multiple scenarios were developed to analyze the impact of economic and development speed conditions on the total cost of ownership and emissions for long-haul trucking. Each scenario is a combination of economic conditions and development speed conditions. The scenarios used are based on the EIA's projected economic conditions and NREL's projected technology development speeds.[4] [36] The scenarios are essential for understanding the feasibility of transitioning to a BEV fleet under different conditions.

Economic Condition Scenarios

The economic condition scenarios evaluate four potential U.S. economic energy pricing conditions, as seen below.

1. Current State
2. High Renewable Cost
3. High Oil Cost
4. Low Oil Cost

The economic conditions and energy pricing used in the scenarios were obtained from the 2021 Annual Energy Outlook for the Transportation Sector published by the U.S. EIA and can be found in Table 5.3.[4] The inflation rate and MSRP values used in the model are based on the assumptions outlined in Chapter 5.1.1.

Table 5.3: Economic Condition Scenarios

Economic Condition	High Renewable Cost	High Oil Cost	Low Oil Cost	Current
Diesel Price ($/Gallon)	$3.57	$5.57	$2.42	$5.33
Electricity Cost ($/kWh)	$0.12	$0.11	$0.12	$0.14
Public Charging Price ($/kWh)	$0.28	$0.27	$0.28	$0.32
Inflation Rate (Excluding Fuel) (%/Year)	2%	2%	2%	9%
Cost of Downtime from Public Charging ($/Hour)	$75	$75	$75	$75
MSRP Average - ICE	$135,000	$135,000	$135,000	$135,000
MSRP Operational Capacity Adjustment - BEV	$198,000	$198,000	$198,000	$198,000
Grid Region	US Average	US Average	US Average	US Average

The main difference in the projected EIA scenarios (high renewable cost, high oil cost, and low oil cost) is the diesel price.

Development Speed Scenarios

The development speed scenarios evaluate three potential technology development conditions:

1. Current Development Speed

2. Medium Development Speed (modest increase from current speed)

3. Aggressive Development Speed

The fuel economy and charging power output projections used in the scenarios were obtained from the *Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis* published by the National Renewable Energy Laboratory(NREL) and can be found in Table 5.4.[36]

Table 5.4: Development Speed Scenarios

Development Type	Current	Medium	Aggressive
MPG	6	6.5	7.5
MPGe	13.5	23	27
Charging Power Output (kW)	350	500	1000

5.2.2 Sensitivity Analysis Scenarios

A sensitivity analysis was performed to assess the impact of various inputs on the outputs. In the analysis performed, all variables except one are held constant, and the impact of changing that variable on the nominal cost per mile is observed. This analysis generated graphs that were used to understand the intercept (or "breakeven") points at which a BEV or ICE vehicle becomes more expensive in each economic and development speed scenario combination. A sensitivity analysis was performed on each of the variables below, within the upper and lower bounds provided in Table 5.5.

Table 5.5: Sensitivity Analysis Scenario Upper and Lower Bounds

Sensitivity Analysis Scenario	Bounds
Diesel Price ($/Gallon)	$0.50 - $6.00
Electricity Cost ($/kWh)	$0.01 -$0.70
Inflation Rate (Excluding Fuel) (%/Year)	2% - 10%
MSRP($)	$50,000 - $200,000
Fuel Economy Diesel (MPG)	6 - 13
Fuel Economy Electric (MPGe)	6 - 27
Annual Vehicle Mileage (VMT/Year)	50,000 - 130,000

5.2.3 TCO and NPV Equations

To compare the total cost of ownership and the net present value of procuring an electric fleet versus a traditional ICE fleet, the model inputs and assumptions outlined in Chapter 5.1.1 were used to create financial models. A financial model was made for each vehicle type under specific economic and development speed scenarios. These financial models evaluated depreciation costs, capital costs, fuel and operating costs, and "other" costs. For the two annualized NPV total cost of ownership models, the respective discount factors defined in Chapter 5.1.1 were applied. Cash flow analyses and results tables, which included the total vehicle cost and the nominal vehicle cost per mile, were then generated for each model and scenario combination. An example of the financial models, cash flow tables, and results tables can be found in Appendix A-2, A-4, and A-3. This approach ensured that the financial implications of procuring electric versus ICE fleets were thoroughly evaluated and that the TCO and NPV of different types of fleets could be assessed and compared to one another.

Standard Cost Calculations

Regardless of the vehicle type (BEV or ICE), the depreciation cost, capital cost, annualized NPV total cost of ownership, maintenance and repair cost, taxes and fees, and insurance cost are all calculated with a standard approach. The costs that are calculated differently depending on the vehicle type are fuel costs. The BEV vehicle also has the additional cost of downtime from public charging. These costs and their calculations are outlined in the equations below.

Depreciation Cost, Capital Cost, and Annualized NPV Total Cost of Ownership Calculations

To calculate depreciation cost, capital cost, and NPV, the inputs and assumptions outlined in Chapter 5.1.1 were used. The calculations for ICE and BEV vehicles are performed in the same way. Based on Chapter 5.1.1, the depreciation rate for both vehicles is assumed to be 23% in the first year and 15% for each subsequent year. Capital costs include the cash payment for the vehicle and the terminal (or salvage) value. The cash payment for the vehicle is set as the average MSRP for the ICE vehicle, and the MSRP with the additional 10% operational capacity hit for the BEV (to compensate for greater downtime due to longer refueling cycles). It is assumed that all vehicles will be purchased in cash outright. The terminal value of the vehicle is the estimated value after depreciation over seven years of ownership. For the annualized NPV total cost of ownership, the discount rate is applied to the total cost for each vehicle type using standard discounting practices.

Maintenance and Repair Costs

To calculate maintenance and repair costs, the inputs and assumptions outlined in Chapter 5.1.1 were used. The calculations for ICE and BEV vehicles are performed in the same way. The maintenance and repair costs change based on the years of operation. The maintenance and repair cost per mile per year for each type of vehicle can be found in Chapter5.1.1 in Table 5.1. The following equation is used with this cost information to find the total maintenance cost per year.

$$\begin{aligned}&\textit{Total Maintenance \& Repair Cost for Specific Year}\\&= \text{Maintenance \& Repair Cost per Year per Mile} \times \text{Annual VMT} \times \text{General Inflation}\end{aligned} \tag{5.1}$$

This value for each year is then summed up to give the total maintenance cost during the expected years of ownership.

Taxes and Fees

The inputs and assumptions outlined in Chapter 5.1.1 were used to calculate taxes and fees. The calculations for ICE and BEV vehicles are performed in the same way. The first year's cost is the initial taxes from the procurement of the vehicle. The subsequent year's costs are the yearly recurring fees and taxes multiplied by the general inflation of that year. The value for each year is then summed up to give the total taxes and fees during the expected years of ownership. These costs are outlined in the Model Inputs and Assumptions of Chapter 5.1.1.

Insurance Costs

The inputs and assumptions outlined in Chapter 5.1.1 were used to calculate insurance costs. The calculations for ICE and BEV vehicles are performed in the same way. The first year's cost is the yearly insurance cost of the vehicle. The subsequent year's costs are the annual insurance costs multiplied by the general inflation of that year. The value for each year is then summed up to give the total insurance costs during the expected years of ownership. These costs are outlined in the Model Inputs and Assumptions of Chapter 5.1.1.

BEV Specific Cost Calculations

BEV Fuel Costs

To calculate fuel cost for BEV vehicles, the total electricity usage, energy inflation, percent of charging in public and at home, and electricity pricing for public and home were used.

First, the collective electricity price was calculated using the following equation:

$$\textit{Collective Electricity Price} = (\%\ \text{Depot Charging} \times \text{Depot Electricity Price} + \%\ \text{Public Charging} \times \text{Public Charging Price}) \tag{5.2}$$

Then, the fuel cost for each year was calculated by using the following equation:

$$\textit{BEV Fuel Cost per Year} = \text{Electricity Usage} \times \text{Energy Inflation} \times \text{Collective Electricity Price} \tag{5.3}$$

The value for each year is then summed up to give the total fuel costs during the expected years of ownership.

EV Charging Infrastructure Cost EV charging infrastructure cost includes capital cost and operating costs. The capital cost includes the cost of the equipment, as well as the construction and installation of the equipment. These costs are assumed to be paid outright in cash. The only operating cost is maintenance cost, which is 3% of the value of the equipment. The maintenance cost per year is calculated in the standard method outlined in the Maintenance Cost section above. The values used for these costs can be found in Chapter 5.1.1. The EV charging infrastructure cost uses the same discounting methods for the annualized NPV total ownership detailed above. The cost of EV charging infrastructure is included in the total cost of the BEV vehicle.

ICE Specific Cost Calculations

ICE Fuel Costs To calculate fuel cost for ICE vehicles, the total diesel usage, the diesel price, and general inflation were used.

$$\textit{ICE Fuel Cost per Year} = \text{Diesel Usage} \times \text{Diesel Price} \times \text{General Inflation} \tag{5.4}$$

The value for each year is then summed up to give the total fuel costs during the expected years of ownership.

5.2.4 Emissions Equations

To compare the environmental impacts of procuring and operating BEV and ICE long-haul Class 8 trucks, GHG and direct emissions from air pollutants were evaluated over the complete lifecycle of the vehicles. An emissions model was made for each vehicle type under specific development speed scenarios. To calculate the Well-to-Wheel (WTW) emissions of each vehicle, a standard approach was taken. First, the energy usage per year was determined, and then the carbon intensity of that energy source was calculated. Using this information, the annual emissions of the vehicle were estimated. This approach and the methods described in this section were used to create a comprehensive assessment of the environmental impacts of using a BEV long-haul Class 8 truck versus an ICE long-haul Class 8 truck.

Important Conversion Constants

The conversions below are used in the emissions model to calculate the emissions output by each type of class 8 long-haul truck.

Table 5.6: General Conversion Constants

Grams per Pound (g/lb)	453.59
kWh per Gasoline Volume (kWh/U.S. gal)	33.7
kWh per Diesel Volume (kWh/U.S. gal)	37.95
kWh per MJ (kWh/MJ)	0.28
MJ per Diesel Volume (MJ/U.S. gal)	136.62

The general conversion constants in Table 5.6 are based on widely known and accepted. They will be used to understand each vehicle type's annual emissions in pounds (lb). Table 5.7 and Table 5.8 are necessary to understand the specific WTW emissions for each energy source, diesel or electricity.

Table 5.7: Diesel Well-to-Wheel Emissions Conversions

Pollutant	**Total Output Emission Rate**
CO2 (g/MJ)	88.16
GHG-100 (g/MJ)	92.26
NOx (mg/MJ)	210
SOx (mg/MJ)	14.66
VOC (mg/MJ)	26.62
PM10 (mg/MJ)	4.11
PM2.5 (mg/MJ)	3.58

All emissions rate data obtained from the GREET Tool[32]

Table 5.8: Average U.S. Grid Electricity Well-to-Wheel Emissions Conversions

Pollutant	**Total Output Emission Rate**
NOx total output (lb/MWh)	0.62
SO2 total output (lb/MWh)	0.68
CO2 total output (lb/MWh)	947.18
CH4 total output (lb/MWh)	0.09
N2O total output (lb/MWh)	0.01
CO2e total output (lb/MWh)	952.88
Upstream Emissions After Transmission Loss (lb/MWh)	117.71
Grid Gross Loss (%)	4.87
PM10 total direct plant output (lb/MWh)	0.07
PM2.5 total direct plant output (lb/MWh)	0.06
VOC total direct plant output (lb/MWh)*	0.02

Table 5.8 presents data specific to the average U.S. grid subregion and its respective emissions. This data is vital for the analysis because it accurately reflects the energy mixture used to power the grid rather than assuming a fully renewable energy source. This approach considers the grid gross loss, upstream emissions after transmission loss, and average U.S. plant output direct emission rates from air pollutants such as PM10, PM2.5, and VOC.[51] The data on grid-associated pollutants (NOx, SO2, CO2, CH4, N2O, CO2e) and grid gross loss was obtained from the U.S. EPA's eGRID database.[52] "The eGRID annual total output emission rate is the measure of the emissions as it relates to the net generation output".[43] In contrast, the eGRID subregion carbon dioxide equivalent (CO2e) output emission rates are "calculated using the eGRID subregion output emission rates for CO2, CH4, and N2O and the Global Warming Potentials from the International Panel on Climate Change's Second Assessment Report" and "shows the relative contributions of including the CH4 and N2O emissions from electric generation along with the CO2 emissions."[43] The data on upstream emissions after transmission loss was obtained from a study performed by the Union of Concerned Scientists(UCS).[39] This comprehensive approach allows

for an accurate assessment of the environmental impacts of using the U.S. grid as an energy source.

BEV Vehicle Emissions Calculations

To calculate the emissions of the BEV vehicle, the following steps were taken:

1. Calculate the annual electricity usage of the vehicle under the economic and development speed scenarios:

$$\text{Annual Electricity Usage(kWh/yr)} = \frac{\text{Annual VMT}}{\text{MPGe}} \times (\text{kWh per Gasoline Volume*}) \tag{5.5}$$

2. Calculate the WTW carbon intensity(CI) per kWh of the grid:

$$= \frac{\text{Grid CO2 Emission Rate} + \text{Upstream Emissions after Transmission Loss}}{1000} \tag{5.6}$$

3. Calculate the total annual pounds of WTW CO2 emissions:

$$\text{Annual CO2 Emissions(lb)} = \text{Annual Electricity Usage} \times \frac{\text{WTW CI of kWh}}{(1 - \text{Grid Gross Loss})} \tag{5.7}$$

4. Calculate the annual pounds of WTW CO2 emissions per mile traveled:

$$\text{Annual CO2 emissions per mile(lb/mi)} = \frac{\text{Annual CO2 Emissions}}{\text{Annual VMT}} \tag{5.8}$$

5. Calculate the other annual WTW emissions per mile traveled:

Annual NOx Emissions per Mile (mg/mi):

$$= \frac{\text{Grid NOx Emission Rate} \times \text{glb con*} \times \text{Annual Electricity Usage}}{\text{Annual VMT}} \tag{5.9}$$

Annual SOx Emissions per Mile (mg/mi):

$$= \frac{\text{Grid SOx Emission Rate} \times \text{glb con*} \times \text{Annual Electricity Usage}}{\text{Annual VMT}} \tag{5.10}$$

Annual VOC Emissions per Mile (mg/mi):

$$= \frac{\text{Grid VOC Emission Rate} \times \text{glb con*} \times \text{Annual Electricity Usage}}{\text{Annual VMT}} \tag{5.11}$$

Annual PM10 Emissions per Mile (mg/mi):

$$= \frac{\text{Grid PM10 Emission Rate} \times \text{glb con*} \times \text{Annual Electricity Usage}}{\text{Annual VMT}} \tag{5.12}$$

Annual PM2.5 Emissions per Mile (mg/mi):

$$= \frac{\text{Grid PM2.5 Emission Rate} \times \text{glb con*} \times \text{Annual Electricity Usage}}{\text{Annual VMT}} \tag{5.13}$$

The general conversions used in these calculations are kWh per Gasoline Volume and Grams per Pound from Table 5.6. The Grams per Pound conversion is denoted as "glb con" in the equations used.

ICE Vehicle Emissions Calculations

To calculate the emissions of the ICE vehicle, the following steps were taken:

1. Calculate the annual gallons of diesel used for the vehicle under the economic and development speed scenarios:

$$\text{Annual Diesel Usage(gal/yr)} = \frac{\text{Annual VMT}}{\text{MPG}} \tag{5.14}$$

2. Calculate the WTW carbon intensity(CI) per gallon of diesel:

$$= \frac{\text{Diesel WTW CO2 Emissions} \times \text{MJ per Diesel Volume*}}{\text{glb con*}} \tag{5.15}$$

3. Calculate the total annual pounds of WTW CO2 emissions:

$$\text{Annual CO2 Emissions(lb)} = \text{Annual Diesel Usage} \times \text{WTW CI of Diesel} \tag{5.16}$$

4. Calculate the annual pounds of WTW CO2 emissions per mile traveled:

$$\text{Annual CO2 emissions per mile(lb/mi)} = \frac{\text{Annual CO2 Emissions}}{\text{Annual VMT}} \tag{5.17}$$

5. Calculate the other annual WTW emissions per mile traveled:

Annual NOx Emissions per Mile (mg/mi):

$$= \frac{\text{Diesel WTW NOx Emissions} \times \text{MJ per Diesel Volume*} \times \text{Annual Diesel Usage}}{\text{Annual VMT}} \tag{5.18}$$

Annual SOx Emissions per Mile (mg/mi):

$$= \frac{\text{Diesel WTW SOx Emissions} \times \text{MJ per Diesel Volume*} \times \text{Annual Diesel Usage}}{\text{Annual VMT}} \tag{5.19}$$

Annual VOC Emissions per Mile (mg/mi):

$$= \frac{\text{Diesel WTW VOC Emissions} \times \text{MJ per Diesel Volume*} \times \text{Annual Diesel Usage}}{\text{Annual VMT}} \tag{5.20}$$

Annual PM10 Emissions per Mile (mg/mi):

$$= \frac{\text{Diesel WTW PM10 Emissions} \times \text{MJ per Diesel Volume*} \times \text{Annual Diesel Usage}}{\text{Annual VMT}} \tag{5.21}$$

Annual PM2.5 Emissions per Mile (mg/mi):

$$= \frac{\text{Diesel WTW PM2.5 Emissions} \times \text{MJ per Diesel Volume*} \times \text{Annual Diesel Usage}}{\text{Annual VMT}} \tag{5.22}$$

The general conversions used in these calculations are MJ per Diesel Volume and Grams per Pound from Table 5.6. The Grams per Pound conversion is denoted as "glb con" in the equations used.

Chapter 6

Results and Analysis of Financial and Environmental Impacts

The analysis of the financial and environmental impacts of transitioning to BEVs from ICE long-haul trucks is based on the models and assumptions outlined in Chapter 5. The financial impact analysis examines the total cost of ownership associated with procuring and maintaining BEVs compared to that of ICE vehicles, the economic and development thresholds for BEV preference, and the potential financial gains from making the investment in BEV instead of ICE long-haul trucks. The environmental impact analysis examines the potential environmental impacts of transitioning to BEVs, such as GHG emissions and direct emissions from air pollution. This comprehensive analysis provides the financial and environmental considerations that must be assessed if a company is considering transitioning to BEVs for long-haul trucking. All figures used in this chapter can be found in a larger format in Appendix A.

6.1 Total Cost of Ownership Analysis

The TCO Analysis calculated the total cost of ownership for the procured vehicle and the annual nominal cost per mile. This analysis outlines the economic and development speed scenarios under which a BEV long-haul truck would be the more economical choice, as well as scenarios where the choice between a BEV and an ICE vehicle could be more uncertain or where an ICE vehicle would be the preferred economical option. The results shown in Figure 6-1 illustrate the significant total cost of ownership difference between BEV and ICE vehicles. This analysis emphasizes the economic benefits of BEVs in terms of costs across a majority of the scenarios evaluated. It demonstrates the increasingly compelling economic case for adopting BEVs in long-haul trucking. For the complete analysis of the Total Cost of Ownership Summary reference Appendix Figure A-5.

Development Speed	Total Cost Cost Difference between BEV and ICE (%) Current	High Oil Cost	High Renewable Cost	Low Oil Cost
Current	22%	34%	2%	-14%
Medium	42%	55%	20%	1%
Aggressive	39%	51%	19%	2%

Figure 6-1: Total Cost Difference Summary

The total cost of ownership summary seen in Figure 6-1 and Appendix Figure A-5 demonstrates that, in general, a BEV is the preferred option or could be the preferred option in most scenarios, except in the scenario of the low oil costs and current (slow) development speed for EV technologies. Under all current economic and high oil economic scenarios, a BEV is the preferred option regardless of development speeds. This means that while it would be desirable for the technology to be further developed, it is not strictly necessary to make the economic case for BEVs in long-haul trucking. In the current economic conditions and with no further development, the total cost of an ICE vehicle is 22%, or $132,199, more expensive than that of a BEV long-haul truck.

In the high renewable cost economic scenario, if medium or aggressive development occurs, the BEV option is the more economical choice. In contrast, if no further development is made, there is only a 2% difference in total cost between the ICE and BEV trucks. Although the BEV option is slightly more favorable, it has been designated as neutral because the total cost is close enough that both vehicles could be favorable.

The low oil cost scenario is the least favorable case for a BEV transition. If no further development takes place in the low oil cost economic scenario, the total cost of an ICE long-haul truck is 14%, or $76,512, less expensive than that of the BEV truck. Therefore, an ICE vehicle would be preferred. Even if medium or aggressive development occurs in the low oil cost economic scenario, the BEV total cost is only 1% and 2% less than that of an ICE truck. Although the BEV option is slightly more favorable, it has been designated as neutral because the total cost is close enough that both vehicles could be favorable.

The TCO analyses performed are broken down in the Appendix in Figures A-6 and A-7. These figures indicate that fuel cost is the major contributor to the cost difference between a BEV and ICE long-haul truck. The fuel costs were then analyzed to understand the significance of these cost differences. The total cost of ownership fuel analysis demonstrates that, concerning fuel costs, a BEV is always the preferred choice, see Appendix Figure A-8. Figure 6-2 provides a summary that illustrates the significant differences in fuel cost between an ICE vehicle and a BEV in each economic and development speed scenario.

	Fuel Cost Cost Difference between BEV and ICE (%)			
Development Speed	Current	High Oil Cost	High Renewable Cost	Low Oil Cost
Current	120%	177%	67%	14%
Medium	246%	336%	163%	80%
Aggressive	252%	344%	168%	83%

Figure 6-2: Fuel Cost Difference Summary

This difference is calculated by using Equation 6.1.

$$\text{Fuel Cost Difference} = \frac{\text{ICE Fuel Cost} - \text{BEV Fuel Cost}}{\text{ICE Fuel Cost}} \tag{6.1}$$

Figure 6-2 shows the disparity in fuel costs between ICE and BEV long-haul trucks. These significant differences drive lower operating costs for BEV and help strengthen the case for a transition to BEV. As shown in Figure 6-2, in the current economic scenario with no further development, the total fuel costs for ICE vehicles are 120%, or \$229,093, more expensive than that of a BEV. Although most economic scenarios demonstrate large savings, it is significant to note that in the low oil cost current development speed scenario, the total fuel cost difference is only 14%, or \$24,070. The low price of diesel drives this small difference. The low diesel price causes a minimal cost savings advantage from switching to BEV. Therefore, ICE will be the preferred option regarding the total cost. In this scenario, the operating cost savings from switching to BEVs will not be sufficient to offset the upfront cost of procuring the vehicle, the operational capacity adjustment, and the charging station. However, across most economic conditions and development speeds, a significant difference in fuel costs makes a compelling case for the adoption of BEVs in the long-haul trucking industry now.

It is important to note for this analysis that the total cost of ownership is not discounted. Discount factors are applied in the NPV analysis in Chapter 6.4.

6.2 Nominal Cost per Mile Sensitivity Analysis

Multiple sensitivity analyses were conducted to understand the impact of changes in various cost variables on the annual nominal cost per mile for each economic and development speed scenario. The statistical significance of each cost-influencing variable was evaluated, and analysis was performed on the variables deemed significant: diesel price, electricity price, MPGe, MPG, annual vehicle miles traveled, and MSRP. These sensitivity analyses can be found in detail in the figures in Appendix Section A.3.

The sensitivity analyses demonstrated the impact of each significant cost-influencing variable on the nominal cost per mile within each economic and development speed scenario. These analyses also illustrated the inflection point at which the nominal cost per mile for an ICE long-haul truck and a BEV long-haul truck would be equivalent for each significant cost-influencing variable under the different economic and development speed scenarios. These inflection points were found by determining the crossover points between the ICE vehicle and BEV data for the respective variable. The inflection points were then compared to the economic and development scenarios in Chapter 6.3 to understand the changes that would have to occur in the respective cost-influencing variable for the BEV truck to be the more economical choice.

Additionally, a significant takeaway from the sensitivity analysis was found in the Annual Vehicle Miles Traveled Sensitivity Analysis, where it was determined that in all economic conditions, except the low oil cost current development scenario, as the mileage increases, the difference in nominal cost per mile of the BEV truck in comparison to the ICE truck increases, with BEVs having the lower nominal cost per mile. This finding demonstrates why BEVs become increasingly competitive when analyzing long-haul trucking scenarios.

6.3 Threshold Analysis for BEV Preference

The nominal cost per mile sensitivity analysis performed in Chapter 6.2 helped determine the inflection points at which the nominal cost per mile for an ICE long-haul truck and a BEV long-haul truck would be equivalent for each significant cost variable under the different economic and development speed scenarios. The figures in section A.4 of the Appendix outline the thresholds for each respective cost-influencing variable that make the BEV truck the more economical choice.

From these figures in section A.4, it is evident that regardless of the development scenario, BEV is the preferred option in most economic scenarios and has significant leeway before the nominal cost per mile for the ICE becomes equivalent. These thresholds were presented together as an individual change in either of these variables for their specific scenario will make BEV the preferred option or maintain BEV as the preferred choice. For example, in the current economic and development scenario, if the diesel price remains above \$3.65, or the MPGe of the BEV truck remains above 8.86 MPGe, or the electricity cost remains below \$0.29, or the MPG of the ICE truck is remains below 8.74 MPG, the BEV would be the preferred choice. If any of these conditions are not met, the BEV would no longer be the preferred economical choice.

The significant findings from this threshold analysis are further broken down in the sections below, according to each of the variables on which the sensitivity analysis was performed.

6.3.1 Diesel and Electricity Price Sensitivity Analysis Results

The key findings from the diesel and electricity sensitivity analyses are analyzed by each specific economic condition and the across all economic conditions. These sensitivity analysis results are presented in Appendix A.4.

Current Economic Condition In the current economic condition, with electricity prices set at ~$0.14 per kWh, the expected price of diesel is $5.33.[4] If the diesel price remains above $3.65 or the electricity price remains below $0.29, regardless of developments made, the BEV will have a lower nominal cost per mile. If medium developments are made, and the diesel price remains above $2.49 or the electricity price remains below $0.53, the BEV will have a lower nominal cost per mile. If aggressive developments are made, and the diesel price remains above $2.44 or the electricity price remains below $0.55, the BEV will have a lower nominal cost per mile. Conversely, if the diesel price drops below these prices or the electricity price increases above these prices, the ICE vehicle will have a lower nominal cost per mile.

Based on the current average diesel price of $5.33 and electricity price of $0.14, BEVs are already a more cost-effective option. Substantial price changes could occur to diesel or electricity prices, and BEVs will still have a lower nominal cost per mile. For instance, with no further development, diesel prices could decrease by up to $1.68 or electricity prices could increase by up to $0.15, and BEVs would remain the cost-effective choice. With medium development, diesel prices could decrease by up to $2.84 or electricity prices could increase by up to $0.40, and BEVs would remain the cost-effective choice. With aggressive development, diesel prices could decrease by up to $2.89 or electricity prices could increase by up to $0.41, and BEVs would remain the cost-effective choice.

High Oil Cost Economic Condition In the high oil cost economic condition scenario based on EIA projections with electricity price set at $0.11 per kWh, the expected price of diesel is $5.57.[4] If the diesel price remains above $3.29 or the electricity price remains below $0.32, regardless of developments made, the BEV vehicle will have a lower nominal cost per mile. If medium developments are made, and the diesel price remains above $2.28 or the electricity price remains below $0.57, the BEV vehicle will have a lower nominal cost per mile. If aggressive developments are made, and the diesel price remains above $2.24 or the electricity price remains below $0.59, the BEV vehicle will have a lower nominal cost per mile. Conversely, if the diesel price drops below these prices or the electricity price increases above these prices, the ICE vehicle will have a lower nominal cost per mile.

BEV would be a more cost-effective option based on the projected diesel price of $5.57 and electricity price of $0.11. Substantial price changes could occur to diesel or electricity prices, and BEVs will still have a lower nominal cost per mile. For instance, with no further development, diesel prices could decrease by up to $2.28 or electricity prices could increase by up to $0.20, and BEVs would remain the cost-effective choice. With medium development, diesel prices could decrease by up to $3.29 or electricity prices could increase by up to $0.46, and BEVs would remain the cost-effective choice. With aggressive development, diesel prices could decrease by up to $3.33 or electricity prices could increase by up to $0.48, and BEVs would remain the cost-effective choice.

High Renewable Cost Economic Condition In the high renewable cost economic condition scenario based on EIA projections with electricity price set at $0.12 per kWh, the expected price of diesel is $3.57.[4] If the diesel price remains above $3.41 or the electricity price remains below $0.13, regardless of developments made, the BEV vehicle will have a lower nominal cost per mile. If medium developments are made, and the diesel price remains above $2.36 or the electricity price remains below $0.29, the BEV vehicle will have a lower nominal cost per mile. If aggressive developments are made, and the diesel price remains above $2.32 or the electricity price remains below $0.30, the BEV vehicle will have a lower nominal cost per mile. Conversely, if the diesel price drops below these prices or the electricity price increases above these prices, the ICE vehicle will have a lower nominal cost per mile.

Based on the projected diesel price of $3.57 and electricity price of $0.12, BEV would be a more cost-effective option in most cases. In the medium and aggressive development speed scenarios, substantial price changes could occur to either the diesel or electricity price. BEVs will still have a lower nominal cost per mile. For instance, with medium development, diesel prices could decrease by up to $1.21 or electricity prices could increase by up to $0.17, and BEVs would remain the cost-effective choice. With aggressive development, diesel prices could decrease by up to $1.25 or electricity prices could increase by up to $0.18, and BEVs would remain the cost-effective choice. However, if no further development occurs, the diesel price could only reduce by up to $0.16 or the electricity price could only increase by up to $0.01 for BEVs to remain the cost-effective choice. Although price changes can occur, the price change allowance for the BEV to remain cost-effective is negligible. Therefore, these scenarios have been designated as neutral because the threshold prices are close enough to the projected prices that both vehicles could potentially be favorable.

Low Oil Cost Economic Condition In the low oil cost economic condition scenario based on EIA projections with electricity price set at $0.12 per kWh, the expected price of diesel is $2.42.[4] If no developments are made, the diesel price must increase by $0.97 to $3.39 or the electricity price must reduce by $0.09 to $0.03, for the BEV vehicle to have a lower nominal cost per mile. In these cases, the ICE vehicle has the lower nominal cost per mile and is the preferred option. This is primarily due to how low the diesel price is. However, if medium developments are made, and the diesel price remains above $2.34 or the electricity price remains below $0.13, the BEV vehicle will have a lower nominal cost per mile. If aggressive developments are made, and the diesel price remains above $2.32 or the electricity price remains below $0.14, the BEV vehicle will have a lower nominal cost per mile.

Based on the projected diesel price of $2.42 and electricity price of $0.12, it is uncertain whether BEVs would be a more cost-effective option in this economic scenario. If no development occurs, the ICE would be a more cost-effective option. Although price changes can occur for medium and aggressive development scenarios, the amount required for BEVs to remain cost-effective is negligible. For the medium development speed scenario, the diesel price can only reduce by $0.08 or the electricity price can only increase by $0.01. For the aggressive development speed scenario, the diesel price can only reduce by $0.12 or the electricity price can only increase by $0.02. Due to the negligible price changes allowed, these scenarios have been designated as neutral because the threshold price is close enough to the projected price that both vehicles could potentially be favorable.

All Economic Conditions The analysis of each economic scenario illustrates that for all economic and development speed conditions, if the diesel price is above $3.65 or the electricity price is below $0.03, the BEV would have a lower nominal cost per mile. If medium developments are made, and the diesel price is above $2.49 or the electricity price is below $0.13, the BEV would have a lower nominal cost per mile. If aggressive developments are made, and the diesel price is above $2.44 or the electricity price is below $0.14, the BEV would have a lower nominal cost per mile. Conversely, if the diesel price is below $2.24 or the electricity price is above $0.59, regardless of developments made, the ICE vehicle will have a lower nominal cost per mile. If no developments are made, and the diesel price is below $3.29 or the electricity price is above $0.32, the ICE vehicle will have a lower nominal cost per mile. If medium developments are made, and the diesel price is below $2.28 or the electricity price is above $0.57, the ICE vehicle will have a lower nominal cost per mile.

Based on the expected prices projected by the EIA in each economic scenario, the BEV will be the preferred choice if any developments are made, as it will have a lower nominal cost per mile. If no development is made, the economic benefit of transitioning to a BEV vehicle will depend on market conditions. If no development occurs and diesel prices remain above $3.65, the BEV truck would be the most cost-effective option. The EIA "expect[s] retail diesel prices to average about $4.20/gal in 2023...[and] in 2024, [they] expect prices to continue to fall, and average near $3.70/gal."[3] Based on these short-term projections, the case for adopting BEV trucks is strengthened under the expected short-term diesel price conditions.

6.3.2 MPGe Sensitivity Analysis Results

The ICE fuel economy sensitivity analysis shows the same trends as the BEV fuel economy sensitivity analysis. Therefore, the focus of this analysis was on MPGe, as the ICE vehicle conditions have limited room for improvement. The key findings from the MPGe sensitivity analysis are analyzed across all economic conditions. The fuel economy sensitivity analyses (MPG and MPGe) results are presented in Appendix A.4.

Similar to the electricity and diesel sensitivity analysis, the BEV truck is the preferred option if any development occurs. The significant finding from the current economic scenario across all development scenarios is that if the BEV truck's fuel economy remains above 9.92 MPGe, the BEV option is the preferred economical choice. This means that the BEV truck still has significant leeway in fuel economy performance to be the preferred option. If no developments are made and current economic scenarios continue, the BEV truck only has to have a fuel economy above 8.86 MPGe to be the preferred option. If no developments are made and the high oil cost economic scenario occurs, the BEV truck must only have a fuel economy above 7.27 MPGe to be the preferred option. If no developments are made and the high renewable cost economic scenario occurs, the BEV truck must only have a fuel economy above 12.5 MPGe to be the preferred option. However, if no developments are made and the low oil cost economic scenario occurs, the BEV truck must have a fuel economy above 22.02 MPGe to be the preferred option.

6.3.3 MSRP Sensitivity Analysis Results

Under each economic and development speed scenario, the MSRP price to ensure the BEV would be the preferred option was determined. These prices were found by understanding the nominal cost per mile of an ICE long-haul truck under each scenario and then determining the MSRP value for a BEV long-haul truck at that nominal cost per mile. The results are illustrated in Figure 6-3.

Threshold Analysis for BEV MSRP Pricing based on Sensitivity Analysis Results

Economic Scenarios	Development Speed	Condition	Nominal Cost per Mile ($)	Average ICE MSRP ($)	Competitive BEV MSRP at Nominal Cost per Mile ($)	Threshold for BEV Preference
Current	Current	BEV Preferred	$1.67	$135,000	$384,375	Can Increase $186,375
	Medium	BEV Preferred	$1.60	$135,000	$488,884	Can Increase $290,884
	Aggressive	BEV Preferred	$1.48	$135,000	$455,059	Can Increase $257,059
High Oil Cost	Current	BEV Preferred	$1.62	$135,000	$451,532	Can Increase $253,532
	Medium	BEV Preferred	$1.54	$135,000	$535,140	Can Increase $337,140
	Aggressive	BEV Preferred	$1.42	$135,000	$494,053	Can Increase $296,053
High Renewable Cost	Current	Neutral	$1.26	$135,000	$216,035	Neutral $18,035
	Medium	BEV Preferred	$1.21	$135,000	$322,406	Can Increase $124,406
	Aggressive	BEV Preferred	$1.13	$135,000	$309,805	Can Increase $111,805
Low Oil Cost	Current	ICE Preferred	$1.05	$135,000	$90,162	Must Reduce $107,838
	Medium	Neutral	$1.02	$135,000	$205,327	Neutral $7,327
	Aggressive	Neutral	$0.97	$135,000	$208,314	Neutral $10,314

Condition: BEV Preferred; ICE Preferred; Neutral

Direction and Msrp broken down by Value vs. Economic Scenarios, Development Speed, Condition and Nominal Cost per Mile ($). Color shows details about Condition. The view is filtered on Value, which keeps Average ICE MSRP ($), Competitive BEV MSRP at Nominal Cost per Mile ($) and Threshold for BEV Preference.

Figure 6-3: Threshold Analysis for BEV MSRP Pricing based on Sensitivity Analysis

These results demonstrate that if any development occurs, the MSRP of the BEV truck can be increased from $198,000 by at least $7,327. Under all current economic condition scenarios, if the MSRP remains below $384,375, the BEV is the preferred economical option. Under all high oil cost economic condition scenarios, if the MSRP remains below $451,532, the BEV is the preferred economical option. Under all high renewable cost economic condition scenarios, if the MSRP remains below $216,035, the BEV is the preferred economical option. However, under the low oil cost current development scenario, the MSRP must reduce to at least $90,162 to make the BEV the preferred economical option. This MSRP is highly unlikely. Therefore, the ICE vehicle would be the preferred option in this scenario.

6.3.4 Low Oil Cost Scenario Feasibility and 2022 EIA Energy Outlook Scenario

Across all analyses, the low oil cost scenario presents a case against adopting BEV vehicles for long-haul trucking. Therefore, the feasibility of this scenario occurring was evaluated. The main driver causing BEV vehicles not to be favorable is the low diesel price of $2.42. This low diesel price means that the lower operating cost of a BEV vehicle cannot offset the upfront cost of investing in BEVs. There is only a

14% difference in the fuel cost, which is the significant cost reduction incentive of transitioning to BEV. To offset this low diesel cost, the electricity cost would have to be unreasonably low or the fuel economy would have to be higher than expected. Therefore, to understand the feasibility of this economic scenario, an additional scenario was developed based on the 2022 EIA Energy Outlook Scenarios of long-term expectations for diesel prices. This scenario was designed to determine if based on long-term baseline projections, the diesel price of $2.42 was probable or if the case for BEV trucks would hold up.

2022 EIA Energy Outlook Scenario Based on the 2022 EIA Energy Outlook, it is unlikely that the low oil cost scenario will come to fruition and the diesel price will drop to $2.42. Based on the 2022 EIA Energy Outlook, the 2025-2050 transportation industry's baseline expected average diesel price is $3.35 and the expected average electricity price is $0.11.[4] These expected prices support the finding that the BEV is the preferred choice if any development occurs. However, each development scenario was analyzed to understand the threshold at the projected baseline diesel price. The projected baseline scenario from the expected 2022 EIA Energy Outlook Scenarios is defined in Table 6.1.

Table 6.1: Expected Baseline 2022 EIA Energy Outlook Scenarios Economic Scenario Conditions

Economic Condition	Baseline - 2022 EIA Energy Outlook
Diesel Price ($/Gallon)	$3.35
Electricity Cost ($/kWh)	$0.11
Public Charging Price ($/kWh)	$0.27
En Route Charging Price ($/kWh)	$0.11
Inflation Rate (Excluding Fuel) (%/Year)	2%
Cost of Downtime from Public Charging ($/Hour)	$75
MSRP Average - ICE	$135,000
MSRP Operational Capacity Adjustment - BEV	$198,000
Grid Region	US Average

While the low oil cost scenario is still included in the analysis, the baseline expected pricing from the 2022 EIA Energy Outlook Scenarios is considered a lower bound to determine if the transition to BEV long-haul trucks is economically feasible. The thresholds of electricity price, fuel economy (MPGe), and BEV MSRP based on the expected baseline scenario conditions were calculated. The results can be found in Table 6-4.

Economic Scenario	Development Speed	Nominal Cost per Mile ($)	Diesel Price ($/gal)	Threshold Electricity Price ($/kWh)	Threshold Fuel Economy (MPGe)	Threshold BEV MSRP
Baseline	Current	$1.23	$3.35	$0.12	12.5	$210,608
Baseline	Medium	$1.18	$3.35	$0.27	13.5	$311,007
Baseline	Aggressive	$1.18	$3.35	$0.28	14.5	$346,031

Figure 6-4: Threshold Analysis for 2022 EIA Energy Outlook

Based on the 2025-2030 baseline projections for diesel prices, the low oil cost economic scenario is unlikely. This would require a reduction of $0.93 in the expected baseline diesel price to occur. This analysis demonstrates that, with a baseline diesel price of $3.35, for BEV trucks to be the preferred economical choice over ICE trucks when no further development occurs, the cost of electricity must be at or below $0.12 per kWh, the MPGe of the BEV truck must be at or above 12.5 MPGe, or the MSRP of the BEV truck must be at or below $210,608. However, based on the 2022 Energy Information Administration (EIA) Energy Outlook, the transportation industry's baseline expected average end consumer electricity price is $0.11. Additionally, the Tesla is priced at $180,000, and with the operational capacity adjustment, the maximum expected MSRP is $198,000, which is $12,608 less than the adjusted price. Furthermore, the expected fuel economy of a BEV in the current development scenario is 13.5MPGe which is above the stated threshold. Thus, BEVs would still be the preferred choice even with no further development based on the baseline scenario.

This comprehensive threshold analysis is significant because it further strengthens the case for adopting BEV long-haul trucks. Almost all projected economic scenarios under the current development speed scenario, including the baseline economic scenario, demonstrate that the BEV truck is the preferred economical choice. If any development occurs, which is likely, the BEV could be the preferred choice for all projected economic scenarios. Development is recommended to ensure there will be a financial incentive to switch to BEV long-haul trucks across all economic scenarios.

6.4 Net Present Value Model Analysis

Through the TCO and sensitivity analyses performed, it is clear that BEV is the preferred option on a nominal cost per mile basis, even using a significantly conservative approach. NPV cash flow analysis was performed to determine the value of investing in BEV long-haul trucks instead of ICE long-haul trucks over the seven years of expected ownership. This analysis calculates the net present value of the expected cash flows from procuring each vehicle. Two industry-specific NPV models were built using the industry's respective WACC. Within each analysis, the payback period was found. The payback period is defined as the year when the NPV of switching to a BEV from an ICE long-haul truck becomes positive. Within each model, two additional scenarios are presented related to charging infrastructure. The first charging infrastructure scenario assumes the expected one-to-one ratio, while the second assumes that four vehicles can use one charging station, a four-to-one ratio. Applying these constraints, the NPV analyses determine the return on investment from procuring a BEV or ICE long-haul truck under multiple realistic scenarios. The details of all NPV analyses can be found in Appendix Section A.5.

Due to the feasibility assessment of the low oil cost scenario from the 2022 EIA Energy Outlook Scenarios, the baseline scenario was included in the NPV analysis. The baseline economic scenario is used as the lower bound in the NPV analysis, instead of the low oil cost economic scenario, to determine if the transition to BEV long-haul trucks is economically feasible. *The low oil cost economic scenario is still included in the analysis but is not considered feasible.*

6.4.1 Trucking Industry Model

This NPV analysis evaluates the potential profitability of transitioning to BEV long-haul trucks in the trucking industry. This approach has a discount factor of 10.3%, an operational capacity adjustment of 10%, and two different charging station scenarios per vehicle procured. This approach is highly conservative and can be seen as an upper bound.

Charging Station Scenario One

One Vehicle per Station at 10.3% Discount Factor

The figures in Appendix Section A.5.1 and Section A.5.2 provide a summary of the cash flows that would occur from procuring an ICE or BEV long-haul truck under the different economic and development speed scenarios with the assumption that for every vehicle procured a charging station will be built.

These cash flows were used to determine the projected average operating savings per year, the BEV savings at the end of the seven years of expected ownership, and the annual net difference from investing in BEV instead of ICE. Figure 6-5, Figure 6-6, and 6-7 are the outcomes of this analysis.

Projected Average Operating Savings per Year from Transition to BEV

	Economic Condition				
Development Speed	Current	High Oil Cost	High Renewable Cost	Low Oil Cost	Baseline
Current	$19,772	$24,786	$7,816	-$1,240	$7,476
Medium	$27,468	$30,954	$15,632	$7,206	$14,830
Aggressive	$25,077	$28,036	$14,765	$7,461	$14,058

Average of NPV broken down by Economic Condition vs. Development Speed. The data is filtered on Time Since Initial Investment (Yrs), Drivetrain Type, Discount Factor and Charging Station Ratio. The Time Since Initial Investment (Yrs) filter excludes 0, 7, Total and Null. The Drivetrain Type filter keeps BEV Savings. The Discount Factor filter keeps 0.103. The Charging Station Ratio filter keeps One to One. The view is filtered on Development Speed, which keeps Aggressive, Current and Medium.

Figure 6-5: Projected Average Operating Savings per Year from Transition to BEV at 10.3% Discount Factor and One-to-One Charging Station Ratio

The projected annual average operating savings from transitioning to a BEV long-haul truck from an ICE long-haul truck demonstrate the benefits of operating a BEV. The lower operating cost of the BEV, due to lower fuel and maintenance costs, provides significant annual savings compared to an ICE vehicle. If any development occurs, across all economic scenarios, excluding the low oil cost scenario, the lowest annual average cost savings per vehicle is $14,058 and the highest potential annual average cost savings per vehicle is $30,954. However, if no development is made, all economic scenarios will see annual cost savings from transitioning to a BEV long-haul truck from an ICE long-haul truck, except the low oil cost scenario. If no development is made and current economic conditions continue, the average annual savings would be $19,772 from transitioning. If no development is made and high oil cost economic conditions occur, the average annual savings would be \$24,786 from transitioning. If no development is made and high renewable cost economic conditions occur, the average annual savings would be \$7,816 from transitioning. If no development is made and low oil cost economic conditions occur, there would not be savings. The average annual loss would be \$1,240 from transitioning to a BEV long-haul truck from an ICE long-haul truck. However, based on the feasibility assessment of the low oil cost scenario, the baseline will be considered as a lower bound. If no development is made, the baseline economic scenario would have an annual savings of \$7,476.

Although there are significant savings per year from operating a BEV truck instead of an ICE truck, it is vital to understand whether those savings are enough to offset the upfront cost of transitioning. This upfront cost includes procuring the vehicle, constructing and installing the charging station, and an operational capacity hit of 10%. To determine whether the average operating savings are enough, the total NPV financial gains from switching to BEV over the expected years of ownership were determined, as seen in Figure 6-6. Figure 6-7 illustrates the annual net difference from investing in BEV instead of ICE long-haul trucks and the payback period. *The Annual Net Differences (Δ) are calculated for each year using the following equation* $\Delta = NPV_{ICE} - NPV_{BEV}$.

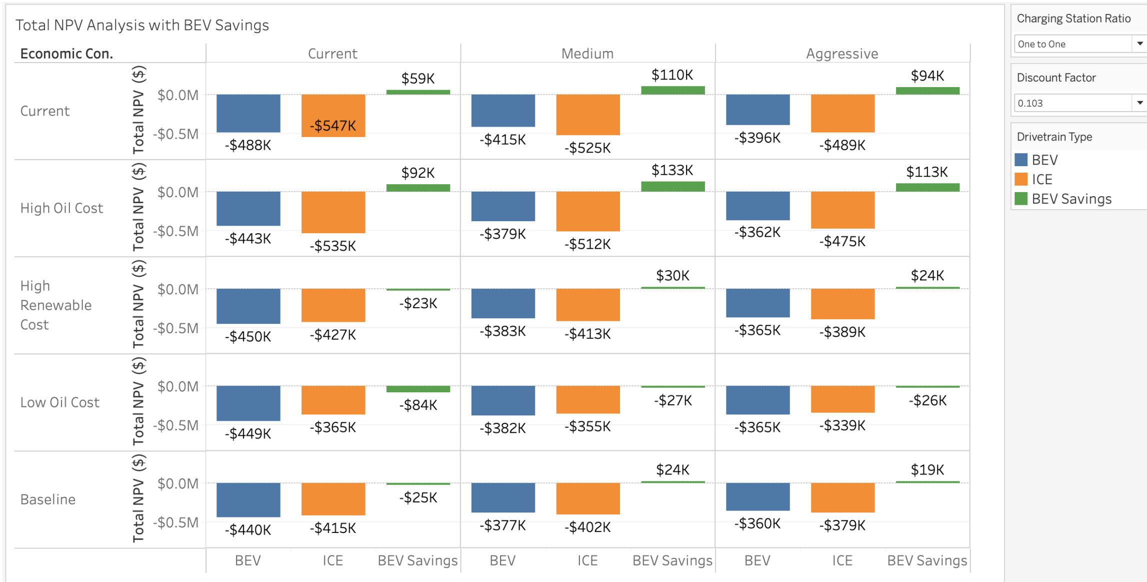


Figure 6-6: Total NPV Analysis with BEV Savings at the end of Expected Years of Ownership at 10.3% Discount Factor and One-to-One Charging Ratio

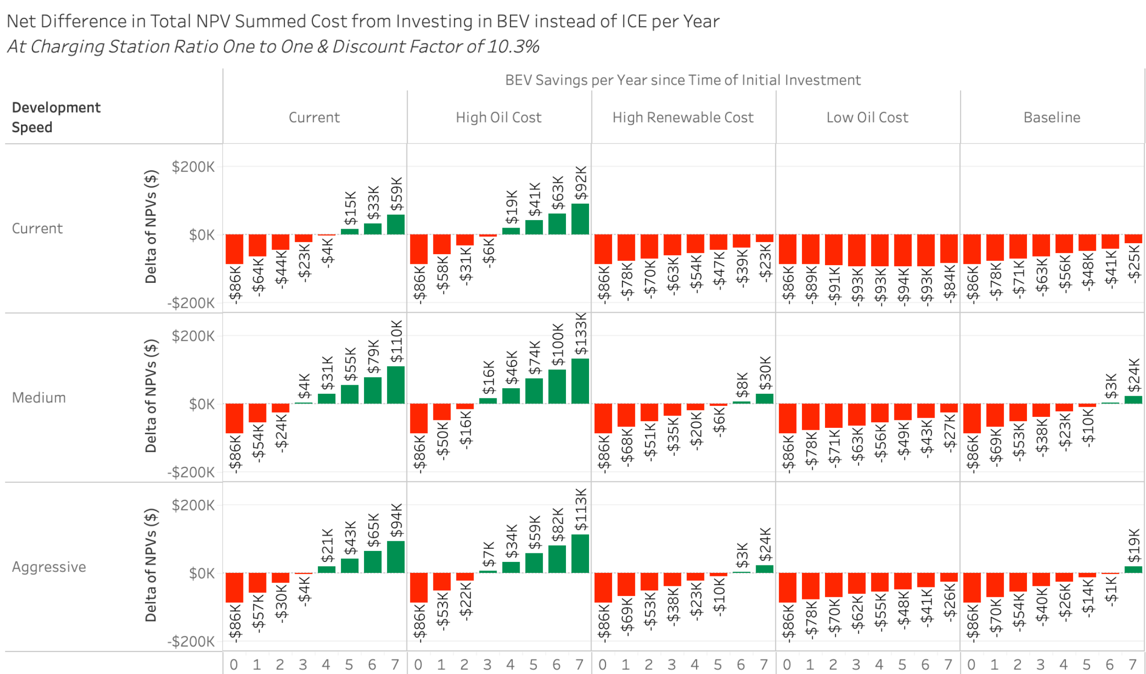


Figure 6-7: Annual Net Difference in Total NPV Summed Cost from Investing in BEV instead of ICE at 10.3% Discount Factor and One-to-One Charging Ratio

This analysis demonstrated that with a discount factor of 10.3% and a one-to-one charging station ratio, development must occur for the BEV to be the preferred economical option in all economic scenarios. If development occurs, in all economic scenarios evaluated, there will be significant cost savings from procuring BEV long-haul vehicles instead of ICE long-haul vehicles by the end of the expected years of ownership. For the medium development speed scenario, the net positive financial gains per vehicle range from \$24K to \$133K, depending on the economic scenario. For the aggressive development speed development scenario, the net positive financial gains per vehicle range from \$19K to \$113K, depending on the economic scenario. The payback period per vehicle ranges from 4 to 7 years for the medium and aggressive development speed scenarios. If no further development occurs, under current economic conditions and high oil cost conditions, there will be net positive financial gains of \$59K with a payback period of 5 years and \$92K with a payback period of 4 years over the seven years of ownership, respectively. However, if no further development occurs in both the high renewable cost economic scenario and the baseline economic scenario, there will not be net positive financial gains from switching to BEV. The ICE vehicle will be a better financial investment by the end of its useful lifetime. This indicates that development must occur parallel to adoption to ensure that the BEV is the preferred economical option across all economic scenarios. The development must either increase the BEV long-haul truck fuel economy from 13.5MPGe to lower operating costs or improve charging capabilities from 350kW to reduce charging downtime. If this development occurs, partner companies will have a financial incentive as investing in BEV long-haul trucks will pay off in the long term.

Tesla Feasibility for Trucking Industry under One-to-One Ratio

Analysis was performed to understand whether the BEV choice would be preferred under the expected Tesla Semi-Truck operating conditions. The expected Tesla Semi-Truck operating conditions are a fuel economy of 19.8MPGe fully loaded and the implementation of a 1MW charger.[46] The aggressive development speed and baseline economic scenario were used for these calculations. For the aggressive development speed scenario, all values were kept the same except the MPGe of the BEV. Tesla's expected value for fuel economy was used instead of the 27MPGe standard. The results of this NPV analysis with a discount factor of 10.3% and a one-to-one charging station ratio are in Figure 6-8.

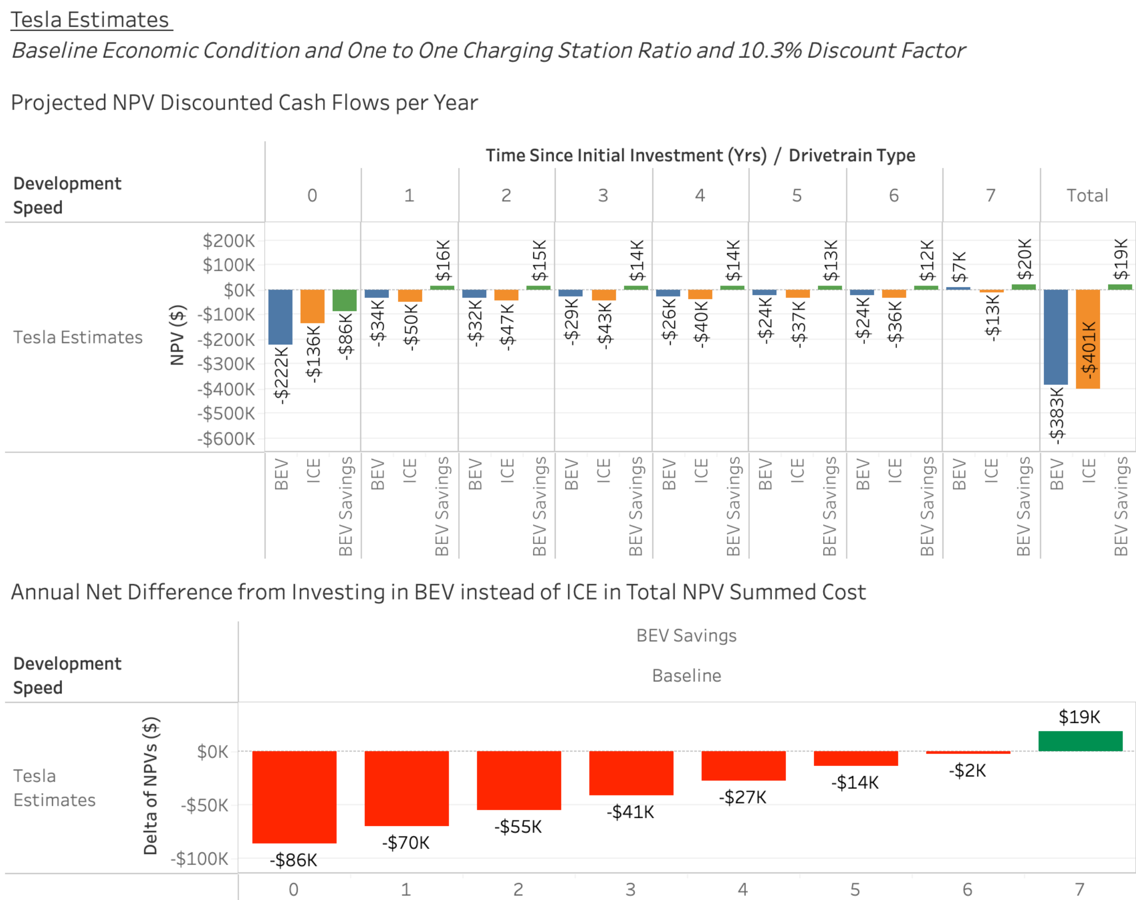


Figure 6-8: Tesla NPV Analysis at 10.3% Discount Factor and One-to-One Charging Ratio A.5.3

Based on these results, the projected average annual savings would be $13,973. In this scenario, there will be net positive financial gains of $19K with a payback period of 7 years. This demonstrates a long-term financial incentive to switch to a BEV, suggesting that the investment will pay off in the long term. Overall, this is a good indication for the trucking industry that if the Tesla semi-truck can meet its operating conditions and a one-to-one charging station ratio is used, investing in it could be a wise financial decision.

It is important to note that these analyses include a 10% operational capacity hit increasing the price of the vehicle from $180,000 to $198,000. The initial upfront cost includes the vehicle, the charging station, and the operational capacity hit.

Charging Station Scenario Two

Four Vehicles per Station at 10.3% Discount Factor

The figures in Appendix Section A.5.1 and Section A.5.2 provide a summary of the cash flows that would occur from procuring an ICE or BEV long-haul truck under the different economic and development speed scenarios with the assumption that for every four vehicles procured a charging station will be built.

These cash flows were used to determine the projected average operating savings per year, the BEV savings at the end of the seven years of expected ownership, and the annual net difference from investing in BEV instead of ICE. Figure 6-9, Figure 6-10, and 6-11 are the outcomes of this analysis.

Projected Average Operating Savings per Year from Transition to BEV

	Economic Condition				
Development Speed	Current	High Oil Cost	High Renewable Cost	Low Oil Cost	Baseline
Current	$19,833	$24,848	$7,878	-$1,178	$7,538
Medium	$27,530	$31,016	$15,693	$7,268	$14,892
Aggressive	$25,138	$28,097	$14,826	$7,523	$14,119

Average of NPV broken down by Economic Condition vs. Development Speed. The data is filtered on Time Since Initial Investment (Yrs), Drivetrain Type, Discount Factor and Charging Station Ratio. The Time Since Initial Investment (Yrs) filter excludes 0, 7, Total and Null. The Drivetrain Type filter keeps BEV Savings. The Discount Factor filter keeps 0.103. The Charging Station Ratio filter keeps One to Four. The view is filtered on Development Speed, which keeps Aggressive, Current and Medium.

Figure 6-9: Projected Average Operating Savings per Year from Transition to BEV at 10.3% Discount Factor and Four-to-One Charging Station Ratio

The projected annual average operating savings from transitioning to a BEV long-haul truck from an ICE long-haul truck demonstrate the benefits of operating a BEV. The lower operating cost of the BEV, due to lower fuel and maintenance costs, provides significant annual savings compared to an ICE vehicle. If any development occurs, across all economic scenarios, excluding the low oil cost scenario, the lowest annual average cost savings per vehicle is $14,119 and the highest potential annual average cost savings per vehicle is $31,016. However, if no development is made, all economic scenarios will see annual cost savings from transitioning to a BEV long-haul truck from an ICE long-haul truck, except the low oil cost scenario. If no development is made and current economic conditions continue, the average annual savings would be $19,833 from transitioning. If no development is made and high oil cost economic conditions occur, the average annual savings would be \$24,848 from transitioning. If no development is made and high renewable cost economic conditions occur, the average annual savings would be \$7,878 from transitioning. If no development is made and low oil cost economic conditions occur, there would not be savings. The average annual loss would be \$1,178 from transitioning to a BEV long-haul truck from an ICE long-haul truck. However, based on the feasibility assessment of the low oil cost scenario, the baseline will be considered as a lower bound. If no development is made, the baseline economic scenario would have an annual savings of \$7,538.

Although there are significant savings per year from operating a BEV truck instead of an ICE truck, it is vital to understand whether those savings are enough to offset the upfront cost of transitioning. This upfront cost includes procuring the vehicle, constructing and installing the charging station, and an operational capacity hit of 10%. To determine whether the average operating savings are enough, the total NPV financial gains from switching to BEV over the expected years of ownership were determined, as seen in Figure 6-10. Figure 6-11 illustrates the annual net difference from investing in BEV instead of ICE long-haul trucks and the payback period. *The Annual Net Differences* (Δ) *are calculated for each year using the following equation* $\Delta = NPV_{ICE} - NPV_{BEV}$.

Figure 6-10: Total NPV Analysis with BEV Savings at the end of Expected Years of Ownership at 10.3% Discount Factor and Four-to-One Charging Ratio

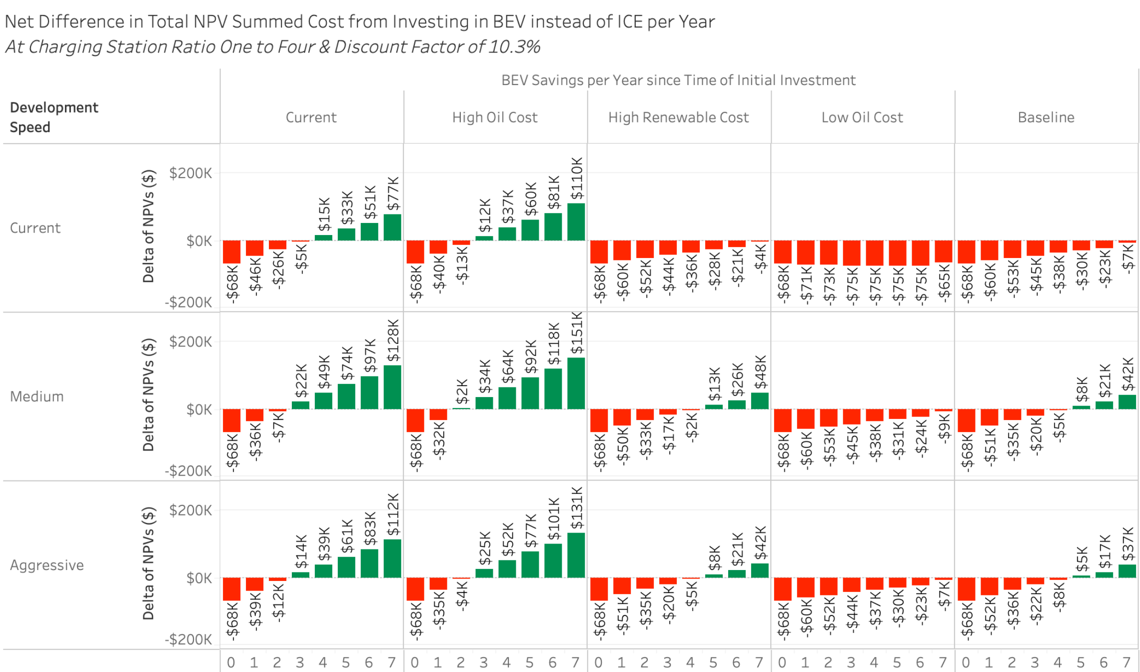


Figure 6-11: Annual Net Difference in Total NPV Summed Cost from Investing in BEV instead of ICE at 10.3% Discount Factor and Four-to-One Charging Ratio

This analysis demonstrated that with a discount factor of 10.3% and a four-to-one charging station ratio, development must occur for the BEV to be the preferred economical option in all economic scenarios. If development occurs, in all economic scenarios evaluated, there will be significant cost savings from procuring BEV long-haul vehicles instead of ICE long-haul vehicles by the end of the expected years of ownership. For the medium development speed scenario, the net positive financial gains per vehicle range from $42K to $151K, depending on the economic scenario. For the aggressive development speed development scenario, the net positive financial gains per vehicle range from $37K to $131K, depending on the economic scenario. The payback period per vehicle ranges from 2 to 5 years for the medium and aggressive development speed scenarios. If no further development occurs, under current economic conditions and high oil cost conditions, there will be net positive financial gains of $77K with a payback period of 4 years and $110K with a payback period of 3 years over the seven years of ownership, respectively. However, if no further development occurs in both the high renewable cost economic scenario and the baseline economic scenario, there will not be net positive financial gains from switching to BEV. The ICE vehicle will be a better financial investment by the end of its useful lifetime. This indicates that development must occur parallel to adoption to ensure that the BEV is the preferred economical option across all economic scenarios. The development must either increase the BEV long-haul truck fuel economy from 13.5MPGe to lower operating costs or improve charging capabilities from 350kW to reduce charging downtime. If this development occurs, partner companies will have a financial incentive as investing in BEV long-haul trucks will pay off in the long term.

Tesla Feasibility for Trucking Industry under Four-to-One Ratio

Analysis was performed to understand whether the BEV choice would be preferred under the expected Tesla Semi-Truck operating conditions. The expected Tesla Semi-Truck operating conditions are a fuel economy of 19.8MPGe fully loaded and the implementation of a 1MW charger.[46] The aggressive development speed and baseline economic scenario were used for these calculations. For the aggressive development speed scenario, all values were kept the same except the MPGe of the BEV. Tesla's expected value for fuel economy was used instead of the 27MPGe standard. The results of this NPV analysis with a discount factor of 10.3% and a four-to-one charging station ratio are in Figure 6-12.

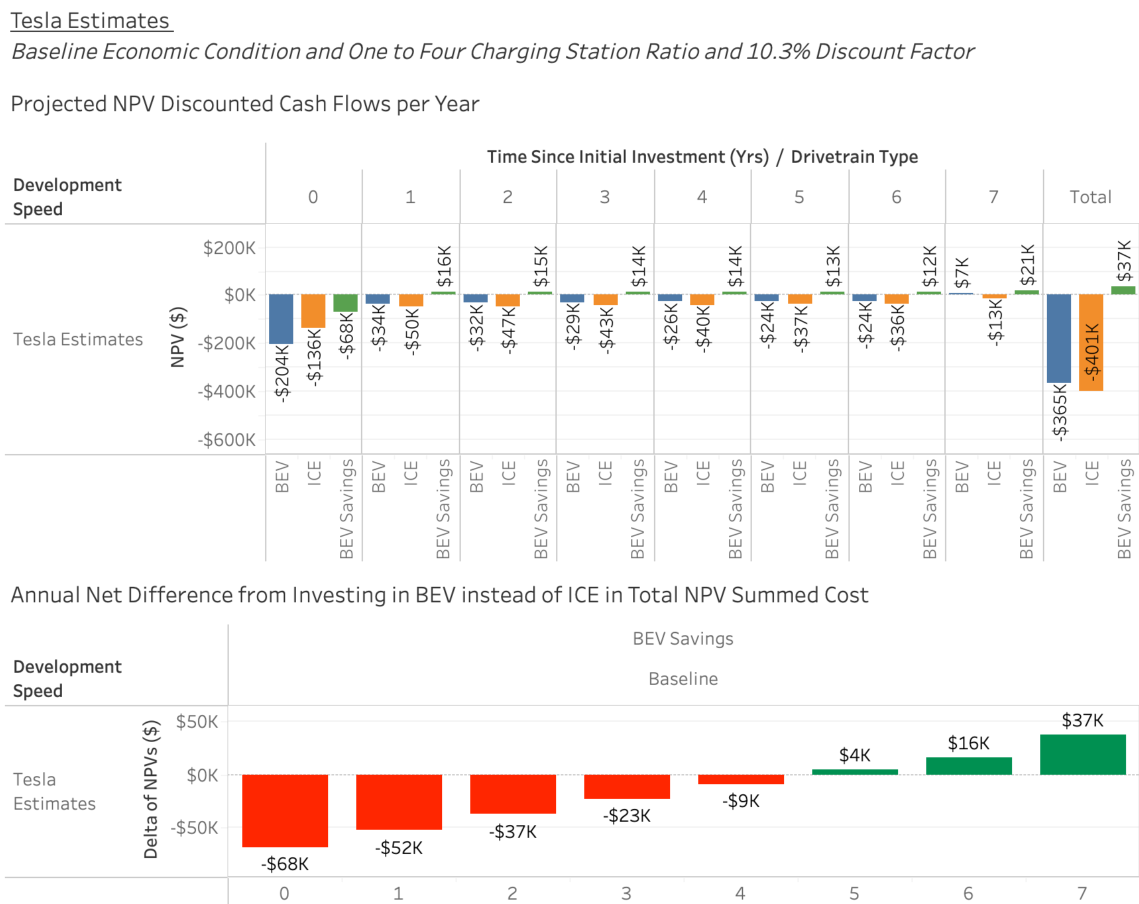


Figure 6-12: Tesla NPV Analysis at 10.3% Discount Factor and Four-to-One Charging Ratio A.5.3

Based on these results, the projected average annual savings would be $14,305. In this scenario, there will be net positive financial gains of $37K with a payback period of 5 years. This strengthens the long-term financial incentive to switch to a BEV, suggesting that the investment will pay off in the long term. Overall, this is a good indication for the trucking industry that if the Tesla semi-truck can meet its operating conditions and a four-to-one charging station ratio is used, investing in it would be a wise financial decision.

It is important to note that these analyses include a 10% operational capacity hit increasing the price of the vehicle from $180,000 to $198,000. The initial upfront cost includes the vehicle, the charging station, and the operational capacity hit.

6.4.2 Partner Companies Industry Model

This NPV analysis evaluates the potential profitability of transitioning to BEV long-haul trucks in the partner companies' industries. This approach uses an average discount factor of 7.61%, an operational capacity adjustment of 10%, and two different charging station scenarios per vehicle procured.

Charging Station Scenario One

One Vehicle per Station at 7.61% Discount Factor

The figures in Appendix Section A.5.1 and Section A.5.2 provide a summary of the cash flows that would occur from procuring an ICE or BEV long-haul truck under the different economic and development speed scenarios with the assumption that for every vehicle procured a charging station will be built.

These cash flows were used to determine the projected average operating savings per year, the BEV savings at the end of the seven years of expected ownership, and the annual net difference from investing in BEV instead of ICE. Figure 6-13, Figure 6-14, and 6-15 are the outcomes of this analysis.

Projected Average Operating Savings per Year from Transition to BEV

	Economic Condition				
Development Speed	Current	High Oil Cost	High Renewable Cost	Low Oil Cost	Baseline
Current	$21,514	$26,938	$8,530	-$1,297	$8,157
Medium	$29,843	$33,612	$16,989	$7,847	$16,117
Aggressive	$27,243	$30,441	$16,043	$8,119	$15,274

Average of NPV broken down by Economic Condition vs. Development Speed. The data is filtered on Time Since Initial Investment (Yrs), Drivetrain Type, Discount Factor and Charging Station Ratio. The Time Since Initial Investment (Yrs) filter excludes 0, 7, Total and Null. The Drivetrain Type filter keeps BEV Savings. The Discount Factor filter keeps 0.0761. The Charging Station Ratio filter keeps One to Four. The view is filtered on Development Speed, which keeps Aggressive, Current and Medium.

Figure 6-13: Projected Average Operating Savings per Year from Transition to BEV at 7.61% Discount Factor and One-to-One Charging Station Ratio

The projected annual average operating savings from transitioning to a BEV long-haul truck from an ICE long-haul truck demonstrate the benefits of operating a BEV. The lower operating cost of the BEV, due to lower fuel and maintenance costs, provides significant annual savings compared to an ICE vehicle. If any development occurs, across all economic scenarios, excluding the low oil cost scenario, the lowest annual average cost savings per vehicle is \$15,274 and the highest potential annual average cost savings per vehicle is \$33,612. However, if no development is made, all economic scenarios will see annual cost savings from transitioning to a BEV long-haul truck from an ICE long-haul truck, except the low oil cost scenario. If no development is made and current economic conditions continue, the average annual savings would be \$21,514 from transitioning. If no development is made and high oil cost economic conditions occur, the average annual savings would be \$26,938 from transitioning. If no development is made and high renewable cost economic conditions occur, the average annual savings would be \$8,530 from transitioning. If no development is made and low oil cost economic conditions occur, there would not be savings. The average annual loss would be \$1,297 from transitioning to a BEV long-haul truck from an ICE long-haul truck. However, based on the feasibility assessment of the low oil cost scenario, the baseline will be considered as a lower bound. If no development is made, the baseline economic scenario would have an annual savings of \$8,157.

Although there are significant savings per year from operating a BEV truck instead of an ICE truck, it is vital to understand whether those savings are enough to offset the upfront cost of transitioning. This upfront cost includes procuring the vehicle, constructing and installing the charging station, and an operational capacity hit of 10%. To determine whether the average operating savings are enough, the total NPV financial gains from switching to BEV over the expected years of ownership were determined, as seen in Figure 6-14. Figure 6-15 illustrates the annual net difference from investing in BEV instead of ICE long-haul trucks and the payback period. *The Annual Net Differences* (Δ) *are calculated for each year using the following equation* $\Delta = NPV_{ICE} - NPV_{BEV}$.

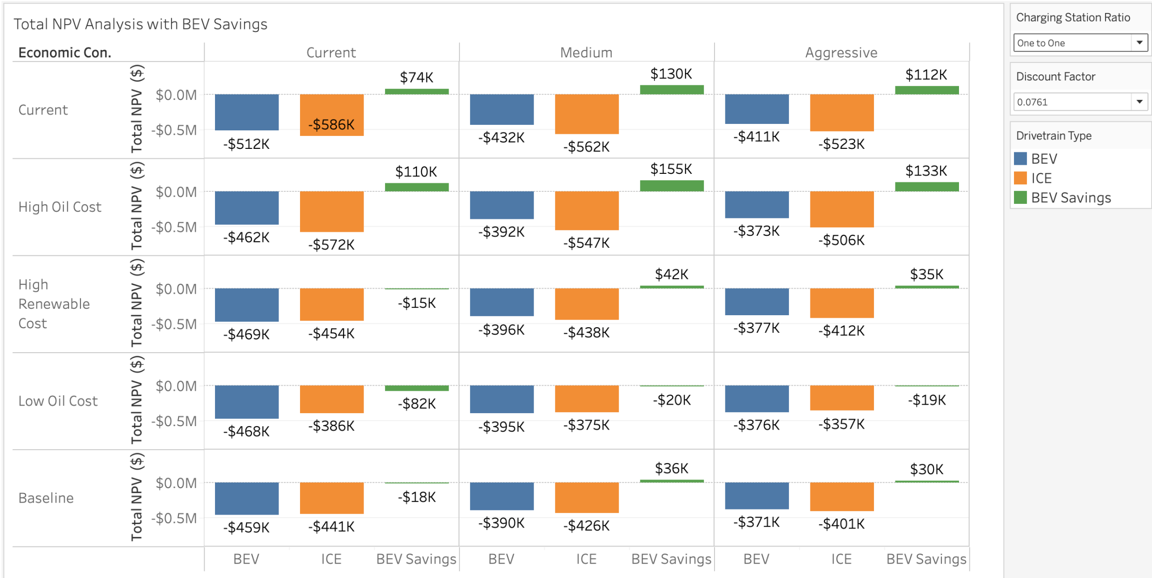


Figure 6-14: Total NPV Analysis with BEV Savings at the end of Expected Years of Ownership at 7.61% Discount Factor and One-to-One Charging Ratio

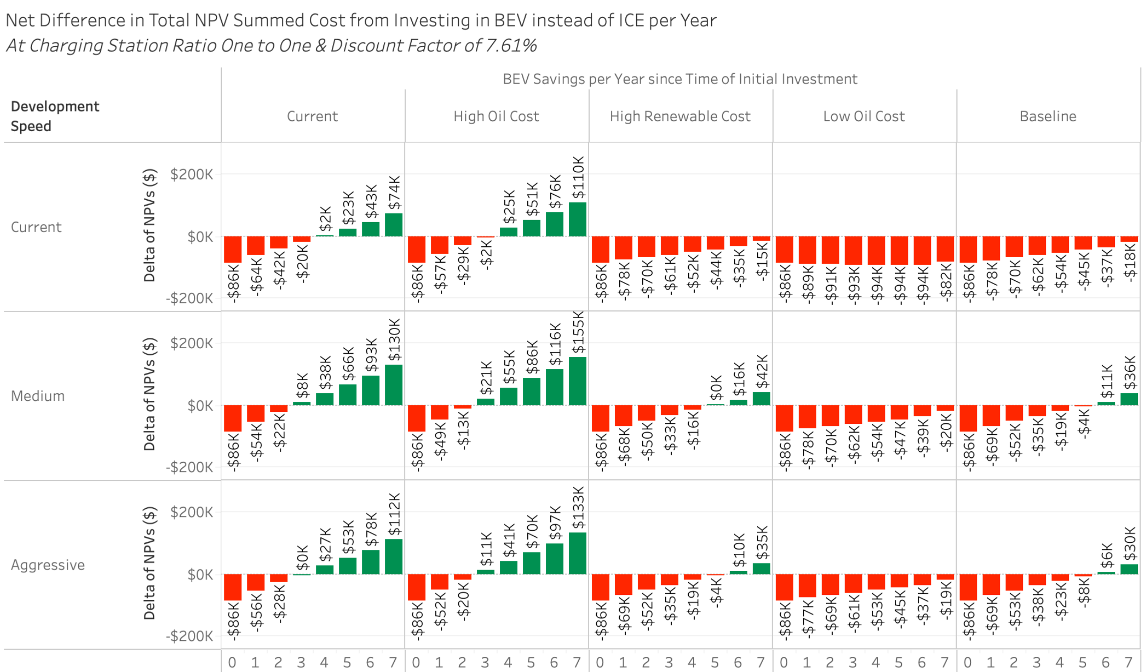


Figure 6-15: Annual Net Difference in Total NPV Summed Cost from Investing in BEV instead of ICE at 7.61% Discount Factor and One-to-One Charging Ratio

This analysis demonstrated that with a discount factor of 7.61% and a one-to-one charging station ratio, development must occur for the BEV to be the preferred economical option in all economic scenarios. If development occurs, in all economic scenarios evaluated, there will be significant cost savings from procuring BEV long-haul vehicles instead of ICE long-haul vehicles by the end of the expected years of ownership. For the medium development speed scenario, the net positive financial gains per vehicle range from $36K to $155K, depending on the economic scenario. For the aggressive development speed development scenario, the net positive financial gains per vehicle range from $30K to $133K, depending on the economic scenario. The payback period per vehicle ranges from 3 to 6 years for the medium and aggressive development speed scenarios. If no further development occurs, under current economic conditions and high oil cost conditions, there will be net positive financial gains of $74K and $110K over the seven years of ownership, respectively, with both having a payback period of 4 years. However, if no further development occurs in both the high renewable cost economic scenario and the baseline economic scenario, there will not be net positive financial gains from switching to BEV. The ICE vehicle will be a better financial investment by the end of its useful lifetime. This indicates that development must occur parallel to adoption to ensure that the BEV is the preferred economical option across all economic scenarios. The development must either increase the BEV long-haul truck fuel economy from 13.5MPGe to lower operating costs or improve charging capabilities from 350kW to reduce charging downtime. If this development occurs, partner companies will have a financial incentive as investing in BEV long-haul trucks will pay off in the long term.

Tesla Feasibility for Partner Companies under One-to-One Ratio

Analysis was performed to understand whether the BEV choice would be preferred under the expected Tesla Semi-Truck operating conditions. The expected Tesla Semi-Truck operating conditions are a fuel economy of 19.8MPGe fully loaded and the implementation of a 1MW charger.[46] The aggressive development speed and baseline economic scenario were used for these calculations. For the aggressive development speed scenario, all values were kept the same except the MPGe of the BEV. Tesla's expected value for fuel economy was used instead of the 27MPGe standard. The results of this NPV analysis with a discount factor of 7.61% and a one-to-one charging station ratio are in Figure 6-16.

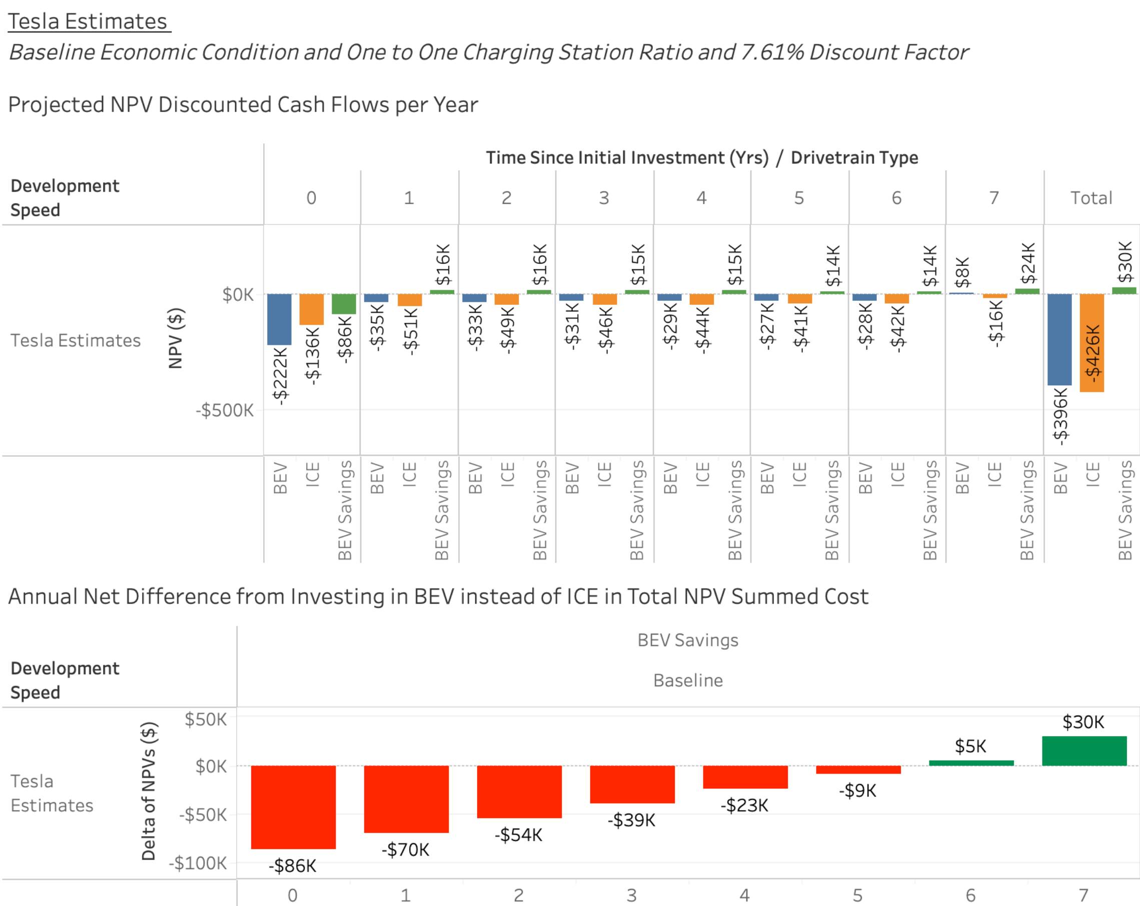


Figure 6-16: Tesla NPV Analysis at 7.61% Discount Factor and One-to-One Charging Ratio A.5.3

Based on these results, the projected average annual savings would be $15,190. In this scenario, there will be net positive financial gains of $30K with a payback period of 6 years. This demonstrates a long-term financial incentive to switch to a BEV, suggesting that the investment will pay off in the long term. Overall, this is a good indication for the partner companies that if the Tesla semi-truck can meet its operating conditions and a one-to-one charging station ratio is used, investing in it would be a wise financial decision.

It is important to note that these analyses include a 10% operational capacity hit increasing the price of the vehicle from $180,000 to $198,000. The initial upfront cost *includes the vehicle, the charging station, and the operational capacity hit.*

Charging Station Scenario Two

Four Vehicles per Station at 7.61% Discount Factor

The figures in Appendix Section A.5.1 and Section A.5.2 provide a summary of the cash flows that would occur from procuring an ICE or BEV long-haul truck under the different economic and development speed scenarios with the assumption that for every four vehicles procured a charging station will be built.

These cash flows were used to determine the projected average operating savings per year, the BEV savings at the end of the seven years of expected ownership, and the annual net difference from investing in BEV instead of ICE. Figure 6-17, Figure 6-18, and 6-19 are the outcomes of this analysis.

Projected Average Operating Savings per Year from Transition to BEV

	Economic Condition				
Development Speed	Current	High Oil Cost	High Renewable Cost	Low Oil Cost	Baseline
Current	$21,581	$27,005	$8,597	-$1,230	$8,223
Medium	$29,910	$33,679	$17,055	$7,914	$16,184
Aggressive	$27,310	$30,507	$16,110	$8,185	$15,341

Average of NPV broken down by Economic Condition vs. Development Speed. The data is filtered on Time Since Initial Investment (Yrs), Drivetrain Type, Discount Factor and Charging Station Ratio. The Time Since Initial Investment (Yrs) filter excludes 0, 7, Total and Null. The Drivetrain Type filter keeps BEV Savings. The Discount Factor filter keeps 0.0761. The Charging Station Ratio filter keeps One to Four. The view is filtered on Development Speed, which keeps Aggressive, Current and Medium.

Figure 6-17: Projected Average Operating Savings per Year from Transition to BEV at 7.61% Discount Factor and Four-to-One Charging Station Ratio

The projected annual average operating savings from transitioning to a BEV long-haul truck from an ICE long-haul truck demonstrate the benefits of operating a BEV. The lower operating cost of the BEV, due to lower fuel and maintenance costs, provides significant annual savings compared to an ICE vehicle. If any development occurs, across all economic scenarios, excluding the low oil cost scenario, the lowest annual average cost savings per vehicle is $15,341 and the highest potential annual average cost savings per vehicle is $33,679. However, if no development is made, all economic scenarios will see annual cost savings from transitioning to a BEV long-haul truck from an ICE long-haul truck, except the low oil cost scenario. If no development is made and current economic conditions continue, the average annual savings per vehicle would be $21,581 from transitioning. If no development is made and high oil cost economic conditions occur, the average annual savings per vehicle would be $27,005 from transitioning. If no development is made and high renewable cost economic conditions occur, the average annual savings per vehicle would be $8,597 from transitioning. If no development is made and low oil cost economic conditions occur, there would not be savings. The average annual loss would be $1,230 from transitioning to a BEV long-haul truck from an ICE long-haul truck. However, based on the feasibility assessment of the low oil cost scenario, the baseline will be considered as a lower bound. If no development is made, the baseline economic scenario would have an annual savings of $8,223.

Although there are significant savings per year from operating a BEV truck instead of an ICE truck, it is vital to understand whether those savings are enough to offset the upfront cost of transitioning. This upfront cost includes procuring the vehicle, constructing and installing the charging station, and an operational capacity hit of 10%. To determine whether the average operating savings are enough, the total NPV financial gains from switching to BEV over the expected years of ownership were determined, as seen in Figure 6-18. Figure 6-19 illustrates the annual net difference from investing in BEV instead of ICE long-haul trucks and the payback period. *The Annual Net Differences (Δ) are calculated for each year using the following equation* $\Delta = NPV_{ICE} - NPV_{BEV}$.

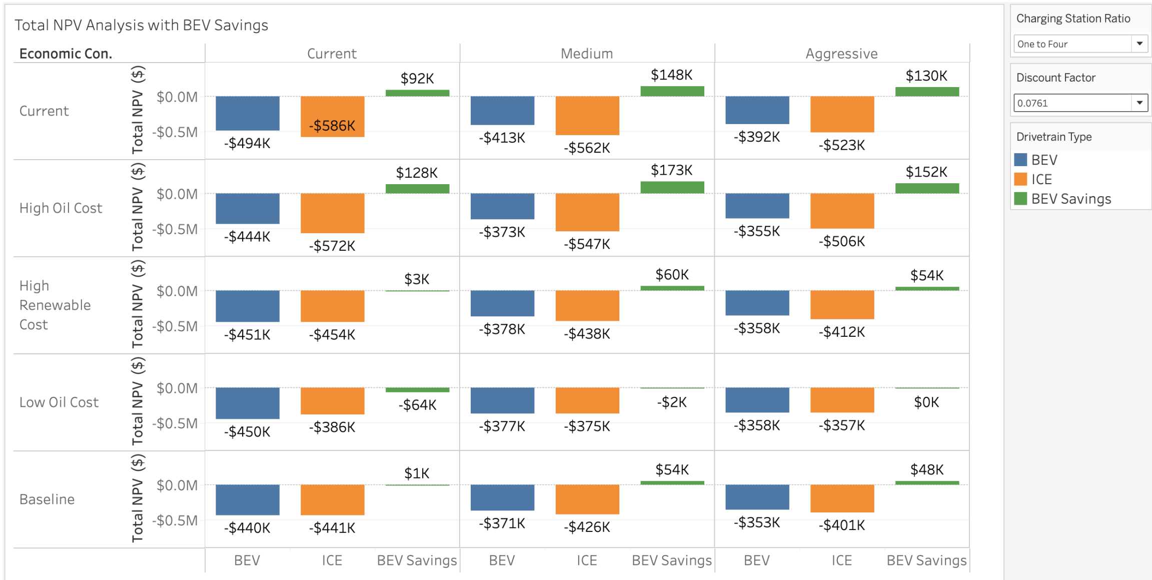


Figure 6-18: Total NPV Analysis with BEV Savings at the end of Expected Years of Ownership at 7.61% Discount Factor and Four-to-One Charging Ratio

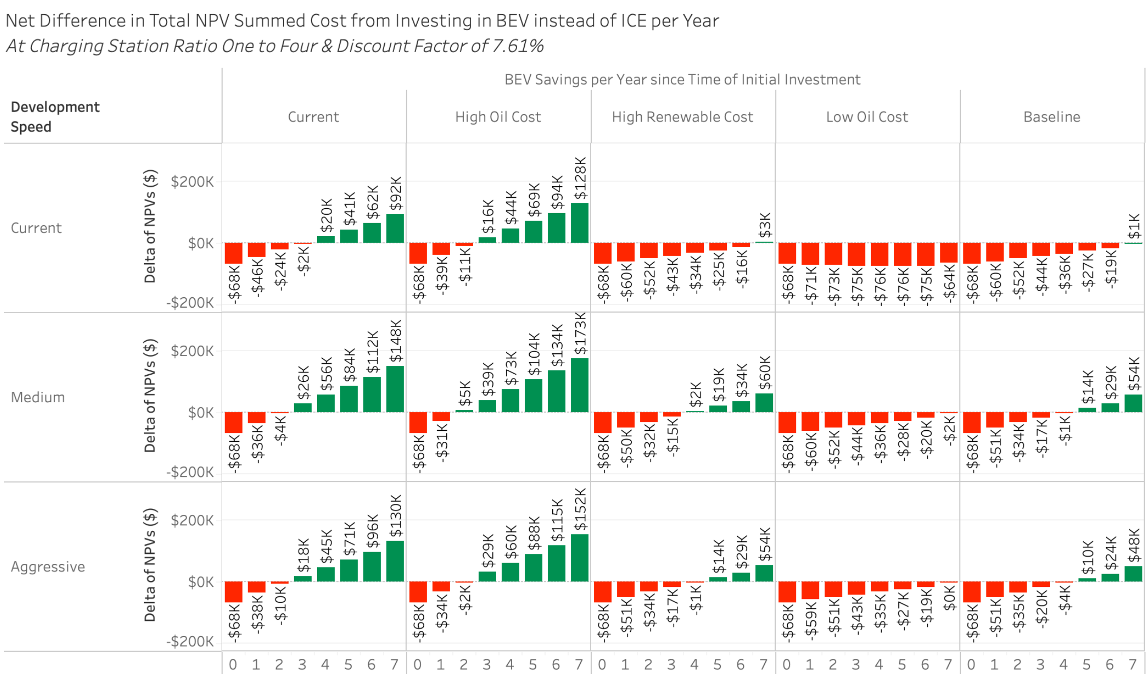


Figure 6-19: Annual Net Difference in Total NPV Summed Cost from Investing in BEV instead of ICE at 7.61% Discount Factor and Four-to-One Charging Ratio

This analysis demonstrated that with a discount factor of 7.61% and a four-to-one charging station ratio, regardless of development, the BEV will be the preference in all economic scenarios. If development occurs, in all economic scenarios evaluated, there will be significant cost savings from procuring BEV long-haul vehicles instead of ICE long-haul vehicles by the end of the expected years of ownership. For the medium development speed scenario, the net positive financial gains per vehicle range from $54K to $173K, depending on the economic scenario. For the aggressive development speed scenario, the net positive financial gains per vehicle range from $48K to $152K, depending on the economic scenario. The payback period per vehicle ranges from 2 to 5 years for medium and aggressive development speed scenarios. If no further development occurs, under current economic conditions and high oil cost conditions, there will be net positive financial gains of $92K with a payback period of 4 years and $128K with a payback period of 3 years over the seven years of ownership, respectively. However, if no further development occurs under the high renewable cost economic scenario and the baseline economic scenario, there will be net positive financial gains of $3K and $1K, respectively, with payback periods of 7 years. Although there are net positive financial gains in these scenarios, the savings from the switch to a BEV will have minimally exceeded the costs of the switch due to the resulting net positive financial gains over the seven years of ownership. Therefore, it is recommended that development occur to ensure that a strong financial incentive exists to make the switch to a BEV. This indicates that for partner companies looking to transition to BEV long-haul trucks, if they implement one charging station for every four vehicles procured, no development has to be made for the BEV to be the preferred economical choice. There is a financial incentive to switch to a BEV, as it suggests that the investment will pay off in the long term, and the benefits will be greater than the costs. However, due to the small net positive financial gains in the high renewable cost and baseline cost economic scenarios, it is recommended that development occurs parallel to adoption.

Tesla Feasibility for Partner Companies under Four-to-One Ratio

Analysis was performed to understand whether the BEV choice would be preferred under the expected Tesla Semi-Truck operating conditions. The expected Tesla Semi-Truck operating conditions are a fuel economy of 19.8MPGe fully loaded and the implementation of a 1MW charger.[46] The aggressive development speed and baseline economic scenario were used for these calculations. For the aggressive development speed scenario, all values were kept the same except the MPGe of the BEV. Tesla's expected value for fuel economy was used instead of the 27MPGe standard. The results of this NPV analysis with a discount factor of 7.61% and a four-to-one charging station ratio are in Figure 6-20.

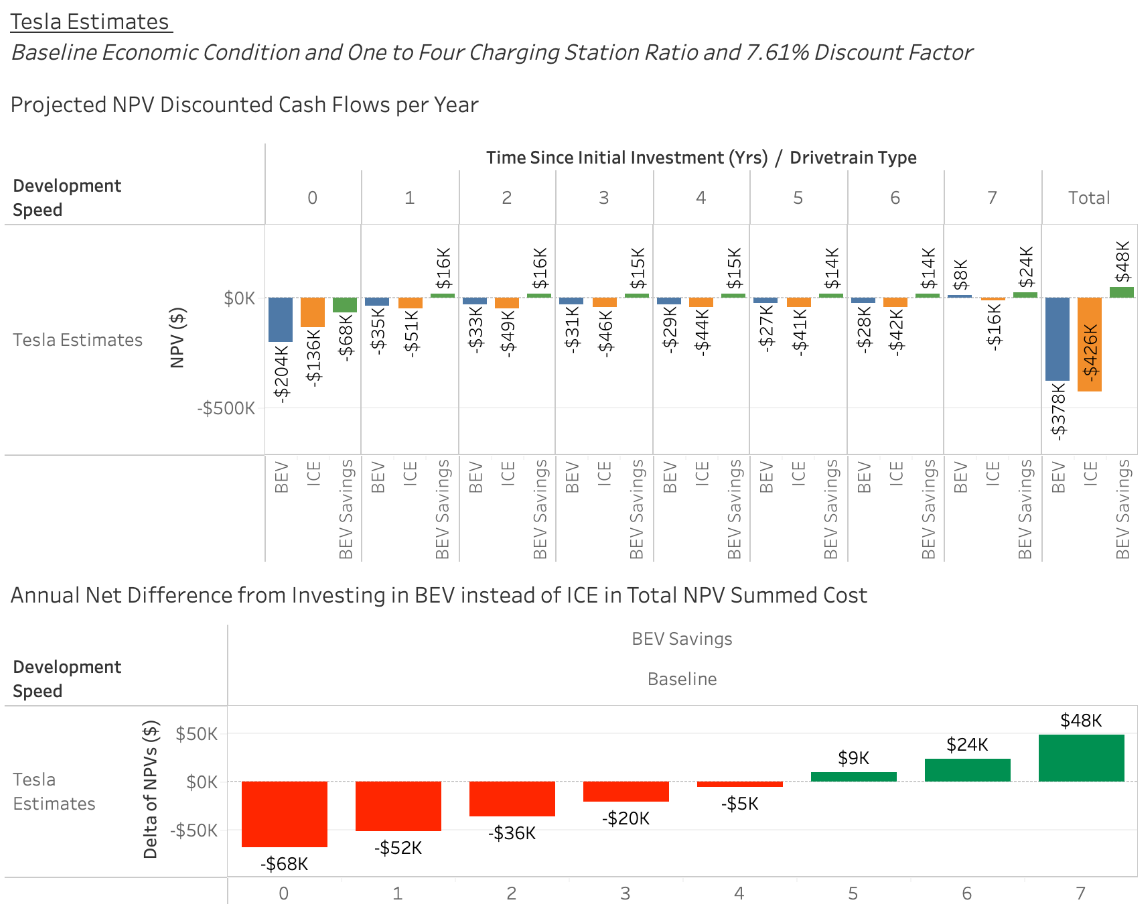


Figure 6-20: Tesla NPV Analysis at 7.61% Discount Factor and One-to-One Charging Ratio A.5.3

Based on these results, the projected average annual savings would be $15,256. In this scenario, there will be net positive financial gains of $48K with a payback period of 5 years. This strengthens the long-term financial incentive to switch to a BEV, suggesting that the investment will pay off in the long term. Overall, this is a good indication for the partner companies that if the Tesla semi-truck can meet its operating conditions and a four-to-one charging station ratio is used, investing in it would be a wise financial decision.

It is important to note that these analyses include a 10% operational capacity hit increasing the price of the vehicle from $180,000 to $198,000. The initial upfront cost includes the vehicle, the charging station, and the operational capacity hit.

6.4.3 Summary of Industry NPV Analysis

The NPV Analysis indicates that development must occur parallel to adoption to ensure that BEV is the preferred economical choice across all economic scenarios. The development must either increase the BEV long-haul truck fuel economy from 13.5MPGe to lower operating costs or improve charging capabilities from 350kW to reduce charging downtime. It is important to remember that within all of the charging station scenarios considered in the analysis, 20% of charging is assumed to be done in public charging stations. Additionally, the financial gains discussed are over the cost of capital. This means that the gains are in addition to the cost of equity and that the companies' equity would be covered. This means that the companies would have a financial gain even after covering the capital cost, including the cost of equity.

If the charging station ratio is one vehicle per charging station for both the trucking industry and the partner companies, there will need to be at least medium development for BEVs to be a solid long-term investment. If the charging station ratio is four vehicles per charging station, the partner companies do not need development to occur for BEVs to be a strong long-term investment, though it is still recommended. Considering the baseline economic scenario as the lower bound rather than the low oil cost scenario, under the medium development speed conditions, which only require 500kW charging stations, the BEV must have a fuel economy above 13.5 MPGe to be the more cost-effective option. Therefore, the development improvement must be of the charging capabilities.

Both of these developments are feasible and likely to happen, especially considering Tesla's expected fuel economy of 19.8MPGe and the current development of a 1MW charger.[46] If Tesla can meet these operational conditions, the trucking industry and partner companies would see significant savings from investing in Tesla's semi. If the charging station ratio is one vehicle per charging station, the trucking industry would have a total NPV savings of $19K with a payback period of 7 years, and the partner companies would have a total NPV savings of $30K with a payback period of 6 years. If the charging station ratio is four vehicles per charging station, the trucking industry would have a total NPV savings of $37K with a payback period of 5 years, and partner companies would have a total NPV savings of $48K with a payback period of 5 years. If Tesla meets these operating conditions, the long-term financial incentive to switch to a BEV is strengthened further, suggesting that the investment will pay off more quickly. Overall, this is a good indication that investing in Tesla's Semi would be a wise financial decision. Although it is not presented, further analysis was performed across all scenarios, which found that if current chargers of 350kW are used or the 500kW charger is implemented, the Tesla semi-truck would still be the better long-term investment.

6.5 Environmental Impact Analysis

To understand the environmental impacts of BEV and ICE long-haul Class 8 trucks, GHG and direct emissions from air pollutants were evaluated over the complete lifecycle to procure each type of vehicle. The models output a comparative analysis of the emissions for each vehicle type under each development speed scenario. Only development speed scenarios are evaluated, as the economic scenarios do not impact the emissions. The emissions analyzed are the well-to-wheel emissions. They are calculated based on energy usage per year and the carbon intensity of that energy source. This method for calculating emissions is significant. For example, by using this method, the calculations for the BEV vehicle are specific to the average U.S. grid and its respective emissions. Therefore, it accurately reflects the energy mixture used to power the grid rather than assuming a fully renewable energy source. This approach considers the grid gross loss, upstream emissions after transmission loss, and average U.S. plant output direct emission rates from air pollutants such as PM10, PM2.5, and VOC. Therefore, this comprehensive approach allows us to accurately assess the environmental impacts of using the U.S. grid as an energy source. Using this approach and the methods described in more detail in Chapter 5.2.4, the annual emissions of each vehicle were estimated. These estimates comprehensively assess the environmental impacts of using a BEV long-haul Class 8 truck versus an ICE long-haul Class 8 truck.

Figure 6-21 illustrates the lifecycle CO2, or GHG, emissions for the procurement and operations of both an ICE and BEV long-haul truck.

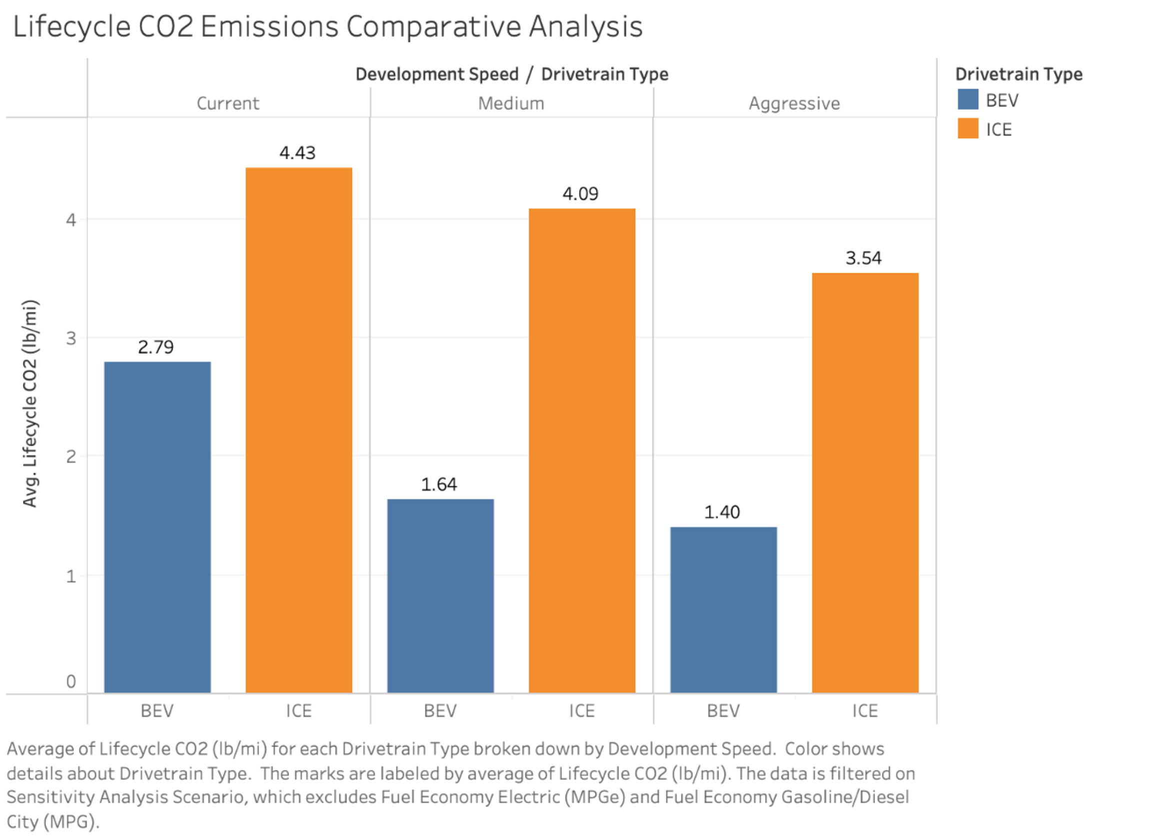


Figure 6-21: Lifecycle CO2 Emissions Comparative Analysis

The results of this analysis demonstrate that even with the energy mix of the U.S. grid not being fully renewable, switching to a BEV vehicle would reduce emissions regardless of the development speed scenario. If no development occurs, switching from an ICE long-haul truck to a BEV will reduce the lifecycle CO2 emissions by 37%. This is because the average pounds of CO2 emitted per mile are 1.6 times more for an ICE long-haul truck. If the medium development speed scenario occurs, the BEV's emissions will reduce by 41% compared to the BEV's emissions in the current development speed scenario. In contrast, the ICE truck's emissions will only reduce by 8% compared to the ICE long-haul truck's emissions in the current development speed scenario. This means that by switching to a BEV long-haul truck from an ICE long-haul truck, the lifecycle CO2 emissions will reduce by 60%. This is because the average pounds of CO2 emitted per mile are 2.5 times more for an ICE long-haul truck. If the aggressive development speed scenario occurs, the BEV's emissions will reduce by 15% compared to the BEV's emissions in the medium development speed scenario and by 50% compared to the current development speed scenario. In contrast, the ICE truck's emissions will reduce by 15% compared to the ICE long-haul truck's emissions in the medium development speed scenario and by 20% compared to the current development speed scenario. Regardless of the ICE emissions savings in the aggressive development speed scenario, by switching to a BEV long-haul truck from an ICE long-haul truck, the lifecycle CO2 emissions will still reduce by 60%. This is because the average pounds of CO2 emitted per mile are 2.5 times more for an ICE long-haul truck.

Figure 6-22 illustrates the direct emissions from air pollutants for the procurement and operations of both an ICE and BEV long-haul truck.

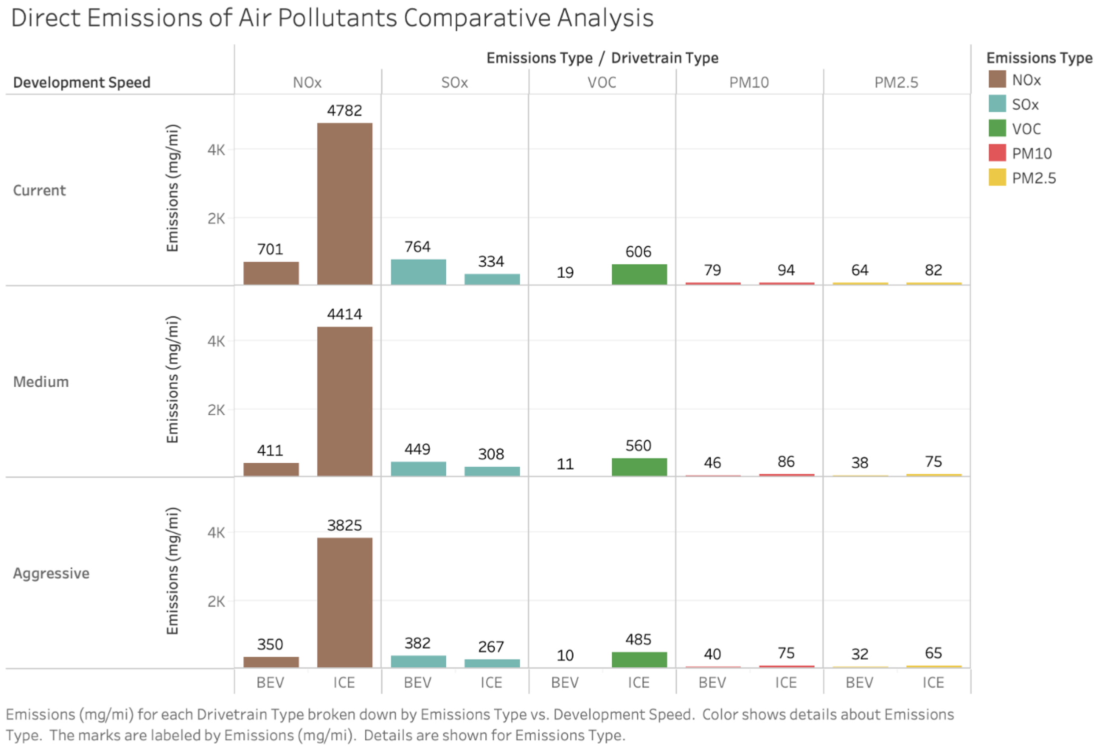


Figure 6-22: Direct Emissions from Air Pollutants Comparative Analysis

Similar to the lifecycle CO2 analysis performed in Figure 6-21, by switching to a BEV long-haul truck, even with the energy mix of the U.S. grid not being fully renewable, all emissions, except SOx, would be reduced regardless of the development speed scenario. If no development occurs by switching from an ICE long-haul truck to a BEV, the following direct emissions reductions will occur:

1. The lifecycle NOx emissions will reduce by 85%, as an ICE long-haul truck emits 6.8 times more milligrams of NOx per mile on average.

2. The lifecycle VOC emissions will reduce by 97%, as an ICE long-haul truck emits 31.9 times more milligrams of VOC per mile on average.

3. The lifecycle PM10 emissions will reduce by 15%, as an ICE long-haul truck emits 1.2 times more milligrams of PM10 per mile on average.

4. The lifecycle PM2.5 emissions will reduce by 21%, as an ICE long-haul truck emits 1.3 times more milligrams of PM10 per mile on average.

If the medium development speed scenario occurs by switching from an ICE long-haul truck to a BEV, the following direct emissions reductions will occur:

1. The BEV's NOx emissions will reduce by 41% compared to the BEV's NOx emissions in the current development speed scenario. In contrast, the ICE truck's NOx emissions will only reduce by 8% compared to the ICE long-haul truck's NOx emissions in the current development speed scenario. This means that by switching to a BEV long-haul truck from an ICE long-haul truck, the lifecycle NOx emissions will reduce by 91%, as an ICE long-haul truck emits 10.7 times more milligrams of NOx per mile on average.

2. The BEV's VOC emissions will reduce by 42% compared to the BEV's VOC emissions in the current development speed scenario. In contrast, the ICE truck's VOC emissions will only reduce by 7.6% compared to the ICE long-haul truck's VOC emissions in the current development speed scenario. This means that by switching to a BEV long-haul truck from an ICE long-haul truck, the lifecycle VOC emissions will reduce by 98%, as an ICE long-haul truck emits 50.9 times more milligrams of VOC per mile on average.

3. The BEV's PM10 emissions will reduce by 42% compared to the BEV's PM10 emissions in the current development speed scenario. In contrast, the ICE truck's PM10 emissions will only reduce by 8.5% compared to the ICE long-haul truck's PM10 emissions in the current development speed scenario. This means that by switching to a BEV long-haul truck from an ICE long-haul truck, the lifecycle PM10 emissions will reduce by 47%, as an ICE long-haul truck emits 1.9 times more milligrams of PM10 per mile on average.

4. The BEV's PM2.5 emissions will reduce by 41% compared to the BEV's PM2.5 emissions in the current development speed scenario. In contrast, the ICE truck's PM2.5 emissions will only reduce by 8.5% compared to the ICE long-haul truck's PM2.5 emissions in the current development speed scenario. This means that by switching to a BEV long-haul truck from an ICE long-haul truck, the lifecycle

PM2.5 emissions will reduce by 49%, as an ICE long-haul truck emits 2 times more milligrams of PM2.5 per mile on average.

If the aggressive development speed scenario occurs by switching from an ICE long-haul truck to a BEV, the following direct emissions reductions will occur:

1. The BEV's NOx emissions will reduce by 14.8% compared to the BEV's emissions in the medium development speed scenario and by 50% compared to the current development speed scenario. In contrast, the ICE truck's emissions will reduce by 13.3% compared to the ICE long-haul truck's emissions in the medium development speed scenario and by 20% compared to the current development speed scenario. Regardless of the ICE emissions savings in the aggressive development speed scenario, by switching to a BEV long-haul truck from an ICE long-haul truck, the lifecycle NOx emissions will still reduce by 91%, as an ICE long-haul truck emits 10.9 times more milligrams of NOx per mile on average.

2. The BEV's VOC emissions will reduce by 9.1% compared to the BEV's emissions in the medium development speed scenario and by 47.4% compared to the current development speed scenario. In contrast, the ICE truck's emissions will reduce by 13.4% compared to the ICE long-haul truck's emissions in the medium development speed scenario and by 20% compared to the current development speed scenario. Regardless of the ICE emissions savings in the aggressive development speed scenario, by switching to a BEV long-haul truck from an ICE long-haul truck, the lifecycle VOC emissions will still reduce by 98%, as an ICE long-haul truck emits 48.5 times more milligrams of VOC per mile on average.

3. The BEV's PM10 emissions will reduce by 13% compared to the BEV's emissions in the medium development speed scenario and by 49.4% compared to the current development speed scenario. In contrast, the ICE truck's emissions will reduce by 12.8% compared to the ICE long-haul truck's emissions in the medium development speed scenario and by 20.2% compared to the current

development speed scenario. Regardless of the ICE emissions savings in the aggressive development speed scenario, by switching to a BEV long-haul truck from an ICE long-haul truck, the lifecycle PM10 emissions will still reduce by 47%, as an ICE long-haul truck emits 1.9 times more milligrams of PM10 per mile on average.

4. The BEV's PM2.5 emissions will reduce by 15.8% compared to the BEV's emissions in the medium development speed scenario and by 50% compared to the current development speed scenario. In contrast, the ICE truck's emissions will reduce by 13.3% compared to the ICE long-haul truck's emissions in the medium development speed scenario and by 20.7% compared to the current development speed scenario. Regardless of the ICE emissions savings in the aggressive development speed scenario, by switching to a BEV long-haul truck from an ICE long-haul truck, the lifecycle PM2.5 emissions will still reduce by 50.8%, as an ICE long-haul truck emits 2 times more milligrams of PM10 per mile on average.

Regardless of development, switching from an ICE long-haul truck to a BEV would significantly increase SOx emissions. Although these emissions would reduce with medium and aggressive development scenarios, they are still significant compared to the ICE long-haul truck. If no development occurs, the lifecycle SOx emissions will increase by 128%, as a BEV long-haul truck emits 0.44 times more milligrams of SOx per mile on average. If the medium development scenario occurs, the BEV's SOx emissions will reduce by 41% compared to the BEV's SOx emissions in the current development speed scenario. In contrast, the ICE truck's SOx emissions will only reduce by 7.8% compared to the ICE long-haul truck's SOx emissions in the current development speed scenario. Even with the reduction in BEV SOx emissions from current to medium development speed scenarios, by switching to a BEV long-haul truck from an ICE long-haul truck, the lifecycle SOx emissions will increase by 45%, as a BEV long-haul truck emits 0.68 times more milligrams of SOx per mile on average. If the aggressive development speed scenario occurs, the BEV's SOx emissions will reduce by 15% compared to the BEV's SOx emissions in the medium development speed scenario and by 50% in the current development speed scenario. In contrast, the ICE truck's SOx emissions will only reduce by 13.3% compared to the ICE long-haul truck's SOx emissions in the medium development speed scenario and by 20% in the current development speed scenario. Even with the reduction in BEV SOx emissions from current to aggressive development speed scenarios, by switching to a BEV long-haul truck from an ICE long-haul truck, the lifecycle SOx emissions will increase by 43%, as a BEV long-haul truck emits 0.7 times more milligrams of SOx per mile on average. The SOx relevant for BEV vehicles is Sulfur Dioxide (SO2). An increase in SO2 can "affect lung function, worsen asthma attacks, and worsen existing heart disease in sensitive groups."[45] To understand if the increase in emissions of SO2 in milligrams per mile will be significant, more analysis will have to be performed. Aside from the additional analysis that must be performed on the potential impacts of the increase in SO2 from transitioning to BEV long-haul trucks, the environmental impacts favor the transition to BEVs. If no development occurs, there would be a 37% reduction in GHG emissions and an 85% reduction in all direct emissions from air pollutants, not including SO2. If medium or aggressive development occurs, there would be a 60% reduction in GHG emissions and a 90% reduction in all direct emissions from air pollutants, not including SO2. By transitioning to BEVs, there can be significant and immediate emissions reductions, even if further development does not occur. This transition could be vital in reducing emissions and addressing climate change.

6.6 Key Takeaways

This comprehensive highly conservative analysis evaluated the economic and environmental impacts of transitioning to BEV long-haul trucks from ICE trucks. The environmental impact analysis demonstrates evident emissions reductions that can occur from transition to a BEV long-haul truck, regardless of development speed. If the transition occurs now, there would be a 37% reduction in GHG emissions and an 85% reduction in all direct emissions from air pollutants, not including SO2, immediately. If medium or aggressive development occurs, there would be a 60% reduction in GHG emissions and a 90% reduction in all direct emissions from air pollutants, not including SO2. The highly conservative financial analysis revealed that BEV long-haul trucks would be the preferred choice if development occurs. This is because BEVs are a better investment over the years of ownership due to lower operating costs, like fuel and maintenance. This is illustrated in the total cost of ownership analysis, threshold analysis, and comprehensive NPV analysis. The TCO analysis demonstrates that BEVs are preferred in most economic scenarios. If development occurs, BEVs would be the preference in all economic scenarios. However, this TCO analysis is based on static scenarios with remaining uncertainties. This means that the analysis takes into account known costs and benefits of electrification, but there may be additional unknown factors that could impact the final outcome. One of the critical considerations in the analysis is the upfront cost of electrification, which is not negligible. This includes the cost of purchasing BEVs, a 10% operational capacity hit, and the cost of constructing and installing charging infrastructure to support them. Therefore, development is recommended parallel to adoption to strengthen the case for BEV long-haul trucks. The threshold analysis demonstrates that the BEV is preferred across all economic scenarios if development occurs. However, the economic benefits are subject to market conditions if no further development occurs. If no further development occurs and the price of diesel remains above $3.65, BEV vehicles will be the preferred option, as there will be net financial gains from transitioning. However, if the price of diesel drops below $2.24 or electricity prices go above $0.59, regardless of developments made, the ICE vehicle will be the preferred investment choice. This demonstrates that if the price of diesel decreases, it would be necessary to decrease the price of electricity to make electrification more compelling. However, if diesel prices remain high, there is a strong case for electrification as the range of acceptable transportation end consumer electricity prices increases. The highest acceptable price for transportation end consumer electricity is $0.12 per kWh for BEVs to be preferred. For transportation end consumer pricing, the baseline pricing is $0.11 per kWh. However, the electricity price could be considerably lower depending on how the energy is sourced. If the energy comes directly from renewable sources, electricity prices are as low as $0.033 per kWh. The Competitiveness of Renewables Continued Amid Fossil Fuel Crisis report published by the International Renewable Energy Agency (IRENA) illustrates that 2021 electricity prices for on-shore wind were $0.033 per kWh, solar PV were $0.048 per kWh, and off-shore wind were $0.075 per kWh.[6] These prices are significantly lower than those assumed in the analysis. This highlights the importance of considering energy sourcing when evaluating the feasibility of electrification of long-haul trucking, as it can significantly impact the financial outcomes transitioning. By utilizing renewable energy sources, companies can substantially decrease operating costs, making the transition to BEVs even more financially viable. The NPV Analysis demonstrates that the BEV is preferred across all economic scenarios if development occurs. However, if no further development occurs, the economic benefits are again subject to market conditions. In the current economic conditions with no further development, BEV long-haul trucks are a good investment for the trucking industry and partner companies. For the trucking industry, depending on the charging station ratio chosen, they will have net financial gains of $59K with a payback period of 5 years or $77K with a payback period of 4 years. Depending on the charging station ratio chosen, partner companies will have net financial gains of $74K with a payback period of 4 years or $92K with a payback period of 4 years. The gains illustrated in the analysis across the many economic and development scenarios occur for companies even after covering the capital cost and include the 20% of charging that is assumed to be performed at public charging stations, which have higher electricity prices. The financial gains demonstrate that BEV is the preferred option. It is important to note that these outcomes occurred even with highly conservative estimates, like the charging station ratios and the 10% operational capacity hit. Regardless, some companies may be hesitant to invest despite the approach's conservatism and the financial gains shown due to concerns about payback periods. They may argue that they are uncertain what the improvements in BEVs will be in the next 5-7 years and, therefore, may not see a return on their investment. However, it is essential to consider the system dynamics model, which shows that with the initial investment, more development will occur.

This initial investment is needed to trigger positive feedback loops, increasing the adoption rate and improving the technology and energy infrastructure. This mentality of being hesitant to invest due to uncertainty is a form of inconsistent discount based on fear around the technology's credibility. The case for BEV long-haul vehicles is straightforward for most economic conditions scenarios. However, for the case for BEV long-haul truck adoption to be strengthened, it is imperative to prepare for all economic scenarios. Developing charging infrastructure to 500kW is seen as crucial in increasing the gap of the financial gains and the cost of transitioning. This is because higher power charging infrastructure allows for faster charging, which reduces trucks' downtime and increases vehicle utilization. Charging station capabilities only need to improve to 500kW for BEVs to be preferred. This increase would reduce charging downtime from $\tilde{4}$ hours to $\tilde{2}$-2.5 hours. This development would ensure that the BEV long-haul truck is the better investment in all feasible projected economic scenarios. Additionally, the Tesla analysis indicates that, regardless of charger development, the Tesla semi-truck, which has a fuel economy of 19.8MPGe, would still be a better long-term investment compared to an ICE long-haul truck for both the trucking industry and partner companies. It is also significant to note that these calculations do not include subsidies or incentives. With subsidies and incentives in place, the case for BEV long-haul trucks is further strengthened.

Chapter 7

Conclusion

7.1 Summary of Key Findings

This thesis investigated the factors that could influence the adoption rate of BEVs for long-haul trucking and provides insights on how to accelerate the transition to BEVs in this industry. The system dynamics model was utilized to identify key factors that need to be considered to increase the adoption rate of BEVs for long-haul trucking, including the battery capabilities of the vehicles, the total cost of ownership, and the leveraging of feedback loops. The results of the system dynamics analysis indicated that the battery capabilities of the vehicles must be sufficient for operations. Additionally, the total cost of ownership was identified as a key driver of adoption, and the reinforcing nature of the feedback loops was found to explain why companies may have been hesitant to invest in the transition to BEVs. However, these loops can be leveraged to positively influence the adoption rate by increasing investment in the space. This investment will improve the available technology and reduce the total cost of ownership, incentivizing more companies to adopt BEVs. Companies can take advantage of these reinforcing loops to their benefit by being a first mover in this space. The environmental impact analysis demonstrates significant emissions reductions that can occur from the transition to BEVs, regardless of the speed of development. By transitioning to BEVs immediately, there can be significant reductions, like a 37% decrease in GHG emissions and an 85% decrease in direct emission from air pollutants, excluding SO2, even if further development does not occur. This transition could be vital in reducing emissions and addressing climate change. The financial impact analysis revealed that BEV long-haul trucks would be the preferred choice if development occurs, as they are a better investment over the years of ownership due to lower operating costs, such as fuel and maintenance. This is illustrated in the total cost of ownership analysis, the threshold analysis, and the comprehensive NPV analysis. These analyses show that the BEV is preferred across all economic scenarios if development occurs, but the economic benefits are subject to market conditions if no further development occurs. It is important to note that these outcomes occurred even with highly conservative estimates, like the charging station ratios and the 10% operational capacity hit. The analysis also takes into account the fluctuation of fuel prices and highlights the importance of considering energy sourcing, as utilizing renewable energy sources can significantly decrease operating costs and make the transition to BEVs even more financially viable. If no further development occurs and the end consumer energy sourcing occurs, if the price of diesel remains above $3.65, BEV vehicles will be the preferred investment option, as there will be net financial gains from transitioning. However, if the price of diesel drops below $2.24 or electricity prices go above $0.59, regardless of developments made, the ICE vehicle will be the preferred investment choice. In the current economic conditions with no further development, BEV long-haul trucks are a better investment than ICE long-haul trucks for both the trucking industry and partner companies. Given the findings from the comprehensive analysis performed, it is recommended that charging station power outputs increase to 500kW to reduce charging downtime from 4 hours to 2-2.5 hours. This would make the BEV long-haul truck the better investment in all feasible projected economic scenarios. Additionally, the Tesla analysis performed indicates that regardless of charger development, the Tesla semi-truck, which has a fuel economy of 19.8MPGe, is a better long-term investment in comparison to an ICE long-haul truck for both the trucking industry and partner companies. It is also significant to note that these calculations do not include subsidies or incentives. With subsidies and incentives in place, the case for BEV long-haul trucks is further strengthened. In conclusion, this thesis provides a comprehensive understanding of the factors influencing the adoption rate of BEVs for long-haul trucking and offers practical recommendations for accelerating the transition to BEVs in this industry. The results of the system dynamics, environmental, and financial impact analysis indicate that the transition to BEVs is favored from various perspectives. To capitalize on the transition to BEVs, companies should consider leveraging the system's feedback loops and the BEV's lower operating cost savings. Additionally, increasing charging station outputs to 500kW can reduce charging downtime and ensure there is a net financial gain from transitioning to BEVs in all projected scenarios. Furthermore, by considering subsidies and incentives in addition to this analysis, the case for BEV long-haul trucks is further strengthened.

7.2 Implications for the Long-Haul Trucking Industry and Transportation Sector

The adoption of electric long-haul trucks has significant implications for the long-haul trucking industry and the broader transportation sector. The major benefits of electric trucks include reduced emissions and operating costs. Electric trucks produce no tailpipe emissions, which can help to reduce greenhouse gas emissions and direct emissions from air pollutants harmful to public health. This is a key advantage for addressing climate change and improving sustainability. Additionally, electric trucks have lower operating costs due to their increased fuel economy and lower energy pricing, as well as lower maintenance costs due to their design. These advantages make electric trucks a more cost-effective option for trucking companies and can help to make the industry more competitive. Furthermore, in comparison to other alternative fuels, electric vehicles have the advantage of being more energy efficient and being able to utilize existing infrastructure. This means the long-haul trucking industry can transition to electric vehicles without investing in completely new infrastructure.

The electrification of long-haul trucking also has broader implications for the transportation sector. It can reduce risk and increase energy security by diversifying the energy mix used in the U.S, reducing reliance on a single source of fuel. This can help to mitigate the risks associated with relying on fossil fuels and can make the transportation sector more resilient to fuel price fluctuations. Additionally, the adoption of electric long-haul trucks can help to create jobs and stimulate economic growth in the manufacturing, sales, and maintenance of electric trucks and related components. Overall, the benefits of electric long-haul trucks for reducing emissions, operating costs, and improving sustainability demonstrate why electrification could be an important and feasible step in the effort to address climate change and improve sustainability in the transportation sector.

7.3 Future Technological Advancements to Increase Adoption

The analysis of future technological advancements that could increase the adoption of electric long-haul trucks is important to consider when assessing the potential for electrification in the long-haul trucking industry. There are several ways that the case for electrification could be bolstered even further through technological advancements. Some examples include charging network advancements, battery advancements, and instituting specific policies and incentives.

Charging network advancements, such as the development of 1MW charging stations that can charge an electric long-haul truck in 30 minutes, could greatly improve the feasibility of electric long-haul trucking. This could reduce downtime for charging, making electric long-haul trucking an even more viable option for trucking companies. Battery advancements, such as reducing the cost or weight-to-power density ratio, could also improve the feasibility of electric long-haul trucking. This could make electric trucks more competitive with traditional ICE trucks in terms of range, cost, and weight.

In addition to technological advancements, policies and incentives can also play a role in increasing the adoption of electric long-haul trucks. Subsidies, offsets, and mandates could support the increased adoption of electric long-haul vehicles. These policies can help to reduce the cost of electric trucks and make them more competitive with traditional ICE trucks. Therefore, it is recommended that subsidies are offered for purchases of electric long-haul vehicles, for the development of electric charging networks and microgrids or alternative energy storage technologies, and for producing electric vehicles until OEMs reach economies of scale. This will help to support the development and implementation of these new technologies and make electric long-haul trucking a more viable option for the industry.

7.4 Suggestions for Future Research and Analysis

This thesis has presented a strong case for the electrification of long-haul trucking. However, there are several areas where future research and analysis could further strengthen the case for electrification. First, the significance of the increase in SO2 emissions from transitioning must be assessed. Second, future research should focus on charging infrastructure analysis. This includes new logistics optimization and current infrastructure capabilities. Companies must also begin strategizing about the implementation of charging infrastructure. For example, partnerships between companies and OEMs/logistics companies could be formed to incentivize the build-out of charging infrastructure along the company's distribution networks. By incentivizing charging infrastructure development, companies could make electric long-haul trucking an even more viable and cost-effective investment for their operations. Third, future research should also focus on electrical grid power requirements. This includes analyzing current grid capabilities and technologies that can address the power demand required for the transition. One promising technology in this area is microgrids and energy storage. "A microgrid is a group of interconnected loads and distributed energy resources that acts as a single controllable entity with respect to the grid. It can connect and disconnect from the grid to operate in grid-connected or island mode. Microgrids can improve reliability and resilience to grid disturbances. Advanced microgrids enable local power generation assets—including traditional generators, renewables, and storage—to keep the local grid running even when the larger grid experiences interruptions or, for remote areas, where there is no connection to the larger grid. In addition, advanced microgrids allow local assets to work together to save costs, extend duration of energy supplies, and produce revenue via market participation." [34] Therefore, microgrids present a good case for improving the reliability and resilience of the overall system, especially during times of high demand or disruption. Lastly, future research should also focus on production volume and cost. This includes analyzing current production volume and identifying ways to increase throughput and reduce costs. This will allow companies to reach economies of scale and produce units for cheaper. However, with more adoption and subsidies, companies will be able to reach economies of scale more easily. Overall, future research and analysis in these areas can help further strengthen the case for the electrification of long-haul trucking and improve the feasibility of this transition.

Appendix A

Figures

A.1 Model Inputs and Assumptions Summary

**This summary only includes Vehicle Inputs, Vehicle Procurement Inputs, and EV Charging Infrastructure Inputs.*

Vehicle Inputs	
Average Fuel Economy Diesel (MPG)	6 - 7 MPG
Average Fuel Economy Electric (MPGe)	13.5 - 27 MPGe
Annual Vehicle Mileage (VMT/Year)	62,750 miles
Expected Years of Ownership (Years)	7 years
Cost to Insure ($/Year)	$10,000
Maintenance and Repair Cost Diesel ($/Mile)	Years 1-5: $0.20 & Year 6+:$0.26
Maintenance and Repair Cost Diesel ($/Mile)	Years 1-5: $0.17 & Year 6+:$0.22
Recurring Taxes and Fees ($/Year)	$1,000

Vehicle Procurement Inputs	
Number of Vehicles to Procure (#)*	1 vehicle
Ownership Structure	Cash Purchase
Initial Tax, Title, and Registration Cost ($/Vehicle)	$1,000
Trucking Industry Discount Rate for NPV Calculations (%)	10.30%
Partner Companies Discount Rate for NPV Calculations (%)	7.61%
MSRP Average ICE	$135,000
MSRP Operational Capacity Adjustment BEV**	$198,000
Depreciation Rate	Year 1: 23%, Years 2-7: 15%

EV Charging Infrastructure Inputs	
Number of EV Charging Stations Needed (#)*	1
Ownership Structure	Cash Purchase
Charging Equipment Cost ($/Station)	$3,800
Construction & Equipment Installation Cost ($/Station)	$20,000
Maintenance Cost ($/Station/Year)***	$114
Depot/Home Charging Time (%)	80%
Public Charging Time (%)	20%
Maximum Power Output for Public Charging Only (kW)	Scenario Dependent (350kW, 500kW, 1MW)

Figure A-1: Model Inputs and Assumptions Summary*

**1 vehicle was used for all analysis, except in NPV Four-to-One Scenario **10% operational capacity adjustment on total MSRP ($180,000) ***3% of total equipment, construction, and installation costs*

A.2 TCO and NPV Analysis

A.2.1 Financial Modeling Examples

Financial Model Example

BEV Vehicle Financial Model

EV Vehicle Cost

		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Depreciation Calculations									
Fair Market Value - BEV		$ 198,000	$ 152,460	$ 129,591	$ 110,152	$ 93,629	$ 79,585	$ 67,647	$ 57,500
Depreciation Rate			*23%*	*15%*	*15%*	*15%*	*15%*	*15%*	*15%*
Capital Costs									
Cash									
Cash Payment		$ (198,000)	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Terminal Value			$ -	$ -	$ -	$ -	$ -	$ -	$ 57,500
Total Capital Costs		**$ (198,000)**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ 57,500**
Fuel and Operating Costs									
Fuel Cost			$ (14,724)	$ (15,379)	$ (15,052)	$ (14,768)	$ (14,550)	$ (14,544)	$ (14,638)
Maintenance and Repair Cost			$ (10,542)	$ (10,753)	$ (10,968)	$ (11,187)	$ (11,411)	$ (15,131)	$ (15,434)
Taxes and Fees		$ (1,000)	$ (10)	$ (10)	$ (10)	$ (11)	$ (11)	$ (11)	$ (11)
Insurance Cost			$ (10,000)	$ (10,200)	$ (10,404)	$ (10,612)	$ (10,824)	$ (11,041)	$ (11,262)
Subtotal Fuel and Operating Costs		**$ (1,000)**	**$ (35,276)**	**$ (36,342)**	**$ (36,435)**	**$ (36,578)**	**$ (36,796)**	**$ (40,727)**	**$ (41,345)**
Other Costs									
Cost of Downtime from Public Charging			$ (1,175)	$ (1,175)	$ (1,175)	$ (1,175)	$ (1,175)	$ (1,175)	$ (1,175)
Subtotal Other Costs		**$ -**	**$ (1,175)**	**$ (1,175)**	**$ (1,175)**	**$ (1,175)**	**$ (1,175)**	**$ (1,175)**	**$ (1,175)**
Total Discounted Costs									
Total Annual Costs		$ (199,000)	$ (36,451)	$ (37,517)	$ (37,610)	$ (37,753)	$ (37,971)	$ (41,901)	$ 14,981
Discount Factor	*3.0%*	100.0%	97.1%	94.3%	91.5%	88.8%	86.3%	83.7%	81.3%
Discounted Total		$ (199,000)	$ (35,390)	$ (35,363)	$ (34,418)	$ (33,543)	$ (32,754)	$ (35,092)	$ 12,181
Cumulative Discounted Total		**$ (199,000)**	**$ (234,390)**	**$ (269,753)**	**$ (304,171)**	**$ (337,713)**	**$ (370,467)**	**$ (405,559)**	**$ (393,378)**
Annualized NPV Total Cost of Ownership		**$ (56,197)**							

EV Charging Infrastructure Cost

		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Capital Costs									
Cash									
Cash Payment		$ (23,800)							
Total Capital Costs		**$ (23,800)**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**
Operating Costs									
Maintenance Cost			$ (114)	$ (116)	$ (119)	$ (121)	$ (123)	$ (126)	$ (128)
Subtotal Operating Costs			**$ (114)**	**$ (116)**	**$ (119)**	**$ (121)**	**$ (123)**	**$ (126)**	**$ (128)**
Total Discounted Costs									
Total Annual Costs		$ (23,800)	$ (114)	$ (116)	$ (119)	$ (121)	$ (123)	$ (126)	$ (128)
Discount Factor	*3.0%*	100.0%	97.1%	94.3%	91.5%	88.8%	86.3%	83.7%	81.3%
Discounted Total		$ (23,800)	$ (111)	$ (110)	$ (109)	$ (107)	$ (106)	$ (105)	$ (104)
Cumulative Discounted Total		**$ (23,800)**	**$ (23,911)**	**$ (24,020)**	**$ (24,129)**	**$ (24,236)**	**$ (24,343)**	**$ (24,448)**	**$ (24,553)**
Annualized NPV Total Cost of Ownership		**$ (3,508)**							

ICE Vehicle Financial Model

		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Depreciation Calculations									
Fair Market Value - ICE		$ 135,000	$ 103,950	$ 88,358	$ 75,104	$ 63,838	$ 54,263	$ 46,123	$ 39,205
Depreciation Rate			*23%*	*15%*	*15%*	*15%*	*15%*	*15%*	*15%*
Capital Costs									
Cash									
Cash Payment		$ (135,000)	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Terminal Value			$ -	$ -	$ -	$ -	$ -	$ -	$ 39,205
Total Capital Costs		**$ (135,000)**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ 39,205**
Fuel and Operating Costs									
Fuel Cost			$ (21,820)	$ (22,784)	$ (23,213)	$ (23,814)	$ (23,877)	$ (24,291)	$ (24,503)
Maintenance and Repair Cost			$ (12,487)	$ (12,737)	$ (12,992)	$ (13,252)	$ (13,517)	$ (17,923)	$ (18,281)
Taxes and Fees		$ (1,000)	$ (10)	$ (10)	$ (10)	$ (11)	$ (11)	$ (11)	$ (11)
Insurance Cost			$ (10,000)	$ (10,200)	$ (10,404)	$ (10,612)	$ (10,824)	$ (11,041)	$ (11,262)
Subtotal Fuel and Operating Costs		**$ (1,000)**	**$ (44,318)**	**$ (45,731)**	**$ (46,619)**	**$ (47,688)**	**$ (48,229)**	**$ (53,266)**	**$ (54,057)**
Other Costs									
Cost of Downtime from Public Charging			$ -	$ -	$ -	$ -	$ -	$ -	$ -
Subtotal Other Costs		**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**	**$ -**
Total Discounted Costs									
Total Annual Costs		$ (136,000)	$ (44,318)	$ (45,731)	$ (46,619)	$ (47,688)	$ (48,229)	$ (53,266)	$ (14,852)
Discount Factor	3.0%	100.0%	97.1%	94.3%	91.5%	88.8%	86.3%	83.7%	81.3%
Discounted Total		$ (136,000)	$ (43,027)	$ (43,106)	$ (42,663)	$ (42,370)	$ (41,602)	$ (44,609)	$ (12,076)
Cumulative Discounted Total		**$ (136,000)**	**$ (179,027)**	**$ (222,133)**	**$ (264,795)**	**$ (307,166)**	**$ (348,768)**	**$ (393,378)**	**$ (405,454)**
Annualized NPV Total Cost of Ownership		**$ (57,922)**							

Figure A-2: Financial Modeling Example

Results Table Example

Total Vehicle Cost	BEV Vehicle	ICE Vehicle
Depreciation (less tax credits and incentives)	$ (140,500)	$ (95,795)
Fuel	$ (103,655)	$ (164,301)
Maintenance and Repairs	$ (85,426)	$ (101,189)
Taxes & Fees	$ (1,074)	$ (1,074)
Insurance	$ (74,343)	$ (74,343)
Cost of Downtime	$ (8,224)	$ -
Total Vehicle Cost	$ (413,221)	$ (436,703)
Infrastructure per Vehicle	$ (24,648)	$ -
Grand Total	$ (437,869)	$ (436,703)

Vehicle Nominal Cost per Mile	BEV Vehicle	ICE Vehicle
Depreciation (less tax credits and incentives)	$ 0.320	$ 0.218
Fuel	$ 0.236	$ 0.374
Maintenance and Repairs	$ 0.194	$ 0.230
Taxes & Fees	$ 0.002	$ 0.002
Insurance	$ 0.169	$ 0.169
Cost of Downtime	$ 0.019	$ -
Vehicle Total	$ 0.941	$ 0.994
Charging Infrastructure	$ 0.056	$ -
Grand Total	$ 0.997	$ 0.994

Figure A-3: Results Table Modeling Example

Cash Flow Analysis

BEV Vehicle Cash Flow

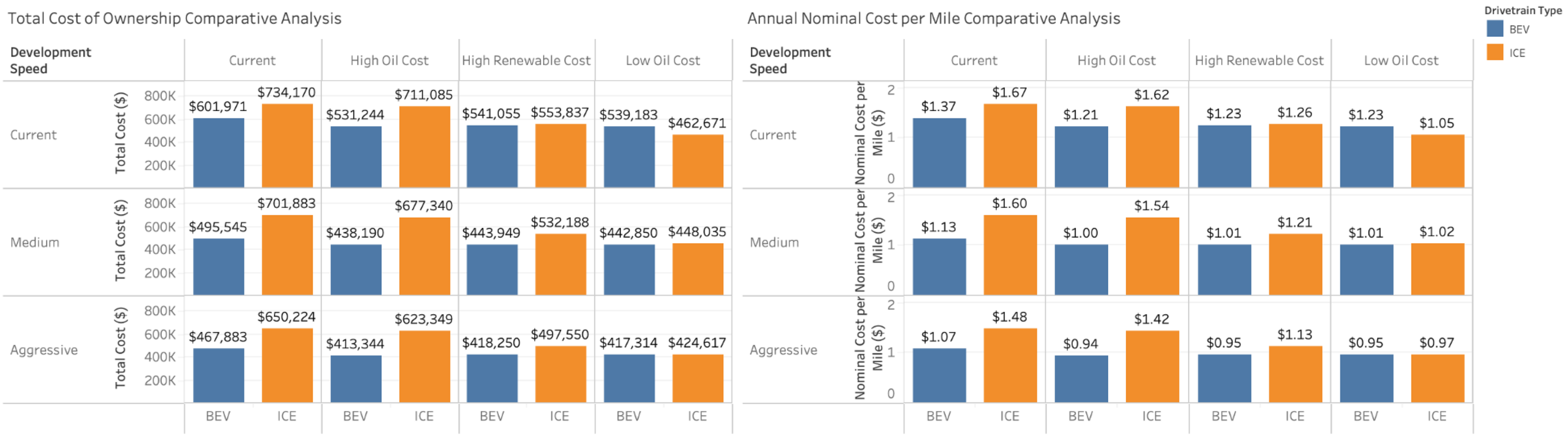
	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Totals
Principal (less tax credits and incentives)	$ (198,000)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ (198,000)
Salvage Value (Vehicle Sale)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 57,500	$ 57,500
Fuel	$ -	$ (14,724)	$ (15,379)	$ (15,052)	$ (14,768)	$ (14,550)	$ (14,544)	$ (14,638)	$ (103,655)
Maintenance and Repairs	$ -	$ (10,542)	$ (10,753)	$ (10,968)	$ (11,187)	$ (11,411)	$ (15,131)	$ (15,434)	$ (85,426)
Taxes & Fees	$ (1,000)	$ (10)	$ (10)	$ (10)	$ (11)	$ (11)	$ (11)	$ (11)	$ (1,074)
Insurance	$ -	$ (10,000)	$ (10,200)	$ (10,404)	$ (10,612)	$ (10,824)	$ (11,041)	$ (11,262)	$ (74,343)
Vehicle Total	$ (199,000)	$ (36,451)	$ (37,517)	$ (37,610)	$ (37,753)	$ (37,971)	$ (41,901)	$ 14,981	$ (413,221)
Charging Infrastructure	$ (23,800)	$ (114)	$ (116)	$ (119)	$ (121)	$ (123)	$ (126)	$ (128)	$ (24,648)
Grand Total	$ (222,800)	$ (36,565)	$ (37,633)	$ (37,728)	$ (37,874)	$ (38,094)	$ (42,027)	$ 14,853	$ (437,869)
Discount Factor	100%	97%	94%	92%	89%	86%	84%	81%	
NPV Total	$ (222,800)	$ (35,500)	$ (35,473)	$ (34,527)	$ (33,650)	$ (32,860)	$ (35,197)	$ 12,076	$ (417,931)

ICE Vehicle Cash Flow

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Totals
Principal (less tax credits and incentives)	$ (135,000)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ (135,000)
Salvage Value (Vehicle Sale)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 39,205	$ 39,205
Fuel	$ -	$ (21,820)	$ (22,784)	$ (23,213)	$ (23,814)	$ (23,877)	$ (24,291)	$ (24,503)	$ (164,301)
Maintenance and Repairs	$ -	$ (12,487)	$ (12,737)	$ (12,992)	$ (13,252)	$ (13,517)	$ (17,923)	$ (18,281)	$ (101,189)
Taxes & Fees	$ (1,000)	$ (10)	$ (10)	$ (10)	$ (11)	$ (11)	$ (11)	$ (11)	$ (1,074)
Insurance	$ -	$ (10,000)	$ (10,200)	$ (10,404)	$ (10,612)	$ (10,824)	$ (11,041)	$ (11,262)	$ (74,343)
Vehicle Total	$ (136,000)	$ (44,318)	$ (45,731)	$ (46,619)	$ (47,688)	$ (48,229)	$ (53,266)	$ (14,852)	$ (436,703)
Charging Infrastructure	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Grand Total	$ (136,000)	$ (44,318)	$ (45,731)	$ (46,619)	$ (47,688)	$ (48,229)	$ (53,266)	$ (14,852)	$ (436,703)
Discount Factor	100%	97.1%	94.3%	91.5%	88.8%	86.3%	83.7%	81.3%	
NPV Total	$ (136,000)	$ (43,027)	$ (43,106)	$ (42,663)	$ (42,370)	$ (41,602)	$ (44,609)	$ (12,076)	$ (405,454)

Figure A-4: Cash Flow Analysis Example

A.2.2 TCO Analysis



Total Cost of Ownership over Expected Years of Usage

Economic Scenario	Development Speed	Condition	BEV (Drivetrain Type)	ICE (Drivetrain Type)	Difference (Drivetrain Type)
Current	Current	BEV Preferred	$601,971	$734,170	$132,199
	Medium	BEV Preferred	$495,545	$701,883	$206,339
	Aggressive	BEV Preferred	$467,883	$650,224	$182,341
High Oil Cost	Current	BEV Preferred	$531,244	$711,085	$179,842
	Medium	BEV Preferred	$438,190	$677,340	$239,150
	Aggressive	BEV Preferred	$413,344	$623,349	$210,004
High Renewable Cost	Current	Neutral	$541,055	$553,837	$12,782
	Medium	BEV Preferred	$443,949	$532,188	$88,239
	Aggressive	BEV Preferred	$418,250	$497,550	$79,300
Low Oil Cost	Current	ICE Preferred	$539,183	$462,671	$76,512
	Medium	Neutral	$442,850	$448,035	$5,185
	Aggressive	Neutral	$417,314	$424,617	$7,303

Annual Nominal Cost per Mile

Economic Scenario	Development Speed	Condition	BEV (Drivetrain Type)	ICE (Drivetrain Type)	Difference (Drivetrain Type)
Current	Current	BEV Preferred	$1.37	$1.67	$0.30
	Medium	BEV Preferred	$1.13	$1.60	$0.47
	Aggressive	BEV Preferred	$1.07	$1.48	$0.42
High Oil Cost	Current	BEV Preferred	$1.21	$1.62	$0.41
	Medium	BEV Preferred	$1.00	$1.54	$0.54
	Aggressive	BEV Preferred	$0.94	$1.42	$0.48
High Renewable Cost	Current	Neutral	$1.23	$1.26	$0.03
	Medium	BEV Preferred	$1.01	$1.21	$0.20
	Aggressive	BEV Preferred	$0.95	$1.13	$0.18
Low Oil Cost	Current	ICE Preferred	$1.23	$1.05	$0.17
	Medium	Neutral	$1.01	$1.02	$0.01
	Aggressive	Neutral	$0.95	$0.97	$0.02

Condition: BEV Preferred; ICE Preferred; Neutral

Figure A-5: Total Cost of Ownership Summary

Total Cost of Ownership over Expected Years of Usage Breakdown

Developme..	Cost Variable	Current BEV	Current ICE	High Oil Cost BEV	High Oil Cost ICE	High Renewable Cost BEV	High Renewable Cost ICE	Low Oil Cost BEV	Low Oil Cost ICE
Current	Depreciation (less tax cre..	$140,500	$95,795	$140,500	$95,795	$140,500	$95,795	$140,500	$95,795
	Fuel	$190,637	$419,731	$158,261	$438,684	$168,073	$281,436	$166,200	$190,270
	Cost of Downtime	$46,993	$0	$46,993	$0	$46,993	$0	$46,993	$0
	Maintenance and Repairs	$106,465	$126,111	$85,426	$101,189	$85,426	$101,189	$85,426	$101,189
	Insurance	$91,442	$91,442	$74,343	$74,343	$74,343	$74,343	$74,343	$74,343
	Taxes & Fees	$1,091	$1,091	$1,074	$1,074	$1,074	$1,074	$1,074	$1,074
	Infrastructure per Vehicle	$24,842	$0	$24,648	$0	$24,648	$0	$24,648	$0
	Grand Total	$601,971	$734,170	$531,244	$711,085	$541,055	$553,837	$539,183	$462,671
Medium	Depreciation (less tax cre..	$140,500	$95,795	$140,500	$95,795	$140,500	$95,795	$140,500	$95,795
	Fuel	$111,896	$387,444	$92,892	$404,939	$98,651	$259,787	$97,552	$175,634
	Cost of Downtime	$19,308	$0	$19,308	$0	$19,308	$0	$19,308	$0
	Maintenance and Repairs	$106,465	$126,111	$85,426	$101,189	$85,426	$101,189	$85,426	$101,189
	Insurance	$91,442	$91,442	$74,343	$74,343	$74,343	$74,343	$74,343	$74,343
	Taxes & Fees	$1,091	$1,091	$1,074	$1,074	$1,074	$1,074	$1,074	$1,074
	Infrastructure per Vehicle	$24,842	$0	$24,648	$0	$24,648	$0	$24,648	$0
	Grand Total	$495,545	$701,883	$438,190	$677,340	$443,949	$532,188	$442,850	$448,035
Aggressive	Depreciation (less tax cre..	$140,500	$95,795	$140,500	$95,795	$140,500	$95,795	$140,500	$95,795
	Fuel	$95,319	$335,785	$79,130	$350,947	$84,036	$225,149	$83,100	$152,216
	Cost of Downtime	$8,224	$0	$8,224	$0	$8,224	$0	$8,224	$0
	Maintenance and Repairs	$106,465	$126,111	$85,426	$101,189	$85,426	$101,189	$85,426	$101,189
	Insurance	$91,442	$91,442	$74,343	$74,343	$74,343	$74,343	$74,343	$74,343
	Taxes & Fees	$1,091	$1,091	$1,074	$1,074	$1,074	$1,074	$1,074	$1,074
	Infrastructure per Vehicle	$24,842	$0	$24,648	$0	$24,648	$0	$24,648	$0
	Grand Total	$467,883	$650,224	$413,344	$623,349	$418,250	$497,550	$417,314	$424,617

BEV Preferred
ICE Preferred
Neutral

Sum of Cost ($) broken down by Economic Scenario and Drivetrain Type vs. Development Speed and Cost Variable. Color shows details about Condition. The data is filtered on Cost Scenario, which keeps Total Cost per Vehicle. The view is filtered on Cost Variable and Drivetrain Type. The Cost Variable filter excludes Vehicle Total. The Drivetrain Type filter excludes Difference and Null.

Figure A-6: Total Cost of Ownership over Expected Usage Breakdown

Annual Nominal Cost per Mile Breakdown

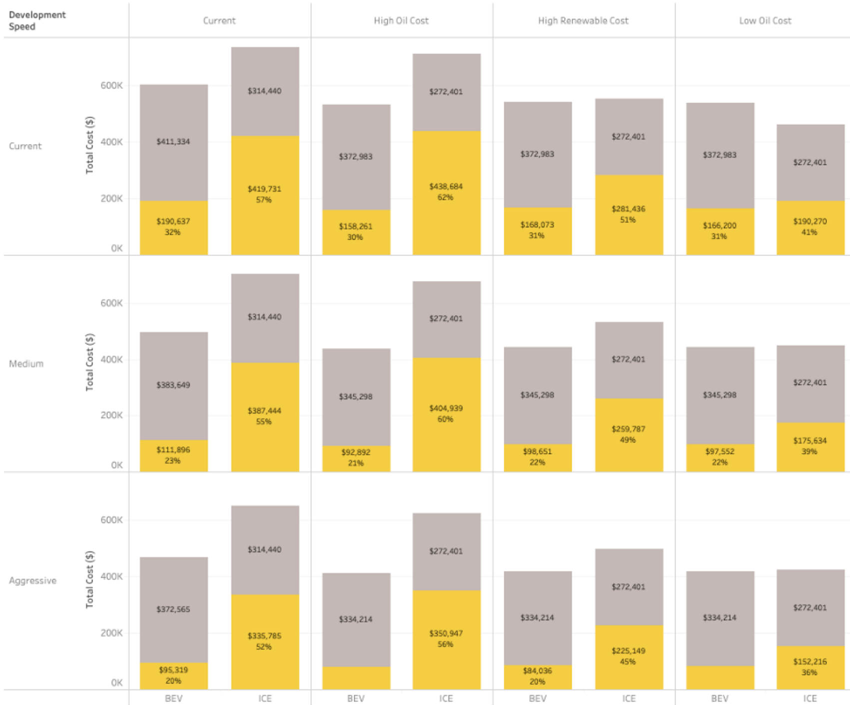
Developme..	Cost Variable	Current BEV	Current ICE	High Oil Cost BEV	High Oil Cost ICE	High Renewable Cost BEV	High Renewable Cost ICE	Low Oil Cost BEV	Low Oil Cost ICE
Current	Depreciation (less tax cre..	$0.32	$0.22	$0.32	$0.22	$0.32	$0.22	$0.32	$0.22
	Fuel	$0.43	$0.96	$0.36	$1.00	$0.38	$0.64	$0.38	$0.43
	Cost of Downtime	$0.11	$0.00	$0.11	$0.00	$0.11	$0.00	$0.11	$0.00
	Maintenance and Repairs	$0.24	$0.29	$0.19	$0.23	$0.19	$0.23	$0.19	$0.23
	Insurance	$0.21	$0.21	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17
	Charging Infrastructure	$0.06	$0.00	$0.06	$0.00	$0.06	$0.00	$0.06	$0.00
	Grand Total	$1.37	$1.67	$1.21	$1.62	$1.23	$1.26	$1.23	$1.05
Medium	Depreciation (less tax cre..	$0.32	$0.22	$0.32	$0.22	$0.32	$0.22	$0.32	$0.22
	Fuel	$0.25	$0.88	$0.21	$0.92	$0.22	$0.59	$0.22	$0.40
	Cost of Downtime	$0.04	$0.00	$0.04	$0.00	$0.04	$0.00	$0.04	$0.00
	Maintenance and Repairs	$0.24	$0.29	$0.19	$0.23	$0.19	$0.23	$0.19	$0.23
	Insurance	$0.21	$0.21	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17
	Charging Infrastructure	$0.06	$0.00	$0.06	$0.00	$0.06	$0.00	$0.06	$0.00
	Grand Total	$1.13	$1.60	$1.00	$1.54	$1.01	$1.21	$1.01	$1.02
Aggressive	Depreciation (less tax cre..	$0.32	$0.22	$0.32	$0.22	$0.32	$0.22	$0.32	$0.22
	Fuel	$0.22	$0.76	$0.18	$0.80	$0.19	$0.51	$0.19	$0.35
	Cost of Downtime	$0.02	$0.00	$0.02	$0.00	$0.02	$0.00	$0.02	$0.00
	Maintenance and Repairs	$0.24	$0.29	$0.19	$0.23	$0.19	$0.23	$0.19	$0.23
	Insurance	$0.21	$0.21	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17
	Charging Infrastructure	$0.06	$0.00	$0.06	$0.00	$0.06	$0.00	$0.06	$0.00
	Grand Total	$1.07	$1.48	$0.94	$1.42	$0.95	$1.13	$0.95	$0.97

BEV Preferred
ICE Preferred
Neutral

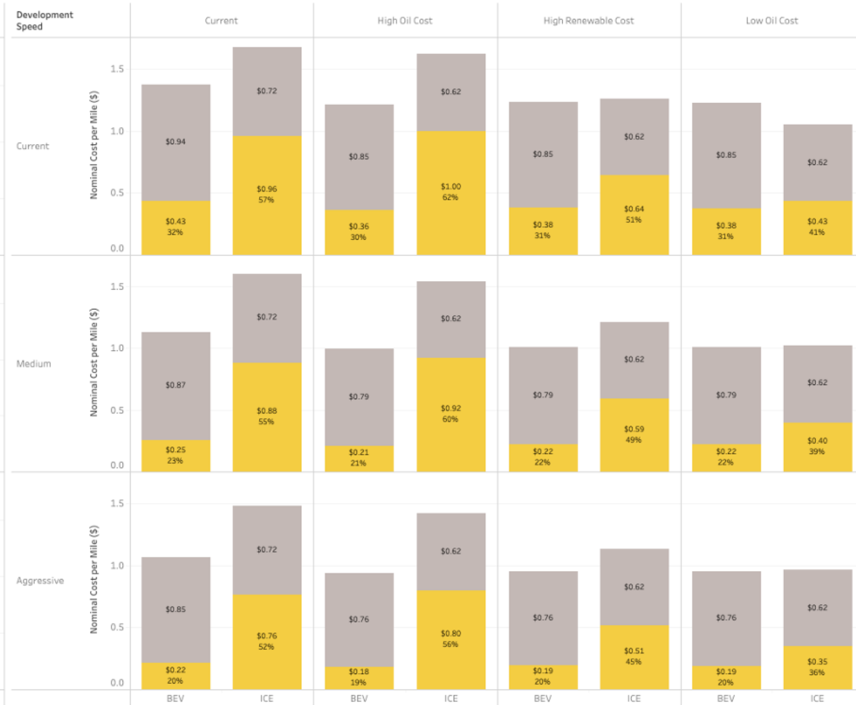
Sum of Cost ($) broken down by Economic Scenario and Drivetrain Type vs. Development Speed and Cost Variable. Color shows details about Condition. The data is filtered on Cost Scenario, which keeps Vehicle Cost per Mile. The view is filtered on Cost Variable and Drivetrain Type. The Cost Variable filter excludes Taxes & Fees and Vehicle Total. The Drivetrain Type filter excludes Difference and Null.

Figure A-7: Annual Nominal Cost Breakdown

Contribution of Fuel Cost to Total Cost of Ownership



Contribution of Fuel Cost to Annual Nominal Cost per Mile



Development Speed	Cost Variable	Current BEV	Current ICE	High Oil Cost BEV	High Oil Cost ICE	High Renewable Cost BEV	High Renewable Cost ICE	Low Oil Cost BEV	Low Oil Cost ICE
Current	Fuel Cost	$190,637	$419,731	$158,261	$438,684	$168,073	$281,436	$166,200	$190,270
	Total Cost	$601,971	$734,170	$531,244	$711,085	$541,055	$553,837	$539,183	$462,671
Medium	Fuel Cost	$111,896	$387,444	$92,892	$404,939	$98,651	$259,787	$97,552	$175,634
	Total Cost	$495,545	$701,883	$438,190	$677,340	$443,949	$532,188	$442,850	$448,035
Aggressive	Fuel Cost	$95,319	$335,785	$79,130	$350,947	$84,036	$225,149	$83,100	$152,216
	Total Cost	$467,883	$650,224	$413,344	$623,349	$418,250	$497,550	$417,314	$424,617

Development Speed	Cost Variable	Current BEV	Current ICE	High Oil Cost BEV	High Oil Cost ICE	High Renewable Cost BEV	High Renewable Cost ICE	Low Oil Cost BEV	Low Oil Cost ICE
Current	Fuel Cost	$0.43	$0.96	$0.36	$1.00	$0.38	$0.64	$0.38	$0.43
	Total Cost	$1.37	$1.67	$1.21	$1.62	$1.23	$1.26	$1.23	$1.05
Medium	Fuel Cost	$0.25	$0.88	$0.21	$0.92	$0.22	$0.59	$0.22	$0.40
	Total Cost	$1.13	$1.60	$1.00	$1.54	$1.01	$1.21	$1.01	$1.02
Aggressive	Fuel Cost	$0.22	$0.76	$0.18	$0.80	$0.19	$0.51	$0.19	$0.35
	Total Cost	$1.07	$1.48	$0.94	$1.42	$0.95	$1.13	$0.95	$0.97

Fuel Cost
Cost Difference between BEV and ICE (%)

Development Speed	Current	High Oil Cost	High Renewable Cost	Low Oil Cost
Current	120%	177%	67%	14%
Medium	246%	336%	163%	80%
Aggressive	252%	344%	168%	83%

Total Cost
Cost Difference between BEV and ICE (%)

Development Speed	Current	High Oil Cost	High Renewable Cost	Low Oil Cost
Current	22%	34%	2%	-14%
Medium	42%	55%	20%	1%
Aggressive	39%	51%	19%	2%

Figure A-8: Total Cost of Fuel Summary

A.3 Sensitivity Analysis

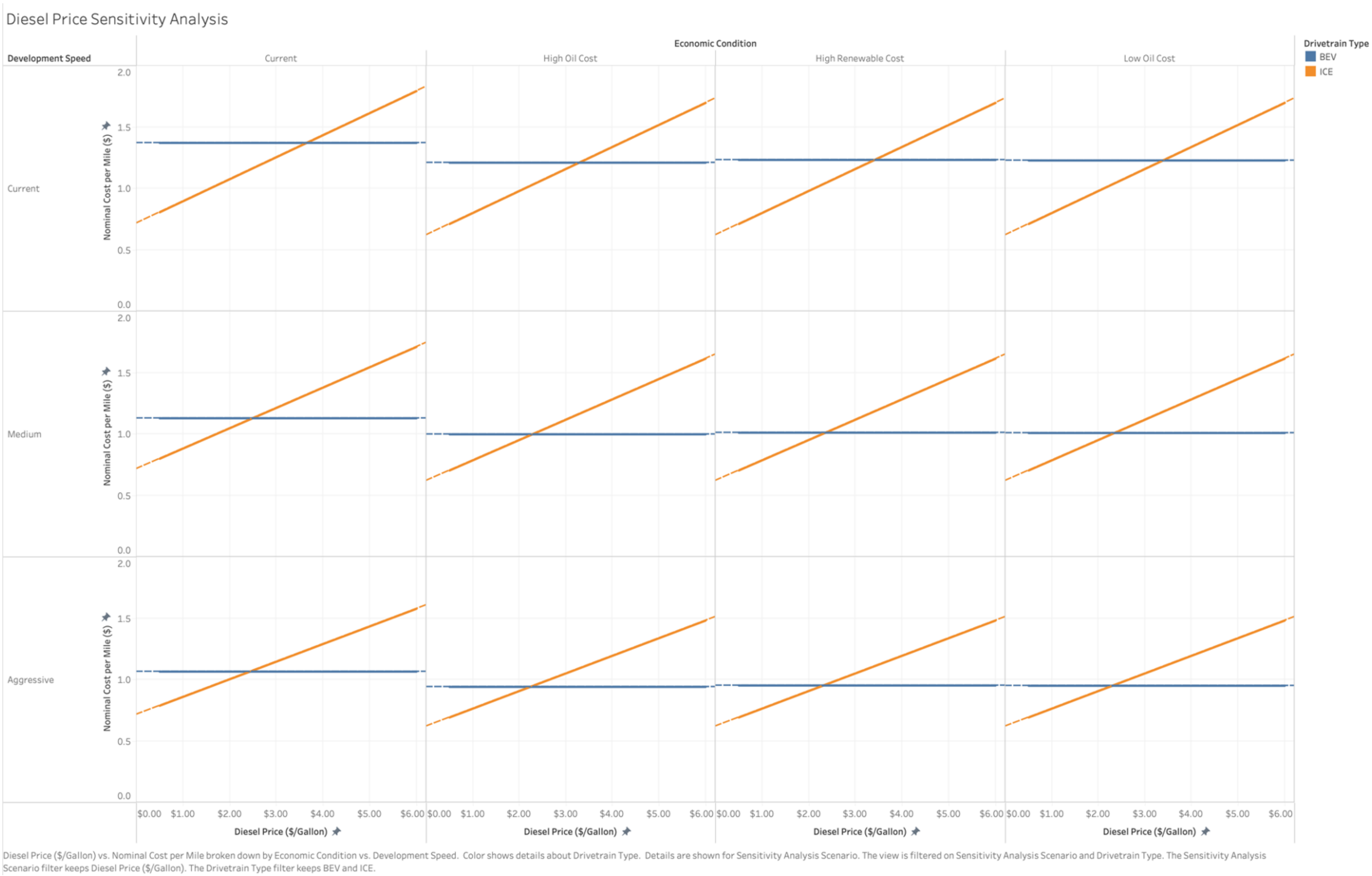


Figure A-9: Diesel Sensitivity Analysis

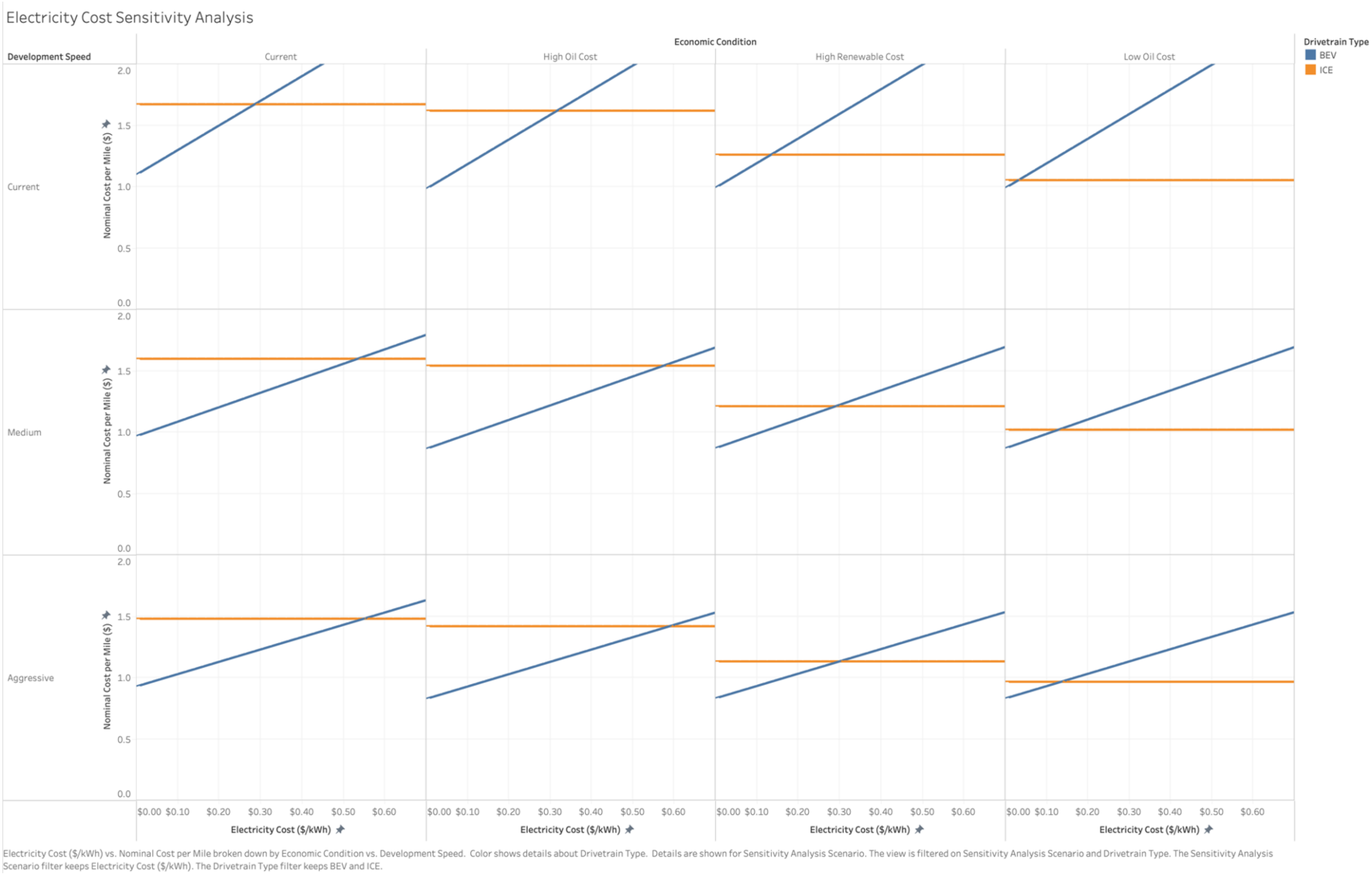


Figure A-10: Electricity Sensitivity Analysis

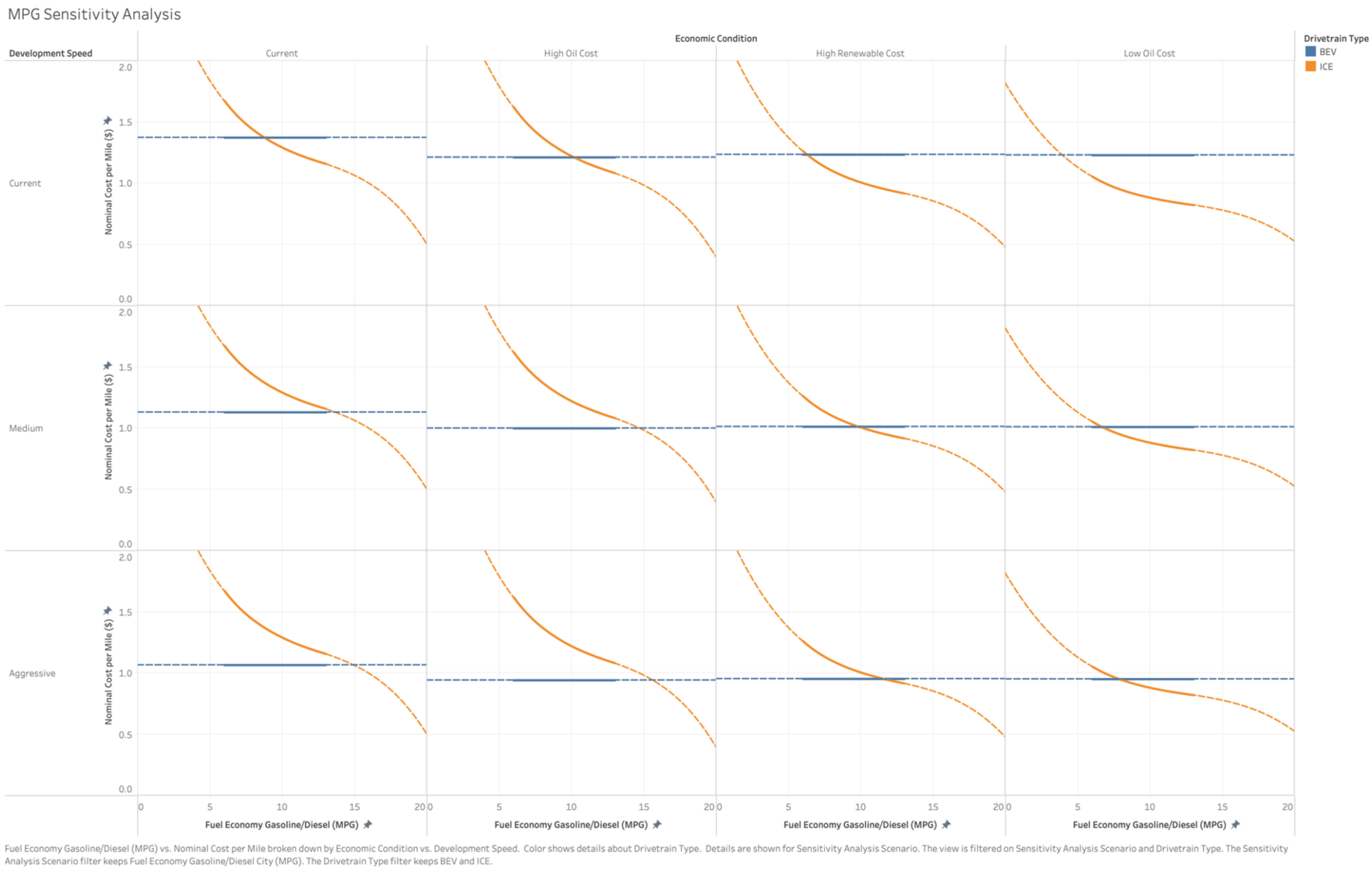


Figure A-11: MPG Sensitivity Analysis

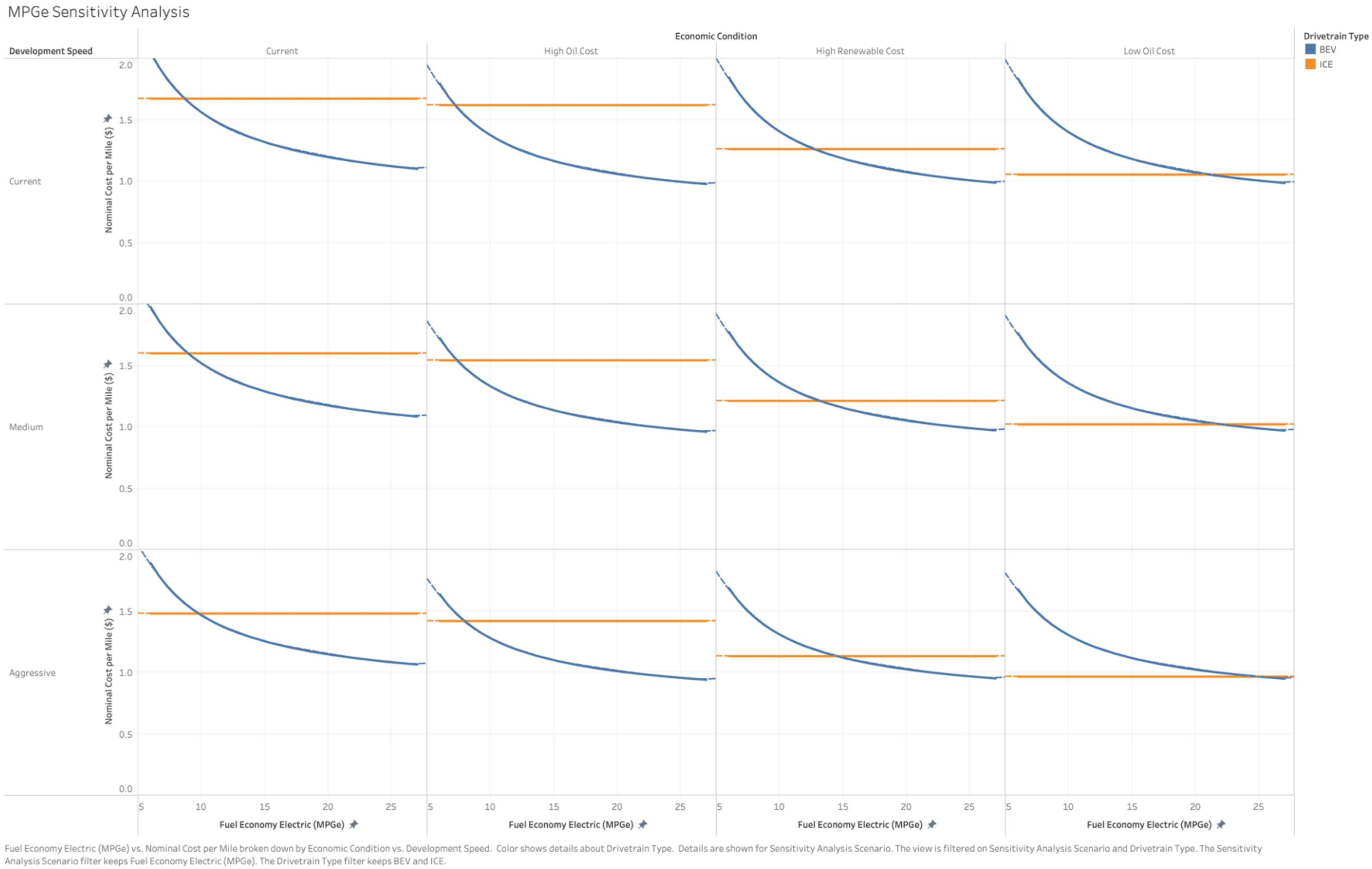


Figure A-12: MPGe Sensitivity Analysis

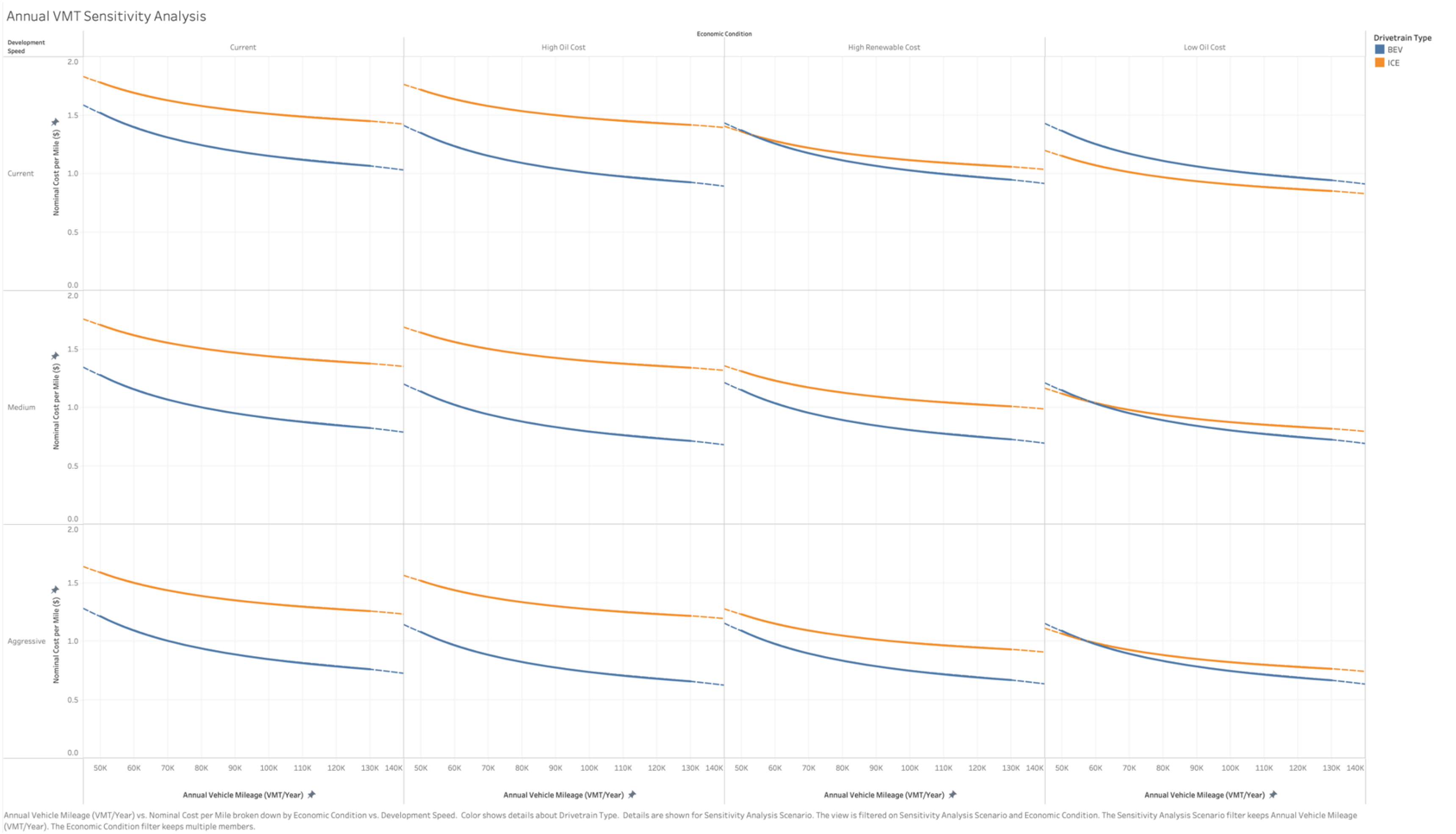


Figure A-13: Annual VMT Sensitivity Analysis

A.4 Threshold for BEV Preference Analysis

Threshold Analysis for BEV Preference based on Diesel Price Sensitivity Analysis Results

			Diesel Price ($/Gallon) *Above Inflection Point BEV Less Expensive*		
Economic Condition	**Development Speed**	**Condition**	Expected Price	Inflection Price	Threshold for BEV Preference
Current	Current	BEV Preferred	$5.33	$3.65	Can Reduce $1.68
	Medium	BEV Preferred	$5.33	$2.49	Can Reduce $2.84
	Aggressive	BEV Preferred	$5.33	$2.44	Can Reduce $2.89
High Oil Cost	Current	BEV Preferred	$5.57	$3.29	Can Reduce $2.28
	Medium	BEV Preferred	$5.57	$2.28	Can Reduce $3.29
	Aggressive	BEV Preferred	$5.57	$2.24	Can Reduce $3.33
Low Oil Cost	Current	ICE Preferred	$2.42	$3.39	Must Increase $0.97
	Medium	Neutral	$2.42	$2.34	Neutral $0.08
	Aggressive	Neutral	$2.42	$2.30	Neutral $0.12
High Renewable Cost	Current	Neutral	$3.57	$3.41	Neutral $0.16
	Medium	BEV Preferred	$3.57	$2.36	Can Reduce $1.21
	Aggressive	BEV Preferred	$3.57	$2.32	Can Reduce $1.25

Condition
- ICE Preferred
- Neutral
- BEV Preferred

If Diesel Prices go below the inflection point value, ICE vehicles have a better nominal cost per mile.
The difference demonstrate how the current price would have to change in order for this to occur.

Figure A-14: Threshold Analysis for BEV Preference based on Diesel Sensitivity Analysis Results

Threshold Analysis for BEV Preference based on Electricity Price Sensitivity Analysis Results

			Electricity Cost ($/kWh) *Below Inflection Point BEV Less Expensive*		
Economic Condition	**Development Speed**	**Condition**	Expected Price	Inflection Price	Threshold for BEV Preference
Current	Current	BEV Preferred	$0.14	$0.29	Can Increase $0.15
	Medium	BEV Preferred	$0.14	$0.53	Can Increase $0.40
	Aggressive	BEV Preferred	$0.14	$0.55	Can Increase $0.41
High Oil Cost	Current	BEV Preferred	$0.11	$0.32	Can Increase $0.20
	Medium	BEV Preferred	$0.11	$0.57	Can Increase $0.46
	Aggressive	BEV Preferred	$0.11	$0.59	Can Increase $0.48
Low Oil Cost	Current	ICE Preferred	$0.12	$0.03	Must Reduce $0.09
	Medium	Neutral	$0.12	$0.13	Neutral $0.01
	Aggressive	Neutral	$0.12	$0.14	Neutral $0.02
High Renewable Cost	Current	Neutral	$0.12	$0.13	Neutral $0.01
	Medium	BEV Preferred	$0.12	$0.29	Can Increase $0.17
	Aggressive	BEV Preferred	$0.12	$0.30	Can Increase $0.18

Condition
- ICE Preferred
- Neutral
- BEV Preferred

If Electricity Prices go above the inflection point value, ICE vehicles have a better nominal cost per mile.
The difference demonstrate how the current price would have to change in order for this to occur.

Figure A-15: Threshold Analysis for BEV Preference based on Electricity Sensitivity Analysis Results

Threshold Analysis for BEV Preference based on MPGe Sensitivity Analysis Results

			MPGe *Above Inflection Point BEV Less Expensive*		
Development Speed	**Economic Condition**	**Condition**	Expected Value	Inflection Point	Threshold for BEV Preference
Current	Current	BEV Preferred	13.5	8.9	Can Reduce 4.6
	High Oil Cost	BEV Preferred	13.5	7.3	Can Reduce 6.2
	Low Oil Cost	ICE Preferred	13.5	22.0	Must Increase 8.5
	High Renewable Cost	Neutral	13.5	12.5	Neutral 1.0
Medium	Current	BEV Preferred	23.0	9.1	Can Reduce 13.9
	High Oil Cost	BEV Preferred	23.0	7.4	Can Reduce 15.6
	Low Oil Cost	Neutral	23.0	23.2	Neutral 0.2
	High Renewable Cost	BEV Preferred	23.0	12.8	Can Reduce 10.2
Aggressive	Current	BEV Preferred	27.0	9.9	Can Reduce 17.1
	High Oil Cost	BEV Preferred	27.0	8.1	Can Reduce 18.9
	Low Oil Cost	Neutral	27.0	25.5	Neutral 1.5
	High Renewable Cost	BEV Preferred	27.0	14.0	Can Reduce 13.0

Condition
- ICE Preferred
- Neutral
- BEV Preferred

Direction and sum of Amount_2 broken down by Sensitivity Analysis, BEV Condition and Value vs. Development Speed, Economic Condition and Condition. Color shows details about Condition. The view is filtered on Value and Sensitivity Analysis. The Value filter keeps Expected Price, Expected Value, Inflection Point, Inflection Price and Threshold for BEV Preference. The Sensitivity Analysis filter keeps MPGe.

Figure A-16: Threshold Analysis for BEV Preference based on MPGe Sensitivity Analysis Results

Threshold Analysis for BEV Preference based on MPG Sensitivity Analysis Results

Development Speed	Economic Condition	Condition	MPG *Below Inflection Point BEV Less Expensive* Expected Value	Inflection Point	Threshold for BEV Preference
Current	Current	BEV Preferred	6.00	8.74	Can Increase 2.74
	High Oil Cost	BEV Preferred	6.00	10.15	Can Increase 4.15
	Low Oil Cost	ICE Preferred	6.00	3.93	Must Reduce 2.07
	High Renewable Cost	Neutral	6.00	6.28	Neutral 0.28
Medium	Current	BEV Preferred	6.50	13.64	Can Increase 7.14
	High Oil Cost	BEV Preferred	6.50	14.70	Can Increase 8.20
	Low Oil Cost	Neutral	6.50	6.71	Neutral 0.21
	High Renewable Cost	BEV Preferred	6.50	9.82	Can Increase 3.32
Aggressive	Current	BEV Preferred	7.50	14.92	Can Increase 7.42
	High Oil Cost	BEV Preferred	7.50	15.61	Can Increase 8.11
	Low Oil Cost	Neutral	7.50	7.88	Neutral 0.38
	High Renewable Cost	BEV Preferred	7.50	11.62	Can Increase 4.12

Condition
- ICE Preferred
- Neutral
- BEV Preferred

Direction and sum of Amount_2 broken down by Sensitivity Analysis, BEV Condition and Value vs. Development Speed, Economic Condition and Condition. Color shows details about Condition. The view is filtered on Value and Sensitivity Analysis. The Value filter keeps Expected Price, Expected Value, Inflection Point, Inflection Price and Threshold for BEV Preference. The Sensitivity Analysis filter keeps MPG.

Figure A-17: Threshold Analysis for BEV Preference based on MPG Sensitivity Analysis Results

A.5 NPV Analysis

A.5.1 Projected NPV Discounted Cash Flow per Year

Discount Factor 10.3% & One to One Ratio

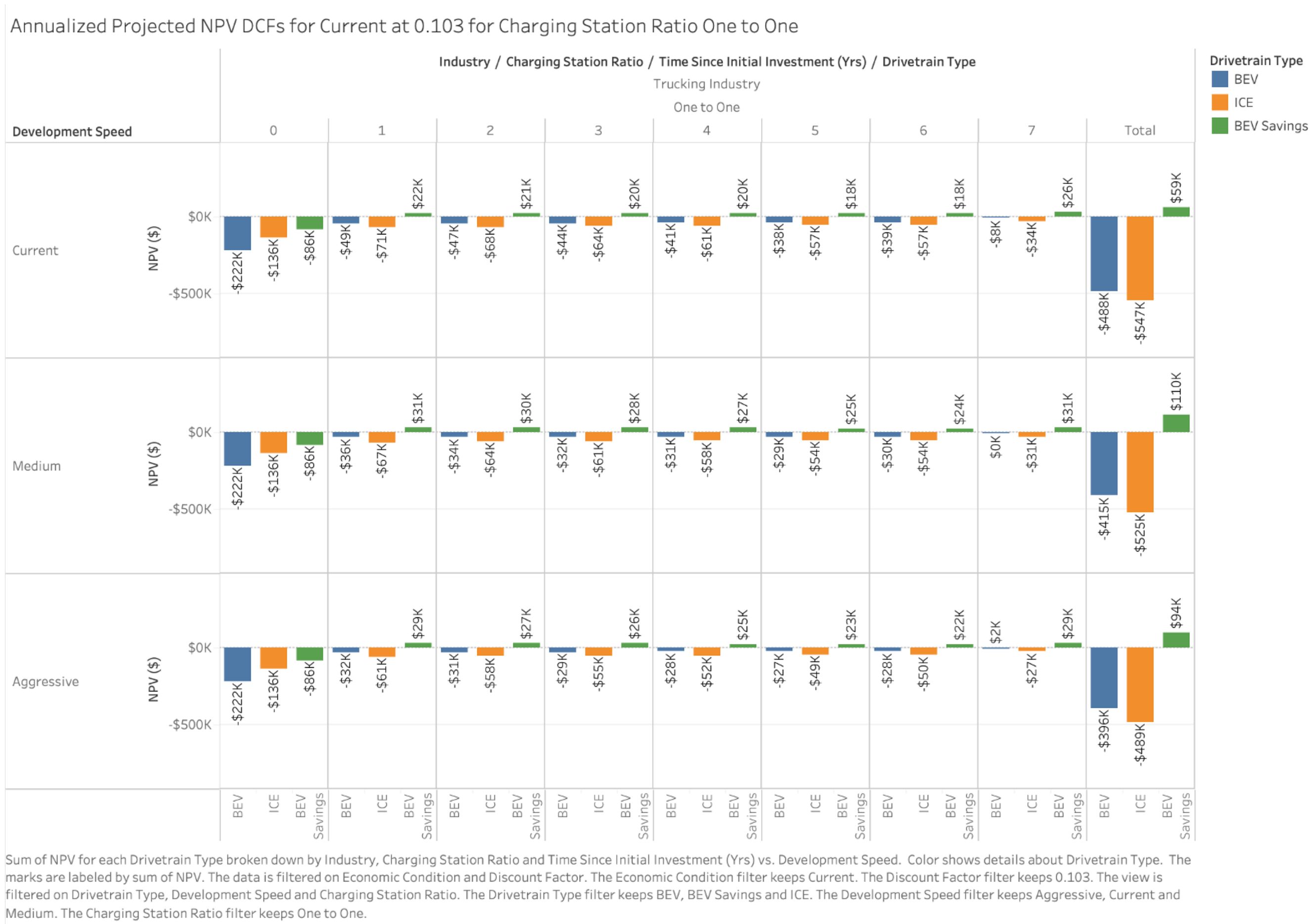
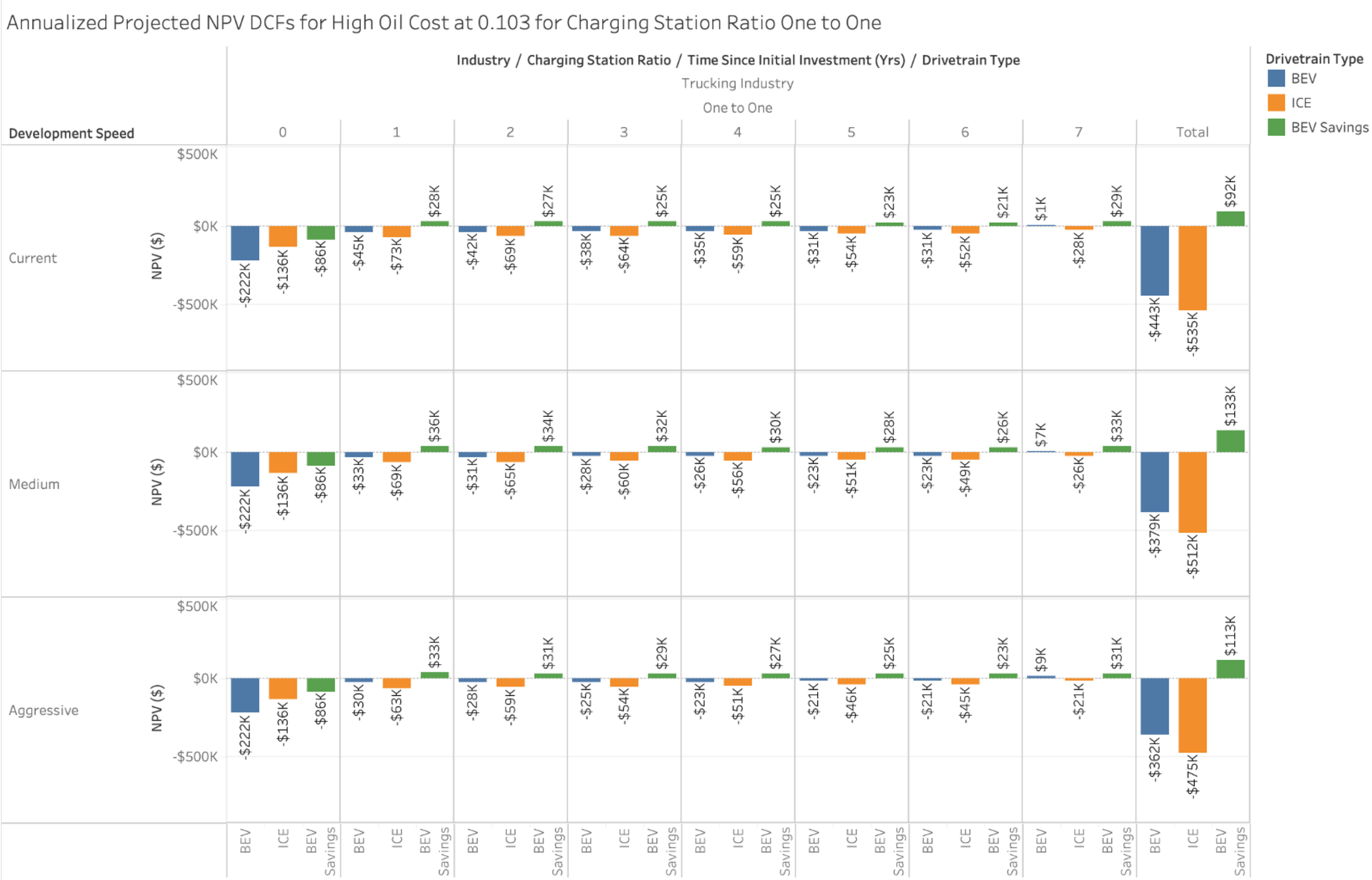
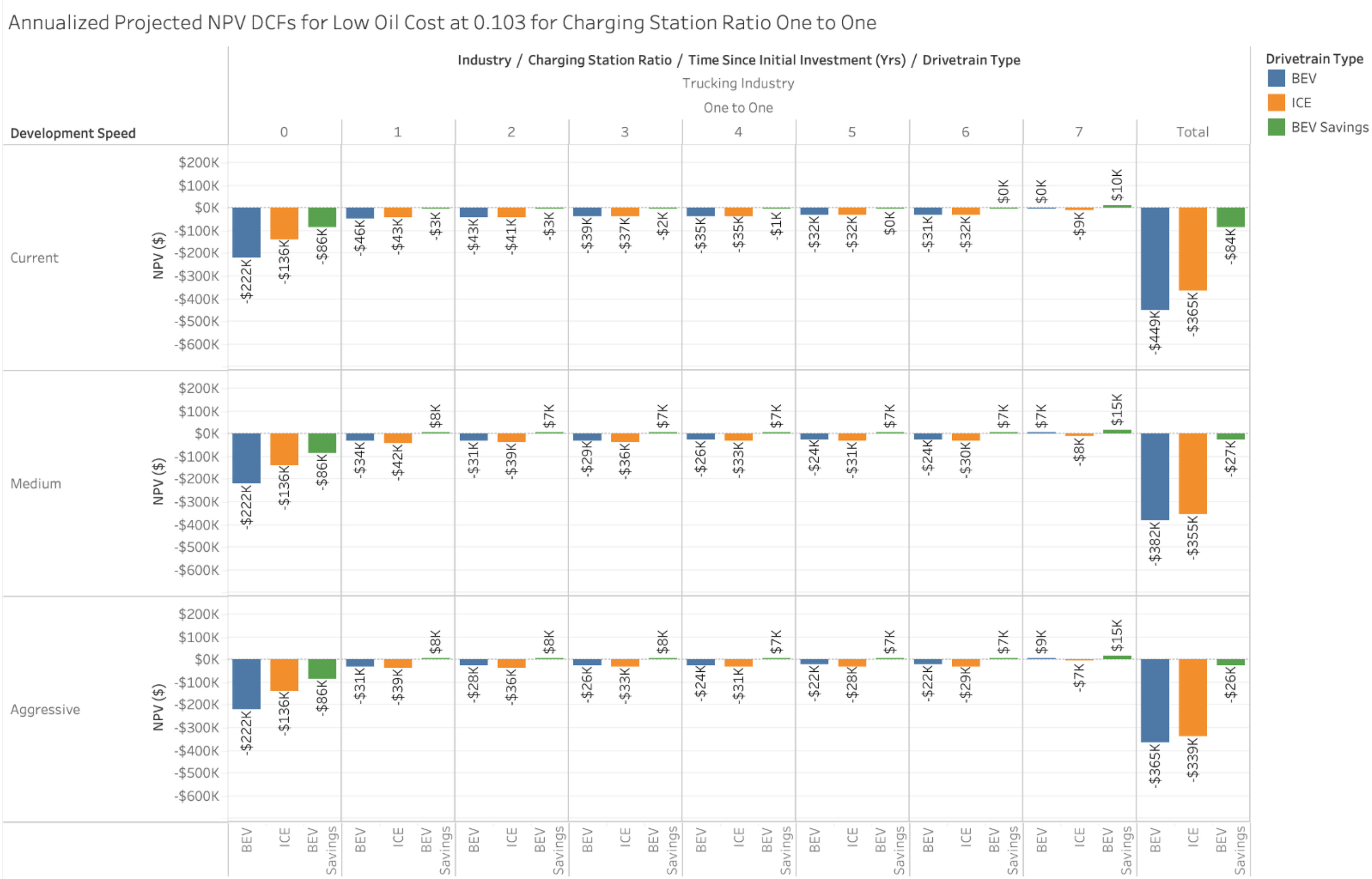


Figure A-18: Projected NPV Discounted Cash Flow per Year for Current Economic Scenario



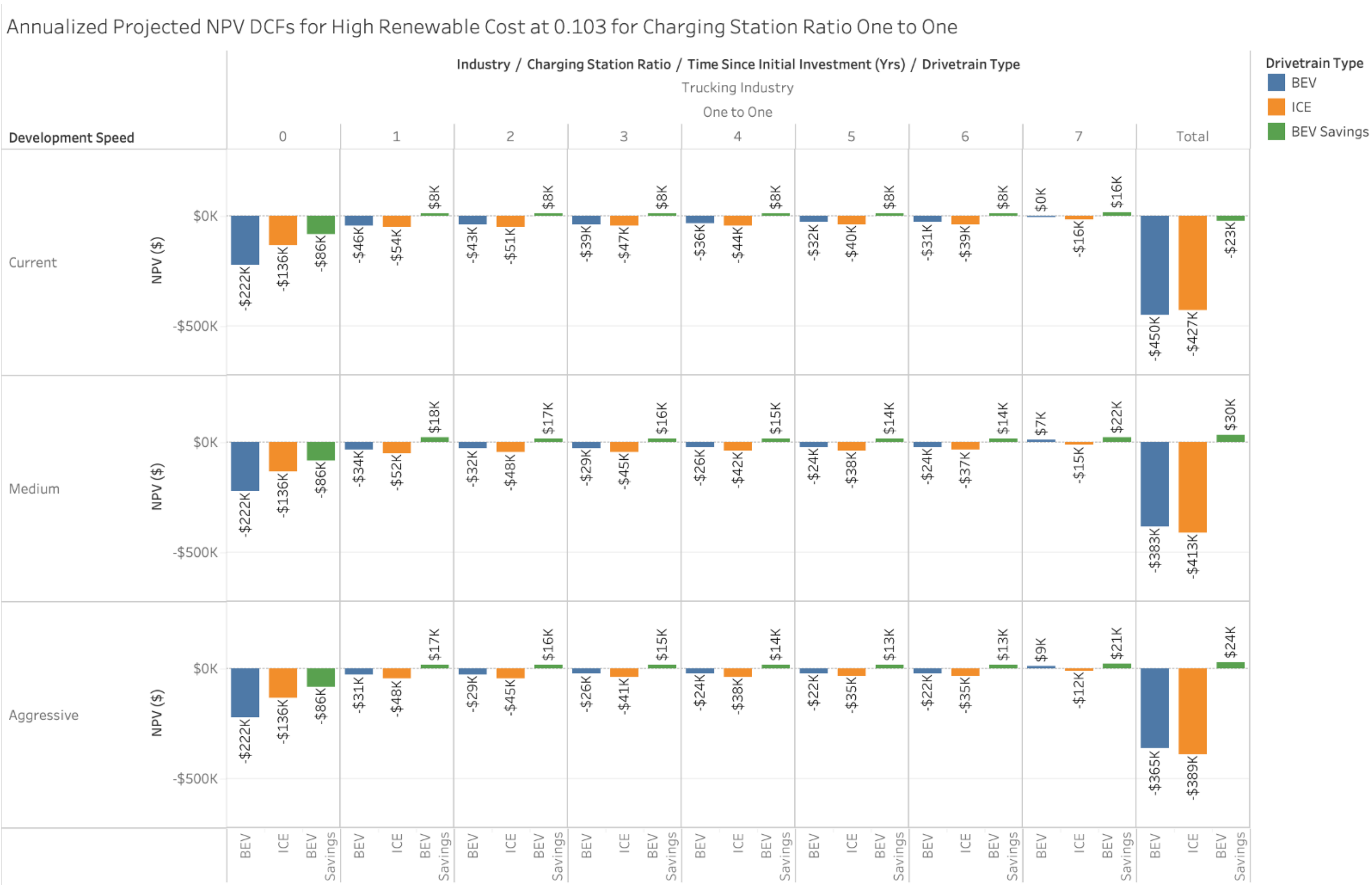
Sum of NPV for each Drivetrain Type broken down by Industry, Charging Station Ratio and Time Since Initial Investment (Yrs) vs. Development Speed. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV. The data is filtered on Economic Condition and Discount Factor. The Economic Condition filter keeps High Oil Cost. The Discount Factor filter keeps 0.103. The view is filtered on Drivetrain Type, Development Speed and Charging Station Ratio. The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Development Speed filter keeps Aggressive, Current and Medium. The Charging Station Ratio filter keeps One to One.

Figure A-19: Projected NPV Discounted Cash Flow per Year for High Oil Economic Scenario



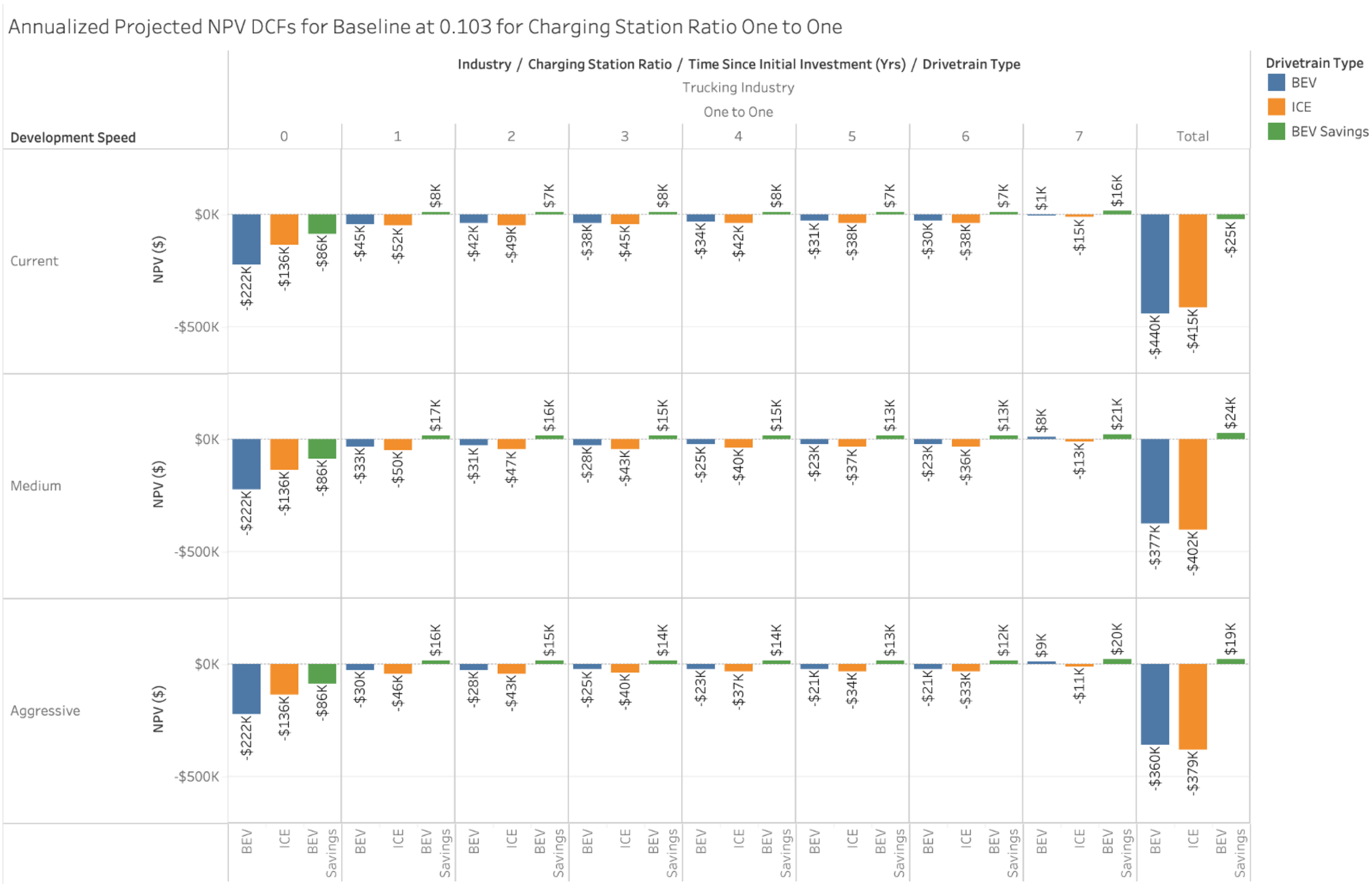
Sum of NPV for each Drivetrain Type broken down by Industry, Charging Station Ratio and Time Since Initial Investment (Yrs) vs. Development Speed. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV. The data is filtered on Economic Condition and Discount Factor. The Economic Condition filter keeps Low Oil Cost. The Discount Factor filter keeps 0.103. The view is filtered on Drivetrain Type, Development Speed and Charging Station Ratio. The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Development Speed filter keeps Aggressive, Current and Medium. The Charging Station Ratio filter keeps One to One.

Figure A-20: Projected NPV Discounted Cash Flow per Year for Low Oil Economic Scenario



Sum of NPV for each Drivetrain Type broken down by Industry, Charging Station Ratio and Time Since Initial Investment (Yrs) vs. Development Speed. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV. The data is filtered on Economic Condition and Discount Factor. The Economic Condition filter keeps High Renewable Cost. The Discount Factor filter keeps 0.103. The view is filtered on Drivetrain Type, Development Speed and Charging Station Ratio. The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Development Speed filter keeps Aggressive, Current and Medium. The Charging Station Ratio filter keeps One to One.

Figure A-21: Projected NPV Discounted Cash Flow per Year for High Renewable Economic Scenario



Sum of NPV for each Drivetrain Type broken down by Industry, Charging Station Ratio and Time Since Initial Investment (Yrs) vs. Development Speed. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV. The data is filtered on Economic Condition and Discount Factor. The Economic Condition filter keeps Baseline. The Discount Factor filter keeps 0.103. The view is filtered on Drivetrain Type, Development Speed and Charging Station Ratio. The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Development Speed filter keeps Aggressive, Current and Medium. The Charging Station Ratio filter keeps One to One.

Figure A-22: Projected NPV Discounted Cash Flow per Year for Baseline Economic Scenario

Discount Factor 10.3% & One to Four Ratio

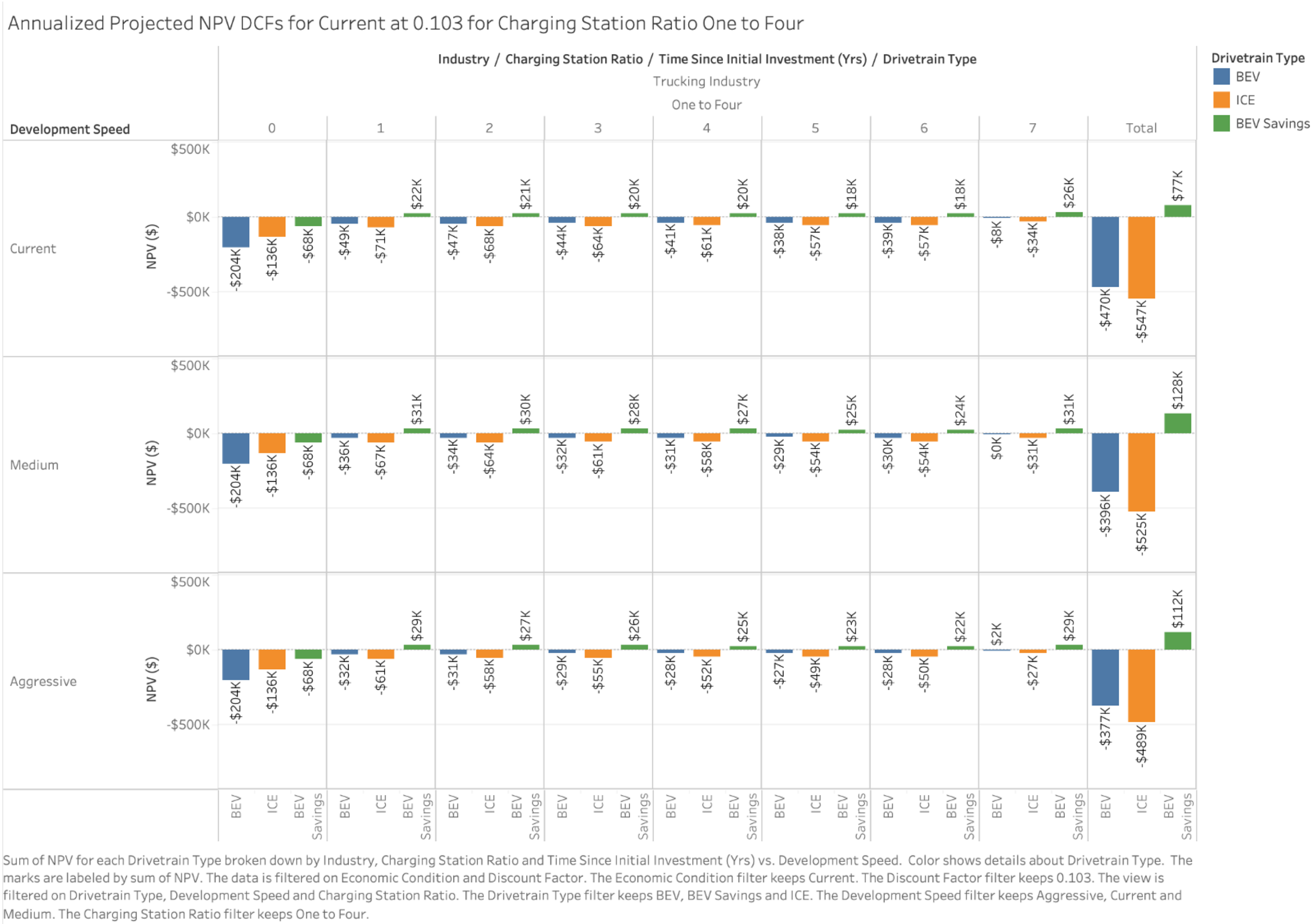


Figure A-23: Projected NPV Discounted Cash Flow per Year for Current Economic Scenario

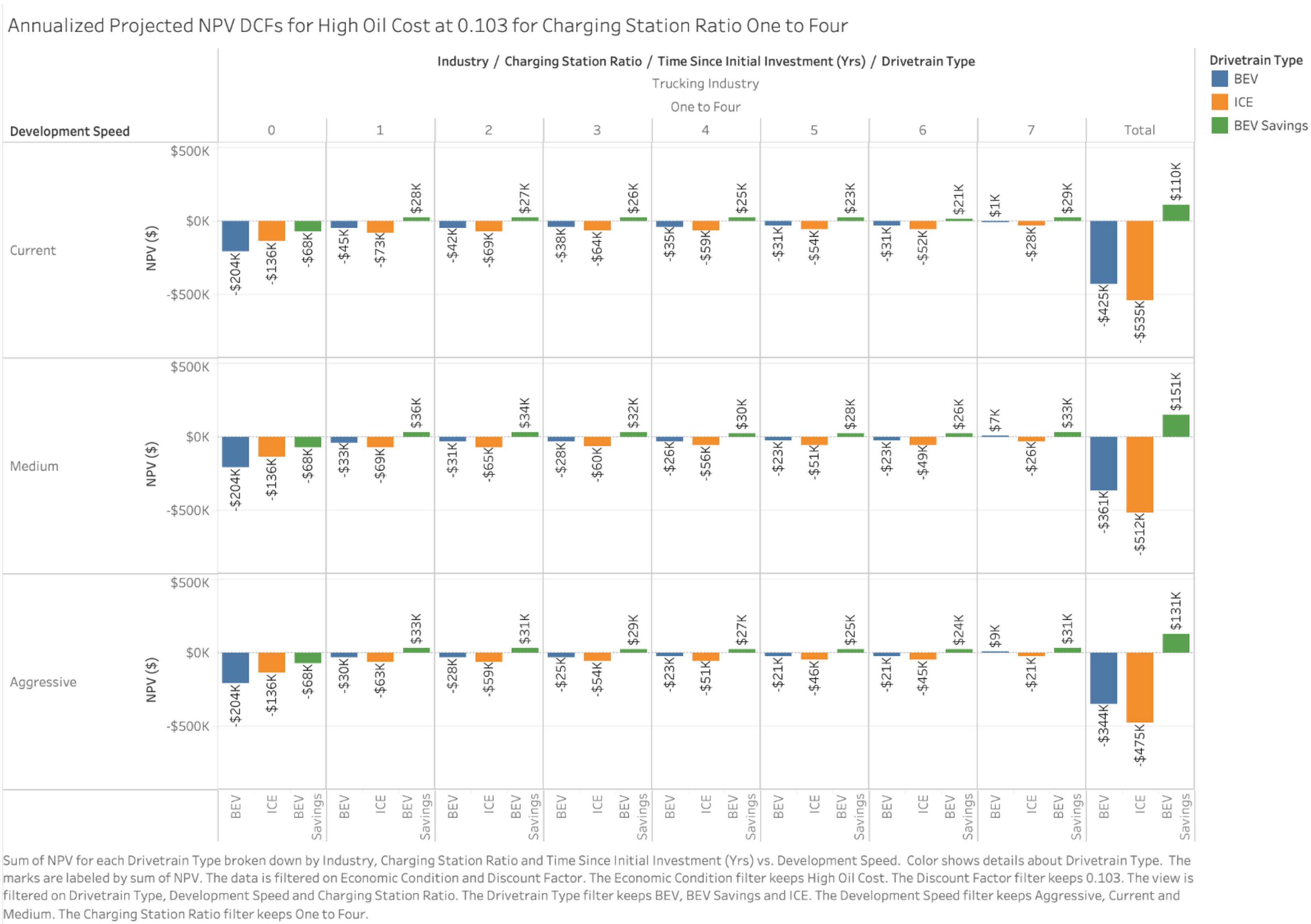
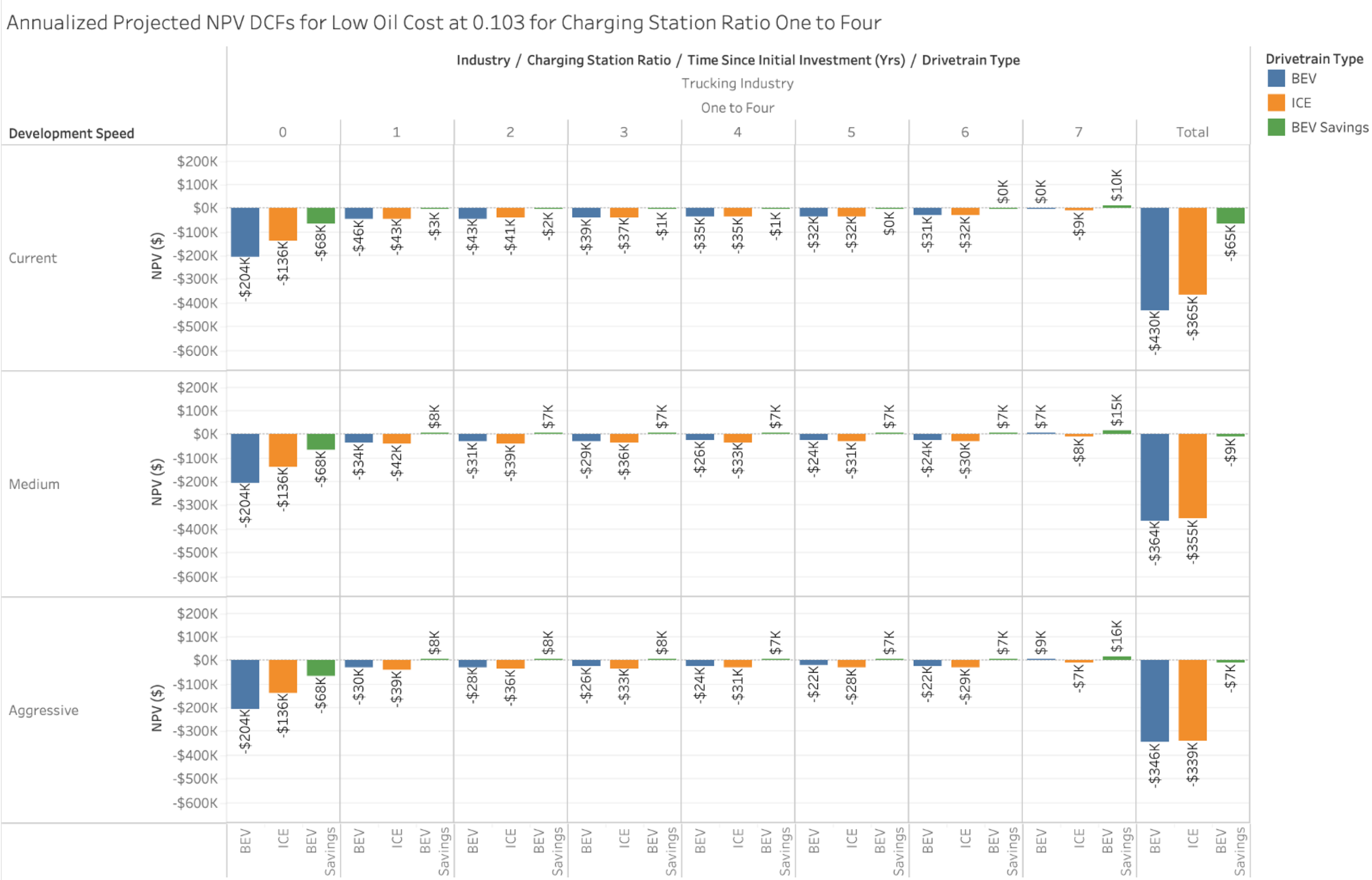


Figure A-24: Projected NPV Discounted Cash Flow per Year for High Oil Economic Scenario



Sum of NPV for each Drivetrain Type broken down by Industry, Charging Station Ratio and Time Since Initial Investment (Yrs) vs. Development Speed. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV. The data is filtered on Economic Condition and Discount Factor. The Economic Condition filter keeps Low Oil Cost. The Discount Factor filter keeps 0.103. The view is filtered on Drivetrain Type, Development Speed and Charging Station Ratio. The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Development Speed filter keeps Aggressive, Current and Medium. The Charging Station Ratio filter keeps One to Four.

Figure A-25: Projected NPV Discounted Cash Flow per Year for Low Oil Economic Scenario

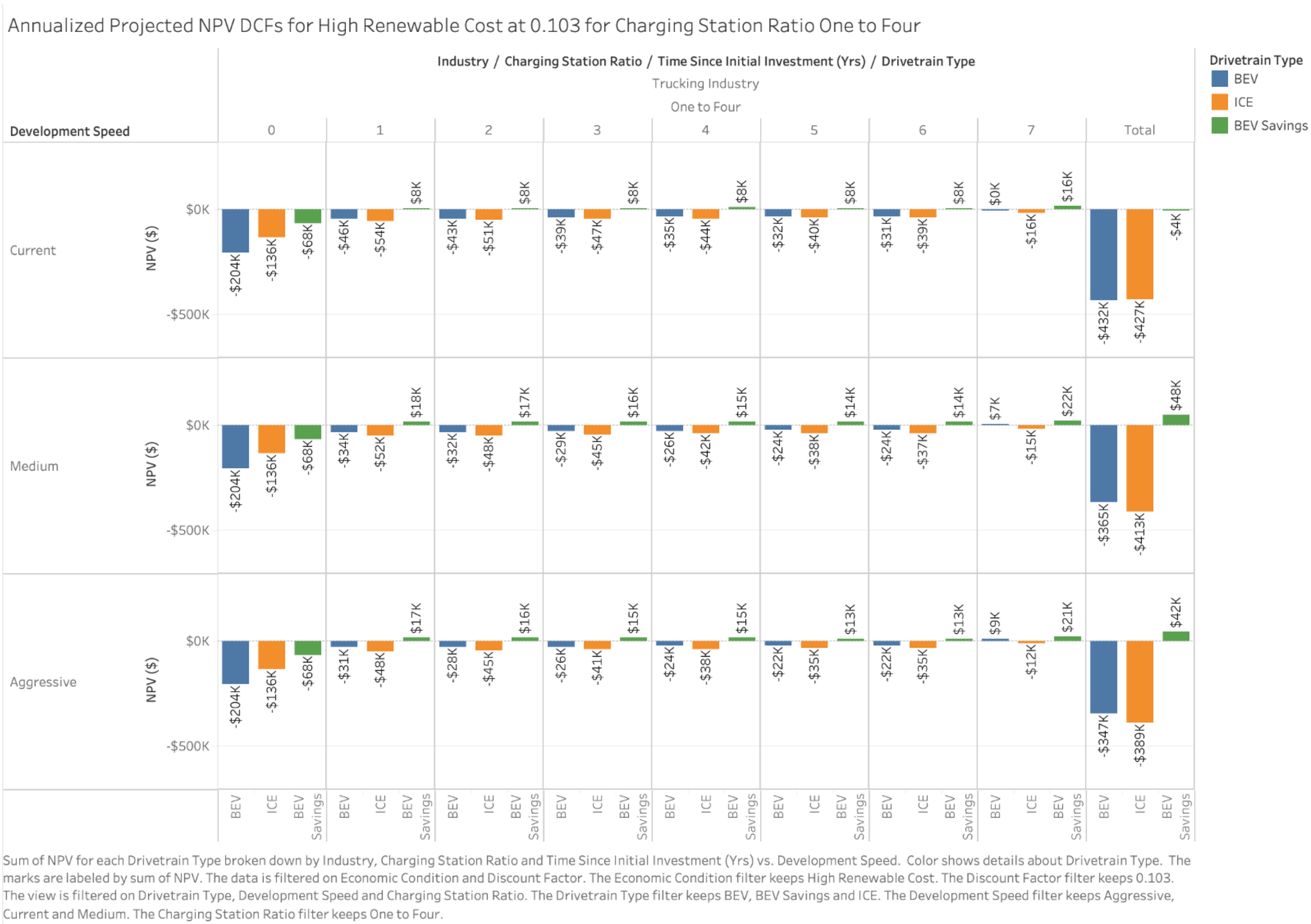
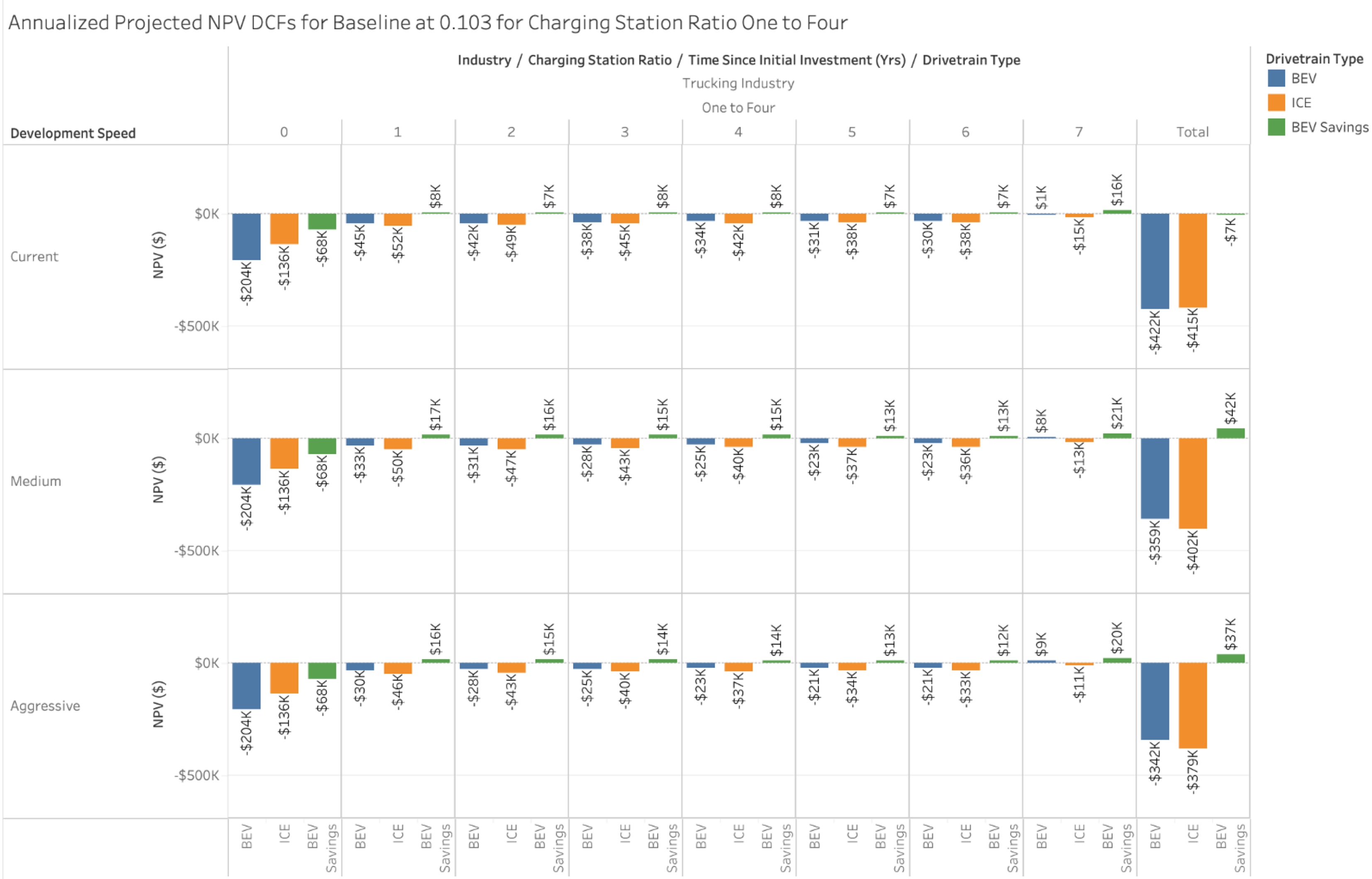


Figure A-26: Projected NPV Discounted Cash Flow per Year for High Renewable Economic Scenario



Sum of NPV for each Drivetrain Type broken down by Industry, Charging Station Ratio and Time Since Initial Investment (Yrs) vs. Development Speed. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV. The data is filtered on Economic Condition and Discount Factor. The Economic Condition filter keeps Baseline. The Discount Factor filter keeps 0.103. The view is filtered on Drivetrain Type, Development Speed and Charging Station Ratio. The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Development Speed filter keeps Aggressive, Current and Medium. The Charging Station Ratio filter keeps One to Four.

Figure A-27: Projected NPV Discounted Cash Flow per Year for Baseline Economic Scenario

Discount Factor 7.61% & One to One Ratio

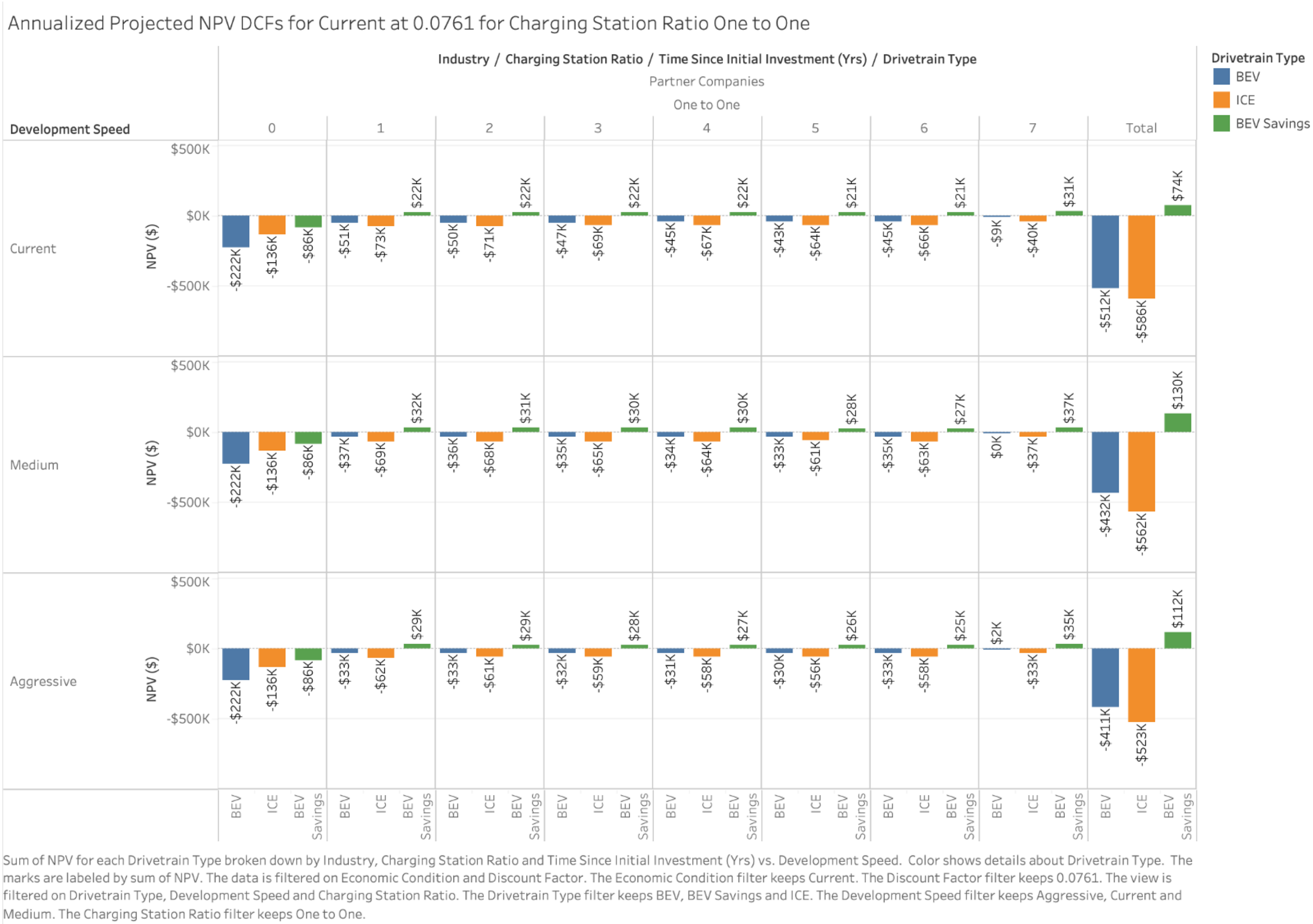
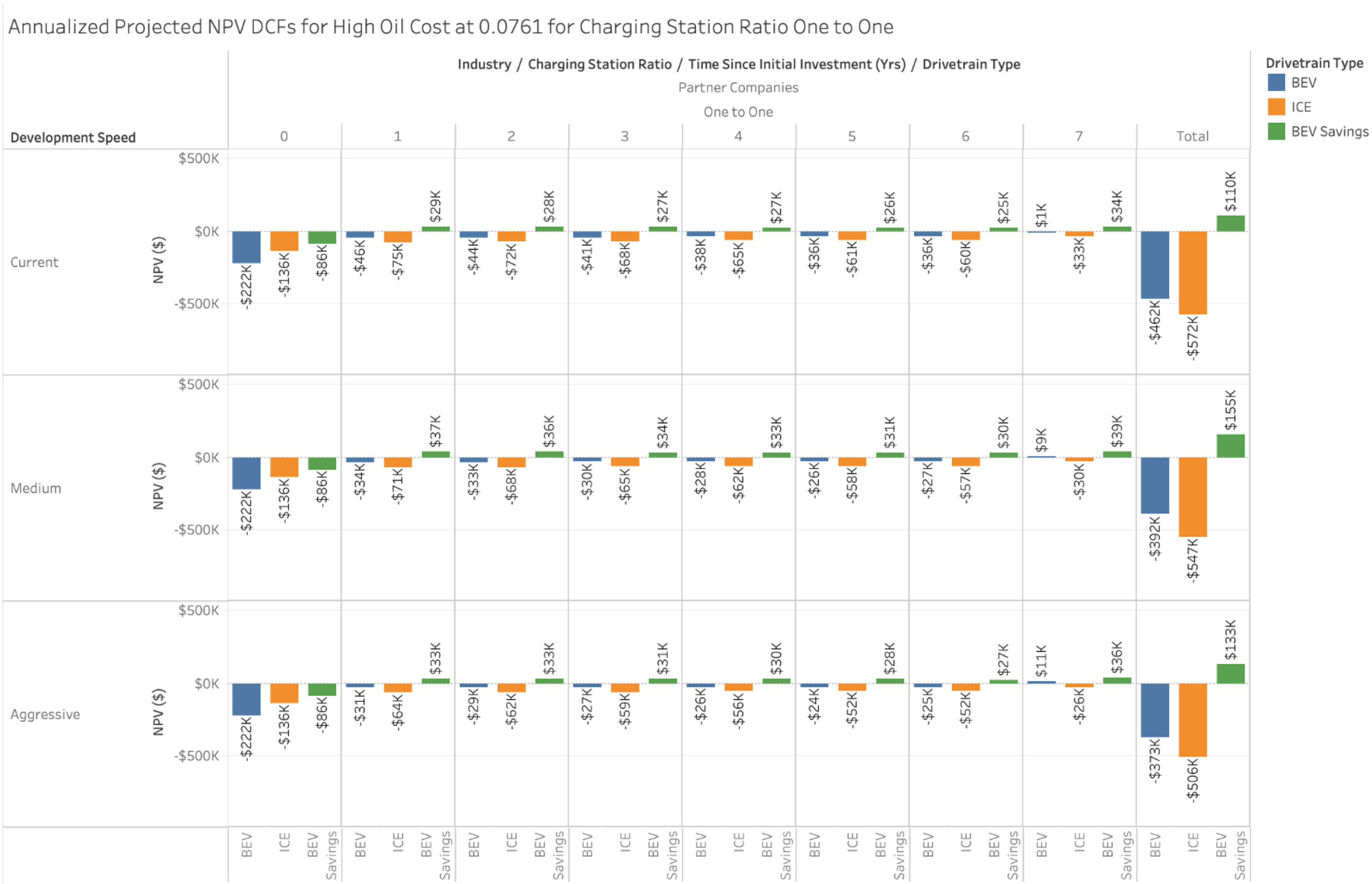


Figure A-28: Projected NPV Discounted Cash Flow per Year for Current Economic Scenario



Sum of NPV for each Drivetrain Type broken down by Industry, Charging Station Ratio and Time Since Initial Investment (Yrs) vs. Development Speed. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV. The data is filtered on Economic Condition and Discount Factor. The Economic Condition filter keeps High Oil Cost. The Discount Factor filter keeps 0.0761. The view is filtered on Drivetrain Type, Development Speed and Charging Station Ratio. The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Development Speed filter keeps Aggressive, Current and Medium. The Charging Station Ratio filter keeps One to One.

Figure A-29: Projected NPV Discounted Cash Flow per Year for High Oil Economic Scenario

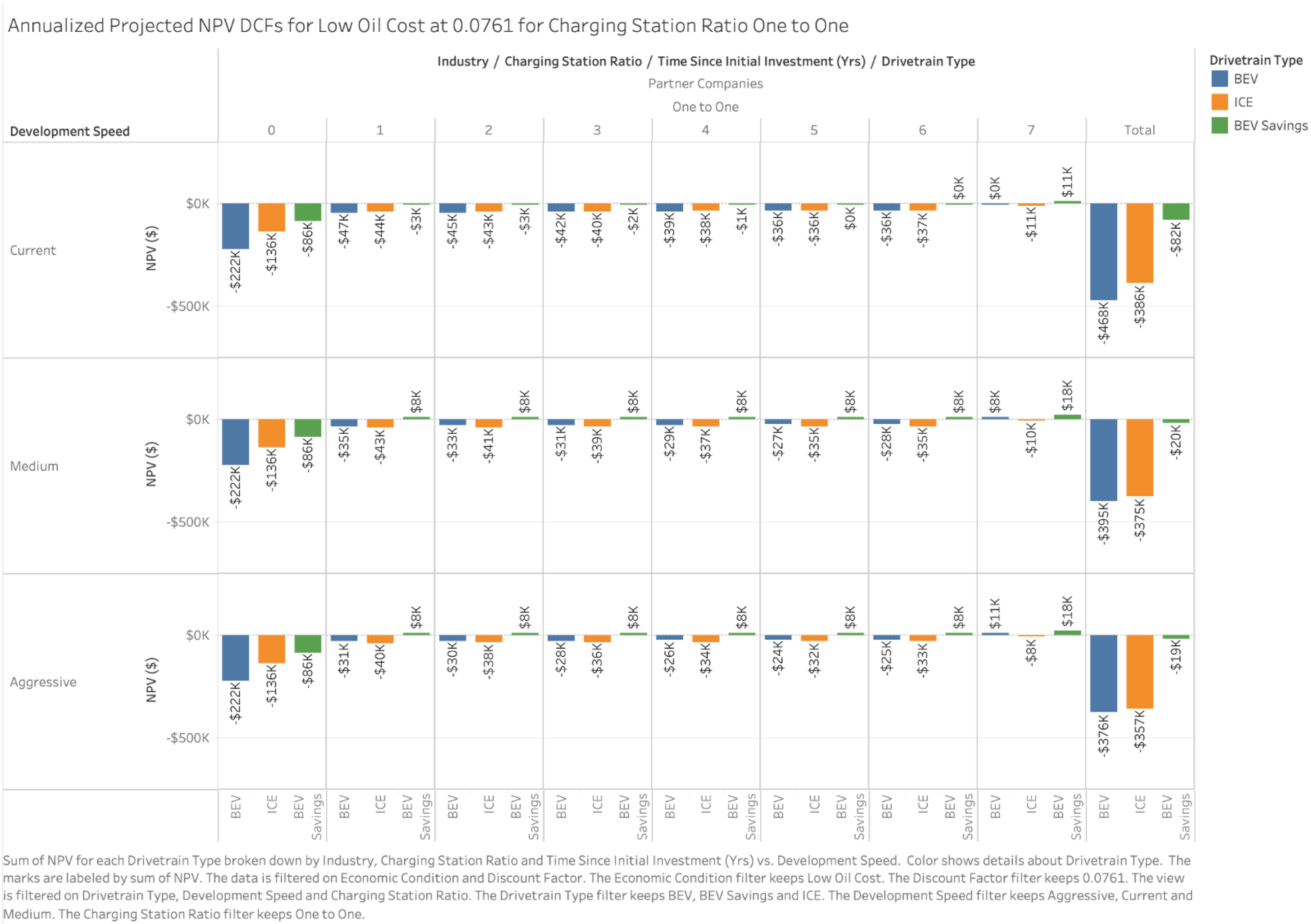
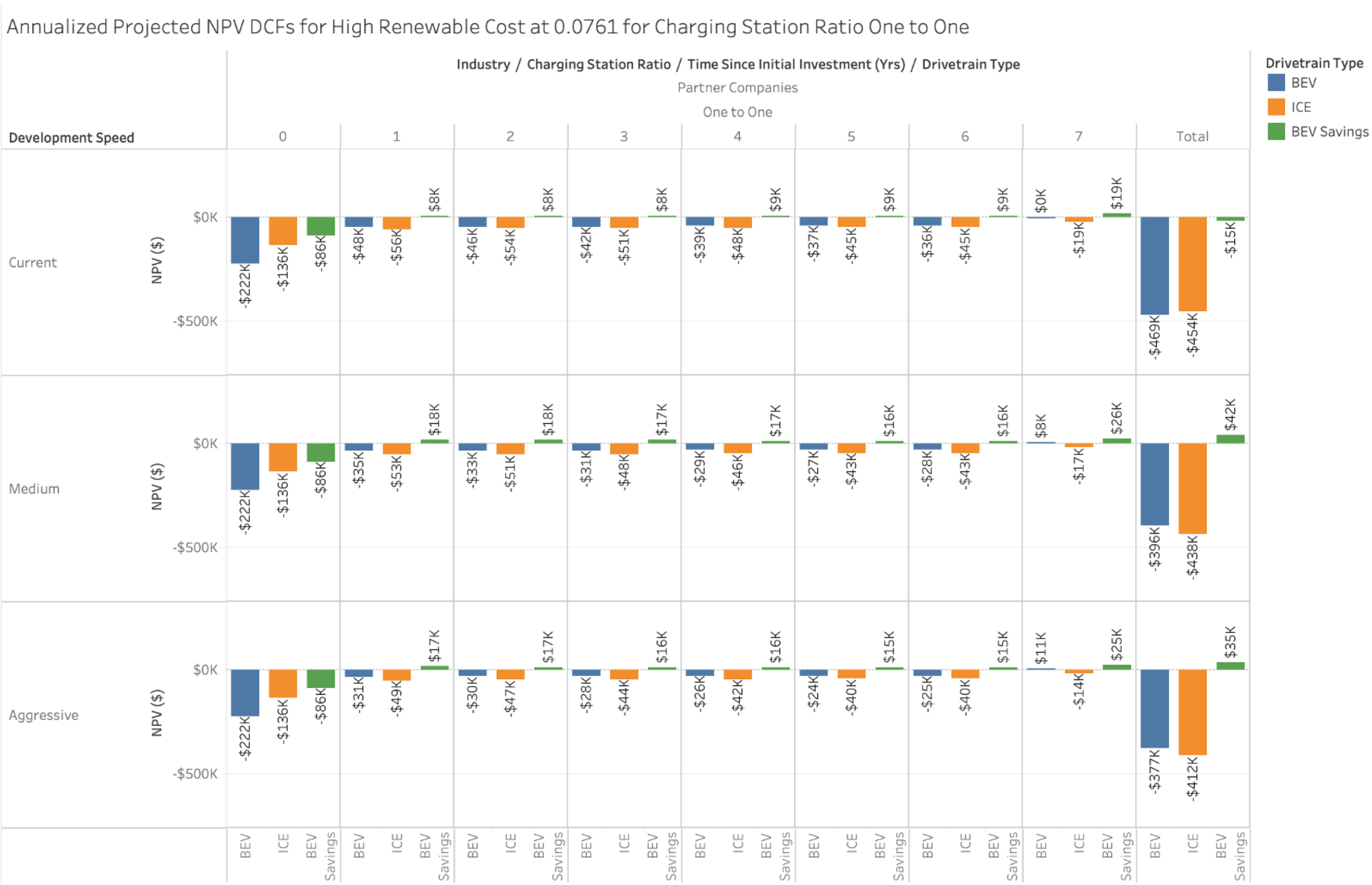
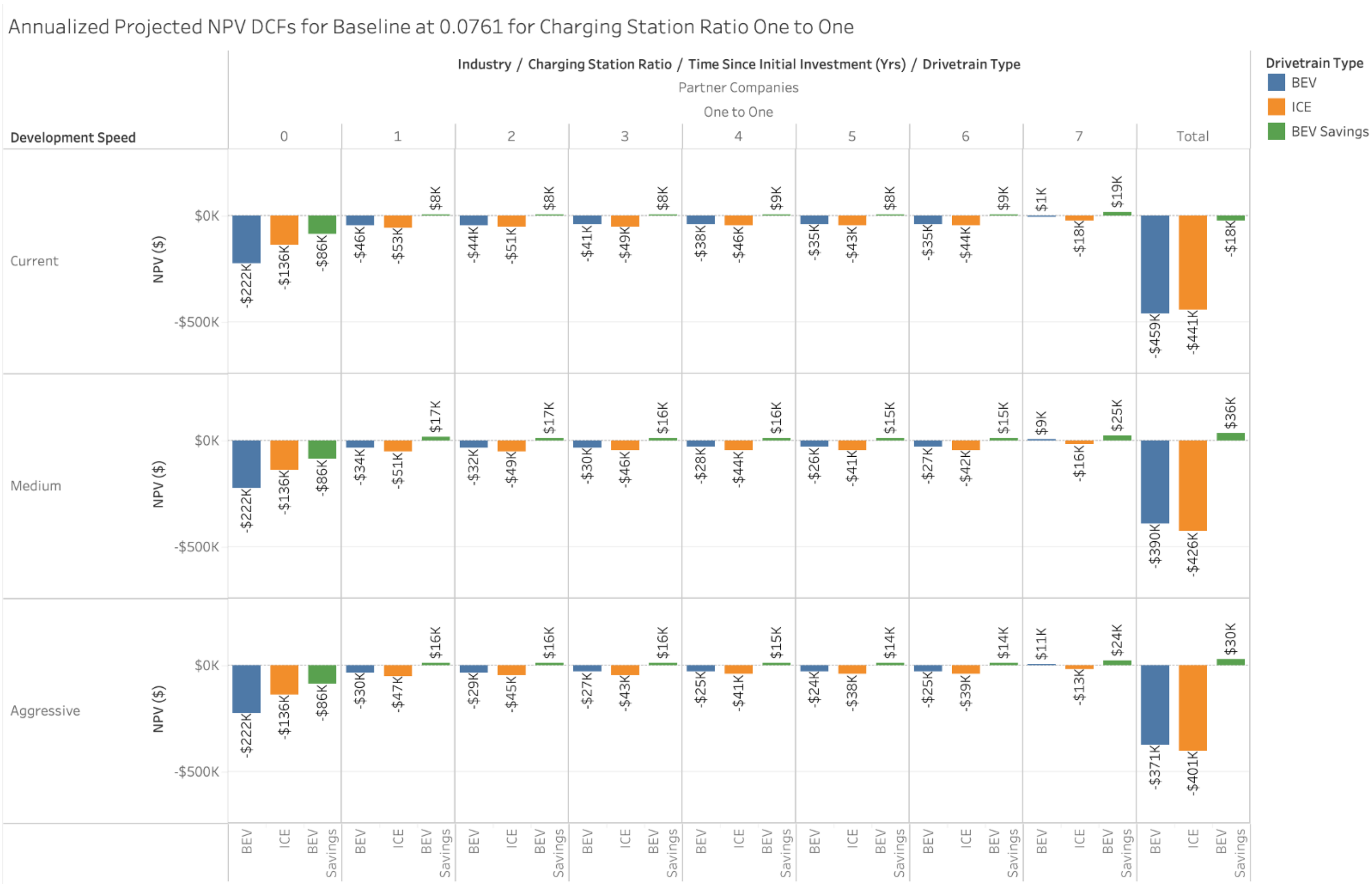


Figure A-30: Projected NPV Discounted Cash Flow per Year for Low Oil Economic Scenario



Sum of NPV for each Drivetrain Type broken down by Industry, Charging Station Ratio and Time Since Initial Investment (Yrs) vs. Development Speed. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV. The data is filtered on Economic Condition and Discount Factor. The Economic Condition filter keeps High Renewable Cost. The Discount Factor filter keeps 0.0761. The view is filtered on Drivetrain Type, Development Speed and Charging Station Ratio. The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Development Speed filter keeps Aggressive, Current and Medium. The Charging Station Ratio filter keeps One to One.

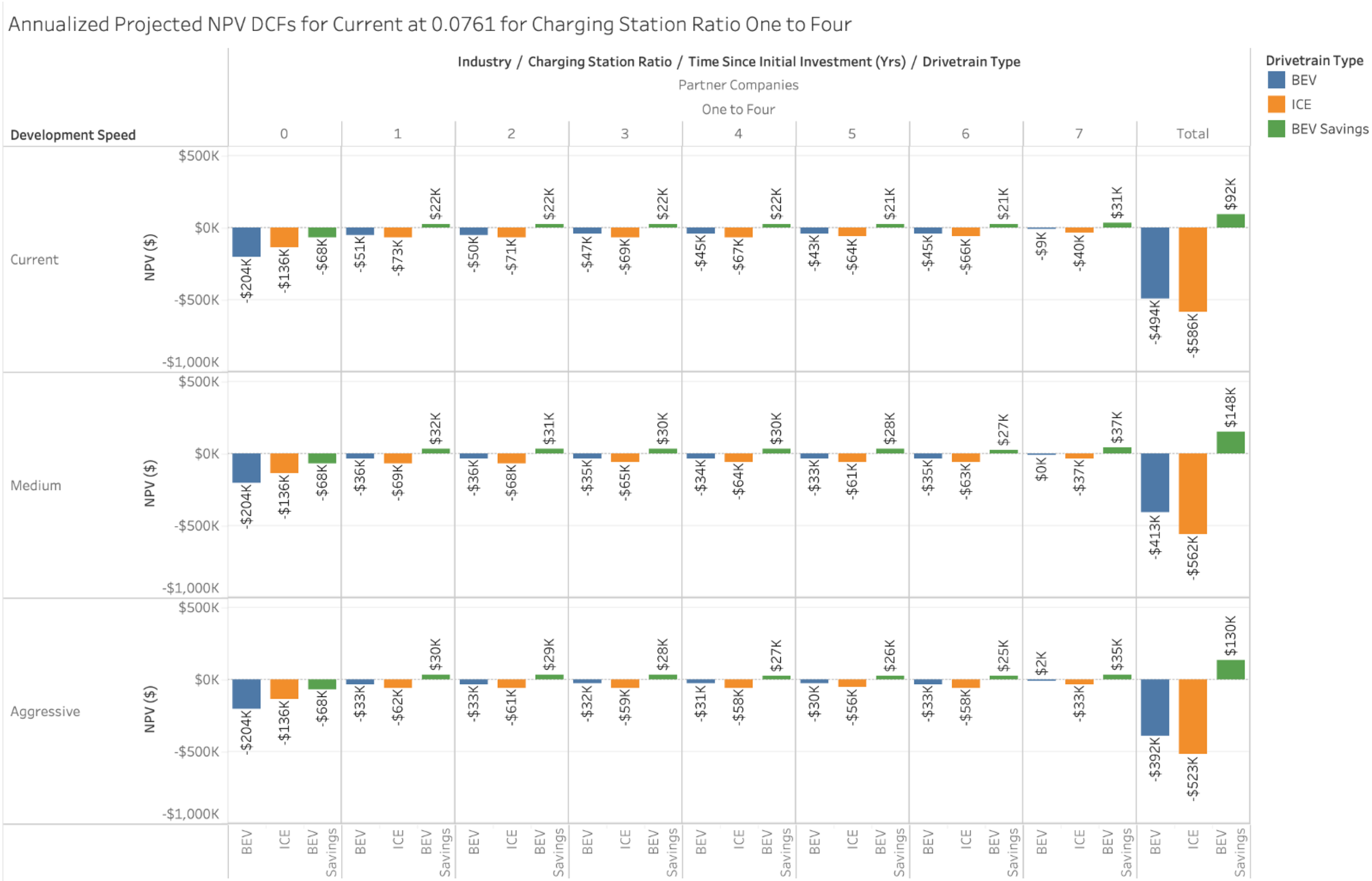
Figure A-31: Projected NPV Discounted Cash Flow per Year for High Renewable Economic Scenario



Sum of NPV for each Drivetrain Type broken down by Industry, Charging Station Ratio and Time Since Initial Investment (Yrs) vs. Development Speed. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV. The data is filtered on Economic Condition and Discount Factor. The Economic Condition filter keeps Baseline. The Discount Factor filter keeps 0.0761. The view is filtered on Drivetrain Type, Development Speed and Charging Station Ratio. The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Development Speed filter keeps Aggressive, Current and Medium. The Charging Station Ratio filter keeps One to One.

Figure A-32: Projected NPV Discounted Cash Flow per Year for Baseline Economic Scenario

Discount Factor 7.61% & One to Four Ratio



Sum of NPV for each Drivetrain Type broken down by Industry, Charging Station Ratio and Time Since Initial Investment (Yrs) vs. Development Speed. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV. The data is filtered on Economic Condition and Discount Factor. The Economic Condition filter keeps Current. The Discount Factor filter keeps 0.0761. The view is filtered on Drivetrain Type, Development Speed and Charging Station Ratio. The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Development Speed filter keeps Aggressive, Current and Medium. The Charging Station Ratio filter keeps One to Four.

Figure A-33: Projected NPV Discounted Cash Flow per Year for Current Economic Scenario

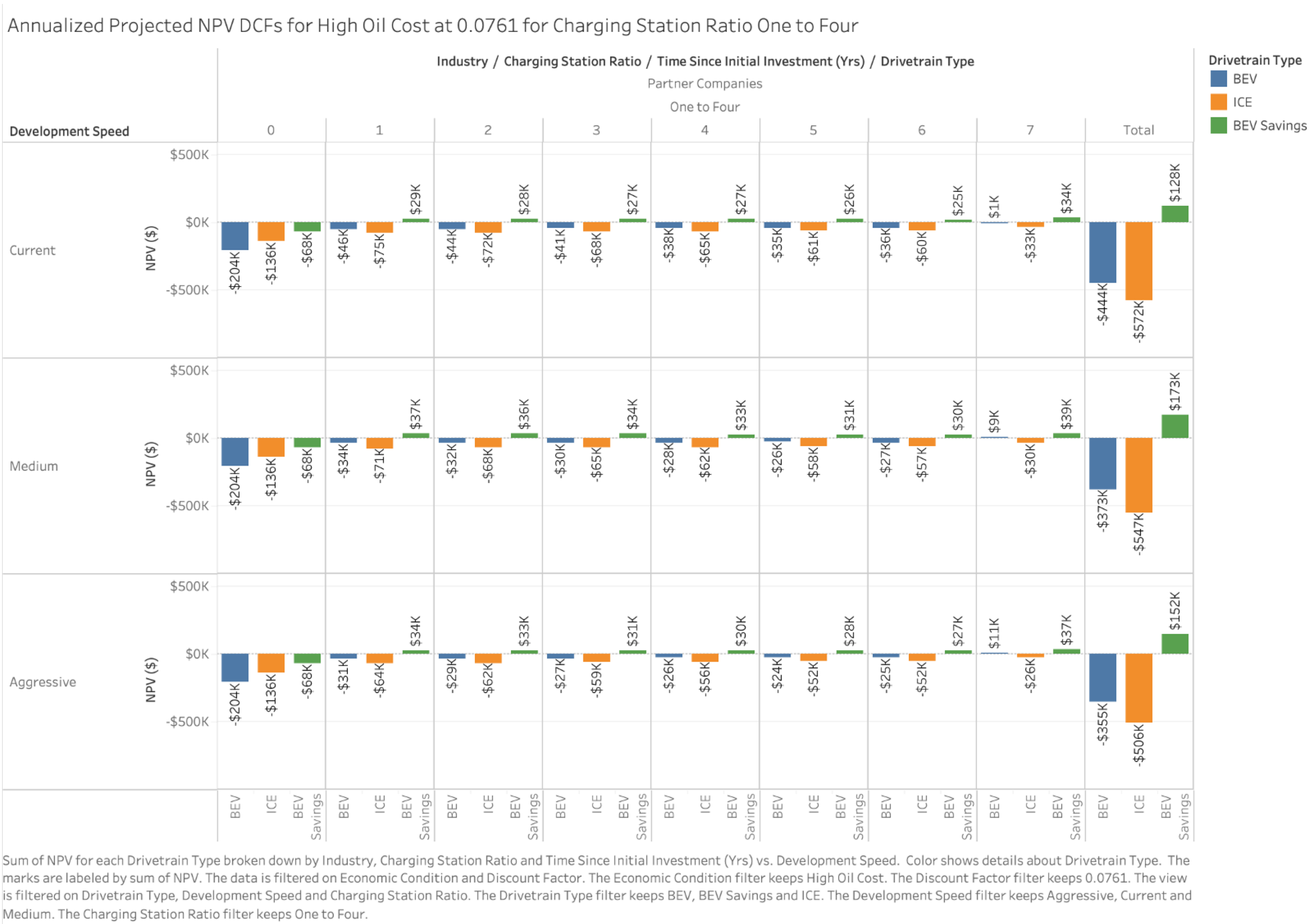


Figure A-34: Projected NPV Discounted Cash Flow per Year for High Oil Economic Scenario

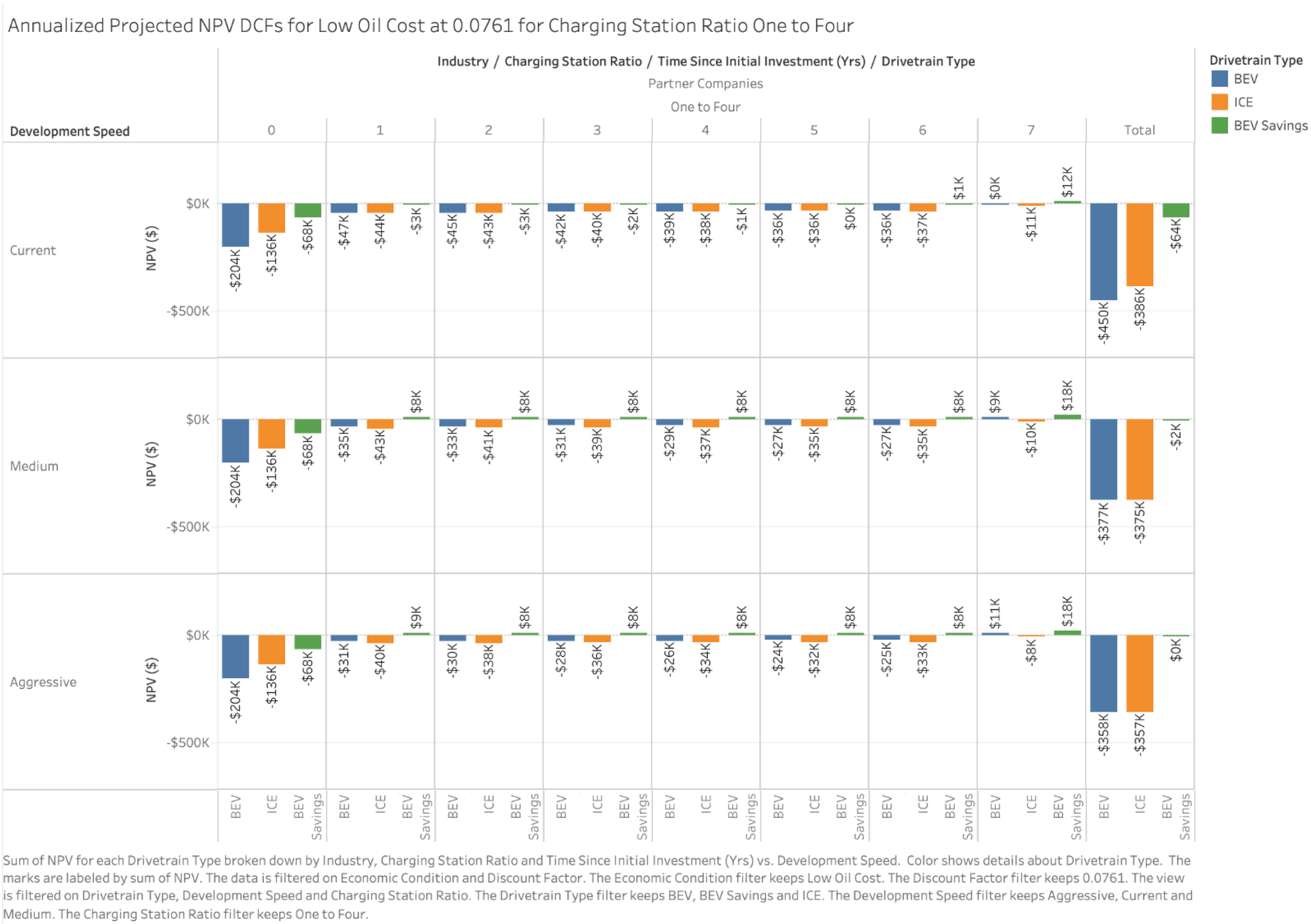


Figure A-35: Projected NPV Discounted Cash Flow per Year for Low Oil Economic Scenario

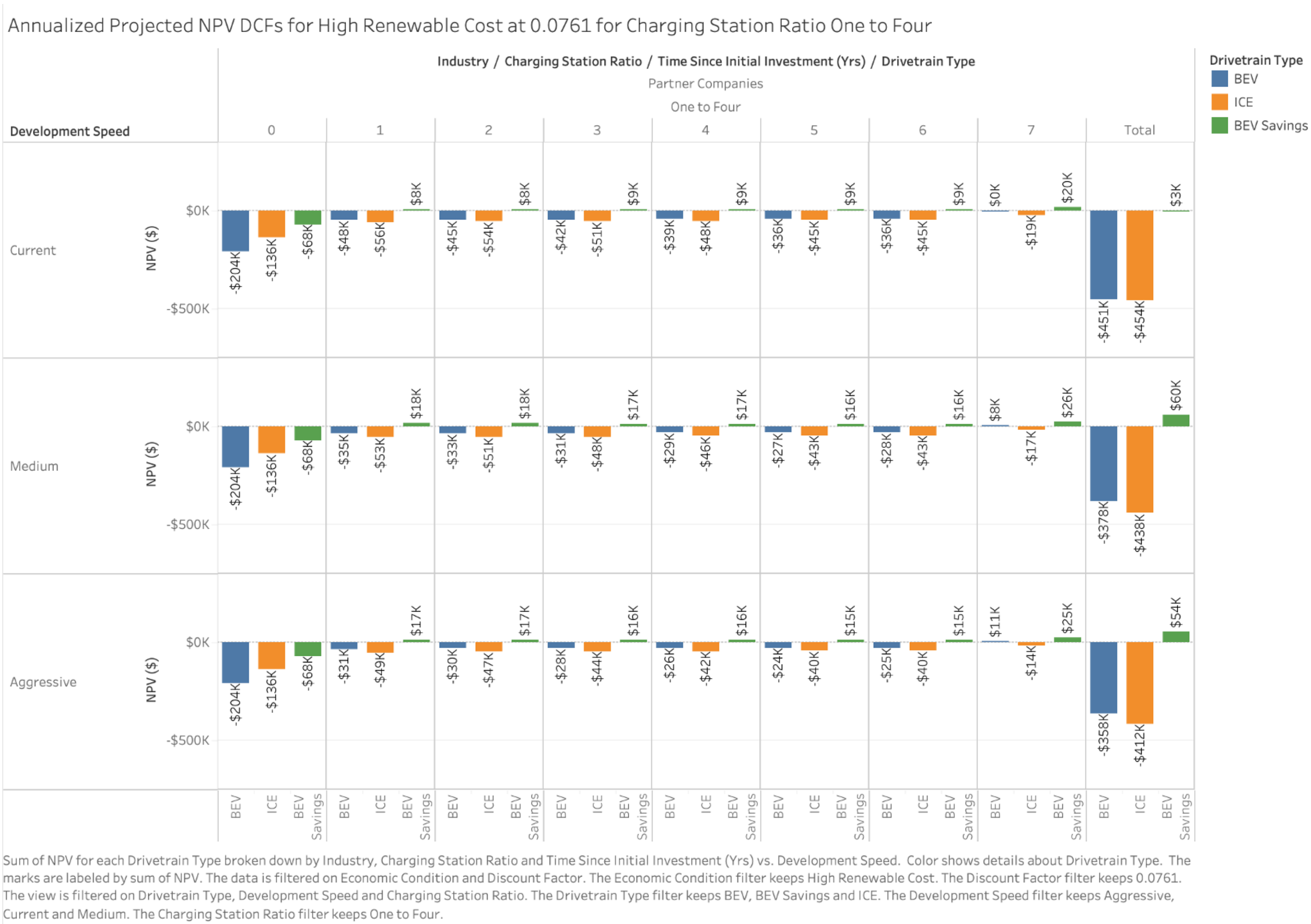
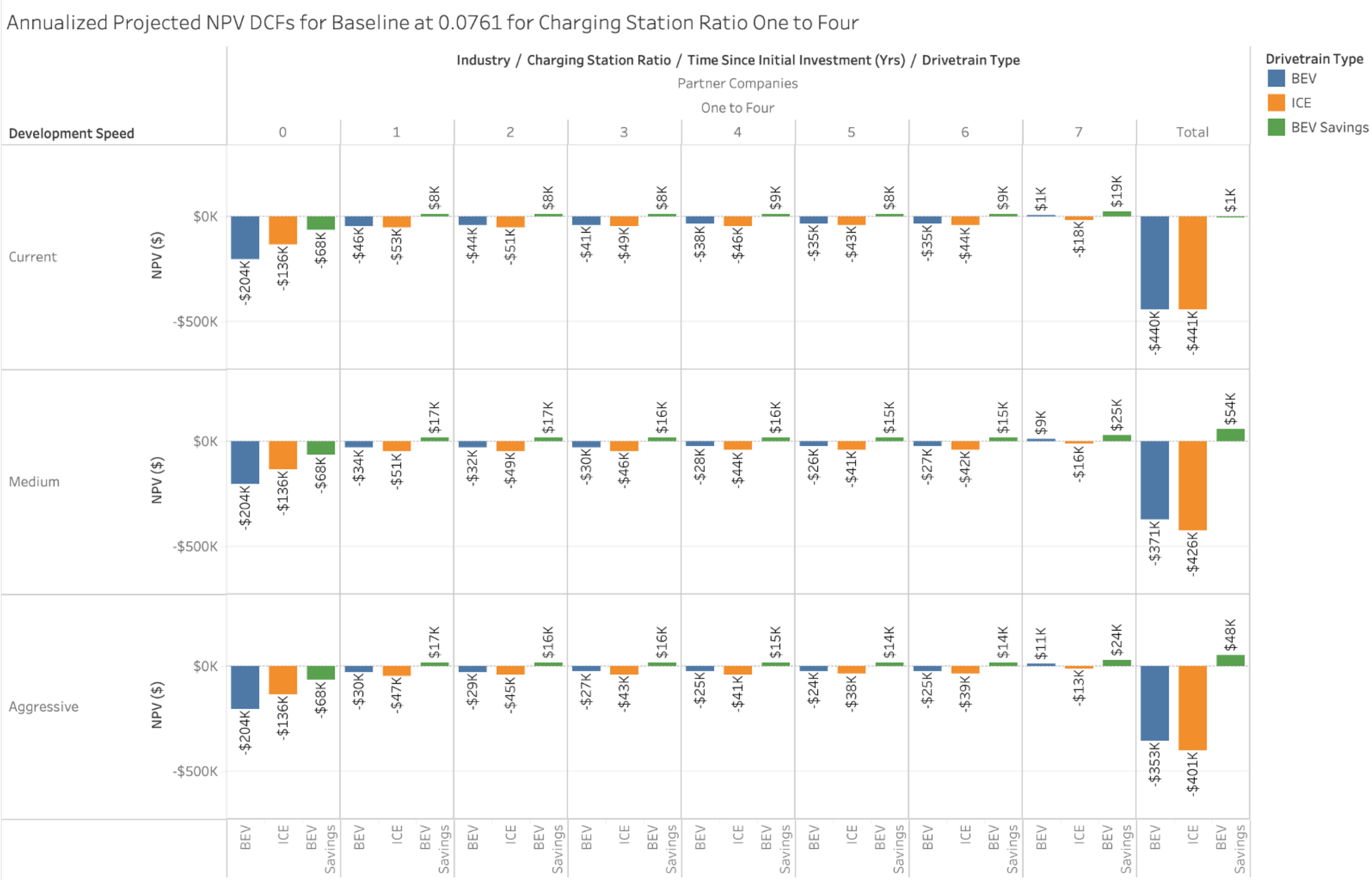


Figure A-36: Projected NPV Discounted Cash Flow per Year for High Renewable Economic Scenario



Sum of NPV for each Drivetrain Type broken down by Industry, Charging Station Ratio and Time Since Initial Investment (Yrs) vs. Development Speed. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV. The data is filtered on Economic Condition and Discount Factor. The Economic Condition filter keeps Baseline. The Discount Factor filter keeps 0.0761. The view is filtered on Drivetrain Type, Development Speed and Charging Station Ratio. The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Development Speed filter keeps Aggressive, Current and Medium. The Charging Station Ratio filter keeps One to Four.

Figure A-37: Projected NPV Discounted Cash Flow per Year for Baseline Economic Scenario

A.5.2 Summed NPV with and without BEV Savings

Discount Factor 10.3% & One to One Ratio

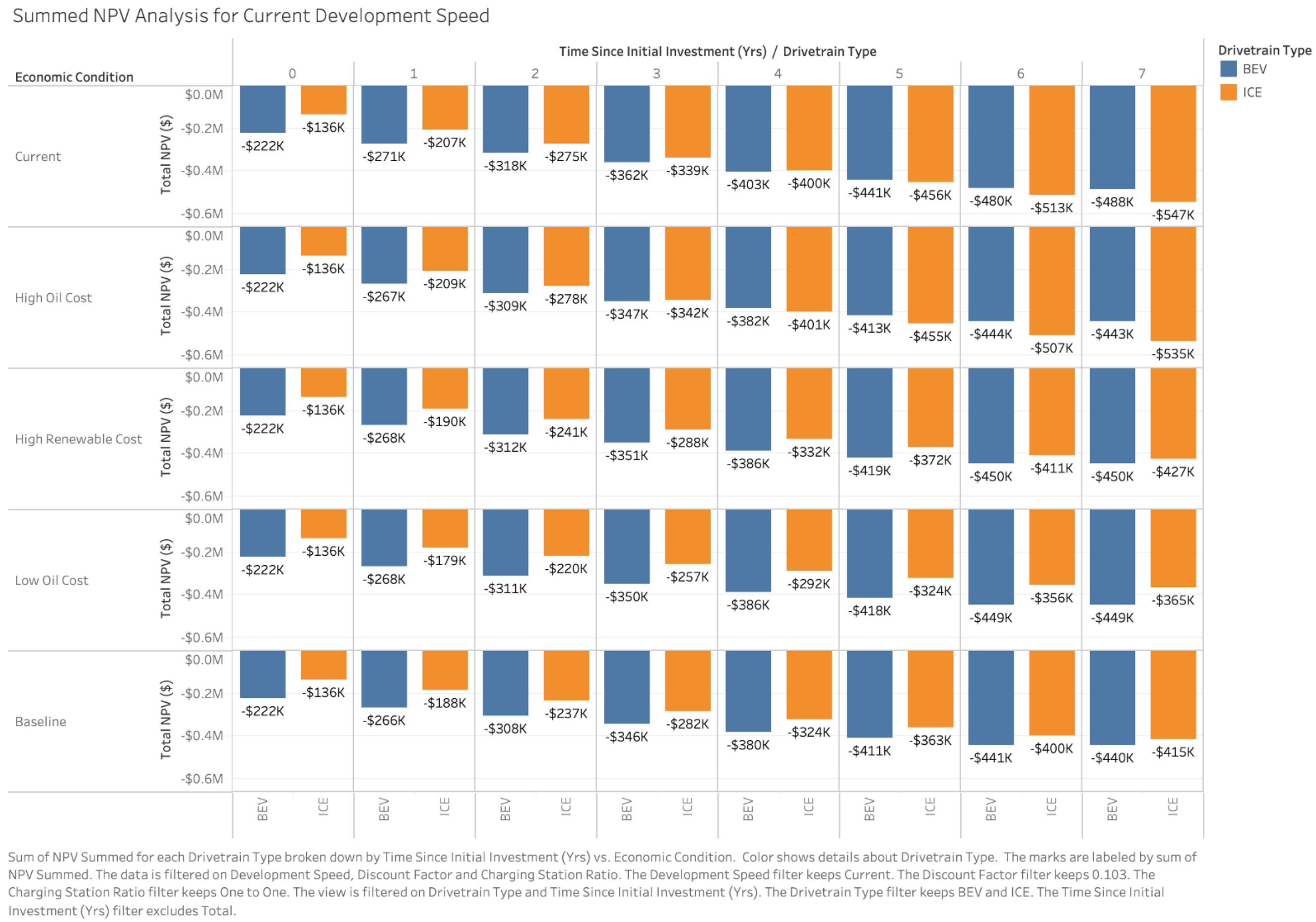


Figure A-38: Summed NPV Analysis for Current Development Speed

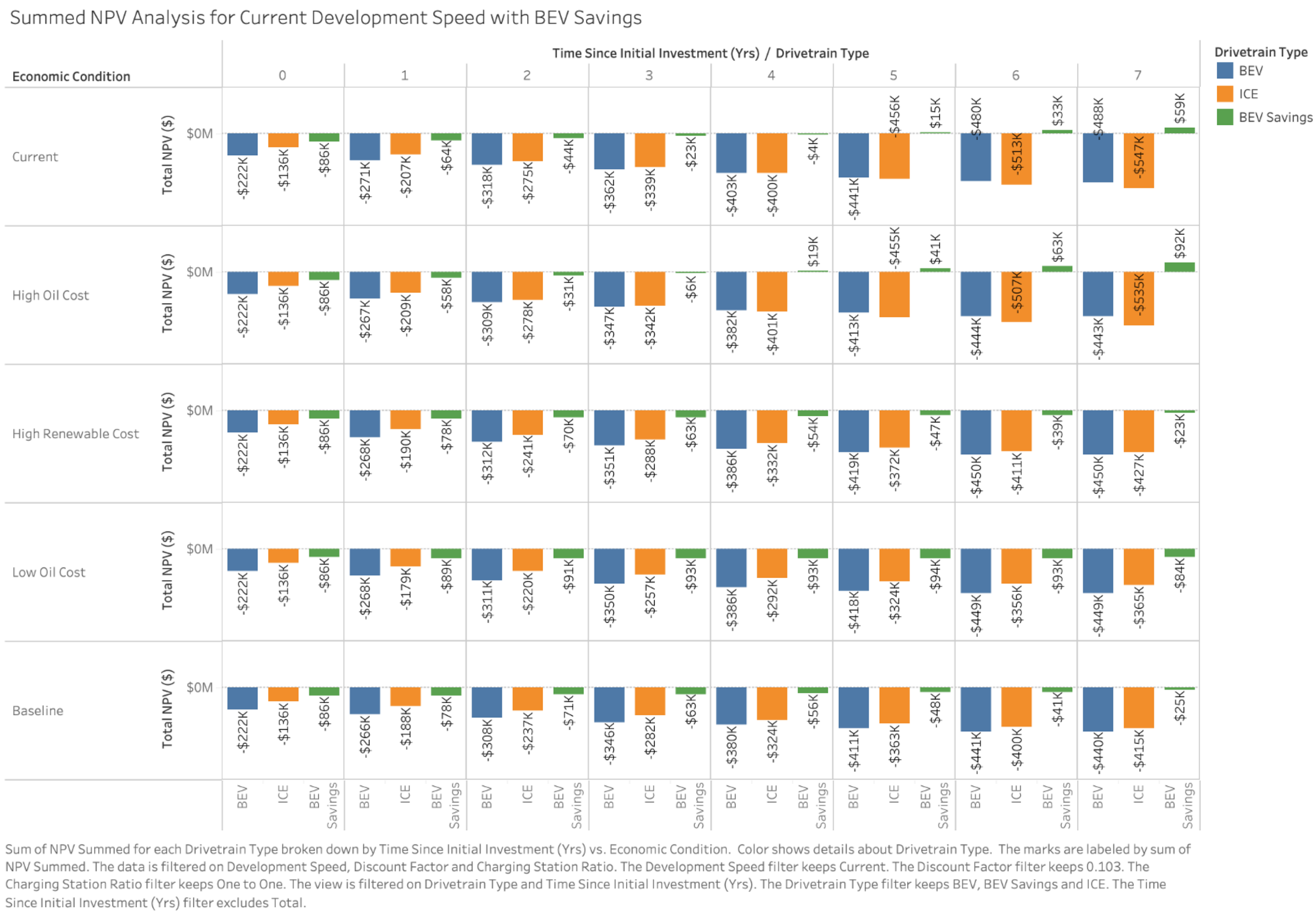


Figure A-39: Summed NPV Analysis with BEV Savings for Current Development Speed

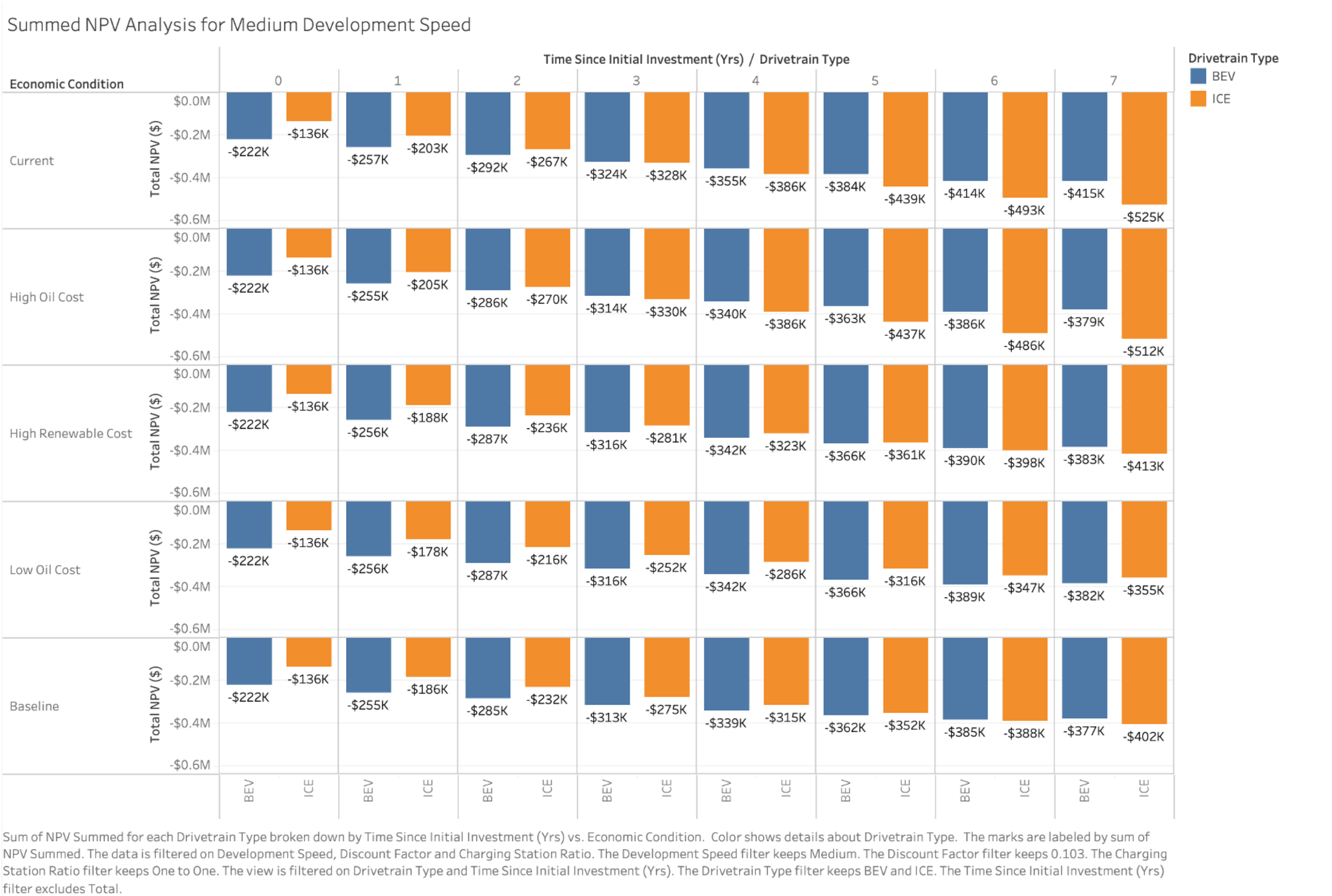
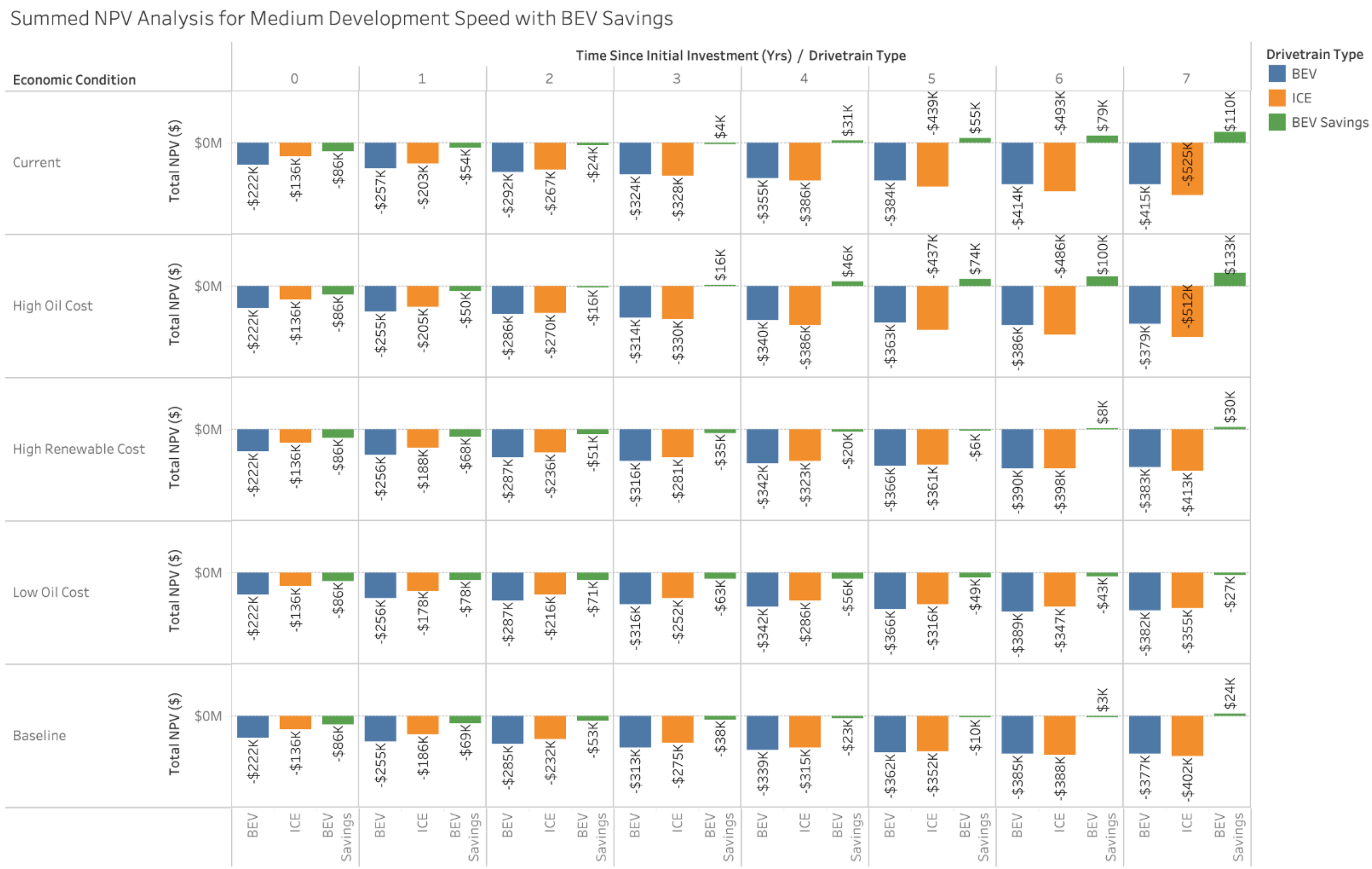


Figure A-40: Summed NPV Analysis for Medium Development Speed



Sum of NPV Summed for each Drivetrain Type broken down by Time Since Initial Investment (Yrs) vs. Economic Condition. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV Summed. The data is filtered on Development Speed, Discount Factor and Charging Station Ratio. The Development Speed filter keeps Medium. The Discount Factor filter keeps 0.103. The Charging Station Ratio filter keeps One to One. The view is filtered on Drivetrain Type and Time Since Initial Investment (Yrs). The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Time Since Initial Investment (Yrs) filter excludes Total.

Figure A-41: Summed NPV Analysis with BEV Savings for Medium Development Speed

Sum of NPV Summed for each Drivetrain Type broken down by Time Since Initial Investment (Yrs) vs. Economic Condition. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV Summed. The data is filtered on Development Speed, Discount Factor and Charging Station Ratio. The Development Speed filter keeps Aggressive. The Discount Factor filter keeps 0.103. The Charging Station Ratio filter keeps One to One. The view is filtered on Drivetrain Type and Time Since Initial Investment (Yrs). The Drivetrain Type filter keeps BEV and ICE. The Time Since Initial Investment (Yrs) filter excludes Total.

Figure A-42: Summed NPV Analysis for Aggressive Development Speed

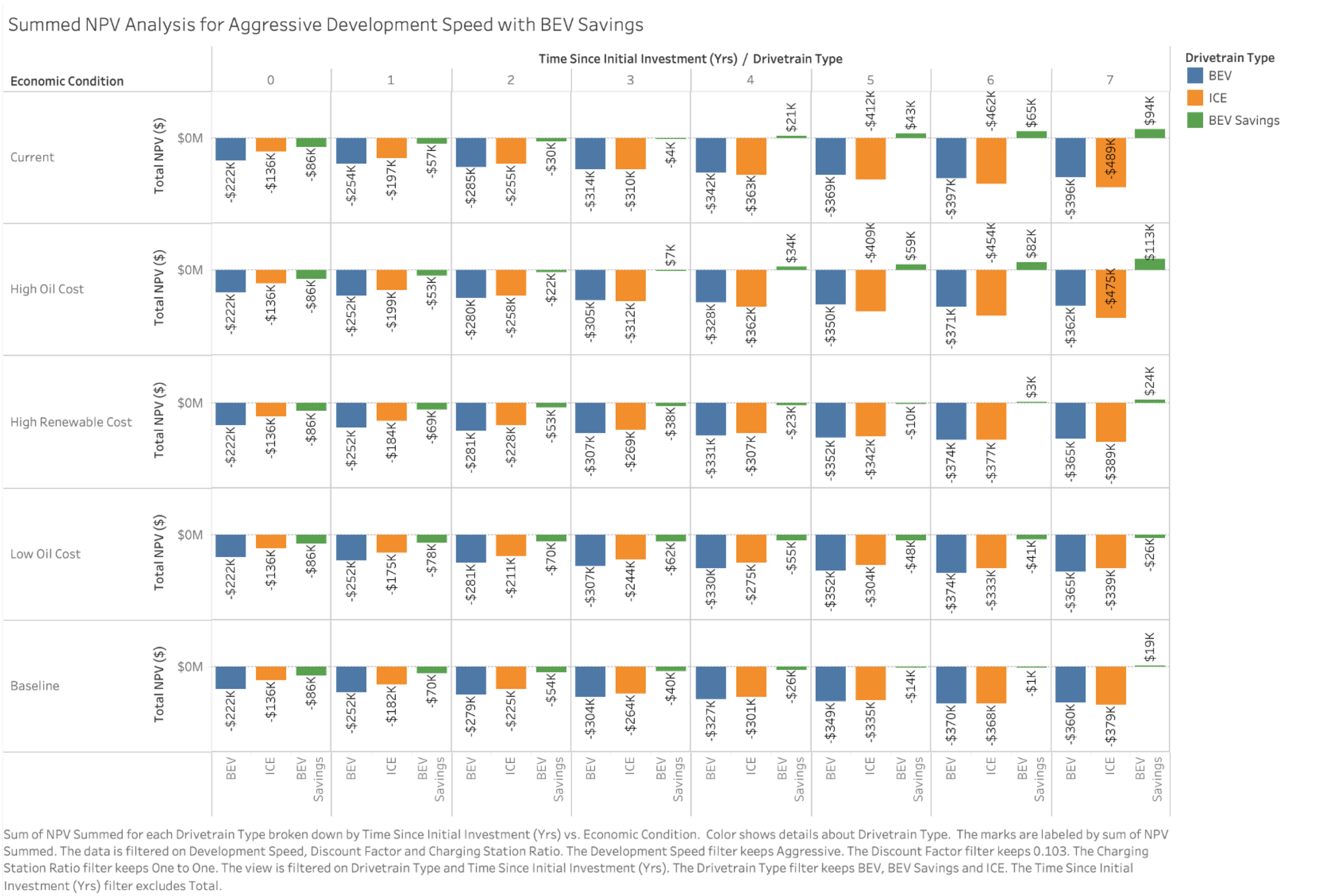
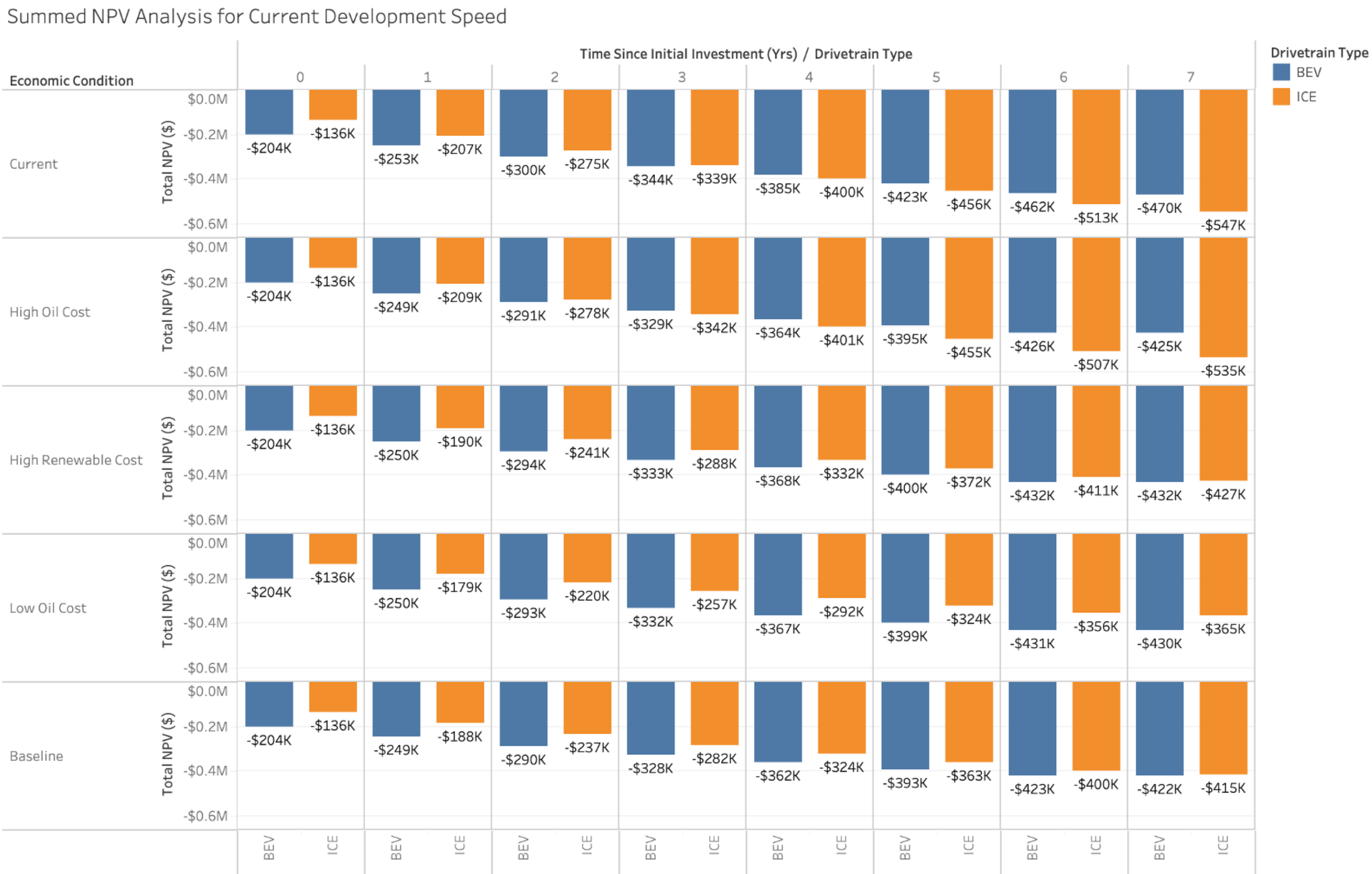


Figure A-43: Summed NPV Analysis with BEV Savings for Aggressive Development Speed

Discount Factor 10.3% & Four to One Ratio



Sum of NPV Summed for each Drivetrain Type broken down by Time Since Initial Investment (Yrs) vs. Economic Condition. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV Summed. The data is filtered on Development Speed, Discount Factor and Charging Station Ratio. The Development Speed filter keeps Current. The Discount Factor filter keeps 0.103. The Charging Station Ratio filter keeps One to Four. The view is filtered on Drivetrain Type and Time Since Initial Investment (Yrs). The Drivetrain Type filter keeps BEV and ICE. The Time Since Initial Investment (Yrs) filter excludes Total.

Figure A-44: Summed NPV Analysis for Current Development Speed

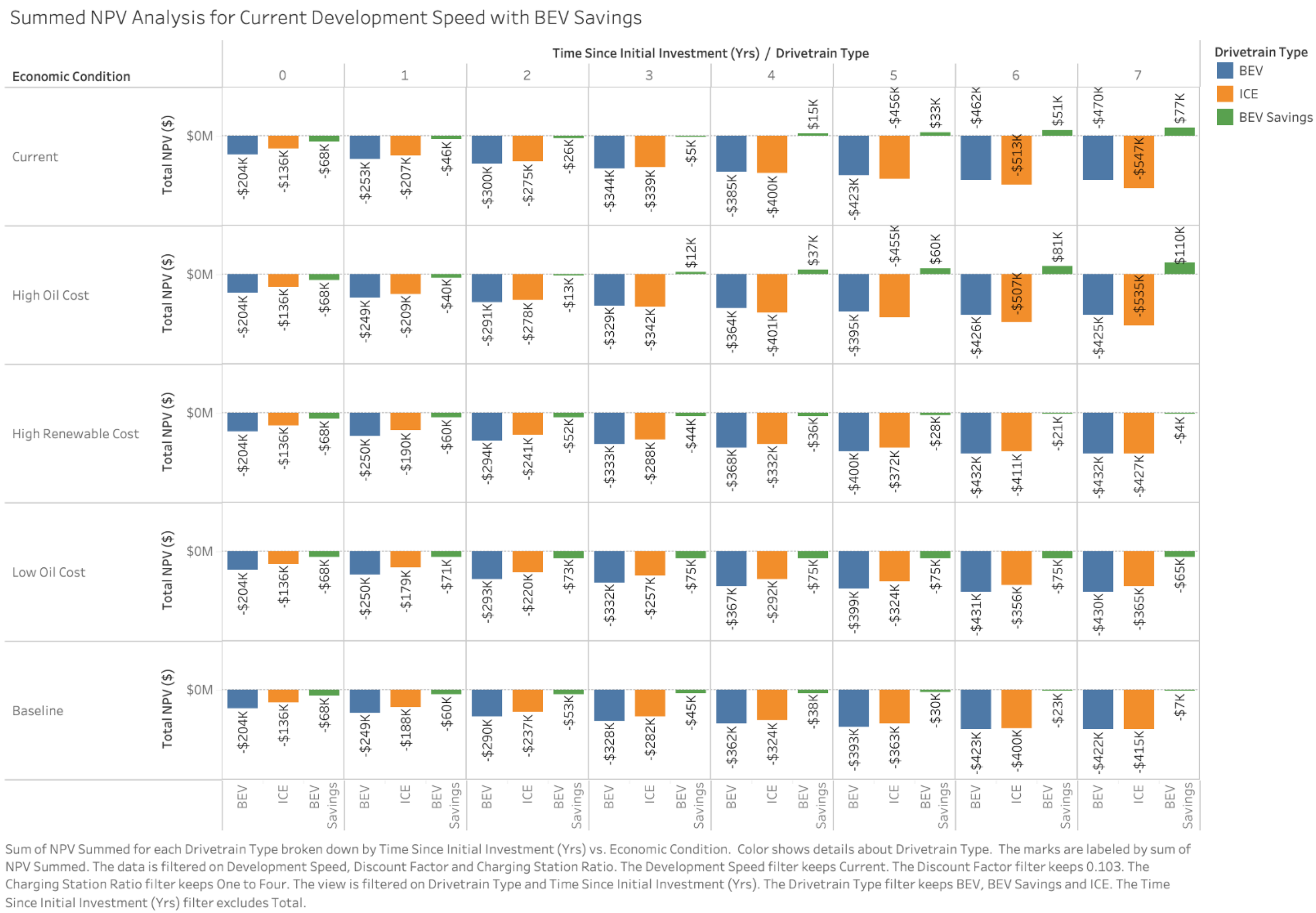


Figure A-45: Summed NPV Analysis with BEV Savings for Current Development Speed

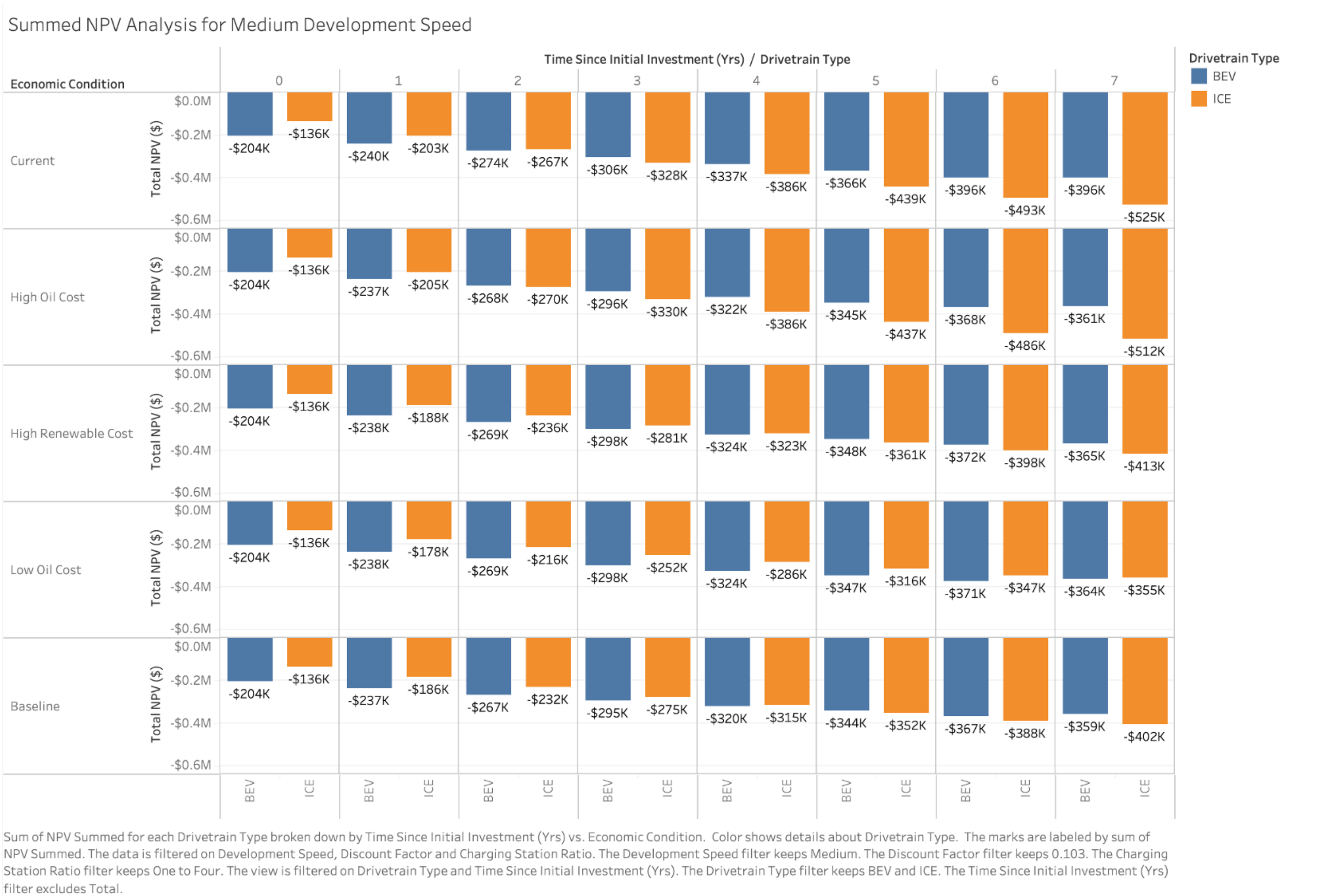
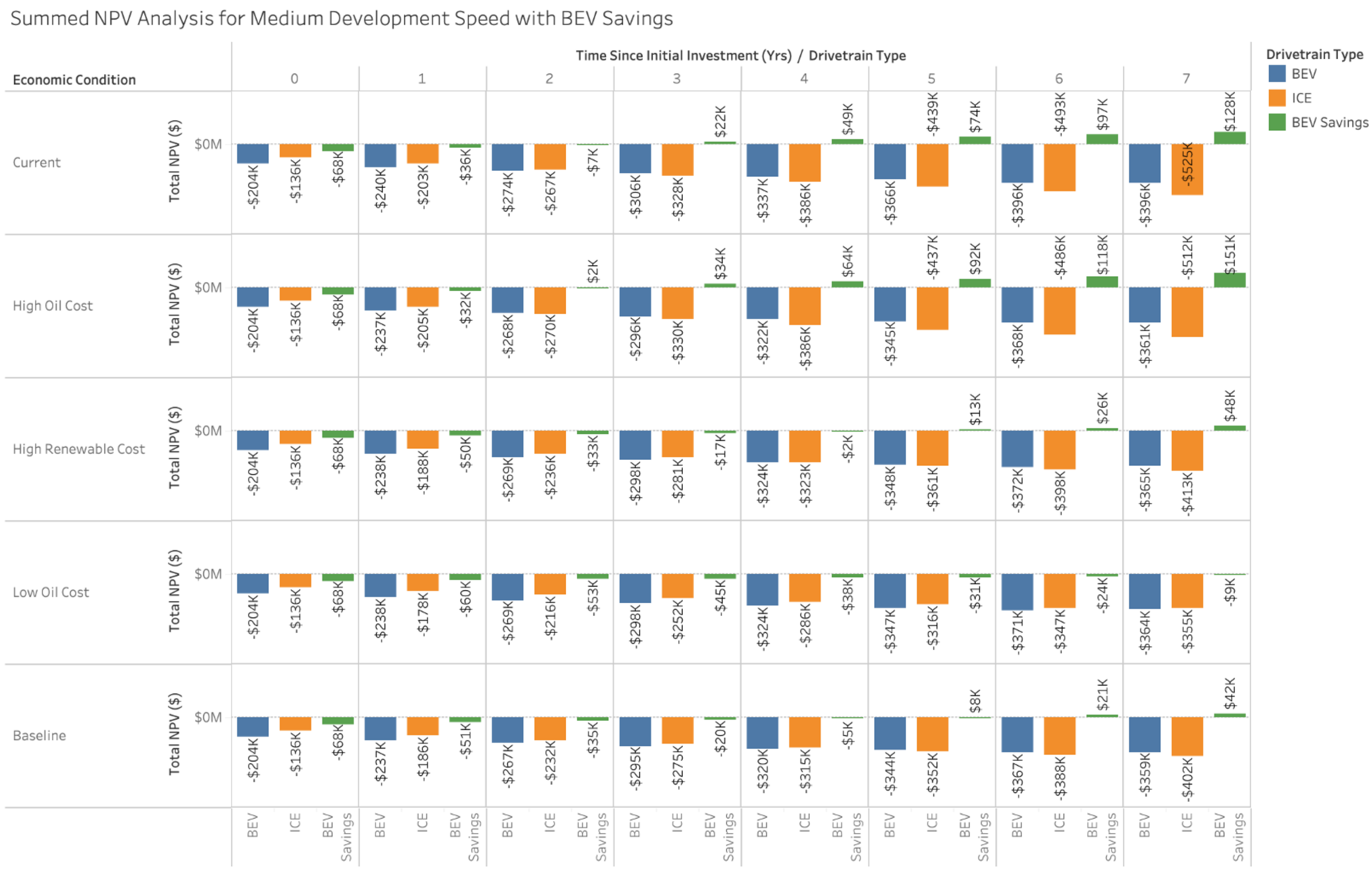


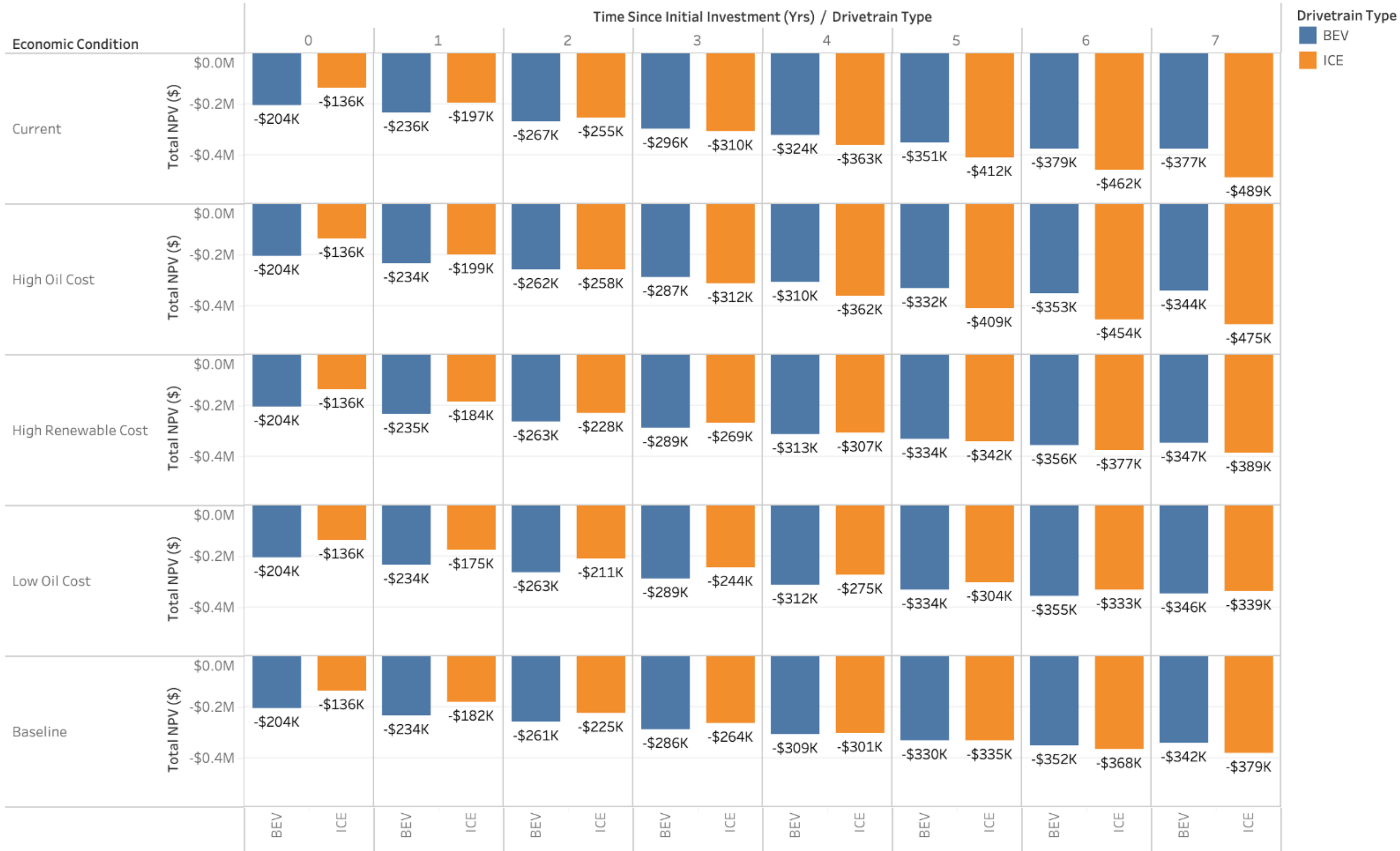
Figure A-46: Summed NPV Analysis for Medium Development Speed



Sum of NPV Summed for each Drivetrain Type broken down by Time Since Initial Investment (Yrs) vs. Economic Condition. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV Summed. The data is filtered on Development Speed, Discount Factor and Charging Station Ratio. The Development Speed filter keeps Medium. The Discount Factor filter keeps 0.103. The Charging Station Ratio filter keeps One to Four. The view is filtered on Drivetrain Type and Time Since Initial Investment (Yrs). The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Time Since Initial Investment (Yrs) filter excludes Total.

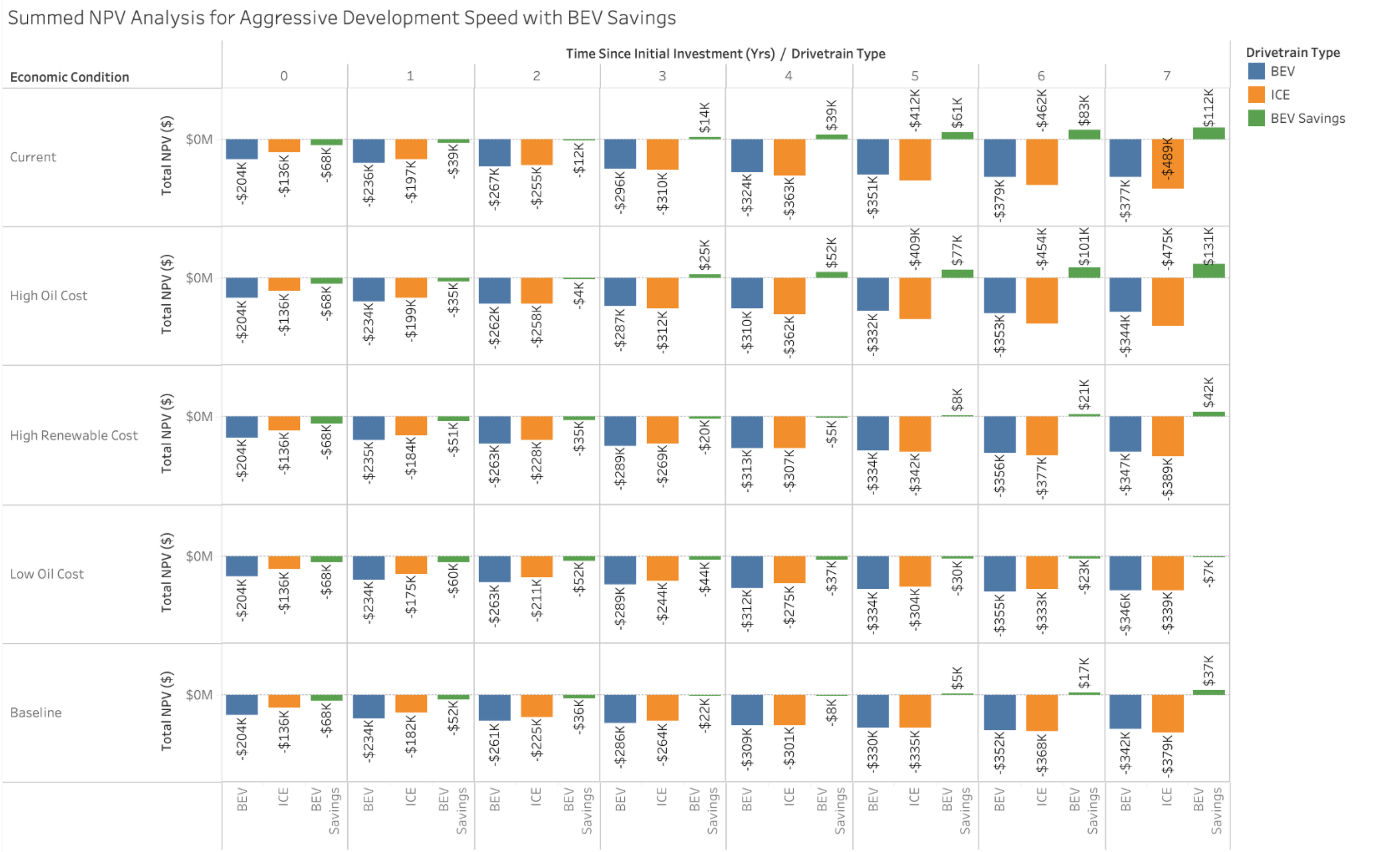
Figure A-47: Summed NPV Analysis with BEV Savings for Medium Development Speed

Summed NPV Analysis for Aggressive Development Speed



Sum of NPV Summed for each Drivetrain Type broken down by Time Since Initial Investment (Yrs) vs. Economic Condition. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV Summed. The data is filtered on Development Speed, Discount Factor and Charging Station Ratio. The Development Speed filter keeps Aggressive. The Discount Factor filter keeps 0.103. The Charging Station Ratio filter keeps One to Four. The view is filtered on Drivetrain Type and Time Since Initial Investment (Yrs). The Drivetrain Type filter keeps BEV and ICE. The Time Since Initial Investment (Yrs) filter excludes Total.

Figure A-48: Summed NPV Analysis for Aggressive Development Speed



Sum of NPV Summed for each Drivetrain Type broken down by Time Since Initial Investment (Yrs) vs. Economic Condition. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV Summed. The data is filtered on Development Speed, Discount Factor and Charging Station Ratio. The Development Speed filter keeps Aggressive. The Discount Factor filter keeps 0.103. The Charging Station Ratio filter keeps One to Four. The view is filtered on Drivetrain Type and Time Since Initial Investment (Yrs). The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Time Since Initial Investment (Yrs) filter excludes Total.

Figure A-49: Summed NPV Analysis with BEV Savings for Aggressive Development Speed

Discount Factor 7.61% & One to One Ratio

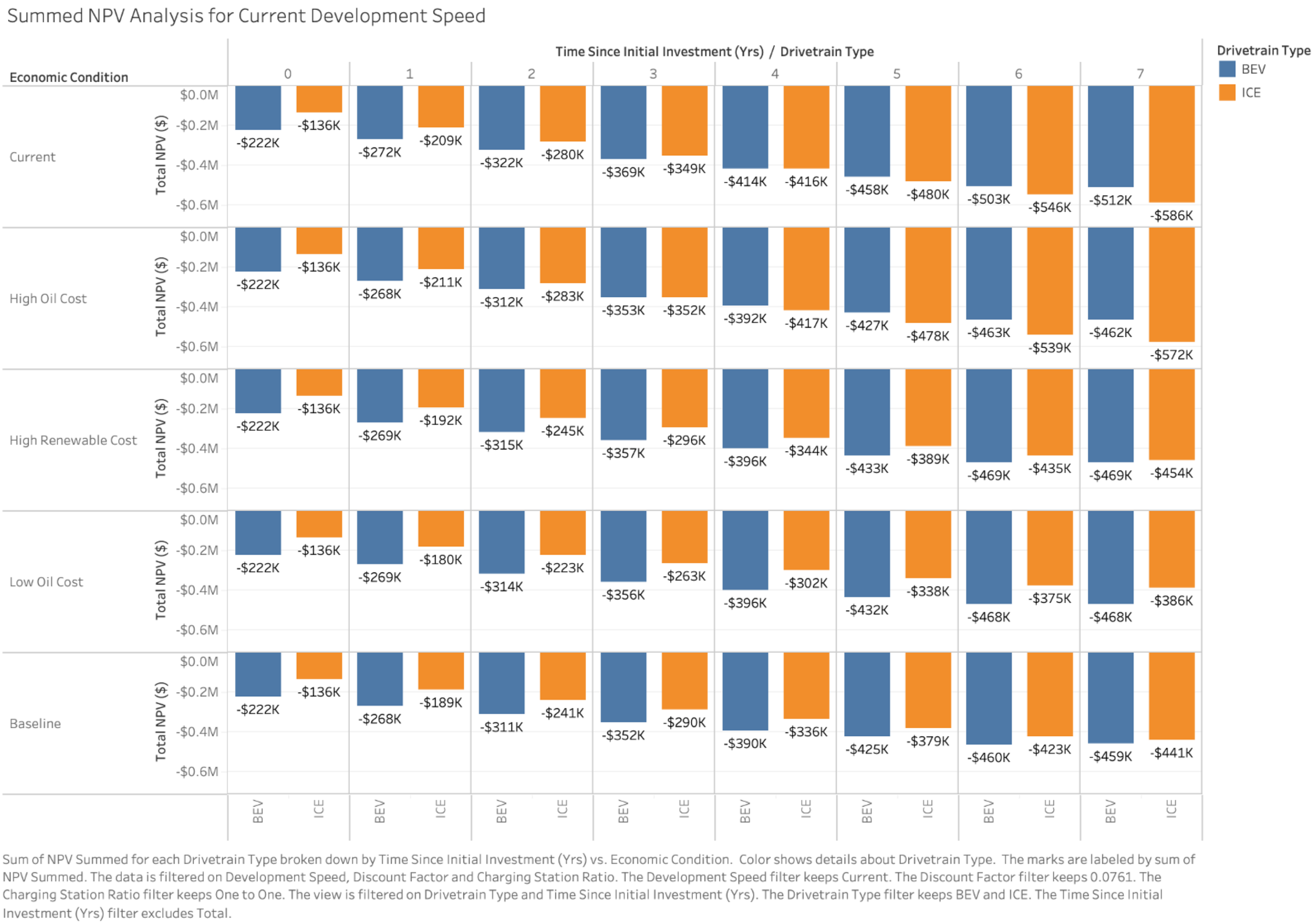
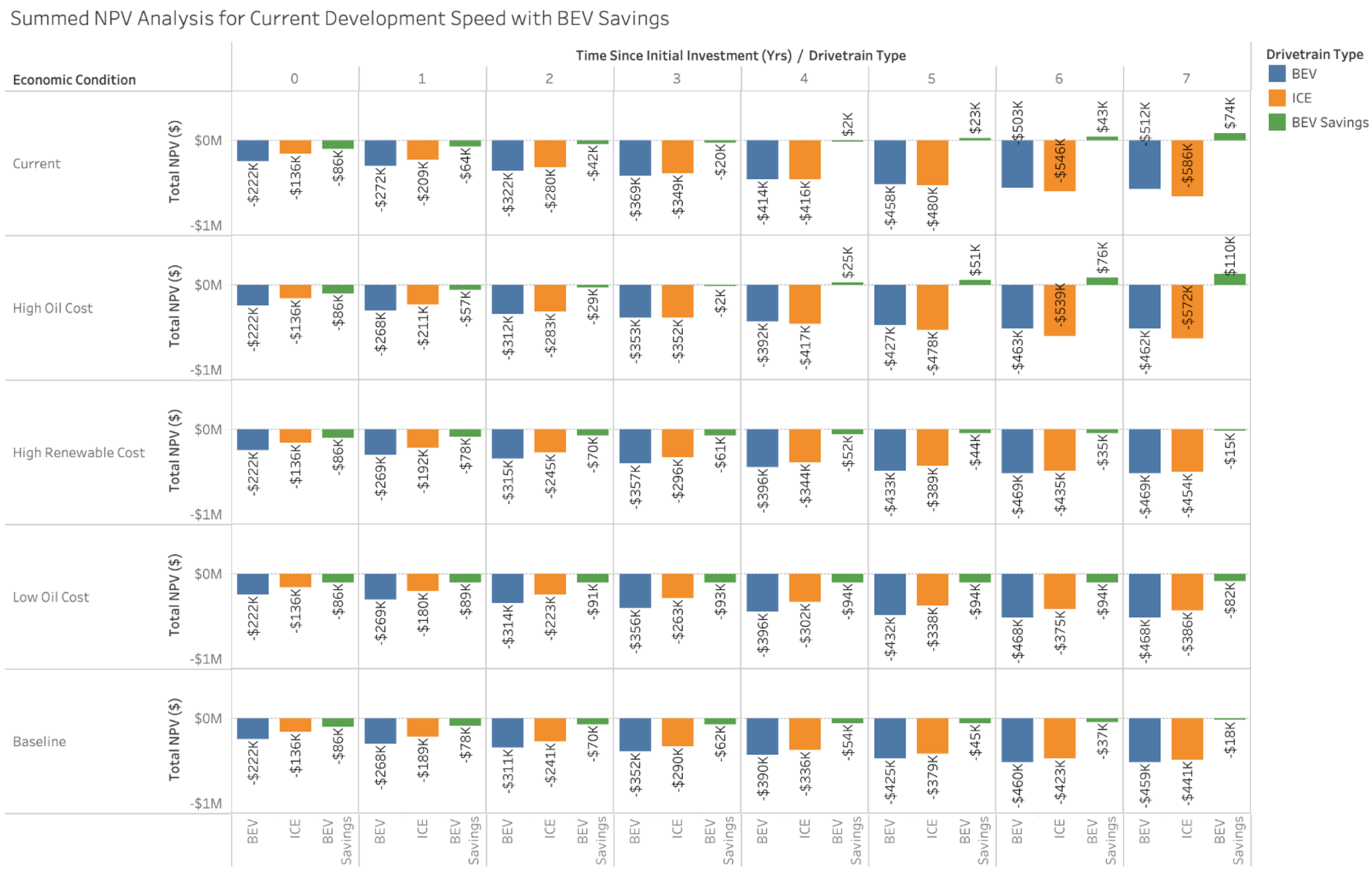


Figure A-50: Summed NPV Analysis for Current Development Speed



Sum of NPV Summed for each Drivetrain Type broken down by Time Since Initial Investment (Yrs) vs. Economic Condition. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV Summed. The data is filtered on Development Speed, Discount Factor and Charging Station Ratio. The Development Speed filter keeps Current. The Discount Factor filter keeps 0.0761. The Charging Station Ratio filter keeps One to One. The view is filtered on Drivetrain Type and Time Since Initial Investment (Yrs). The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Time Since Initial Investment (Yrs) filter excludes Total.

Figure A-51: Summed NPV Analysis with BEV Savings for Current Development Speed

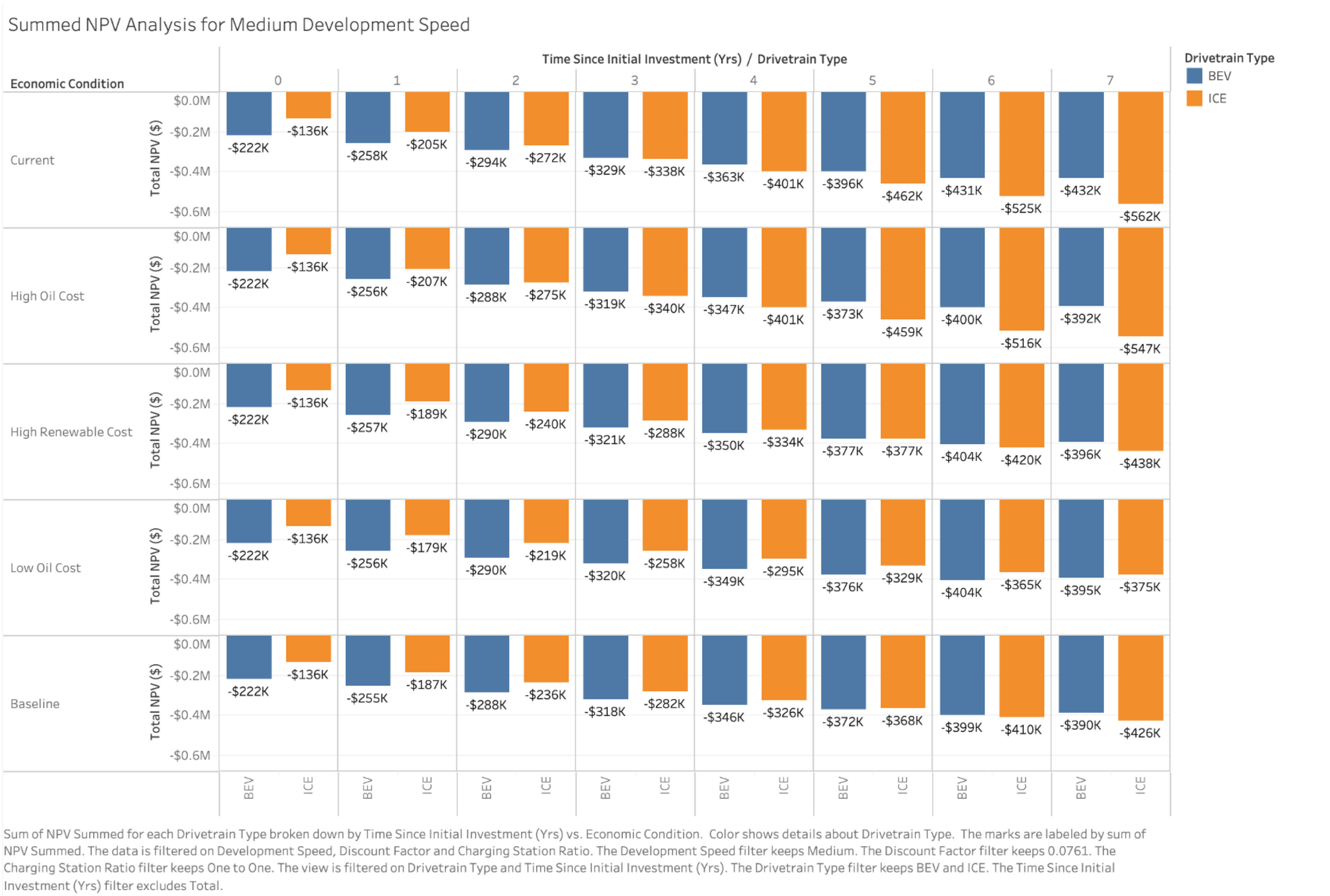
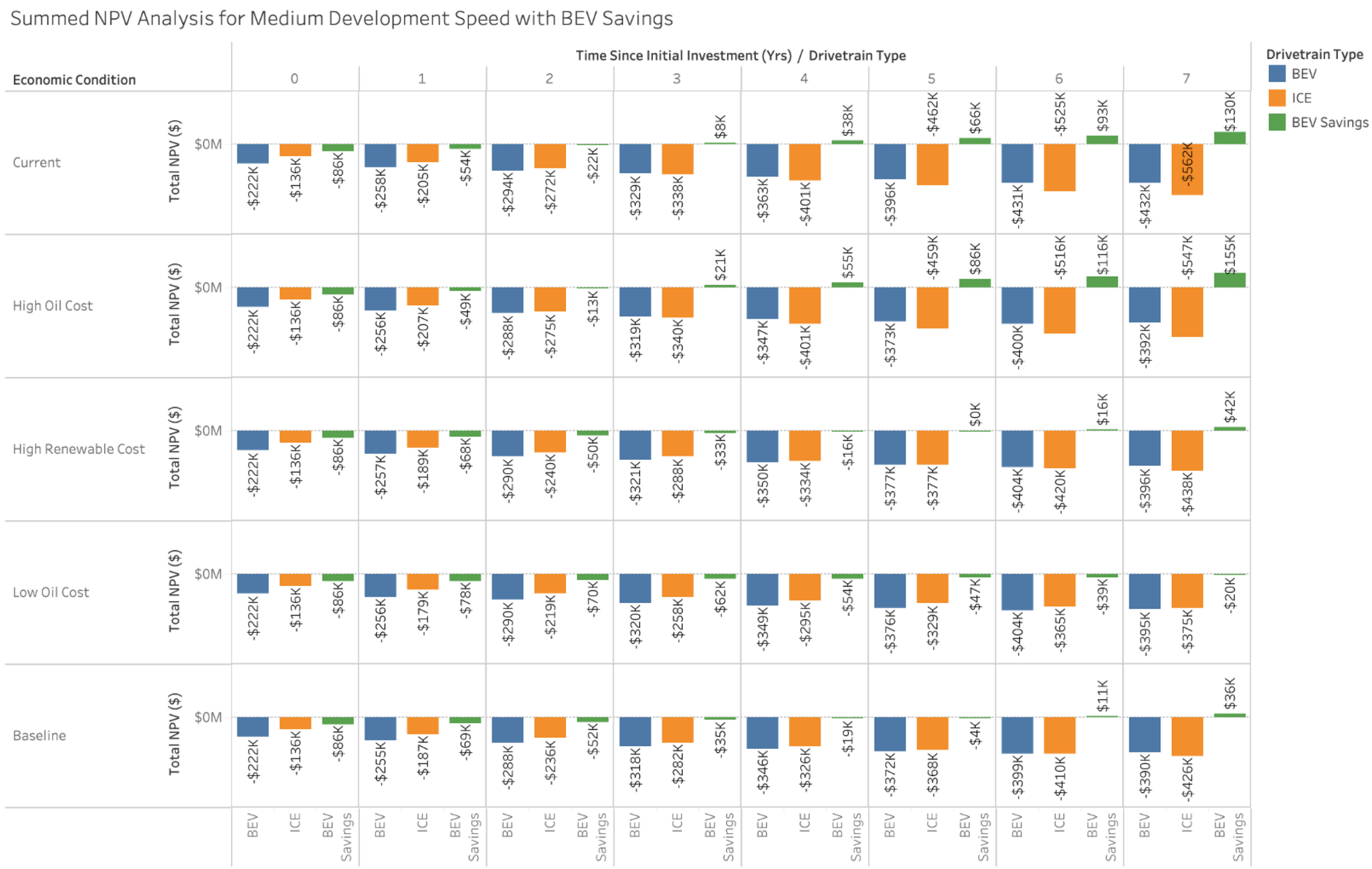


Figure A-52: Summed NPV Analysis for Medium Development Speed

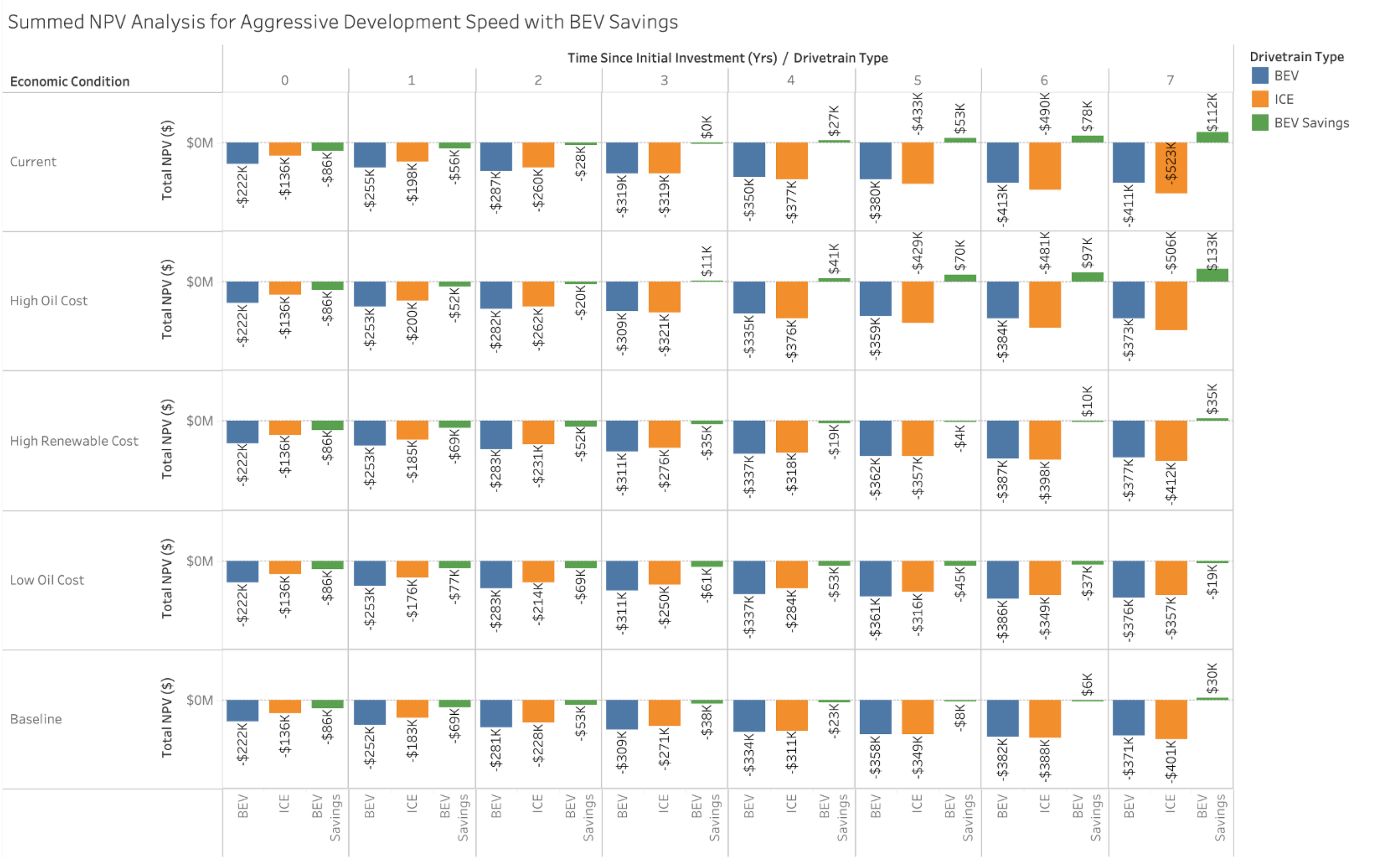


Sum of NPV Summed for each Drivetrain Type broken down by Time Since Initial Investment (Yrs) vs. Economic Condition. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV Summed. The data is filtered on Development Speed, Discount Factor and Charging Station Ratio. The Development Speed filter keeps Medium. The Discount Factor filter keeps 0.0761. The Charging Station Ratio filter keeps One to One. The view is filtered on Drivetrain Type and Time Since Initial Investment (Yrs). The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Time Since Initial Investment (Yrs) filter excludes Total.

Figure A-53: Summed NPV Analysis with BEV Savings for Medium Development Speed

Sum of NPV Summed for each Drivetrain Type broken down by Time Since Initial Investment (Yrs) vs. Economic Condition. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV Summed. The data is filtered on Development Speed, Discount Factor and Charging Station Ratio. The Development Speed filter keeps Aggressive. The Discount Factor filter keeps 0.0761. The Charging Station Ratio filter keeps One to One. The view is filtered on Drivetrain Type and Time Since Initial Investment (Yrs). The Drivetrain Type filter keeps BEV and ICE. The Time Since Initial Investment (Yrs) filter excludes Total.

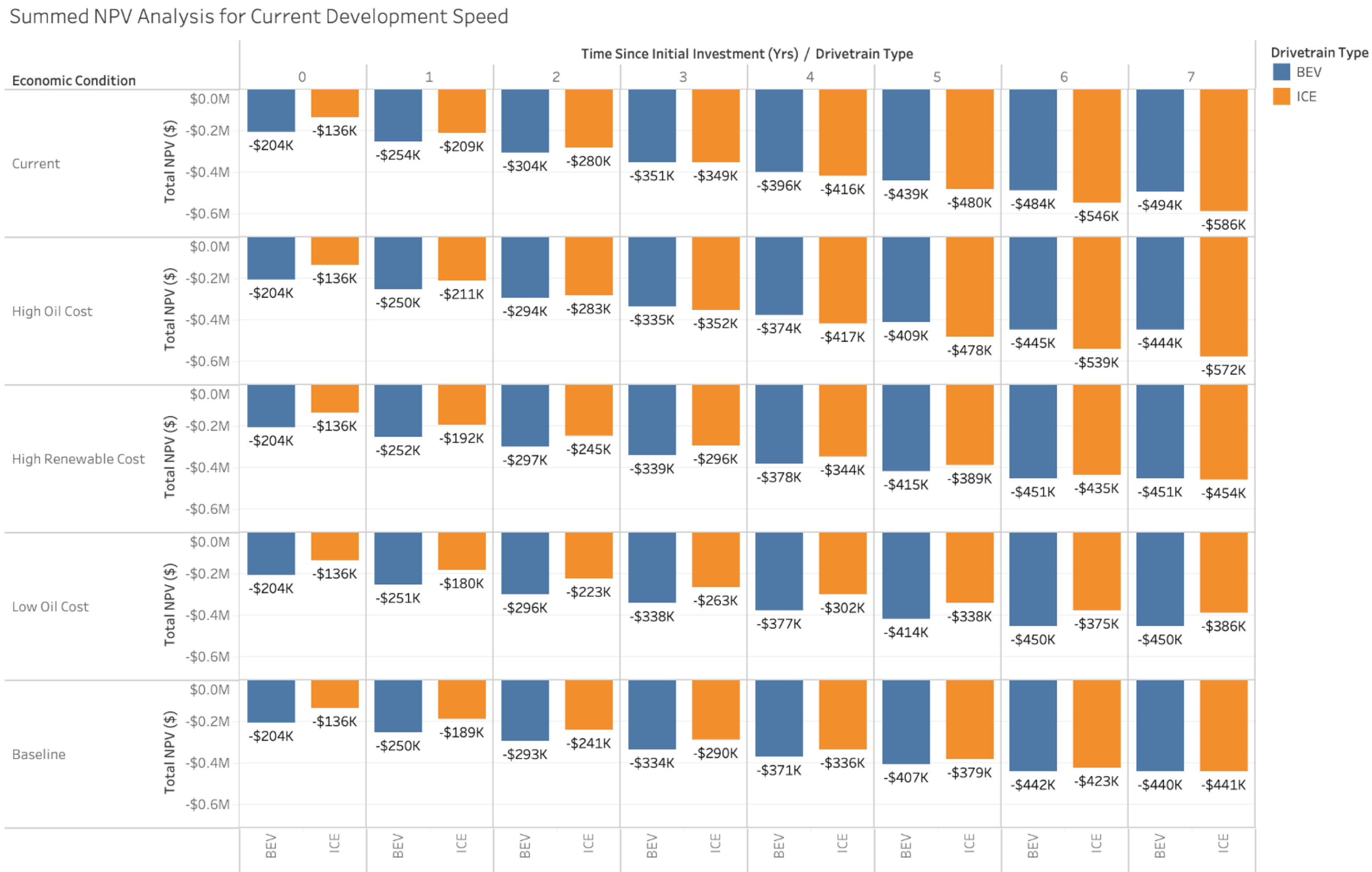
Figure A-54: Summed NPV Analysis for Aggressive Development Speed



Sum of NPV Summed for each Drivetrain Type broken down by Time Since Initial Investment (Yrs) vs. Economic Condition. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV Summed. The data is filtered on Development Speed, Discount Factor and Charging Station Ratio. The Development Speed filter keeps Aggressive. The Discount Factor filter keeps 0.0761. The Charging Station Ratio filter keeps One to One. The view is filtered on Drivetrain Type and Time Since Initial Investment (Yrs). The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Time Since Initial Investment (Yrs) filter excludes Total.

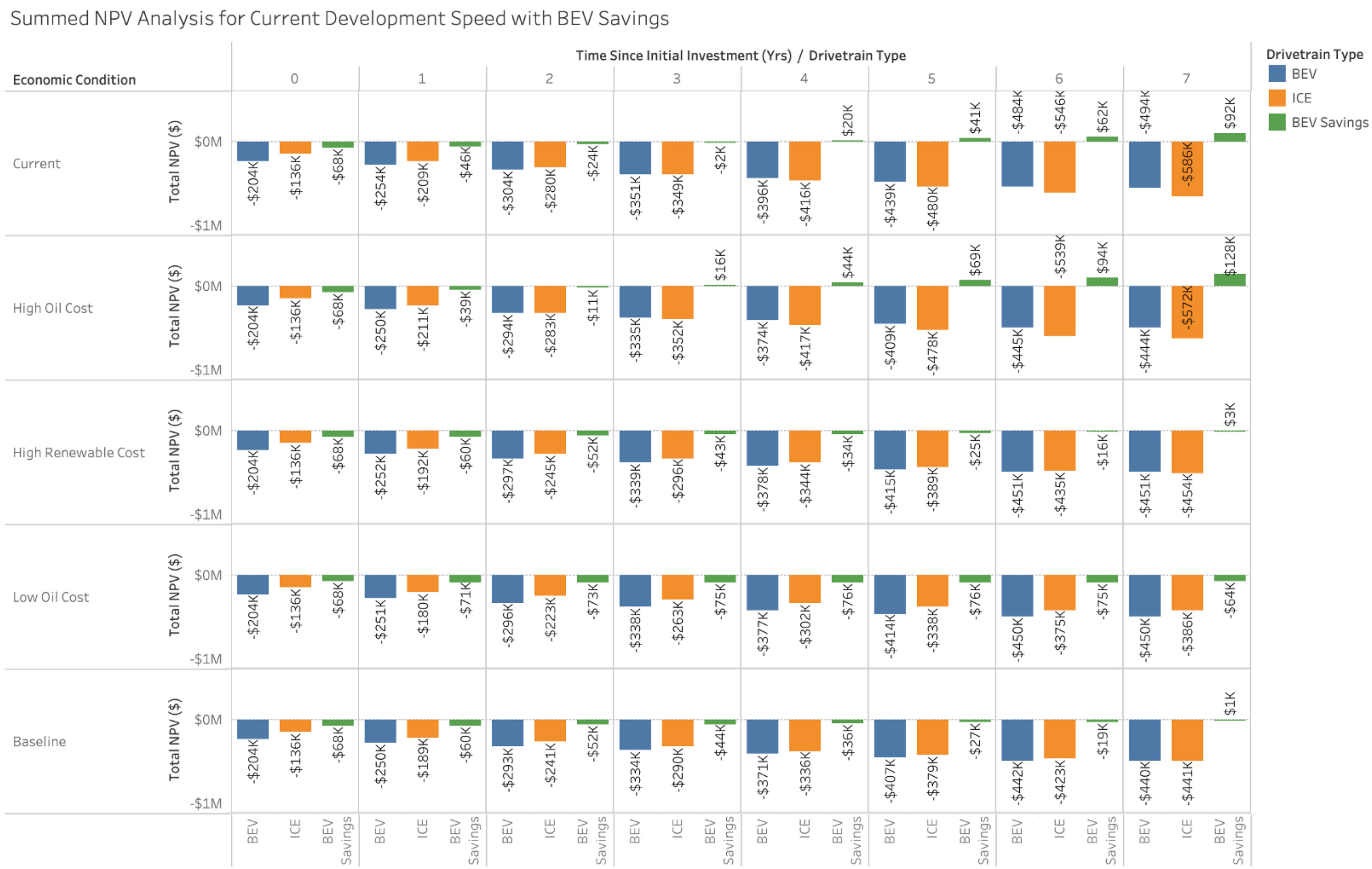
Figure A-55: Summed NPV Analysis with BEV Savings for Aggressive Development Speed

Discount Factor 7.61% & Four to One Ratio



Sum of NPV Summed for each Drivetrain Type broken down by Time Since Initial Investment (Yrs) vs. Economic Condition. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV Summed. The data is filtered on Development Speed, Discount Factor and Charging Station Ratio. The Development Speed filter keeps Current. The Discount Factor filter keeps 0.0761. The Charging Station Ratio filter keeps One to Four. The view is filtered on Drivetrain Type and Time Since Initial Investment (Yrs). The Drivetrain Type filter keeps BEV and ICE. The Time Since Initial Investment (Yrs) filter excludes Total.

Figure A-56: Summed NPV Analysis for Current Development Speed



Sum of NPV Summed for each Drivetrain Type broken down by Time Since Initial Investment (Yrs) vs. Economic Condition. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV Summed. The data is filtered on Development Speed, Discount Factor and Charging Station Ratio. The Development Speed filter keeps Current. The Discount Factor filter keeps 0.0761. The Charging Station Ratio filter keeps One to Four. The view is filtered on Drivetrain Type and Time Since Initial Investment (Yrs). The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Time Since Initial Investment (Yrs) filter excludes Total.

Figure A-57: Summed NPV Analysis with BEV Savings for Current Development Speed

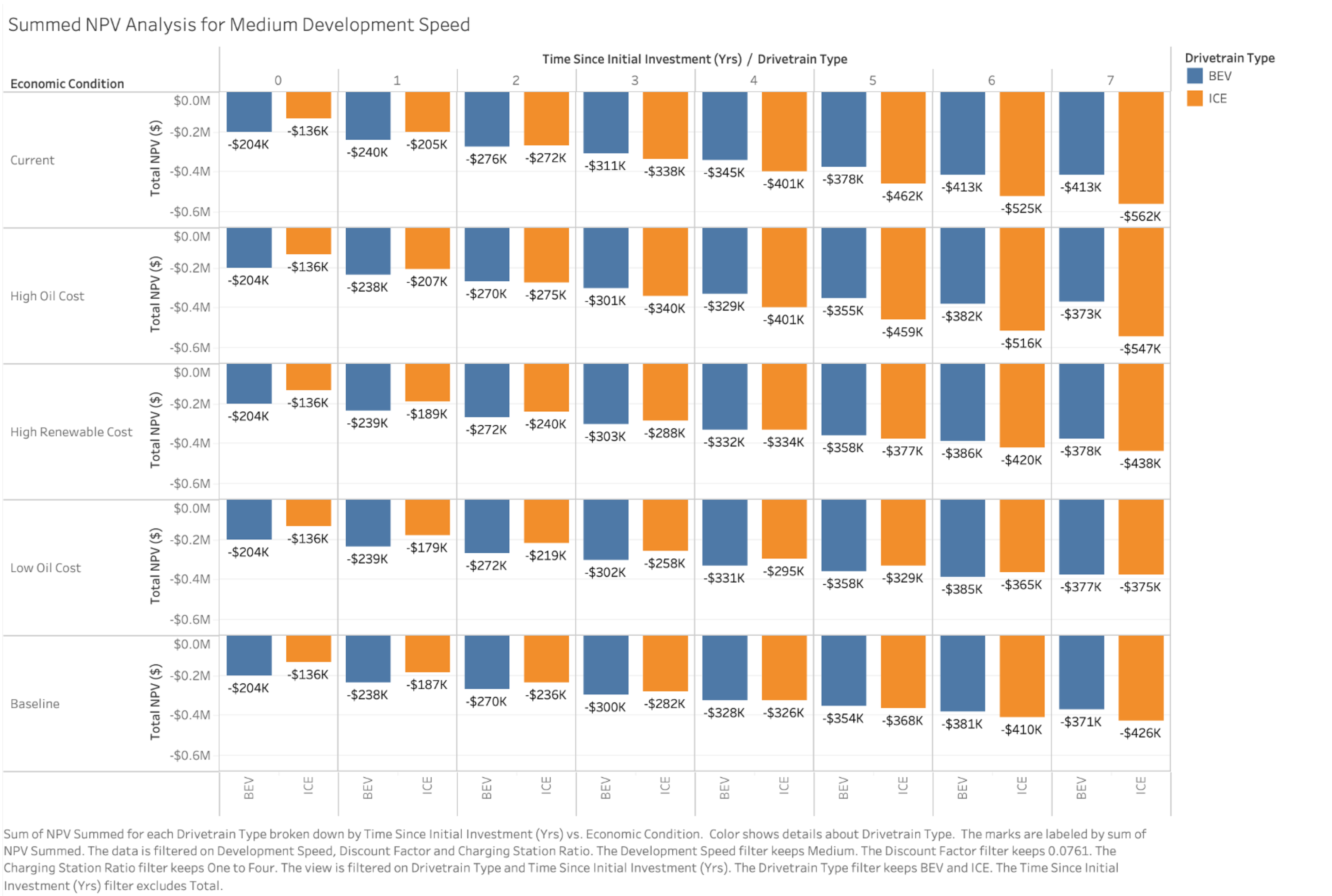


Figure A-58: Summed NPV Analysis for Medium Development Speed

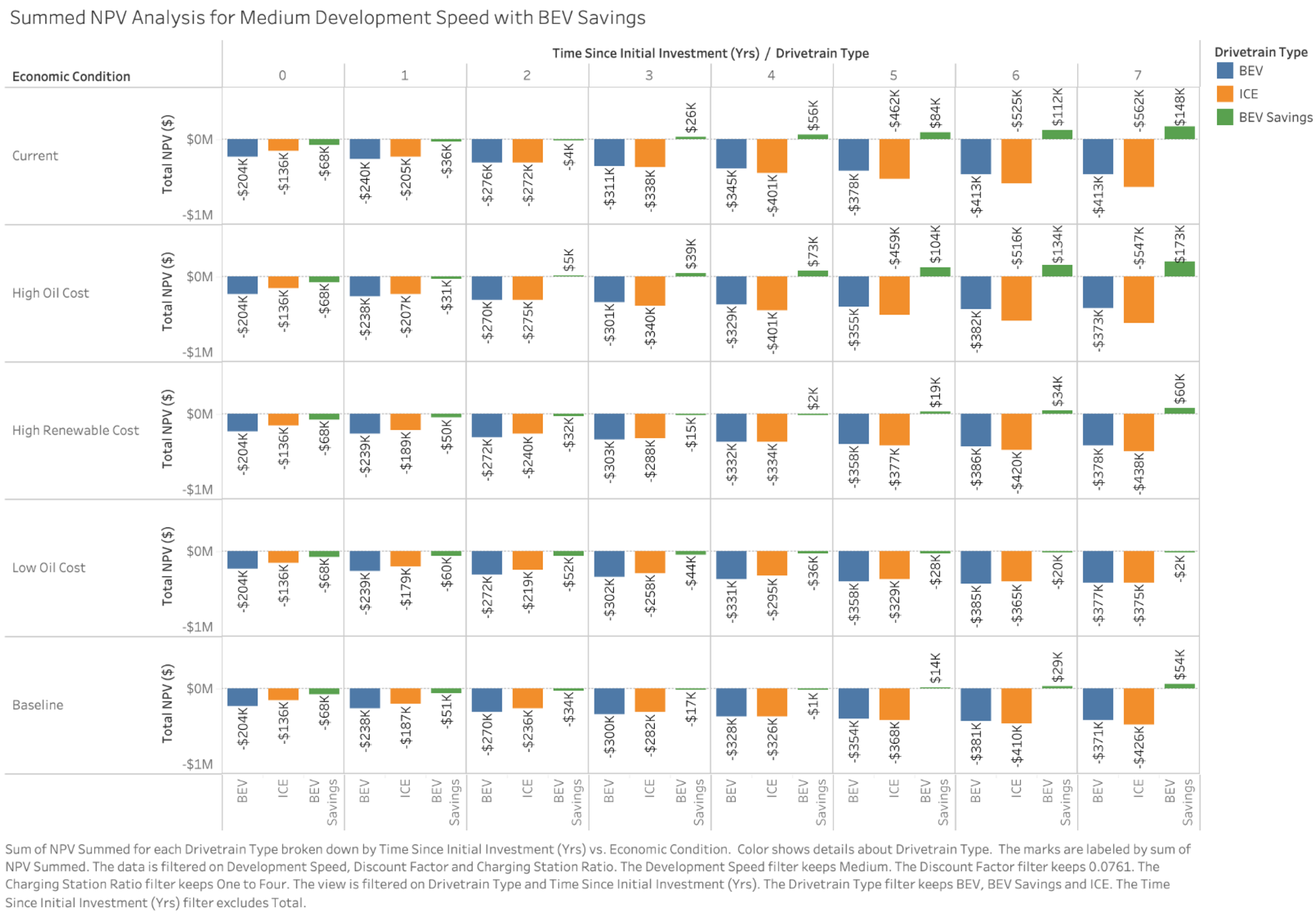


Figure A-59: Summed NPV Analysis with BEV Savings for Medium Development Speed

Sum of NPV Summed for each Drivetrain Type broken down by Time Since Initial Investment (Yrs) vs. Economic Condition. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV Summed. The data is filtered on Development Speed, Discount Factor and Charging Station Ratio. The Development Speed filter keeps Aggressive. The Discount Factor filter keeps 0.0761. The Charging Station Ratio filter keeps One to Four. The view is filtered on Drivetrain Type and Time Since Initial Investment (Yrs). The Drivetrain Type filter keeps BEV and ICE. The Time Since Initial Investment (Yrs) filter excludes Total.

Figure A-60: Summed NPV Analysis for Aggressive Development Speed

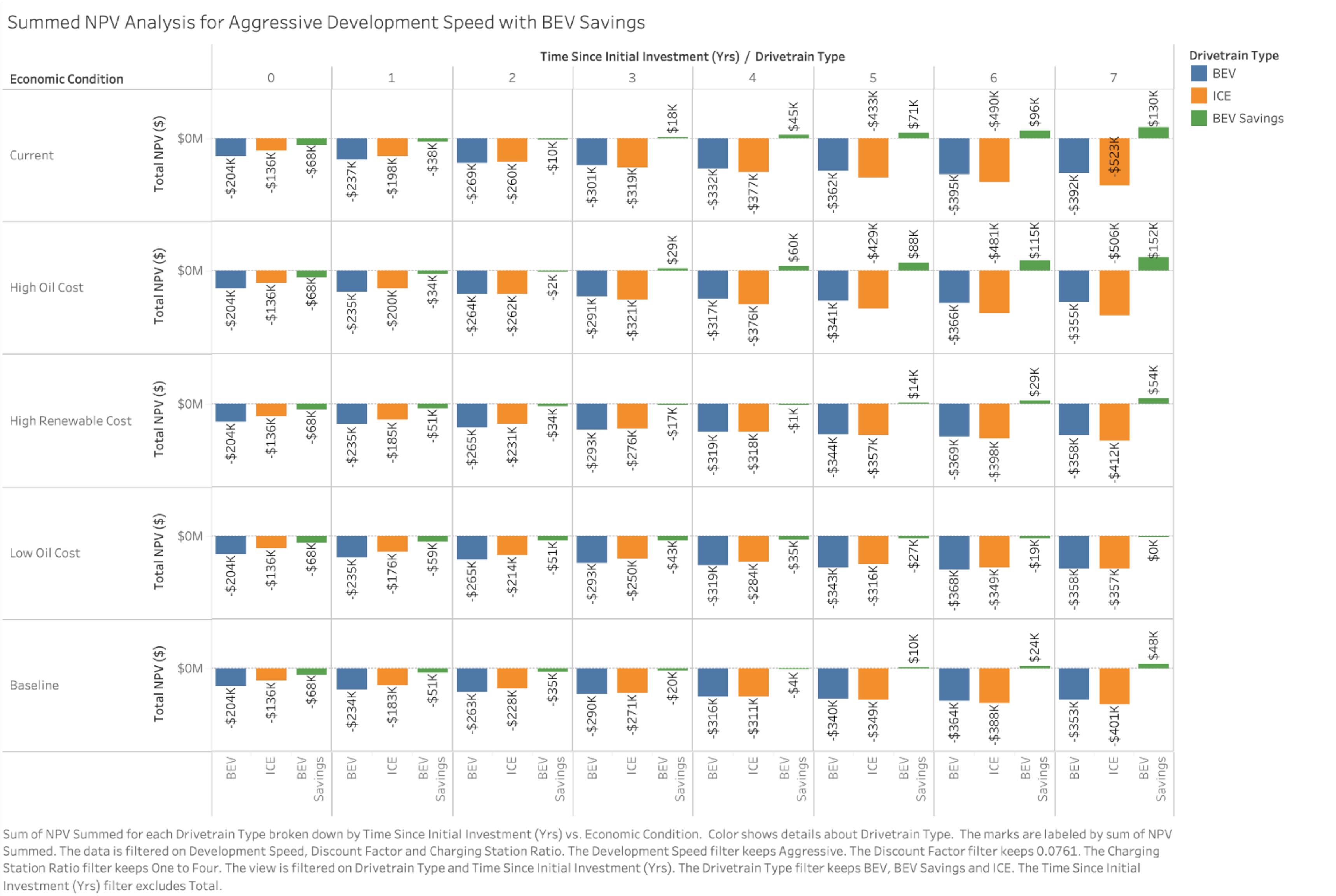


Figure A-61: Summed NPV Analysis with BEV Savings for Aggressive Development Speed

A.5.3 Tesla Analysis

Discount Factor 10.3% & One to One Ratio

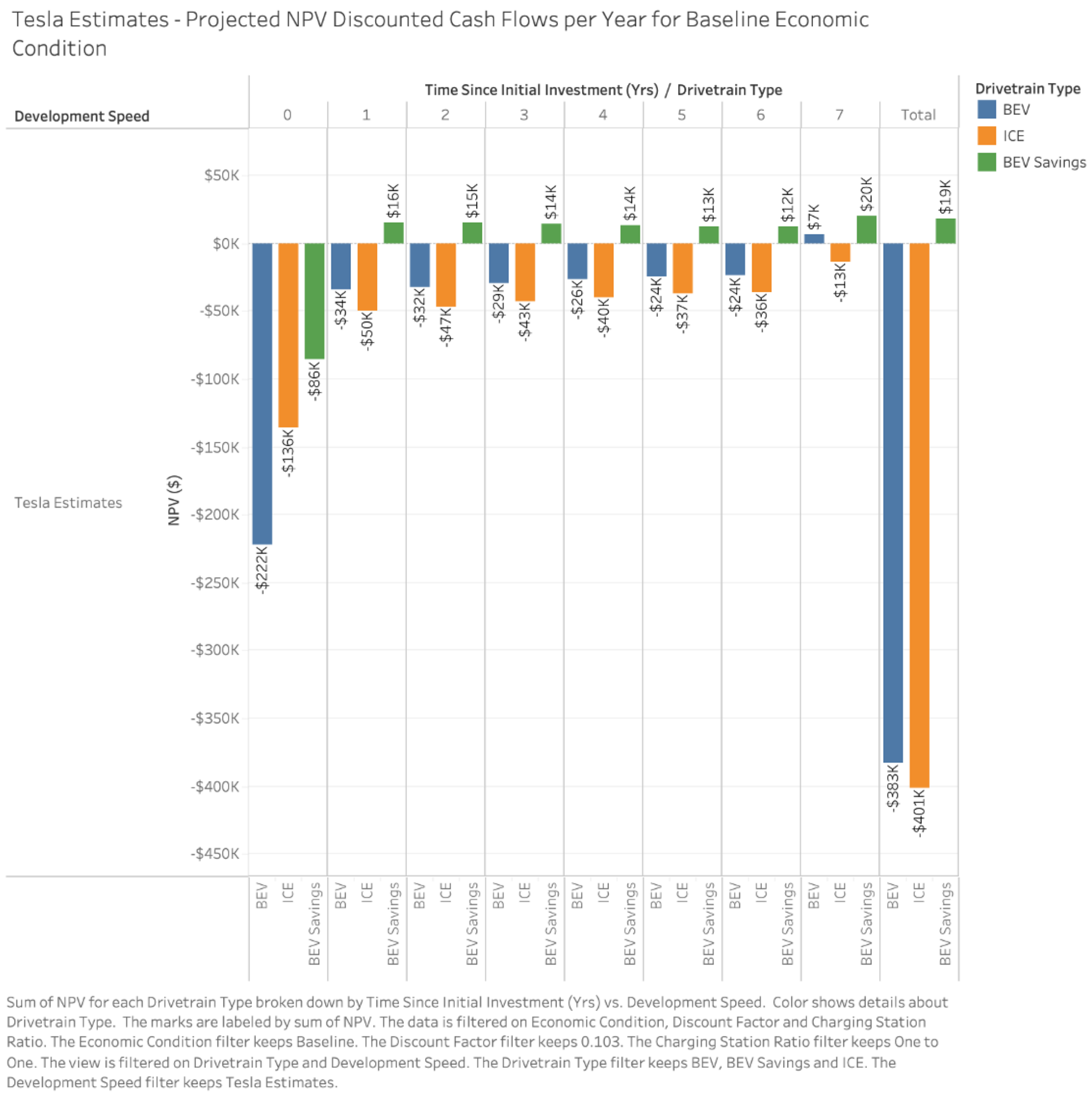


Figure A-62: Tesla Estimates - Projected NPV Discounted Cash Flow per Year for Baseline Economic Scenario

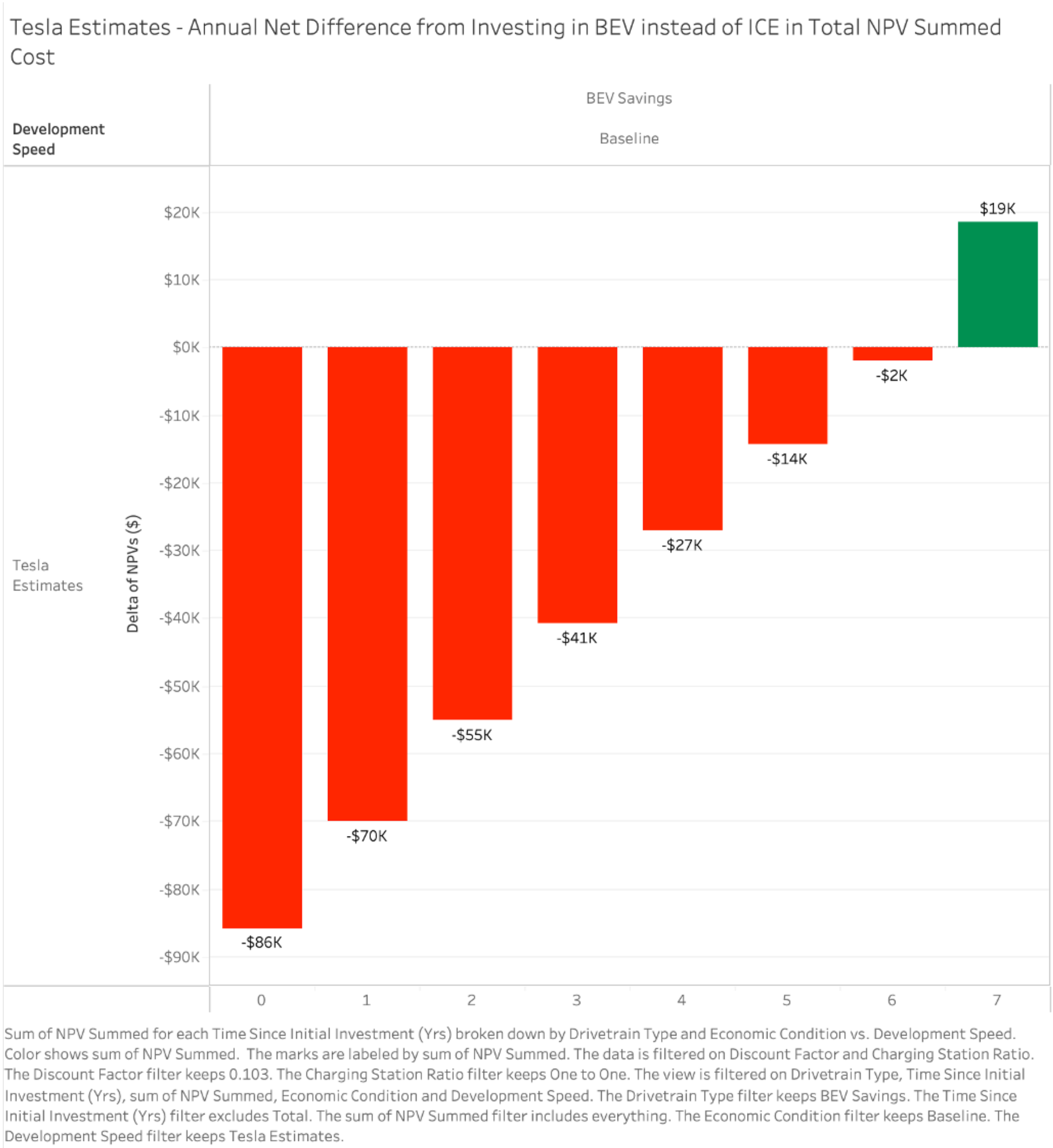


Figure A-63: Tesla Estimates - Annual Net Difference from Investing in BEV instead of ICE in Total NPV Summed Cost

Discount Factor 10.3% & Four to One Ratio

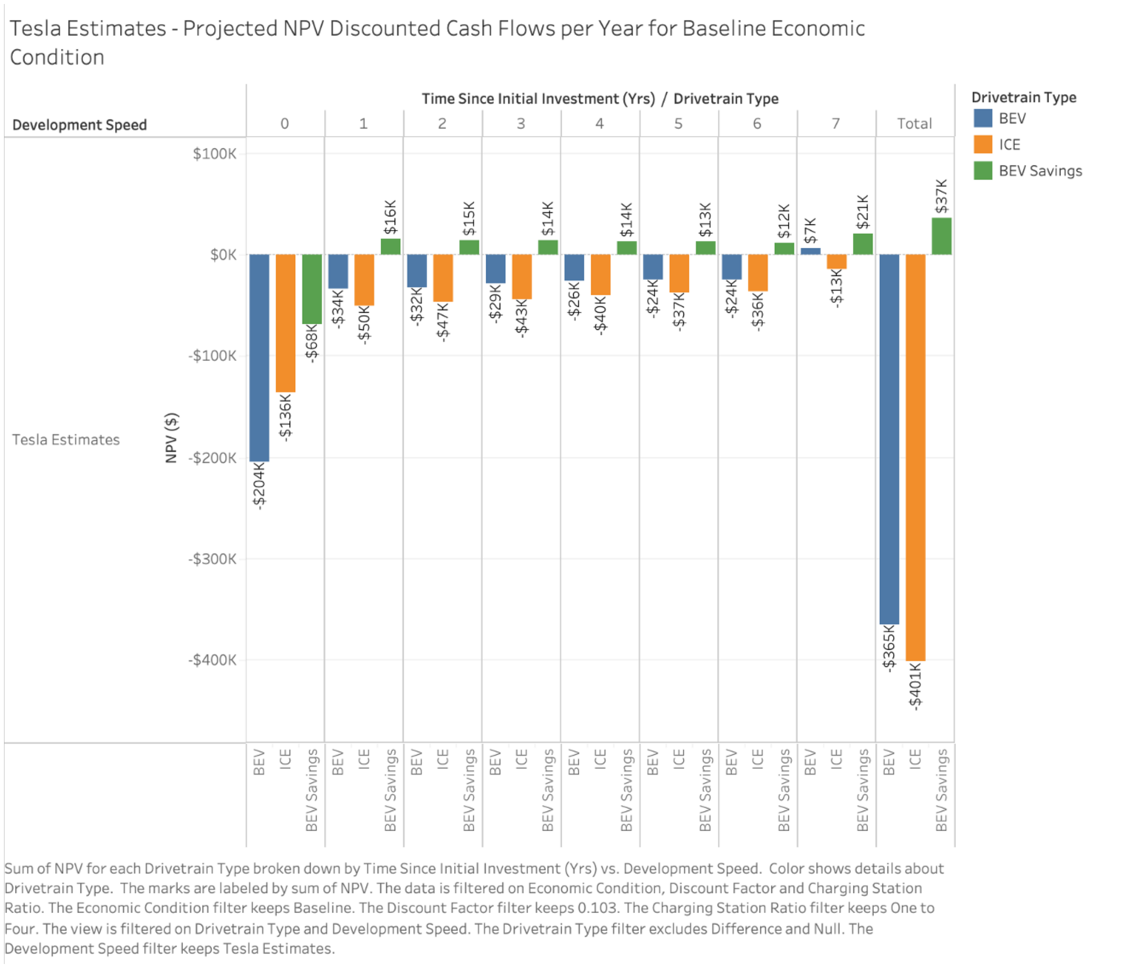


Figure A-64: Tesla Estimates - Projected NPV Discounted Cash Flow per Year for Baseline Economic Scenario

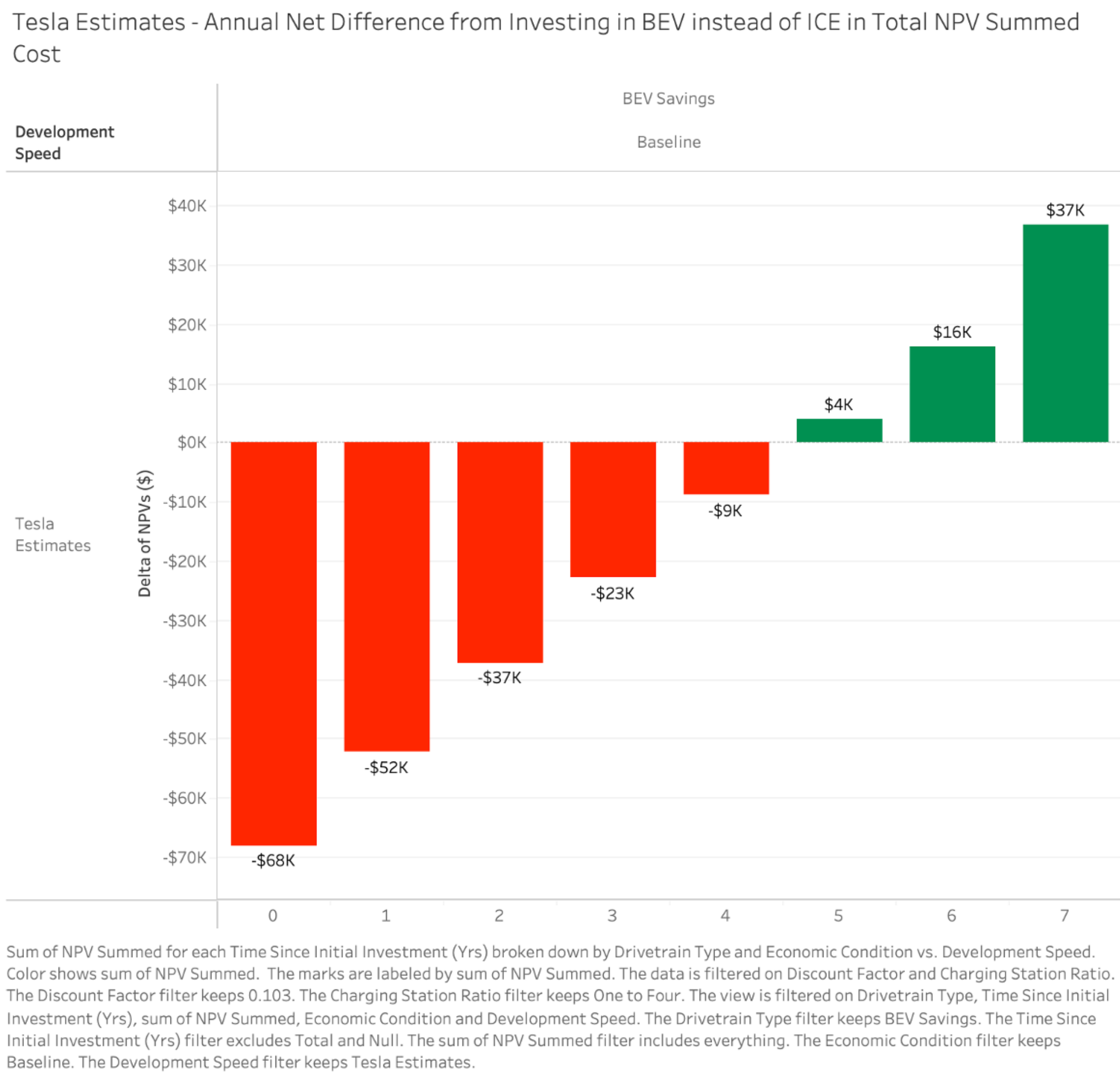
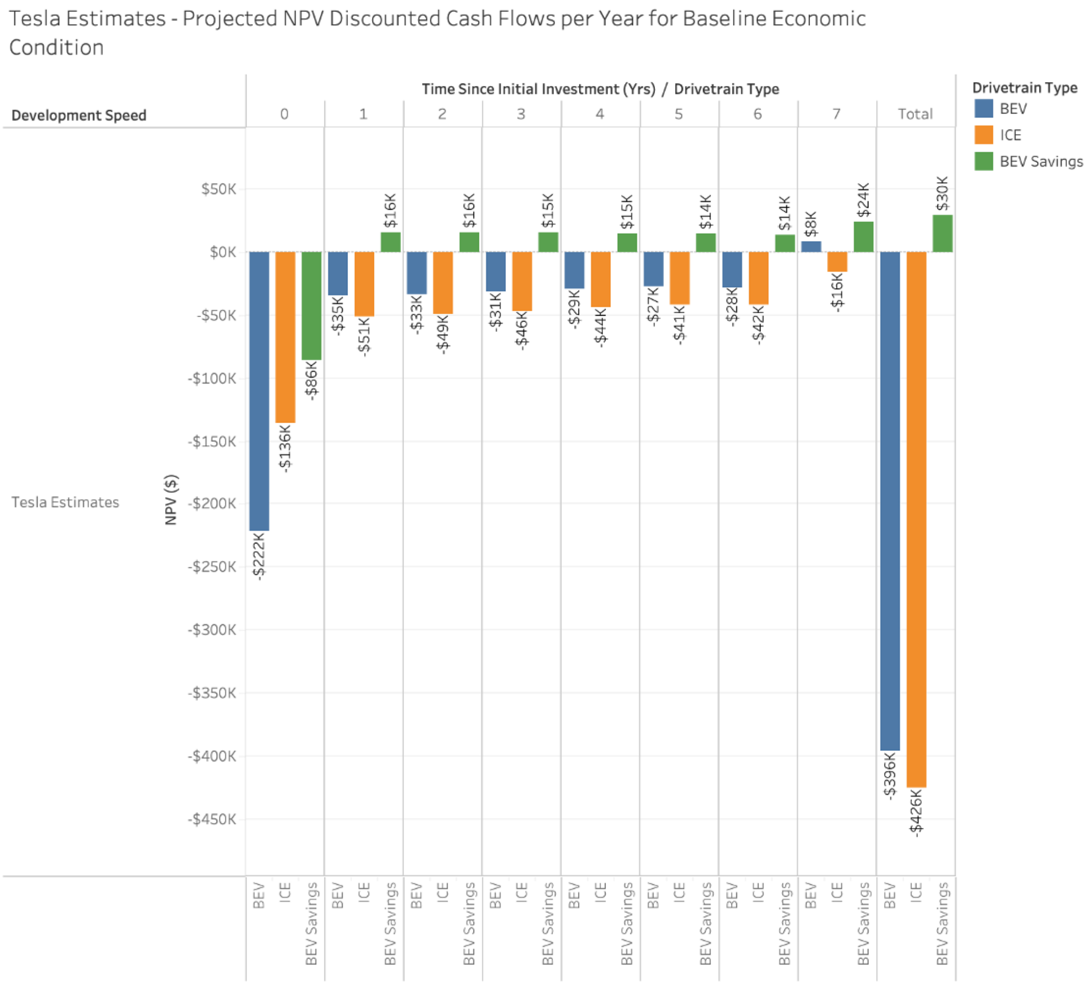


Figure A-65: Tesla Estimates - Annual Net Difference from Investing in BEV instead of ICE in Total NPV Summed Cost

Discount Factor 7.61% & One to One Ratio



Sum of NPV for each Drivetrain Type broken down by Time Since Initial Investment (Yrs) vs. Development Speed. Color shows details about Drivetrain Type. The marks are labeled by sum of NPV. The data is filtered on Economic Condition, Discount Factor and Charging Station Ratio. The Economic Condition filter keeps Baseline. The Discount Factor filter keeps 0.0761. The Charging Station Ratio filter keeps One to One. The view is filtered on Drivetrain Type and Development Speed. The Drivetrain Type filter keeps BEV, BEV Savings and ICE. The Development Speed filter keeps Tesla Estimates.

Figure A-66: Tesla Estimates - Projected NPV Discounted Cash Flow per Year for Baseline Economic Scenario

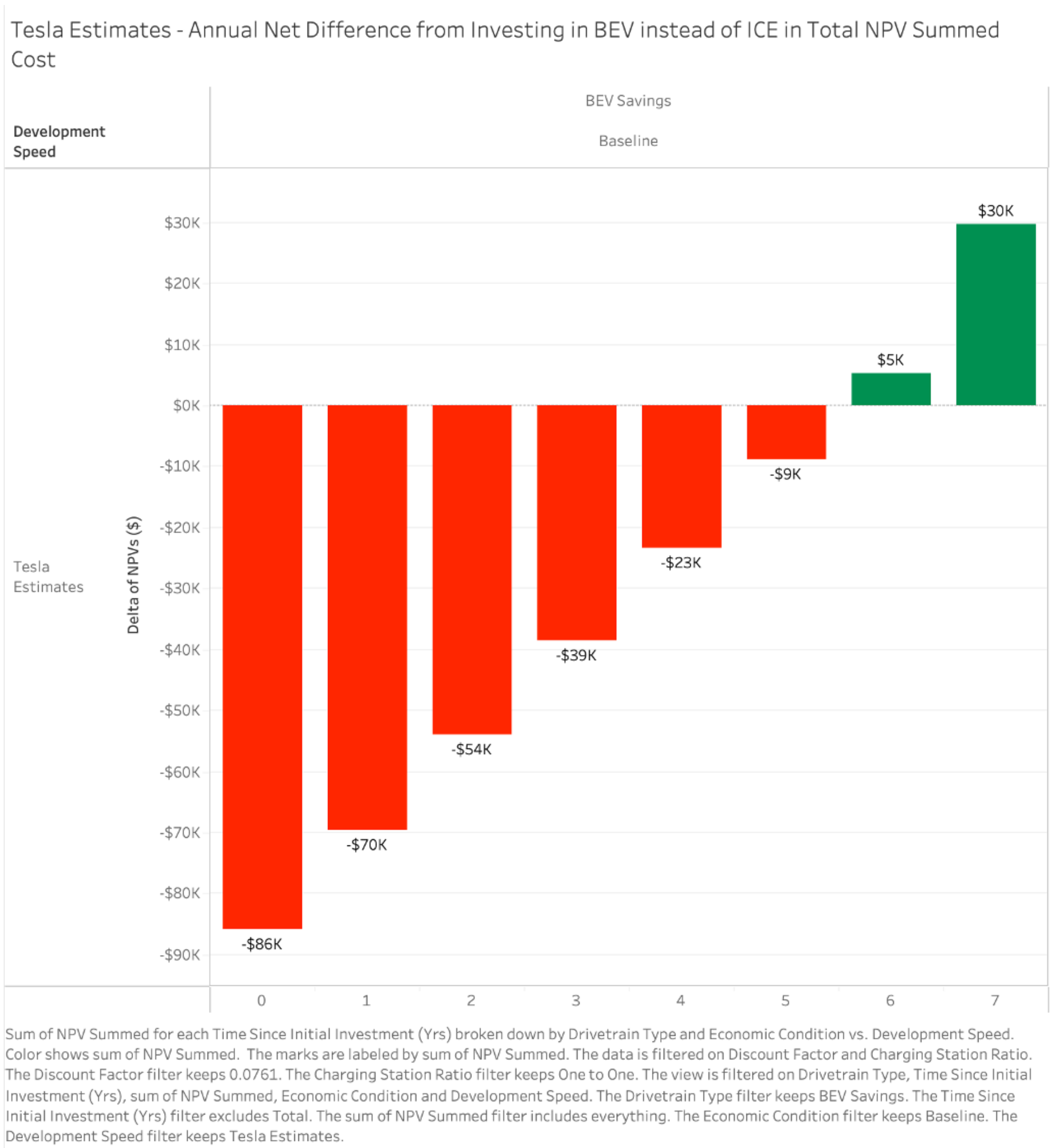


Figure A-67: Tesla Estimates - Annual Net Difference from Investing in BEV instead of ICE in Total NPV Summed Cost

Discount Factor 7.61% & Four to One Ratio

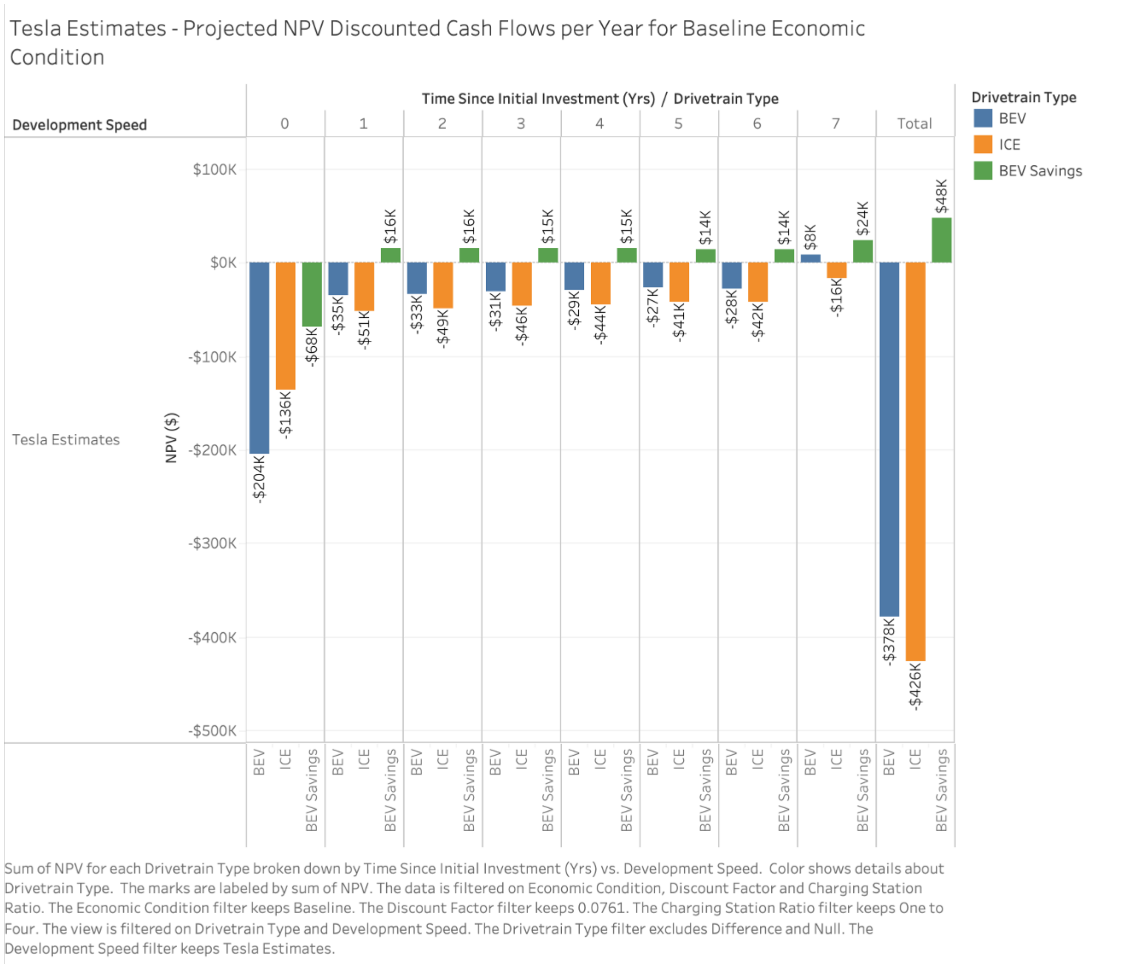


Figure A-68: Tesla Estimates - Projected NPV Discounted Cash Flow per Year for Baseline Economic Scenario

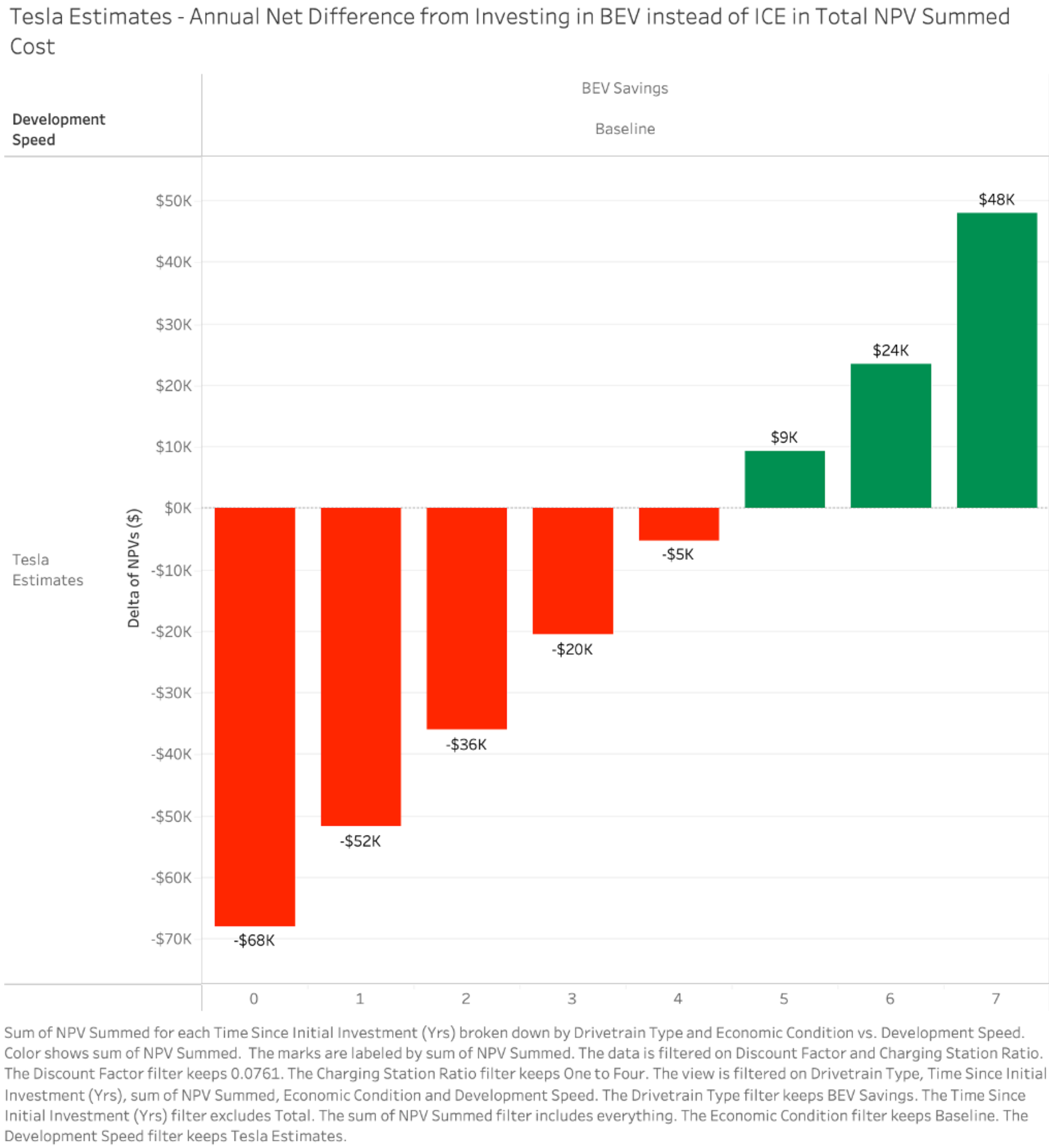


Figure A-69: Tesla Estimates - Annual Net Difference from Investing in BEV instead of ICE in Total NPV Summed Cost

A.6 Emissions Sensitivity Analysis

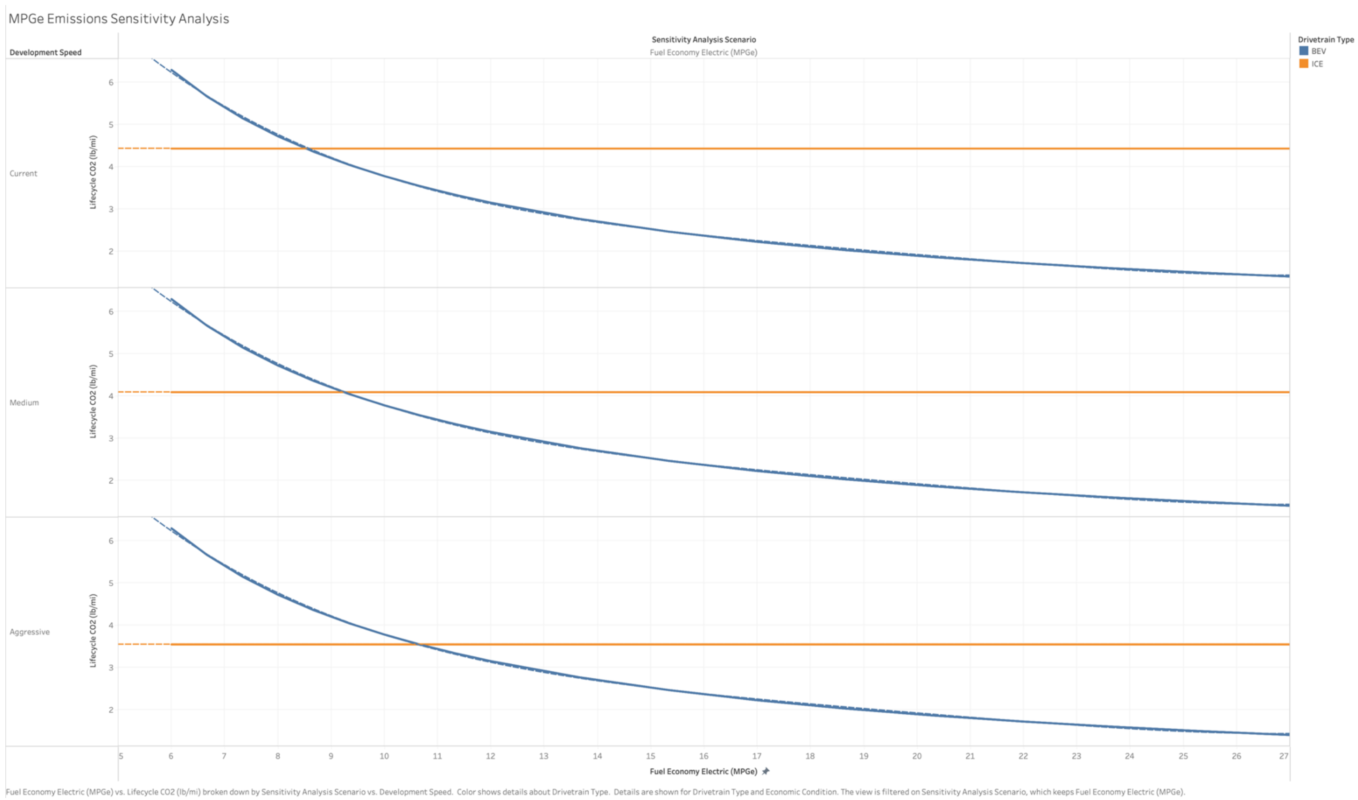


Figure A-70: MPGe Emissions Sensitivity Analysis

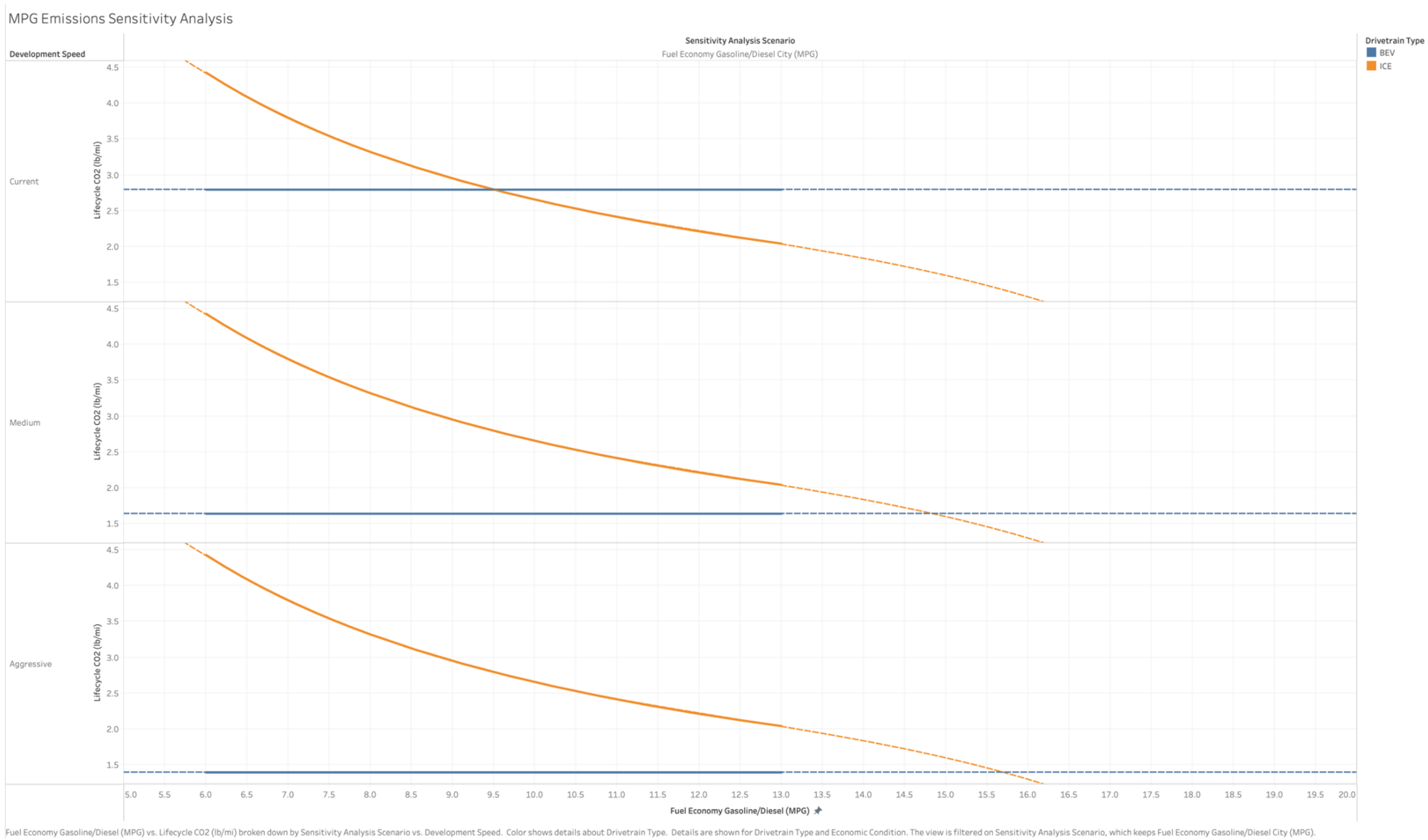


Figure A-71: MPG Emissions Sensitivity Analysis

Bibliography

[1] Energy Information Administration. *Factors affecting diesel prices - U.S. Energy Information Administration (EIA)*. Feb. 2022. URL: https://www.eia.gov/energyexplained/diesel-fuel/factors-affecting-diesel-prices.php (visited on 01/07/2023).

[2] Energy Information Administration. *Frequently Asked Questions (FAQs) - How much of U.S. energy consumption and electricity generation comes from renewable energy sources?* Nov. 2022. URL: https://www.eia.gov/tools/faqs/faq.php (visited on 01/07/2023).

[3] Energy Information Administration. *Short-Term Energy Outlook - Diesel Prices*. Jan. 2023. URL: https://www.eia.gov/outlooks/steo/ (visited on 01/12/2023).

[4] Energy Information Administration. *U.S. Energy Information Administration - EIA - Independent Statistics and Analysis - Annual Energy Outlook 2021 - Transportation*. URL: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2021&region=1-0&cases=highprice~lowprice~hirencst&start=2019&end=2050&f=A&linechart=~~~~~~~~~highprice-d113020a.28-3-AEO2021.1-0~lowprice-d113020a.28-3-AEO2021.1-0~hirencst-d113020a.28-3-AEO2021.1-0~~~~highprice-d113020a.30-3-AEO2021.1-0~lowprice-d113020a.30-3-AEO2021.1-0~hirencst-d113020a.30-3-AEO2021.1-0~~~~highprice-d113020a.32-3-AEO2021.1-0~lowprice-d113020a.32-3-AEO2021.1-0~hirencst-d113020a.32-3-AEO2021.1-0~highprice-d113020a.33-3-AEO2021.1-0~lowprice-d113020a.33-3-AEO2021.1-0~hirencst-d113020a.33-3-AEO2021.1-0&map=lowprice-d113020a.3-3-AEO2021.1-0&sourcekey=0 (visited on 12/30/2022).

[5] Energy Information Administration. *Where our diesel comes from - U.S. Energy Information Administration (EIA)*. July 2022. URL: https://www.eia.gov/energyexplained/diesel-fuel/where-our-diesel-comes-from.php (visited on 01/07/2023).

[6] International Renewable Energy Agency. *Competitiveness of Renewables Continued amid Fossil Fuel Crisis*. en. July 2022. URL: https://www.irena.org/News/articles/2022/Jul/Competitiveness-of-Renewables-Continued-Amid-Fossil-Fuel-Crisis (visited on 01/17/2023).

[7] James Anthony. *104 Transportation Industry Statistics You Can't Ignore: 2022 Market Share & Data Analysis*. en. Oct. 2019. URL: https://financesonline.com/transportation-industry-statistics/ (visited on 12/30/2022).

[8] American Trucking Associations. *Economics and Industry Data*. en. URL: https://www.trucking.org/economics-and-industry-data (visited on 12/30/2022).

[9] BMW. *MPG vs MPGe | What is the Difference between them? | BMW of Owings Mills*. URL: https://www.bmwofowingsmills.com/mpg-vs-mpge-what-is-the-difference-between-them/ (visited on 03/08/2023).

[10] Brennan Borlaug et al. "Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems". en. In: *Nature Energy* 6.6 (June 2021). Number: 6 Publisher: Nature Publishing Group, pp. 673–682. ISSN: 2058-7546. DOI: 10.1038/s41560-021-00855-0. URL: https://www.nature.com/articles/s41560-021-00855-0 (visited on 01/02/2023).

[11] Robert Gary Boundy. *Transportation Energy Data Book: Edition 37*. English. Tech. rep. ORNL/TM-2018/987. Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States), Jan. 2019. DOI: 10.2172/1493136. URL: https://www.osti.gov/biblio/1493136 (visited on 12/31/2022).

[12] US Census Bureau. *Most Goods Americans Use in Their Daily Lives Are Transported and Delivered by Truck*. Section: Government. URL: https://www.census.gov/library/stories/2021/02/what-is-in-that-truck-i-just-passed-on-the-highway.html (visited on 12/31/2022).

[13] Alternative Fuels Data Center. *Average Annual Vehicle Miles Traveled by Major Vehicle Category*. en. URL: https://afdc.energy.gov/data/10309 (visited on 12/31/2022).

[14] Alternative Fuels Data Center. *Energy Use by Transportation Mode and Fuel Type*. en. URL: https://afdc.energy.gov/data/10661 (visited on 12/31/2022).

[15] Alternative Fuels Data Center. *Vehicle Weight Classes & Categories*. URL: https://afdc.energy.gov/data/10380 (visited on 12/30/2022).

[16] MIT Climate & Sustainability Consortium. *MIT Climate & Sustainability Consortium – MIT*. URL: https://impactclimate.mit.edu/ (visited on 12/30/2022).

[17] MIT Climate & Sustainability Consortium. *Our Work – MIT Climate & Sustainability Consortium*. URL: https://impactclimate.mit.edu/our-work/ (visited on 12/30/2022).

[18] Bob Costello. "TRUCK DRIVER SHORTAGE ANALYSIS 2019". en. In: ().

[19] Aswath Damodaran. *Cost of Capital Tables*. Jan. 2023. URL: https://pages.stern.nyu.edu/~adamodar/New_Home_Page/datafile/wacc.html (visited on 01/09/2023).

[20] Drive Electric. *Maintenance Costs for EVs vs. ICE Vehicles*. URL: https://www.driveelectrictn.org/maintenance-costs-for-evs-vs-ice-vehicles/ (visited on 03/08/2023).

[21] U.S. Department of Energy. *All-Electric Vehicles*. en. URL: http://www.fueleconomy.gov/feg/evtech.shtml (visited on 01/07/2023).

[22] Energy.Gov. *Transportation Contributed 8% to U.S. Gross Domestic Product in 2020*. en. July 2022. URL: https://www.energy.gov/eere/vehicles/articles/fotw-1247-july-18-2022-transportation-contributed-8-us-gross-domestic (visited on 12/30/2022).

[23] Nick Ferris. *Will hydrogen trucks power the supply chains of the future?* en-US. Feb. 2022. URL: https://www.energymonitor.ai/tech/hydrogen/will-hydrogen-trucks-power-the-supply-chains-of-the-future/ (visited on 01/07/2023).

[24] Kyle Field. *Lithium-Ion Battery Cell Densities Have Almost Tripled Since 2010 - CleanTechnica*. Feb. 2020. URL: https://cleantechnica.com/2020/02/19/bloombergnef-lithium-ion-battery-cell-densities-have-almost-tripled-since-2010/ (visited on 01/04/2023).

[25] Anthony Foxx. *Compilation of Existing State Truck Size and Weight Limit Laws - FHWA Freight Management and Operations*. May 2015. URL: https://ops.fhwa.dot.gov/freight/policy/rpt_congress/truck_sw_laws/index.htm (visited on 12/30/2022).

[26] North American Council for Freight Efficiency. *Electric Trucks - Where They Make Sense*. en-US. 2018. URL: https://nacfe.org/research/electric-trucks/ (visited on 01/04/2023).

[27] Nanette Gibbs. *Research Guides: The Trucking Industry: A Research Guide: Definitions*. en. research guide. URL: https://guides.loc.gov/trucking-industry/definitions (visited on 12/31/2022).

[28] Adam Hayes. *Transportation Sector and Transportation Industry Investments*. en. Apr. 2021. URL: https://www.investopedia.com/terms/t/transportation_sector.asp (visited on 12/30/2022).

[29] Chad Hunter et al. *Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks*. en. Tech. rep. NREL/TP-5400-71796, 1821615, MainId:6232. Sept. 2021, NREL/TP–5400–71796, 1821615, MainId:6232. DOI: 10.2172/1821615. URL: https://www.osti.gov/servlets/purl/1821615/ (visited on 12/30/2022).

[30] Pawan Kumar et al. *Handbook of Research on Power and Energy System Optimization*. English. Publication Title: https://services.igi-global.com/resolvedoi/resolve.aspx?doi=10
1-5225-3935-3. IGI Global, Jan. 2001. ISBN: 978-1-5225-3935-3. URL: https://www.igi-global.com/book/handbook-research-power-energy-system/www.igi-global.com/book/handbook-research-power-energy-system/181914 (visited on 12/31/2022).

[31] Bureau of Labor Statistics. *Heavy and Tractor-trailer Truck Drivers : Occupational Outlook Handbook: : U.S. Bureau of Labor Statistics*. en. URL: https://www.bls.gov/ooh/transportation-and-material-moving/heavy-and-tractor-trailer-truck-drivers.htm (visited on 12/31/2022).

[32] Argonne National Laboratory. *GREET Model*. 2022. URL: https://greet.es.anl.gov/.

[33] National Renewable Energy Laboratory. *EV Charging Stations Pricing*. en. URL: https://www.nrel.gov/about/ev-charging-stations-pricing.html (visited on 12/30/2022).

[34] National Renewable Energy Laboratory. *Microgrids*. en. URL: https://www.nrel.gov/grid/microgrids.html (visited on 01/15/2023).

[35] Oak Ridge National Laboratory. *Transportation Energy Data Book: Edition 40*. en-US. June 2022. URL: https://tedb.ornl.gov/data/ (visited on 01/04/2023).

[36] Catherine Ledna et al. *Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis*. en. Tech. rep. NREL/TP-5400-82081, 1854583, MainId:82854. Mar. 2022, NREL/TP–5400–82081, 1854583, MainId:82854. DOI: 10.2172/1854583. URL: https://www.osti.gov/servlets/purl/1854583/ (visited on 12/30/2022).

[37] Abby McCain. *23+ Trucking Industry Statistics [2022]: Surprising Facts On American Trucking – Zippia*. en. Nov. 2022. URL: https://www.zippia.com/advice/trucking-industry-statistics/ (visited on 12/30/2022).

[38] United Nations. *Climate Change*. en. Publisher: United Nations. URL: https://www.un.org/en/global-issues/climate-change (visited on 12/31/2022).

[39] Rachael Nealer, David Reichmuth, and Don Anair. *Cleaner Cars from Cradle to Grave*. Tech. rep. Union of Concerned Scientists, 2015, pp. i–ii. URL: https://www.jstor.org/stable/resrep17225.1 (visited on 01/02/2023).

[40] Amol Phadke et al. *Why Regional and Long-Haul Trucks are Primed for Electrification Now*. en. Tech. rep. None, 1834571, ark:/13030/qt3kj8s12f. Mar. 2021, None, 1834571, ark:/13030/qt3kj8s12f. DOI: 10.2172/1834571. URL: https://www.osti.gov/servlets/purl/1834571/ (visited on 12/30/2022).

[41] Atlas Public Policy. *Electrification Assessment of Public Vehicles in Washington – Atlas Public Policy*. Nov. 2020. URL: https://atlaspolicy.com/electrification-assessment-of-public-vehicles-in-washington/ (visited on 01/04/2023).

[42] Atlas Public Policy. *Fleet Procurement Analysis Tool*. en-US. URL: https://atlaspolicy.com/fleet-procurement-analysis-tool/ (visited on 01/02/2023).

[43] Cristina Quiroz, E H Pechan, and B Hempstead Way. "How to use eGRID for Carbon Footprinting Electricity Purchases in Greenhouse Gas Emission Inventories". en. In: ().

[44] Theodore Roosevelt. *A quote by Theodore Roosevelt*. URL: https://www.goodreads.com/quotes/312751-nothing-in-the-world-is-worth-having-or-worth-doing (visited on 12/31/2022).

[45] National Park Service. *Sulfur Dioxide Effects on Health - Air (U.S. National Park Service)*. en. URL: https://www.nps.gov/subjects/air/humanhealth-sulfur.htm (visited on 01/15/2023).

[46] Jon Stewart. *INSANE Tesla Semi Truck Efficiency Explained*. en-US. URL: https://www.cleanerwatt.com/articles/insane-tesla-semi-truck-efficiency-explained (visited on 01/12/2023).

[47] Kyle Stock. "Robot Truckers Could Replace 500K U.S. Jobs". en. In: *Bloomberg.com* (Mar. 2022). URL: https://www.bloomberg.com/news/articles/2022-03-19/self-driving-trucks-could-replace-90-of-long-haul-jobs (visited on 03/05/2023).

[48] Andrew Stocking and Maureen Costantino. *Energy Security in the United States / Congressional Budget Office*. en. May 2012. URL: https://www.cbo.gov/publication/43012 (visited on 03/08/2023).

[49] Bureau of Transportation. *Transportation Economic Trends: Transportation Employment - Industry*. 2021. URL: https://data.bts.gov/stories/s/Transportation-Economic-Trends-Transportation-Empl/caxh-t8jd/ (visited on 12/30/2022).

[50] Fedor Unterlohner. *Why the future of long-haul trucking is electric*. en. June 2021. URL: https://www.transportenvironment.org/discover/why-the-future-of-long-haul-trucking-is-electric/ (visited on 01/07/2023).

[51] OAR US EPA. *Air Pollutant Emissions Trends Data*. en. Other Policies and Guidance. July 2015. URL: https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data (visited on 12/30/2022).

[52] OAR US EPA. *eGRID Data Explorer*. en. Data and Tools. Mar. 2020. URL: https://www.epa.gov/egrid/data-explorer (visited on 12/30/2022).

[53] OAR US EPA. *Fast Facts on Transportation Greenhouse Gas Emissions*. en. Overviews and Factsheets. Aug. 2015. URL: https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions (visited on 12/30/2022).

[54] OAR US EPA. *Plug-in Hybrid Electric Vehicle - Learn More About the New Label*. en. Overviews and Factsheets. Oct. 2016. URL: https://www.epa.gov/fueleconomy/plug-hybrid-electric-vehicle-learn-more-about-new-label (visited on 01/03/2023).

[55] Volkswagen. *What's more efficient? Hydrogen or battery powered?* URL: https://www.volkswagenag.com/en/news/stories/2019/08/hydrogen-or-battery--that-is-the-question.html (visited on 01/07/2023).

[56] Wikipedia. *Truck classification*. en. Page Version ID: 1128737959. Dec. 2022. URL: https://en.wikipedia.org/w/index.php?title=Truck_classification&oldid=1128737959#Table_of_US_GVWR_classifications (visited on 12/31/2022).