Strategic Analysis of Technical, Commercial, and Regulatory Influences on the Commercialization of Hydrogen Fuel Cell Vehicles

by

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Abstract

Increasing regulatory pressures are being applied to automotive manufacturers requiring them to reduce the negative impacts that their vehicles have on the environment. In response to these regulations, and evolving consumer preferences, manufacturers are heavily invested in identifying technologies to increase fuel economy and reduce greenhouse gas emissions. Alternative propulsion technologies, such as fuel cells, are of tremendous interest to provide these benefits. However, factors including refueling infrastructure requirements, technology costs, and consumer willingness-to-consider all significantly impact the commercial viability of hydrogen fuel cell vehicles (HFCVs).

I develop a system dynamics model to explore the temporal importance of critical factors required to build a market for HFCVs that is sustainable in the long-term. This methodology allows for the following:

1) Infrastructure: Identification of optimal hydrogen infrastructure growth necessary in order to support HFCV adoption and minimize required fueling stations. Additionally, the conditions in which external construction and operational support may give way to organic growth can be determined.

2) HFCV Ownership Costs: A time-dependent characterization of vehicle price and ownership subsidies can be ascertained to facilitate adoption.

3) Familiarity Accumulation: Assessment of the marketing investment necessary to yield desired HFCV adoption while minimizing costs.

4) Regulatory Requirements: Projection of compliance with Zero Emission Vehicle (ZEV) Action Plan requirements, highlighting potential impacts and possible mitigation measures.

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1.0 Introduction

1.1 Motivation

1.1.1 Environmental Impact

The United States (U.S.) emitted 6.7 billion metric tons of carbon dioxide (CO_2) in 2013, of which the transportation sector was responsible for an estimated 27 percent of the emissions, second only to the electricity sector. Given that a significant proportion of greenhouse gas (GHG) emissions (CO_2 makes up 82 percent of all GHGs) are attributable to transportation, vehicle manufacturers have come under increasing scrutiny to increase fuel economy (FE) and decrease emissions.[1]

1.1.2 Foreign Oil Dependence

Until the Arab-Israeli War in 1973, the U.S. had not shown a strong concern towards improving vehicle fuel economy (FE). As a result of an oil embargo proclaimed by the Organization of Petroleum Exporting Countries (OPEC) in October of 1973, the supply of petroleum to the U.S. was significantly diminished. By January 1974, the price of oil had risen from \$3 to \$12 per barrel. This volatility was jarring to the U.S. economy, and while measures have been taken to reduce future instability, the nation's crude oil supply is still dependent on foreign imports today. The net import of crude oil and petroleum was 33 percent of the total supply in 2013, and the U.S. Energy Information Administration (EIA) expects the fraction of imports to decrease to 17 percent by 2040.[2] Coincident efforts by the National Highway Traffic Safety Administration (NHTSA) aimed at reducing petroleum consumption have placed significant pressure on vehicle manufacturers to increase FE and develop alternative fuel vehicles (AFV).[3]

1.2 Problem Statement

While progress has been achieved in regards to AFV development, significant barriers (such as technology cost and infrastructure availability) impede their commercialization. This research aims to answer the following questions:

What barriers to consumer adoption of HFCVs exist,
and under what conditions does a sustainable market for HFCVs form?

The insights from this research intend to inform the relative importance of major factors in consumer adoption of HFCVs, and highlight actionable strategies to influence short-term and long-term HFCV adoption.

1.3 Project Approach

I employ a system dynamics modelling approach to simulate the complex feedbacks influencing HFCV commercialization, building on extensive work on this topic undertaken at the Massachusetts Institute of Technology (MIT), which forms the foundation for this analysis.[4,5,6]

I parameterize the model based on the geography, demographics, and regulatory stance of the state of California to establish a baseline. From this, I conduct a scenario analysis involving the following vehicle platforms: gasoline internal combustion engine (ICE) vehicles, hybrid electric vehicles (HEV), plug-in HEVs (PHEV), battery electric vehicles (BEV), and HFCVs. The results of the scenarios are then synthesized into insights that a vehicle manufacturer or other entity could leverage when considering HFCV commercialization strategies.

2.0 Vehicle Platform Summary

2.1 Vehicle Propulsion Technologies

2.1.1 Gasoline / Internal Combustion Engine

Since the early 1900s, the Internal Combustion Engine (ICE) has been the most prevalent vehicle propulsion technology on the market. ICE vehicles work by combusting a fuel-air mixture within the engine and converting the energy into mechanical work that routes through the transmission and allows the rest of the powertrain to distribute power to the vehicle's wheels.

2.1.2 Hybrid Electric Vehicle (HEV)

Common HEV designs employ an on-board battery to recoup energy from regenerative breaking that can power an electric motor to aid in vehicle propulsion. Mild hybrids allow the vehicle's engine to automatically stop while not in motion, but they are not powerful enough to independently drive the vehicle using electricity only. More common are full hybrids, which make use of the same power generating techniques as mild hybrids, but typically have a larger battery and electric motor that can independently power the vehicle. Full hybrids offer greater FE improvement compared to mild hybrids, but have a higher purchase price.[7]

2.1.3 Plug-in Hybrid Electric Vehicle (PHEV)

The PHEV takes the HEV one step further as is implied by the abbreviation, "plug-in". While similar in architecture, the PHEV has the added capability of being able to charge the on-board battery by plugging it into an electricity source.

2.1.4 Battery Electric Vehicle (BEV)

BEVs remove the ICE all together and instead rely on electric motor(s) powered by an on-board battery to propel the vehicle. Historically, BEV adoption has been limited due to the high cost of the battery, and limited vehicle range. However, recent technological advancements have significantly lowered the cost and weight of battery and motor components. Given that BEVs produce no tailpipe emissions during operation, they are classified as ZEVs. Currently, only BEVs and HFCVs are considered to be ZEVs. While the BEV is technically a ZEV, the magnitude of GHG emissions that result from BEV operation depend on the method of electricity generation.

2.1.5 Hydrogen Fuel Cell Electric Vehicle (HFCV)

Similar to BEVs, HFCVs use electric motors to propel the vehicle, but the bulk of the electricity is delivered from a fuel cell. The most common fuel cell for vehicle applications makes use of polymer electrolyte membrane (PEM) technology. The hydrogen used by the PEM fuel cell is stored in on-board tanks, most commonly at 700 bar. While HFCVs have been under development for decades, only recently have OEMs began to offer them to the general public. The HFCV is technically considered to be a ZEV, although it does emit water during operation. Similar to BEVs, the GHG emissions associated with HFCV operation depend on the upstream fuel pathway by which hydrogen fuel is produced.

2.2 Vehicle Attributes

Table 1 provides an overview of the vehicle types considered in the model, and identifies their assumed performance and cost characteristics.

Table 1: Vehicle Attributes

Vehicle Type	ICE	HEV	PHEV	BEV	HFCV
Vehicle Model	2015 Chevy Malibu[8]	2015 Ford Fusion Hybrid S[9]	2016 Chevy Volt[10]	2016 Nissan Leaf[11,12]	2016 Toyota Mirai[13,14]
MSRP ($)	22,465	26,085	33,170	29,010	57,500
Operating Cost ($/year)	2,716	3,154	4,010	3,507	6,952
Gasoline Tank (gallons)	15.8	13.5	8.9	-	-
Hydrogen Tank (kg)	-	-	-	-	5
Fuel Economy (MPGe)	30.5	42.5	42.0	114.0	-
Fuel Economy (mi/kg)	-	-	-	-	62.4
Battery Size (kWh)	-	1.4	18.4	24.0	1.6
Energy Efficiency (kWh/mi)	-	-	0.34	0.28	-
AER (miles)	-	-	53	84	312
Total Vehicle Range (miles)	482	574	420	84	312
0-30 MPH (seconds)*	3.0	3.1	4.2	5.1	4.5
Top Speed (mph)*	130	124	98	94	111

**Author assumptions were made for acceleration and top speed values that were not publically available*

3.0 Fuel and Electricity Production, Transportation, and Cost

3.1 Gasoline Production, Transportation, and Cost

Gasoline Production

In 2015, the U.S. used between 18 and 21 million barrels of crude oil per day to produce petroleum products. A large quantity of this consumption was used for the production of gasoline by distilling and refining the crude oil. Through this multi-stage process, approximately 44 percent of the petroleum becomes gasoline and the remainder is split between lighter chemical byproducts such as natural gas, kerosene and heavier products including lubricants and asphalt. In 2014, the U.S. imported approximately 9.2 million barrels of crude oil per day from other countries, accounting for 46 percent of the crude oil processed in the nation.[3]

Gasoline Transportation

According to the American Petroleum Institute (API), there are 153,000 stations in the U.S. that provide consumers with approximately 368 million gallons of gasoline per day. The 142 gasoline production refineries in the U.S. transport a majority of the fuel via underground pipelines to above ground storage tanks. From the more than 1,300 storage tank locations throughout the country, transport trucks then deliver the petroleum product to the retail locations.[15]

Gasoline Cost

I use forecasts from the Energy Information Administration (EIA) as the baseline input for gasoline prices in the model. The EIA projects an annual growth rate of gasoline fuel to be 0.30 percent until 2050. I use this rate to extrapolate the fuel price over the 50-year duration of the simulation ($2.65/gallon in 2015 to $6.65/gallon in 2065 in real terms).[2]

3.2 Electricity Production, Transportation, and Cost

3.2.1 Electricity Production and Transportation

The U.S. generated 4,093 billion kilowatt-hours (kWh) of electricity in 2014, with 67 percent produced using fossil fuels. Due to the pre-existing grid throughout the U.S., delivery of electricity to electric charging infrastructure is not a primary concern in this research. Additionally, while the current electricity grid can handle the demand from BEV charging, future impacts that charging would have on the grid are not explored.

3.2.2 Electricity Cost

Like gasoline, electricity prices are highly volatile and hence are hard to predict. For the baseline scenario, data is incorporated from the *2015 Annual Energy Outlook* prepared by the EIA. The EIA found that retail electricity in the U.S. was priced at an average of 10.1 cents/kWh in 2013. Several cases (high, low, and average oil and gas prices) were considered, with the base case yielding an electricity price increase of 18 percent to 11.8 cents/kWh by 2040.[2] I use linear extrapolation to project electricity prices for the last 25 years of the model timeline. Accordingly, the retail electricity price rises linearly from 10.23 cents/kWh in 2015 to 13.37 cents/kWh in 2065.

3.3 Hydrogen

While few HFCVs exist in the U.S. currently, approximately 100 billion cubic feet of hydrogen is produced within the country each year for applications from fertilizer production to crude oil refinement and powering forklifts.

3.3.1 Hydrogen Production

Hydrogen can be produced in many ways. Currently the most prevalent method is Steam Methane Reforming (SMR). Accounting for 95 percent of production, SMR involves the reaction of steam and methane at high temperatures in the presence of a metal-based catalyst to produce Carbon Monoxide (CO) and hydrogen. At least in the short-term, SMR will be the leading production method of hydrogen, although one attractive aspect of hydrogen is that it can be produced by a variety of large- or small-scale techniques. One area of significant interest is the product of hydrogen at the fuel station using electrolysis, an energy intensive process that uses electricity to split water molecules into their respective components, oxygen and hydrogen. While electrolysis is not new, the notion of using renewable energy sources such as wind, solar, or geothermal power to produce an energy carrier such as hydrogen has only recently gained noteworthy support.

3.3.2 Hydrogen Transportation

A necessary enabler of HFCV adoption is supplying the growing refueling infrastructure with hydrogen fuel. Even though hydrogen's Lower Heating Value (LHV) of 52,217 btu/lb is nearly three times greater than gasoline (18,676 btu/lb), its volumetric energy content is much less than that of gasoline.[16] For this reason, the manner by which hydrogen is transported is critical. Currently, hydrogen is distributed in three primary methods; high-pressure tubes, liquefied tankers, and pipelines.

High-Pressure Tubes: Transporting hydrogen via high-pressure tubes is expensive due to the aforementioned relatively low energy density. Furthermore, current Department of Transportation (DOT) regulations limit hydrogen pressures on delivery trucks to 250 bar. Accordingly, more trips must be made in comparison to transporting traditional liquid fuels such as gasoline. The pressure limitation arises from the weight attributed to the steel tubes that hold approximately 280 kg of hydrogen, but technological advances are being made in this area. Composite transportation tubes have been developed within the DOT's dimensional requirements that are capable of holding 560-720 kg of hydrogen.

Liquefied Tankers: Cryogenic liquefaction is a costly means by which hydrogen can be cooled to the point where its state changes to a liquid. This allows for the transportation of significantly more hydrogen than high-pressure tubes, and is preferred for long distances due to the increased energy density that can be obtained. In addition to being pricier than transporting hydrogen via high pressure tubes, liquid hydrogen must be kept at -252.78 °C (at 1.013 bar) to avoid boiling off.[17] Accordingly, the delivery and consumption of liquid hydrogen must be closely matched to avoid waste.

Pipelines: Once installed, delivering hydrogen via permanent pipelines is the most economical method. However, there are only around 700 miles of hydrogen pipelines in the US currently, many of which are concentrated in CA and around the Gulf Coast.[7] Given that these pipelines are used primarily for industrial applications, it would be inordinately expensive to construct a hydrogen infrastructure for public HFCVs in this manner.

3.3.3 Hydrogen Cost

Contrary to projections for retail electricity and gasoline prices, it is expected that the price of hydrogen in 'gallons of gasoline-equivalent' (GGE) terms will decrease over time due to advancements in production methods. As with electricity and gasoline, the price of hydrogen can vary significantly as a result of how it is produced and distributed. A large hydrogen production facility can produce hydrogen at the lowest price, but the retail price will then incorporate the non-trivial expense of transportation. Conversely, on-site production via electrolysis is a costly process, but no delivery expenses are incurred.

The Department of Energy (DOE) has a price target of reducing the retail price of hydrogen to $4/kg by 2020. Current estimates suggest that this target may be overly optimistic, and although the price point is achievable via some production methods, these methods do not currently produce significant amounts of hydrogen. Given the lack of reliable hydrogen price forecasts, the baseline scenario utilizes an initial hydrogen price of $7/kg that linearly drops to $4/kg by 2065 as a result of attaining economies of scale in hydrogen production.[16]

4.0 Fuel Station Infrastructure and Incentives

While it is difficult to travel any considerable distance in a populated region without seeing a gas station, this is not the case for electric charging stations, and is certainly not the case for hydrogen fueling stations. Any vehicle for which refueling stations are not conveniently located is significantly less attractive to potential customers. Similarly, if there are few vehicles that require electricity or alternative fuel, there is little incentive for fuel station owners to invest in stations that serve this small market. This predicament is of concern to any entity promoting AFVs. In light of this dilemma, considerable investments are being made by federal and state governments, as well as by individual companies, to aid the development of AFV infrastructure.

4.1 Hydrogen Infrastructure

One of the largest obstacles to HFCV commercialization is the lack of refueling infrastructure that exists within the U.S. Hydrogen stations are costly to install, and there is little incentive for potential station owners to invest as there is no meaningful installed base of HFCVs currently. Historically, this has negated the construction of hydrogen refueling stations for public use. In addition to federal efforts, the state of California has recently begun to support the development of hydrogen refueling stations. There are currently 58 hydrogen refueling infrastructure projects in California. Of the stations that will be available to the public, 44 are in development, and five are operational. Figure 1 identifies the station locations that are largely grouped around San Francisco and Los Angeles. Station groupings, along with connecting stations, are critical in fostering the practicality of HFCVs should drivers wish to travel outside their regular routes.[18]

Figure 1: California Hydrogen Station Map

Estimated to cost between $0.9-1.5M per hydrogen refueling station, the capital cost of HFCV refueling infrastructure is significantly more than what is required for electric vehicles. Furthermore, limited progress on the hydrogen refueling stations has hindered the demand for HFCVs available currently, including the Toyota Mirai launched in 2015. To remedy this, Toyota made plans to supply California dealerships selling the Mirai with temporary hydrogen stations for consumers looking to purchase the vehicle immediately.[19] While this stop-gap may be an adequate short-term solution, the construction and operation of hydrogen fuel stations is likely to require external support to make the business case attractive to most investors.

4.1.1 Hydrogen Infrastructure Incentives

In 2013, California Governor Jerry Brown signed Assembly Bill 8 into law with the purpose of expediting the adoption of AFVs, as well as increasing the FE of vehicles on the market.[20] One stipulation includes funding up to $20M per year on hydrogen infrastructure, with the assurance that at least 100 hydrogen fuel stations will be operational in California within the next ten years. Since the law does not stipulate the annual rate of station construction, I assume a linear accumulation.

4.2 Electric Charging Stations

Like HFCVs, electric vehicles face similar adoption challenges due to the limited availability of recharging infrastructure currently. One relative advantage for PHEV and BEV owners, however, is that most homes have the ability to charge electric vehicles with limited or no additional capital cost, although limitations in charge rate do exist. Furthermore, due to the existence of the ubiquitous electrical gird, charging stations are much cheaper to install than those for hydrogen. Table 2 below outlines the charging options for PHEV and BEV owners based on the currently accepted common charge levels.[21]

Table 2: Current Electric Vehicle Charging Options

Charge Level	Location	Voltage	Charge Rate (miles/hr.)	Capital Cost ($/port)
AC Level 1	Home/public	120 V	2-5	0
AC Level 2	Home/public	240 V	10-20	$1.2k-$10k
Level 3 (DC Fast)	Public	480 V	150-210	$60k-$100k

4.2.1 Electric Charging Station Incentives

Various federal, state, and local grants have been established to promote electric charging station infrastructure development. In addition to the federal subsidy on construction costs of 30% up to $30k, the California Energy Commission has approved multiple grants to aid infrastructure development. Approved in 2013, these 15 grants will support the installation of 475 electric vehicle chargers in communities throughout California.[22]

5.0 State and Federal Vehicle Regulations and Incentives

5.1 California Regulations and Incentives

Of the estimated 260 million registered passenger vehicles in the U.S., nearly eight percent reside in the state of California.[23] However, this concentration of vehicles has left California with some of the worst air pollution in the nation. Beginning in 1967, California's Legislature passed the Mulford-Carrell Act that ultimately spawned the Air Resources Board (ARB), with the intent to, *"...promote and protect public health, welfare and ecological resources through the effective and efficient reduction of air pollutants, while recognizing and considering the effects on the state's economy."* [24] Beginning in 1966, the ARB established the nation's first motor vehicle emission standards, resulting in new vehicles today polluting 99 percent less than their counterparts 30 years ago. Still, over half of the state's smog-forming emissions are produced by gasoline and diesel vehicles.[24]

5.1.1 ZEV Action Plan

In 2012, California Governor Edmund G. Brown issued an executive order aimed at increasing the number of ZEVs in the state to further accelerate the reduction of GHG emissions. The order outlined several milestones including a directive that California reach a target of 1.5 million ZEVs on its roads by 2025.[20] As a result, the ZEV Action Plan was created as a roadmap to achieve the following goals:

- Complete needed infrastructure and planning
- Expand consumer awareness and demand
- Transform fleets
- Grow jobs and investments in the private sector

With regard to AFV adoption, the infrastructure development and fleet transformation portions of the plan are of most interest when considering regulations and incentives. Consumer awareness and demand is discussed in Section 6.1.1, with job growth insights outside the scope of this analysis.

5.1.1.1 Infrastructure and Planning

In order to foster AFV commercialization, California is incentivizing the construction and operation of infrastructure for PHEVs, BEVs, and HFCVs. For PHEVs and BEVs, this entails subsidizing installation of vehicle chargers in homes, workplaces, as well as public areas. As mentioned previously, California is providing \$20M annually to develop an initial network of 100 hydrogen fueling stations for HFCVs by 2024, as well as supporting operational costs.[22]

5.1.1.2 Fleet Transformation

Another way in which the ZEV Action Plan aims to foster progress towards increased vehicle FE and reduced GHG emissions is by establishing mandates for state departments as well as for OEMs that wish to sell vehicles within the state. By 2020, the ZEV Action Plan dictates that at least 25 percent of state owned vehicle fleet purchases must be ZEVs.[20] This is significant for commercialization of HFCVs and BEVs as it mandates a certain level of early adoption of ZEVs.

While the state mandated purchase of ZEVs is considerable, the requirements placed on the OEMs are even more impactful. In July 2014, the ARB released the latest ZEV emission standards for manufacturers selling passenger cars, light-duty trucks, and medium duty vehicles in the state of California. Despite the straightforward purpose, the ZEV emission standards are quite complex. A few of the major points are discussed below. For complete details refer to *Zero-Emission Vehicle Standards for 2018 and Subsequent Model Year Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles.*[24]

Manufacturer Classification

It is helpful to understand that the full ZEV requirements are only applicable to Large Volume Manufacturers (LVM). An OEM is considered to be a LVM if it sells more than 20,000 vehicles in the state of California. Intermediate Volume Manufacturers (IVM) are allowed to meet the ZEV percent requirement completely from TZEVs if they choose. IVMs are considered as such if the quantity of vehicles delivered for sale does not exceed 20,000. Lastly, with annual sales of up to 4,500 vehicles, Small Vehicle Manufacturers (SVM) are not required to meet the ZEV credit requirements.

Vehicle Type Classification

Although referred to as ZEV emission standards, the requirements contain provisions that allow ZEV credits to be earned from a range of vehicle types including Transitional Zero Emission Vehicles (TZEV), Neighborhood Electric Vehicles (NEV), Partial Zero Emission Vehicles (PZEV), and Advanced Technology PZEVs (AT PZEV). Table 3 provides information on these vehicles as well as examples of specific models currently available.

Table 3: Vehicle Class Types and Examples[25]

Vehicle Class	Vehicle Type	Example Vehicle
ZEV	BEV, HFCV	Nissan LEAF
TZEV	PHEV, EREV	Chevrolet Volt
NEV	Short range EV	ParCar
PZEV	Conventional	Ford Focus
AT PZEV	HEV	Toyota Prius

Annual ZEV Requirements

The ZEV requirements for vehicle model years (MY) from 2015 through 2025 are shown in Table 4, indicating what proportion of an LVM's total vehicle sales must result from ZEVs and TZEVs.

Table 4: Annual ZEV Requirements[24]

Vehicle MY	Total ZEV Percent Requirement (%)	Minimum ZEV Floor (%)	Maximum TZEV (%)	Maximum AT PZEV (%)	Maximum PZEV (%)
2015	14.0	3.0	3.0	2.0	6.0
2016	14.0	3.0	3.0	2.0	6.0
2017	14.0	3.0	3.0	2.0	6.0
2018	4.5	2.0	2.5	-	-
2019	7.0	4.0	3.0	-	-
2020	9.5	6.0	3.5	-	-
2021	12.0	8.0	4.0	-	-
2022	14.5	10.0	4.5	-	-
2023	17.0	12.0	5.0	-	-
2024	19.5	14.0	5.5	-	-
2025	22.0	16.0	6.0	-	-

In addition to the annual increase in ZEV credit requirements, the allowable impact that certain vehicle types have toward this percentage will change in future years. Figure 2 illustrates this change over time. Beginning in 2018, all ZEV credits must be satisfied by ZEVs, TZEVs, and NEV's. Further range-dependent credit determinations are discussed in Section 6.2.1.1.

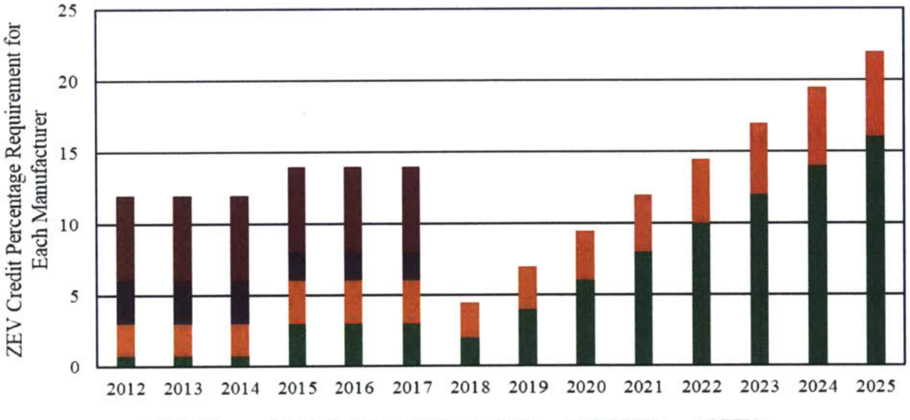


Figure 2: Graphical Representation of ZEV Requirements[24]

ZEV Credit Procurement

While the state of California is providing considerable funding to support the development of the market for ZEVs, the requirements placed on LVMs and IVMs to achieve AFV adoption are considerable. If these companies wish to sell vehicles in CA, they must meet the ZEV Action Plan requirements. Beyond the federal and state support for ZEV and TZEV adoption, the burden falls on the OEM to accelerate adoption by ensuring that the ZEV credit requirement is met. ZEV credits can be earned in three ways.

1) Sell more ZEVs and TZEVs

An OEM can take action to increase sales of ZEVs and TZEVs, such as by allocating resources for additional marketing investment or subsidizing vehicle purchases.

2) Purchase ZEV Credits

A lucrative market exists in which OEMs can buy and sell ZEV credits between each firms to meet their requirements. In this manner, manufacturers can meet the required ZEV credit level without having sold an adequate percentage of complying vehicle types.

3) Credit Deficiency Fines

If LVMs and IVMs do not meet the ZEV requirement in a given year, they have an additional two years to make up a ZEV deficit. If the manufacturer still fails to comply after that period, the company is subject to financial penalties of $5,000 per deficient ZEV credit as outlined in Section 43211 of the Health and Safety Code (HSC).[26]

ZEV Mandate Proliferation

Under Section 209 of the Clean Air Act, California has the authority to issue the ZEV emission standards on the basis that they are stricter than the Corporate Average Fuel Economy (CAFE) requirements established by the federal government. Similarly, other states can agree to abide by federal regulations or adopt California's vehicle emissions requirements. Nine additional states (Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont) have agreed to follow the stricter regulations to date.[27]

5.1.2 California State Vehicle Incentives

In addition to the regulations that California has imposed, the state currently offers several rebates to purchasers of qualifying AFVs. One of the larger subsidies is through the Clean Vehicle Rebate Project (CVRP), whereby consumers who purchase PHEVs and ZEVs receive rebates of $5,000 of the purchase price, irrespective of electric range.[7]

5.2 Federal Regulations and Incentives

In addition to the mandates and incentives established by each state within the U.S., the federal government has overarching policies that regulate vehicle performance. As a result of the societal and economic impacts of the OPEC oil embargo, the U.S. Congress passed the Energy Policy Conservation Act (EPCA) in 1975, pushing NHTSA to promote a reduction in vehicle energy consumption by improving FE within the country.

5.2.1 Federal Vehicle Regulations

Established in 1975, the Corporate Average Fuel Economy (CAFE) standards set fleet-wide FE averages for new vehicle sales that automakers must meet in order to avoid financial penalties. These standards are sales weighted and apply to passenger cars and light trucks that have a Gross Vehicle Weight Rating (GVWR) of less than 8,500 lbs.[25] Table 5 illustrates the FE requirements established through the CAFE standards in terms of miles per gallon (MPG). While there are multiple nuances to the manner in which CAFE is calculated, this trend provides an overview of the progression that is expected of automakers selling vehicles in the U.S.

Table 5: Projected CAFE Fuel Economy Standards (values in MPG)[25]

Vehicle Type	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Passenger Cars	36.4	38.2	39.6	41.1	42.5	44.2	46.1	48.2	50.5	52.9	55.3
Light Trucks	27.1	28.9	29.1	29.6	30.0	30.6	32.6	34.2	35.8	37.5	39.3
Combined	32.6	34.3	35.1	36.1	37.1	38.3	40.3	42.3	44.3	46.5	48.7

**Note that CAFE values are not representative of fuel economy labels identified on vehicles at dealerships*

A manufacturer faces a penalty if the CAFE of its passenger car or light truck fleet does not meet the standard as identified for the given vehicle MY. The penalty amounts to $5.50 per tenth of a MPG under the target multiplied by the volume of that vehicle model manufactured for the given MY. Similar to the California ZEV program, credits can be accumulated if a vehicle's CAFE beats the target value. This is determined by multiplying the amount by which the CAFE target is beat by the volume of that model vehicle manufactured in the given year. These credits are forfeited if not used within three users. Historically, domestic manufacturers have met the CAFE targets, and thus have avoided the aforementioned penalties.[25]

To encourage market deployment, PHEVs and HFCVs are afforded a multiplying factor to assist the manufacturer in complying with CAFE standards. EVs are given a multiplier of 2.0 in MY 2017 that phases down to 1.5 in MY 2021. Similarly, PHEVs yield a multiplier of 1.6 for MY 2017 that is reduced to 1.3 in MY 2021. No multipliers have been established for MYs beyond 2022 as of yet.[1]

Simultaneous to NHTSA's efforts, the EPA has promulgated regulations that restrict the amount of GHG emissions permissible for all vehicles on a per mile basis. The emissions requirements are shown in Table 6 in terms of g CO_2e/mi.

Table 6: Projected GHG Emissions Targets (g CO_2e/mi)[25]

Vehicle Type	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Passenger Cars	235	225	212	202	191	182	172	164	157	150	143
Light Trucks	317	298	295	285	277	269	249	237	225	214	203
Combined	263	250	243	232	222	213	199	190	180	171	163

Similar to the CAFE regulations, automotive manufacturers face financial penalties if their vehicle fleets do not meet the prescribed emissions requirements. While most large vehicle manufacturers easily meet the GHG requirements, NHTSA has collected nearly $820 million throughout the duration of the CAFE program.[25]

5.2.2 Federal Vehicle Incentives

In addition to the regulations that are in place to improve FE and reduce GHG emissions, the federal government also provides incentives to consumers to accelerate the adoption of HEVs and AFVs. HFCV customers currently receive a $4,000 tax credit, while BEV and PHEV customers receive $2,500 plus an additional $417 for each kWh of battery capacity in excess of 5 kWh (up to $7,500).[28]

6.0 Model Overview

6.1 Model Foundation

As mentioned previously, the base model used for the analysis was developed by the MIT System Dynamics Group.[4,5,6] This simulation model builds off the foundation of Bass-type diffusion of durable goods, where the interaction of multiple feedbacks is considered in determining product adoption rates.[6] The model consists of three significant elements that address how consumer multinomial choice between competing vehicle platforms is influenced: 1) the accumulation of consumer familiarity; 2) technological change in critical vehicle components, and; 3) the coevolution of refueling infrastructure. Thorough discussion of the model's architecture and use cases can be found in *Essays on the Dynamics of Alternative Fuel Vehicle Adoption: Insights from the Market for Hybrid-Electric Vehicles in the United* States.[6]

6.1.1 Consumer choice

Utility

For my purposes, utility is defined as, "the factors that influence attractiveness".[6] Utility captures all attributes that influence consumer choice, weighted according to consumer preferences. An empirical study to determine consumer choice in reference to the automotive market was used to estimate the relative utility for the vehicle types considered, using the following utility function:

$$Utility_j = \beta_1\left(\frac{Purchase\ Price_j}{\ln(Income)}\right) + \beta_2(Operating\ Cost_j) + \beta_3(Acceleration_j) + \beta_4(Top\ Speed_j)$$
$$+ \beta_5(Emissions_j) + \beta_6(Refueling\ Cost_j) + \beta_7(Scope_j)$$

Where the coefficients, β_n identify the weight for each of the attributes.[29] Table 7 lists the coefficients for the baseline model. Understanding that every consumer has different preferences for vehicle utility, these coefficients capture utility at the population level.

Table 7: Utility Parameter Weights[29]

Attribute	Units	Coefficient
Purchase Price/ln(Income)	$ '000s	-0.361
Operating Cost	cents/mile	-0.170
Acceleration (0-30 mph)	seconds	-0.149
Top Speed	mph	0.272
Emissions	dimensionless	-0.149
Refueling Cost	cents/mile	-0.170
Scope	dimensionless	-0.500

Familiarity

The decision for a consumer to adopt an AFV requires not only that the vehicle has high utility, but also that the consumer is sufficiently familiar with that technology that they include it in their purchase decision. Familiarity accumulates in three primary ways: 1) the initial vehicle installed base which fosters social exposure as a result of contact between prospective buyers and people who have already adopted (very high for ICE vehicles and very low for HFCVs); 2) through social exposure from consumer interactions; and 3) as a result of product marketing. I concentrate on product marketing due to the significant impact that vehicle manufacturers and other entities can have in this area.

6.1.2 Infrastructure growth

Irrespective of the existence of demand for AFVs, if the infrastructure is not available, adoption will never occur. This is less critical for BEVs in relation to HFCVs due to the fact that home charging is an option. Furthermore, the presence of infrastructure alone does not necessarily create demand. With regards to station placement, I assume that the stations and consumers are placed at random throughout the given area. Other studies such as, *Hydrogen Dynamic Infrastructure and Vehicle Evolution Model analysis*, have explored station placement optimality based on refueling station proximity, trip length (as a result of population, population density, and driving habits), and importance of initiating diffusion in urban geographies, and so on.[30] Primary infrastructure assumptions can be viewed in Table 8.

Table 8: General Infrastructure Assumptions

Parameter	Gasoline[31]	Electricity (level 2)[32]	Hydrogen
Initial Stations	2000	368	3
Stations Under Construction*	100	18	25*
Station Installation Time (years)	1	1	1
Station Cost ($M)	0.2	0.2	1.2
Station Pumps/Charge Points	10	2	2
Fuel Dispense Rate (GGE/min)[1,33]	5	0.016	2

**Includes ZEV Action Plan support used only in the ZEV scenario, all other scenarios assume no stations initially under construction*

6.2 Model Adjustments

6.2.1 ZEV Action Plan

The ZEV Action Plan was added to the model to simulate the current regulatory environment of California. Since the model does not distinguish between multiple competing OEMs, I assume that the market is operating under an LVM scenario, in which all ZEV credit requirements must be satisfied by ZEVs, Type 0 ZEVs, TZEVs, and NEVs. For the purpose of this analysis, I exclude NEVs (short range vehicles used in neighborhoods) and Type 0 ZEVs (vehicles with a range less than 50 miles which are not permitted to travel on highways).

6.2.1.1 TZEV and ZEV Credit Calculations

TZEV Credit Calculation

TZEV credit amounts are based on the vehicle's all electric range (AER), which is assessed by the EPA through use of the Urban Dynamometer Driving Schedule (UDDS). The UDDS is a drive cycle simulated by dynamometers that is meant to represent city driving conditions in order to determine vehicle FE or AER. Table 9 identifies the method to determine ZEV credit allowances for TZEV Vehicles.

Table 9: ZEV Credit Determination (TZEV)[24]

UDDS AER	Qualifying ZEV Credits
< 10 AER	0
≥ 10 AER	0.01 · UDDS AER + 0.30
> 80 AER	1.10

ZEV Credit Calculation

ZEVs with a range of more than 50 miles receive credit based on,

$$ZEV\ Credit = 0.01 \cdot UDDS\ AER + 0.50$$

No credit is granted if the ZEV range is less than 50 miles. Table 10 highlights the credit limits for all vehicle types as established by California's ARB.

Table 10: ZEV Credit Ranges based on Vehicle Type[25]

Vehicle	Credits MY2012-2017	Credits MY2018-2025
ZEV*	1-9	1-4
TZEV*	1-3	0.4-1.3
NEV	0.3	0.15
PZEV	0.2	-
AT PZEV*	0.2-3	-

**Credits depend on technology type and vehicle range*

6.2.1.2 Modeling ZEV Credit Dynamics

Table 4 identifies the breakdown of ZEV requirements through the year 2025. For the baseline scenario, I make a conservative assumption that no subsequent increase in ZEV requirements is made after 2025, as shown in Table 11.

Table 11: ZEV Credit Requirement Assumption[24]

Vehicle MY	Total ZEV Percent Requirement (%)	Minimum ZEV Floor (%)	Maximum TZEV (%)	Maximum AT PZEV (%)	Maximum PZEV (%)
2015	14.0	3.0	3.0	2.0	6.0
2016	14.0	3.0	3.0	2.0	6.0
2017	14.0	3.0	3.0	2.0	6.0
2018	4.5	2.0	2.5	-	-
2019	7.0	4.0	3.0	-	-
2020	9.5	6.0	3.5	-	-
2021	12.0	8.0	4.0	-	-
2022	14.5	10.0	4.5	-	-
2023	17.0	12.0	5.0	-	-
2024	19.5	14.0	5.5	-	-
2025	22.0	16.0	6.0	-	-
2030	22.0	16.0	6.0	-	-
2035	22.0	16.0	6.0	-	-
2040	22.0	16.0	6.0	-	-
2045	22.0	16.0	6.0	-	-
2050	22.0	16.0	6.0	-	-
2055	22.0	16.0	6.0	-	-
2060	22.0	16.0	6.0	-	-
2065	22.0	16.0	6.0	-	-

ZEV Credit Deficiency Impact

As mentioned in section 5.1.1.2, credits can be obtained in three ways: 1) sell more ZEVs and TZEVs; 2) purchase ZEV credits, or 3) face a fine of $5,000 per deficient ZEV credit. Due to the variance in vehicle offerings, OEMs may follow different strategies to comply with the ZEV Action Plan. For this analysis, I model ZEV compliance (Appendix 1), and assess fines on the basis of ZEV credit deficiency.

7.0 Scenario Results and Analysis

7.1 Scenario One: Baseline

In order to draw comparisons from subsequent scenarios, I first establish a baseline scenario representing the vehicle market in Los Angeles County, California. Here I calculate performance against the ZEV mandate target, but do not include the policy measures implemented with the ZEV mandate, in order to understand the behavior of the model with the baseline parameterization. In addition to the inputs identified previously, Table 12 provides parameters for the initial vehicle fleet as well as geography and demographic information.

Table 12: Vehicle Fleet, Geographic, and Demographic Parameters

	Parameter	Value
Vehicle Fleet	Total Fleet Size (vehicles)[34]	6.1M
	Initial Vehicle Distribution (vehicles) (ICE,HEV,PHEV,BEV,HFCV)[2,35]	6.09M, 60,000, 10,400, 7,000, 150
	Average Vehicle Lifetime (years)[36]	11.4
	Average Annual VMT (miles)[36]	11,500
	Average Speed (miles/hour) [37]	30
Geography and Demographics	Land Area (miles^2)	4,000
	Median Household Income ($/year)[38]	63,000
	Annual Income Growth (%)[39]	4.8

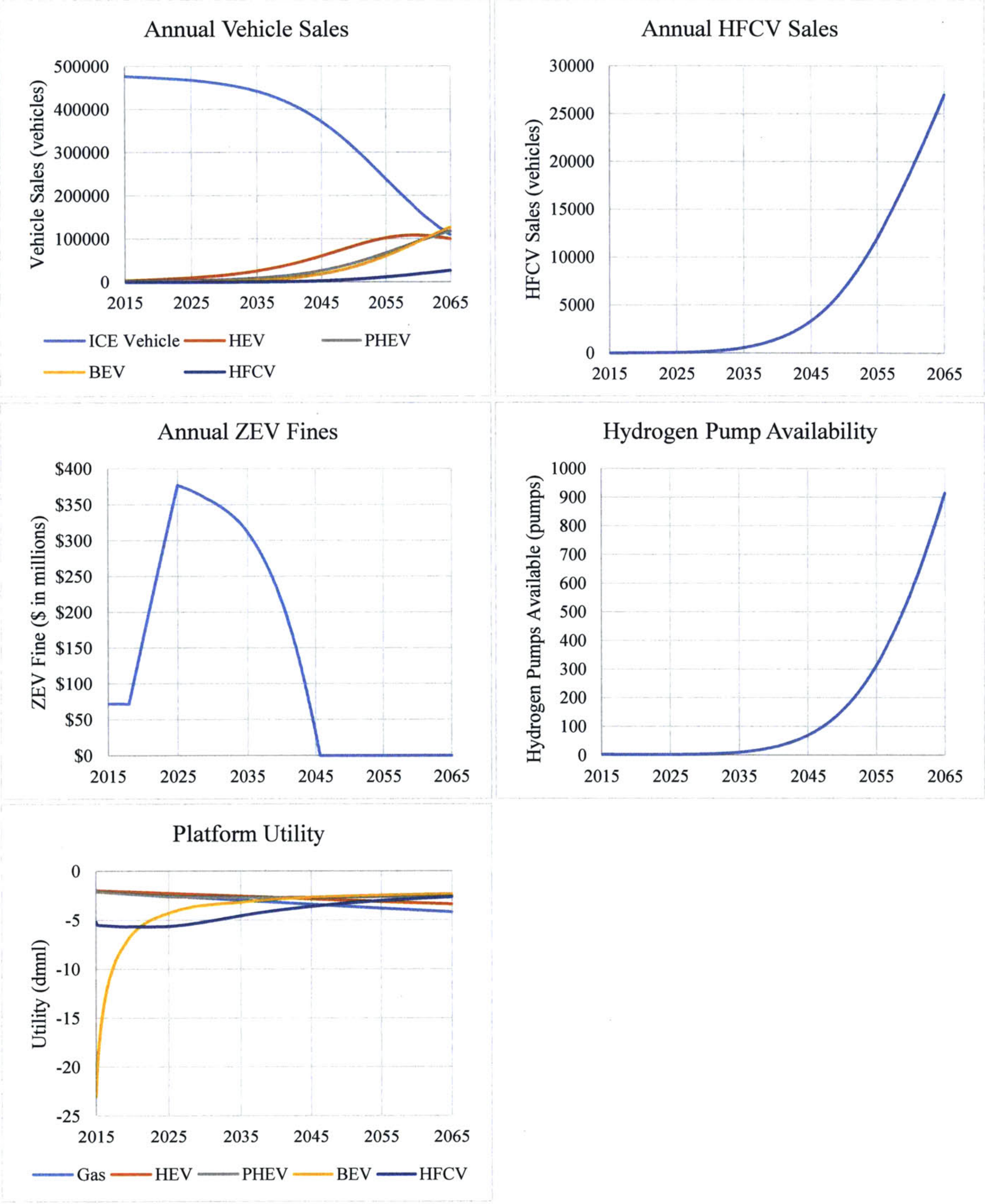
In this baseline scenario, ICE vehicles dominate annual sales for nearly the entire timeline, but lose market share at an increasing rate after 2035 due to increasing fuel prices and a decreasing difference between the utility of ICE vehicles and the other architectures. HEV sales peak around 2060, and begin to decline shortly thereafter, while HFCVs sales begin to grow increasingly around 2035. BEV and PHEV sales track closely and reach considerable annual sales by the end of the model timeline.

To gain a better understanding of the sales trends it is helpful to compare how the utilities of the vehicle platforms behave over time. The utility of ICE vehicles, HEVs, and PHEVs gradually decline in comparison to HFCVs and BEVs due to the operating cost increase of gasoline in relation to electricity and hydrogen, reductions in technology costs, and increase in available hydrogen and electric infrastructure. While excessive charging time hindered BEV utility early on, improvements in charging time and an increase in infrastructure availability increase BEV attractiveness and its utility becomes the highest among all of the vehicle types by 2065.

Additionally, I find that the low HFCV sales do not provide enough demand for hydrogen, thereby causing the few existing hydrogen stations to exit the market. This in turn increases the distance HFCV owners must travel which decreases vehicle utility.

As mentioned previously, the ZEV Action Plan imposes strict regulations on vehicle manufacturers, requiring them to obtain a certain amount of ZEV credits annually. While the baseline scenario excludes subsidies and incentives offered by the ZEV Action Plan, it is helpful to observe what the compliance would be so that there is a comparison for subsequent scenarios. Assuming that a manufacturer would pay the $5,000 fine for each delinquent ZEV credit, the single LVM operating in an LA county area would incur significant financial liabilities annually, ranging from $75M to over $350M until 2045.

Figure 3: Baseline Scenario



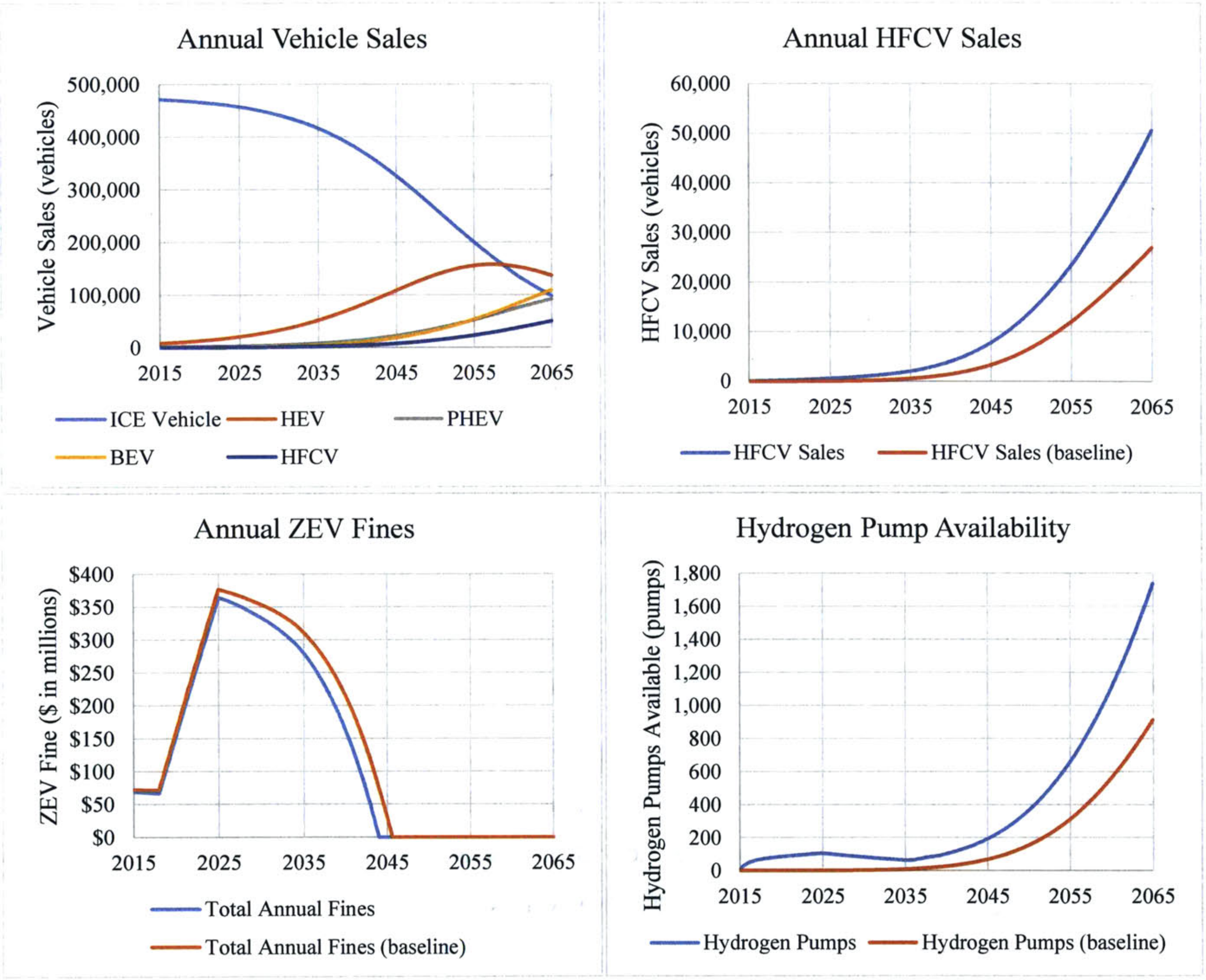
7.2 Scenario Two: ZEV Action Plan Policies

In this next scenario, I consider the potential impacts that the ZEV Action Plan has on consumer vehicle adoption. As previously mentioned, the Assembly Bill 8 that governor Jerry Brown signed into law provides up to \$20M per year up to 2025 for at least 100 hydrogen fuel stations in California. Furthermore, the mandate dictates that state owned fleet purchases are at least 25% ZEVs by 2020.[20] Scaling this requirement for my purpose equates to annual state purchases increasing linearly from 153 AFVs in 2015 to 383 AFVs in 2025 (it is assumed that these purchases are shared evenly between BEVs and HFCVs). These parameters allow for an updated model that considers ZEV Action Plan implications.

By providing infrastructure support and mandating state fleet purchases of ZEV's, the relatively modest program greatly increases the utility of BEVs and HFCVs. Subsidizing the construction and operation of hydrogen stations nearly doubles the pumps that are available by 2065 in the ZEV Action Plan scenario as compared to the baseline case. HFCV sales also almost double by 2065 for this case when related to baseline. The increase in ZEV adoption yields a gain in familiarity for PHEVs and HEVs thereby also increasing the adoption rates for these vehicles.

Although components of the ZEV Action Plan support HFCV adoption considerably, the resulting increase in ZEV credits does not meaningfully impact the level of compliance with total credit requirements. Assuming regulations do not change and tax credits remain untouched, manufacturers pursuing sales within California would potentially not be in compliance until just before 2045. Forcing ZEV sales at the prescribed rate has significant implications for automakers' wishing to sell vehicles in the state. OEM strategies will likely require allocation of considerable resources toward subsidizing and incentivizing the adoption of AFVs. Subsequent scenarios explore actions that can be taken to mitigate these potential financial penalties.

Figure 4: ZEV Action Plan Policy Scenario



7.3 Scenario Three: Additional HFCV Marketing

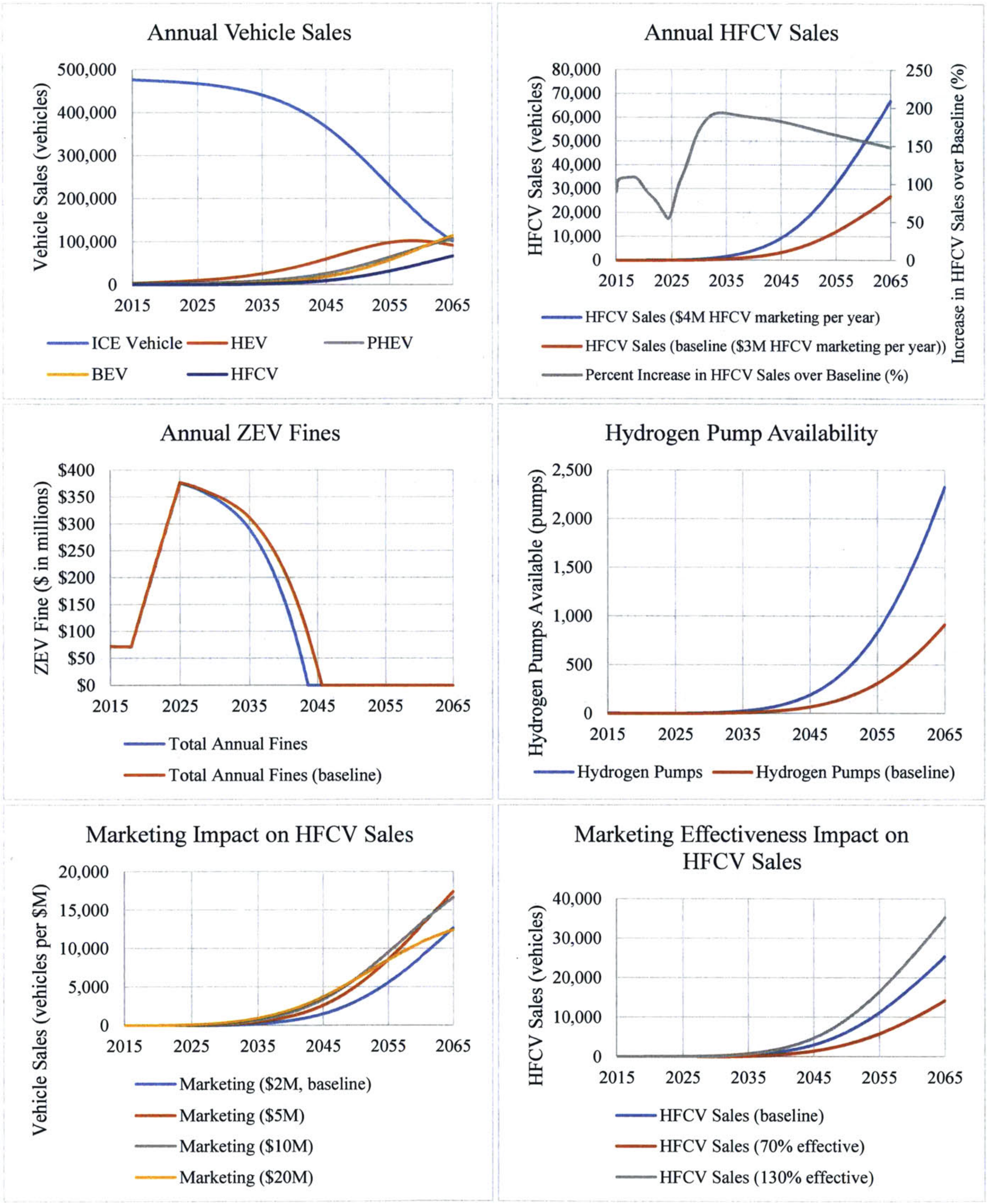
In the next scenario I investigate the impact that additional HFCV marketing intended to increase public familiarity has on HFCV sales. Garnering familiarity through marketing has substantial impact on vehicle sales, particularly for vehicles that have initially low levels of familiarity, such as AFVs in relation to ICE vehicles. For that reason, it is necessary to broadly understand the consequences of vehicle marketing. For the baseline scenario, the marketing expenditure was set at $2M per year. For this scenario, I modify the resources allocated toward HFCV marketing.

Doubling HFCV marketing to $4M per year has noteworthy impacts on HFCV familiarity which yields increases in adoption. By 2065, this marketing investment is responsible for more than doubling annual HFCV sales over baseline as a result of increases in familiarity. Much of this market share is taken from ICE vehicles due to the relative changes between consideration of the respective vehicle architectures. While increased marketing is a step toward compliance with the ZEV Action Plan mandates, the reduction in annual fines is minimal, as HFCV sales remain low for over two decades.

What I find to be more interesting is the relationship between HFCV sales and annual marketing on a per million-dollar basis. Over the last decade, the derivative of the curves for annual marketing expenditures of $10M and $20M begin to become less positive while the derivative for the baseline and $5M curves continue to increase, illustrating diminishing returns to marketing spend. Consequently, once a vehicle installed base reaches a certain point, it becomes less impactful to allocate significant resources towards marketing without addressing other barriers to HFCV adoption.

Understanding that the impact of marketing is dependent on a myriad of variables, it is necessary to keep in mind how sensitive these results are to the effectiveness of marketing. Irrespective of the validity of the previous insights, varying marketing effectiveness has considerable influence on vehicle sales. Varying marketing effectiveness by +/- 30% from the baseline value has a +/- 40% impact on HFCV sales.

Figure 5: HFCV Marketing Scenario

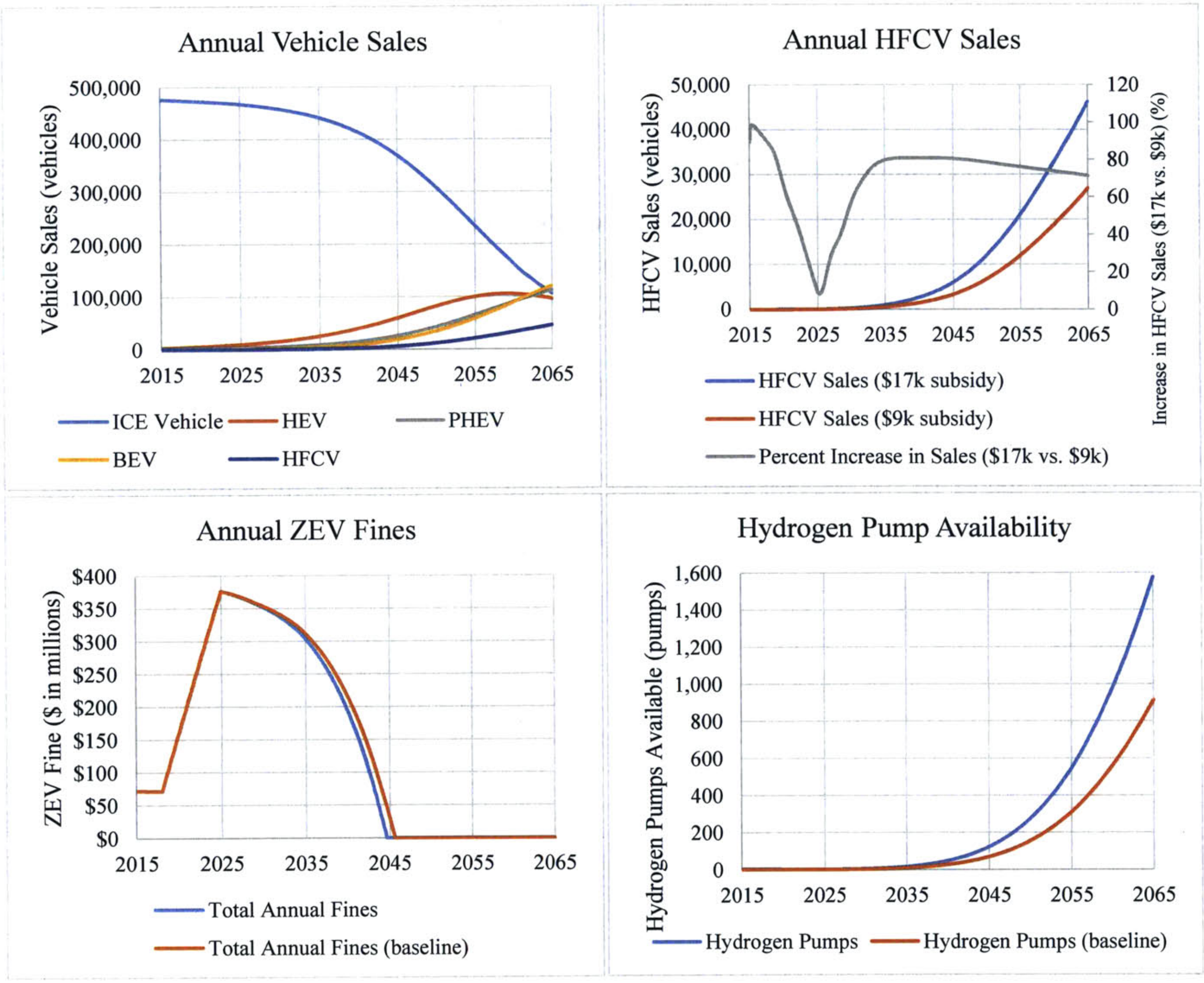


7.4 Scenario Four: HFCV Purchase Incentives

In the next scenario, I assess the sensitivity of HFCV adoption to purchase price through the influence of subsidies. Despite incentives offered by the federal and state governments, the higher purchase price of ZEVs remain a barrier for many consumers. The current total subsidy available to HFCV buyers in California is $9,000 off the purchase price. This was reduced drastically from the incentives previously in place which offered customers a $17,000 reduction.[24] To understand the impacts of these two subsidies, it is straightforward to modify the baseline subsidy amount. Both subsidies depreciate linearly until expiring in 2025.

HFCV sales for the $17,000 subsidy are nearly 100 percent greater than those for the lesser subsidy initially, dropping to around 15 percent in 2025 when the subsidy expires. As a result of the significantly higher HFCV sales for the first decade, there is a sustained increase in sales after the subsidies expire due to the expedited accrual of familiarity. In the next section of this scenario I look at subsidizing the operating cost of HFCVs, and compare the relative impacts between each subsidy type.

Figure 6: HFCV Purchase Incentives



7.5 Scenario Five: HFCV Hydrogen Subsidies

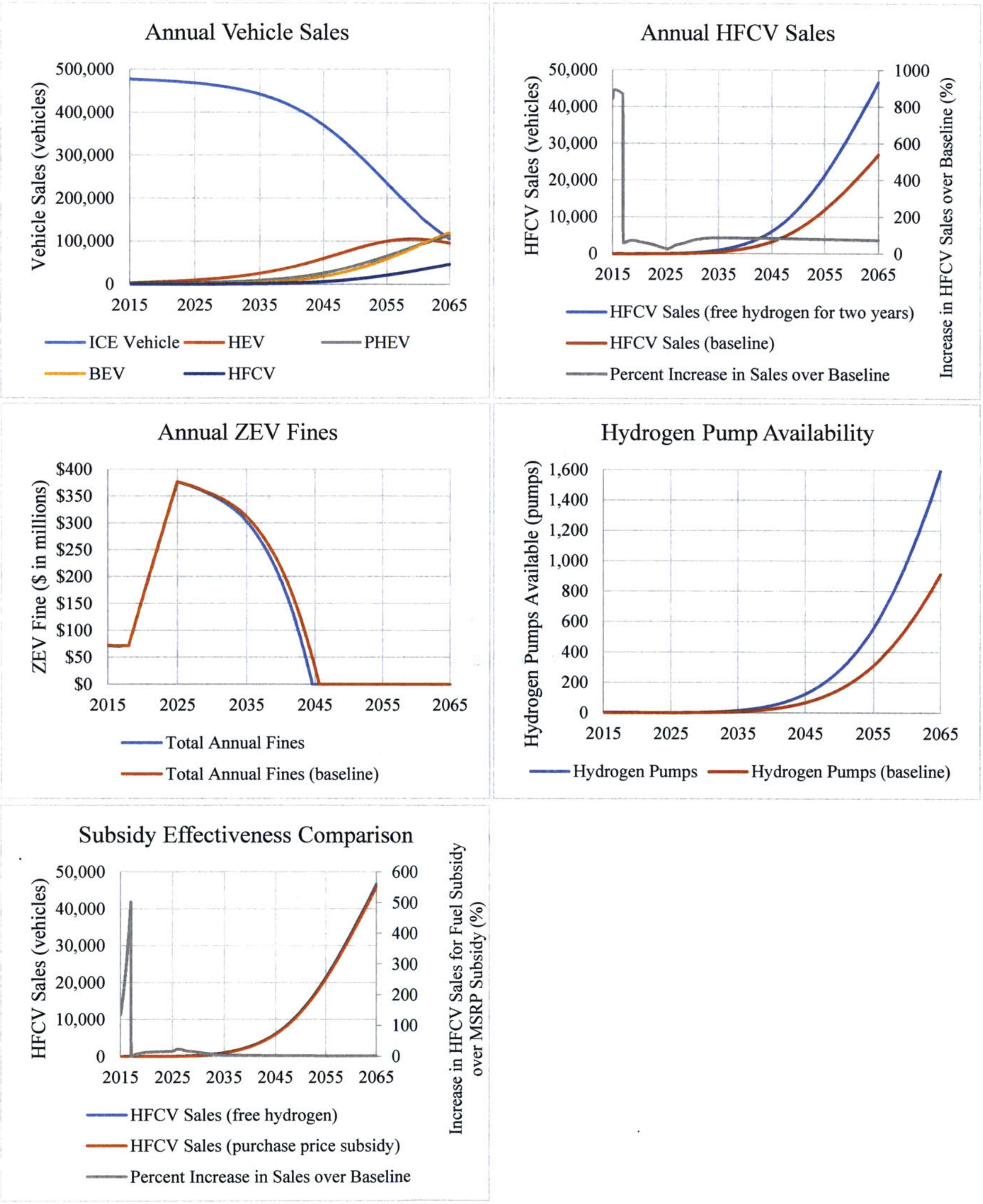
In this scenario, I assess the effect that subsidizing ownership cost has on HFCV adoption. A considerable portion of ownership cost is due to fuel, especially for HFCVs as hydrogen is currently priced around $7/GGE, significantly higher than that for electricity or gasoline.[15] For this scenario, I subsidize hydrogen completely for all HFCV adopters until 2017.

Subsidizing hydrogen until 2017 has a substantial impact on HFCV sales. In the first two years, HFCV sales are 800 percent greater than for the baseline as a result of an increase in utility due to the decrease in hydrogen cost. Even after the hydrogen subsidy expires, there is a residual influence on vehicle sales as the larger initial installed base helps to spur familiarity.

To understand the relative magnitude of fuel subsidies, I compare hydrogen and purchase price subsidies directly. In order to provide a fair comparison, I look at the total cost of subsidizing fuel for two years, and then apply a purchase price subsidy that equates to the same value (total expenses are within one percent) over the same two-year period. The results, which show that subsidizing hydrogen produces substantially more sales than subsidizing the purchase price of the vehicle, result from the model assumptions about the relative weight placed on purchase price and operating costs in the utility function. As witnessed in previous examples, there is a lasting increase in HFCV sales even after both subsidies expire as a result of the boost in the initial installed base.

With regards to short-term adoption, it is apparent that automakers are aware of the advantages associated with subsidizing the electricity and hydrogen for their AFVs. While there are certainly other reasons for providing these types of subsidies, it is of note that Ford and Tesla are subsidizing electricity for certain BEVs, and Hyundai and Toyota are subsidizing hydrogen for their HFCVs.[40,41]

Figure 7: HFCV Hydrogen Subsidies



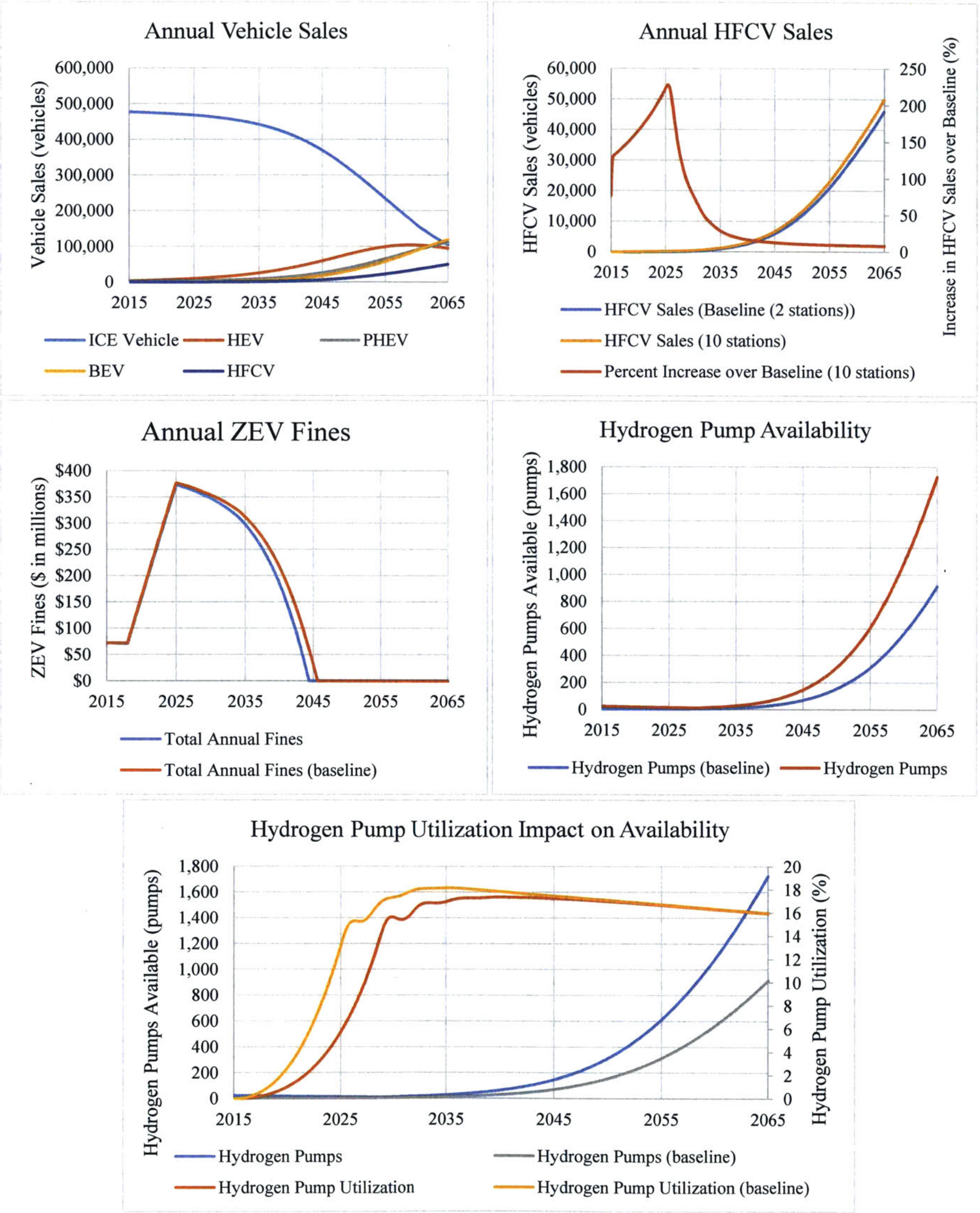
7.6 Scenario Six: Infrastructure Development

Infrastructure availability is critical to the adoption of PHEVs and BEVs, but understanding its growth is perhaps more important to HFCV commercialization due to the complexity and cost of constructing and operating hydrogen stations. Not only is there already an electrical grid in place to easily power most charging stations, but the cost of charging stations is a fraction of what it is for hydrogen fuel stations. In order to best understand the dynamics associated with infrastructure growth, I look at short-term and long-term implications. As mentioned previously, the ZEV Action Plan is providing subsidies for the construction and operational support of at least 100 hydrogen stations by 2025 in the state of California. In the ZEV scenario, I model this added infrastructure growth (based off the population ratio between LA County and California), but I also include other components of the plan. Here, I find it necessary to directly assess the impact of solely adding infrastructure. The baseline for this hypothetical region is initialized with two hydrogen stations, and in this scenario I observe the consequences of seeding the model with ten hydrogen stations instead of two.

Short-Term: This initial surge of stations is cause for over 200 percent additional HFCV sales in 2025 and takes advantage of the reinforcing loop that is maintained between infrastructure availability and increases in hydrogen demand (increased infrastructure availability reduces fuel search costs which makes HFCV adoption more appealing, in turn promoting infrastructure growth to satisfy the increased hydrogen demand).

Long-Term: I am also interested in the point at which hydrogen construction and support can give way to organic hydrogen infrastructure growth. In each scenario, I find that once hydrogen pump utilization reaches a particular level (around 18 percent in this case), hydrogen pump availability begins to drastically increase as a result of station ownership becoming a more profitable endeavor. This is explained by the reinforcing relationship previously described, and note that the utilization threshold is particular to this hypothetical region and would vary based on initial geographic, demographic, and ancillary station revenue assumptions.

Figure 8: Infrastructure Development



8.0 Recommendations, Further Research, and Conclusions

8.1 Recommendations

The preceding analysis generated noteworthy insights grouped into four primary areas: 1) Consumer choice; 2) HFCV ownership costs; 3) Infrastructure growth; and 4) Regulatory impacts from the ZEV Action Plan.

Consumer Choice

For early adoption of AFVs, vehicle utility is important, but as long as vehicle manufacturers can ensure the utility of their vehicles is commensurate with their competition, it is the accumulation of familiarity that becomes more vital. While it is not cost-effective to garner familiarity by giving away vehicles in order to generate an initial installed base, I find that some amount of marketing has a significant impact on consumer familiarity and resulting sales. This is especially the case for HFCV familiarity, as the technology is not well known to most consumers at present. As a result of societal norms, prospective buyers will be initially apprehensive about HFCVs until they are adequately educated and accept HFCVs as a viable substitute for other vehicle platforms.

It did not take the model to highlight the fact that marketing is important, but the analysis shows the degree of importance that developing familiarity through 'marketing has with respect to time and vehicle adoption rates.

HFCV Ownership Costs

The high vehicle purchase price of HFCVs poses a further substantial barrier to adoption. While lowering the vehicle purchase price does help the adoption of AFVs, subsidizing the operational costs has a much greater influence, at least with the parameterization of the utility function as assumed from the report, *Joint Mixed Logit Models of Stated and Revealed Preferences for Alternative-Fuel Vehicles*.[29] Even a short duration of fuel or electricity subsidies has significant impacts on short-term and long-term AFV adoption. This finding is bolstered by the fact that several HFCV and BEV models are currently being offered to consumers with subsidized hydrogen and electricity, respectively.

Initially, subsidizing operating costs is extremely beneficial for AFV adoption, but as vehicle sales increase, this subsidy will either become prohibitively expensive or the subsidy benefit per vehicle will become too diluted. Accordingly, it is necessary to consider vehicle utility once providing significant subsidies becomes no longer realistic.

Infrastructure Growth

The relationship between HFCV adoption and hydrogen infrastructure growth is commonly construed as a "chicken and egg" scenario, but this is only the case in an organic setting where there is no influence from external factors. It is possible to have operational hydrogen station infrastructure without demand from operational HFCVs, but it is impossible to have functioning HFCVs in the absence of hydrogen stations. That being said, the success of an HFCV market is certainly reliant upon an adequate hydrogen infrastructure and vice versa. While HFCV commercialization will slowly take place in the baseline scenario, the limited adoption creates for a fragile market. Initial external support significantly increases HFCV adoption, and makes for a healthier long-term HFCV market.

An initial amount of stations helps to spur vehicle adoption, and operational support serves to maintain hydrogen station profitability until the demand is high enough that organic growth is all that is required to maintain a healthy HFCV market. This finding is important when assessing the extent of external support that is necessary to expedite HFCV adoption.

ZEV Action Plan

The ZEV Action Plan significantly benefits AFV adoption, especially for HFCVs. Many components of the plan fall in line with the major insights gained from this analysis: 1) the plan supports infrastructure construction and operation costs that are needed to initialize hydrogen supply; 2) the plan mandates AFV purchases by state agencies that aids in increasing familiarity; and 3) the plan provides pressure on vehicle manufacturers to meet the strict regulations thereby necessitating that resources are allocated toward subsidies and investments in AFV research and development.

8.2 Future Research Opportunities

Consumer Behavior Trends

Consumer behavior can vary drastically by geographic location, as can be observed by the breakdown of vehicle sales in California compared to the rest of the U.S. The disparity is considerable, and in conjunction with stricter regulations, is why automakers are targeting regions such as California for commercialization of AFVs. Previous research offers a methodology by which utility coefficients can be determined.[29] This same process could be followed to target specific behaviors of particular states or regions and would offer more fidelity on differences in consumer behavior that exist within the U.S.

Not only are other states within the U.S. beginning to adopt similar ZEV Action Plans, but several other countries are aggressively pressuring vehicle manufacturers to improve fleet FE. While consumer preferences may not change, adoption behavior will change as a result of the increased resources that vehicle manufacturers will need to allocate in order to sell more fuel efficient vehicles.

Consolidation of Vehicle Adoption Barriers

This analysis showed an overview of various barriers to market entry faced by HFCVs, and emphasized that the importance of each varied with time as well as vehicle adoption rate. A more comprehensive assessment would consider the interdependencies of the various scenario conditions that were simulated. Further research could shed light on these relations in order to quantify the dynamics shown in Figure 9. While this is purely speculative, it is interesting to observe the relative importance of each factor over time, assuming demand for the vehicle persists.

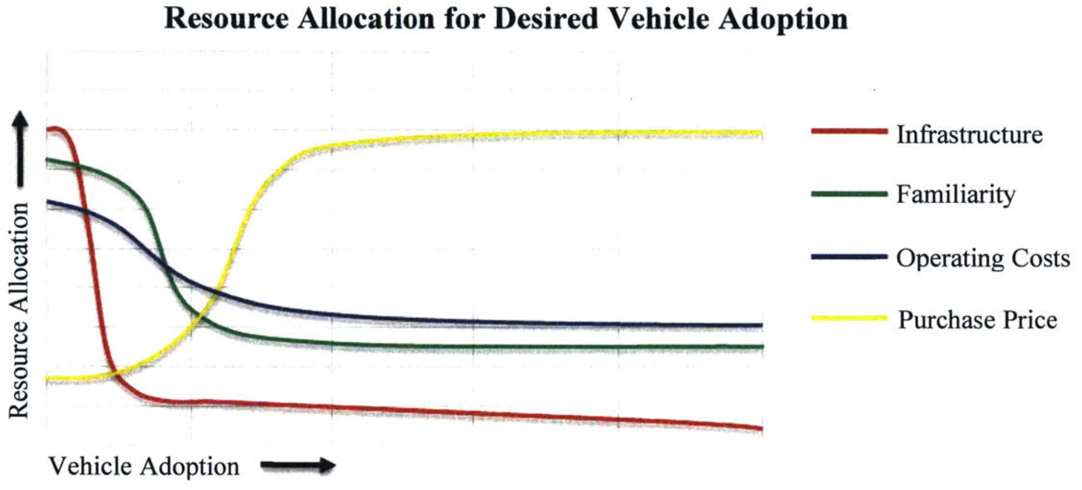


Figure 9: Relative Importance of HFCV Resource Allocation

Developing a suite of strategies in the manner suggested in Figure 9 could aid in the structuring of an AFV commercialization strategy. For example:

Infrastructure: Infrastructure support is critical initially, but after sufficient demand develops, there may be less need to support the infrastructure further.

Familiarity: Accumulation of familiarity is paramount to HFCV commercialization. Through marketing and other endeavors, an upfront investment would accelerate adoption. This investment could be decreased as the installed base grows whereby familiarity would be garnered primarily from word-of-mouth.

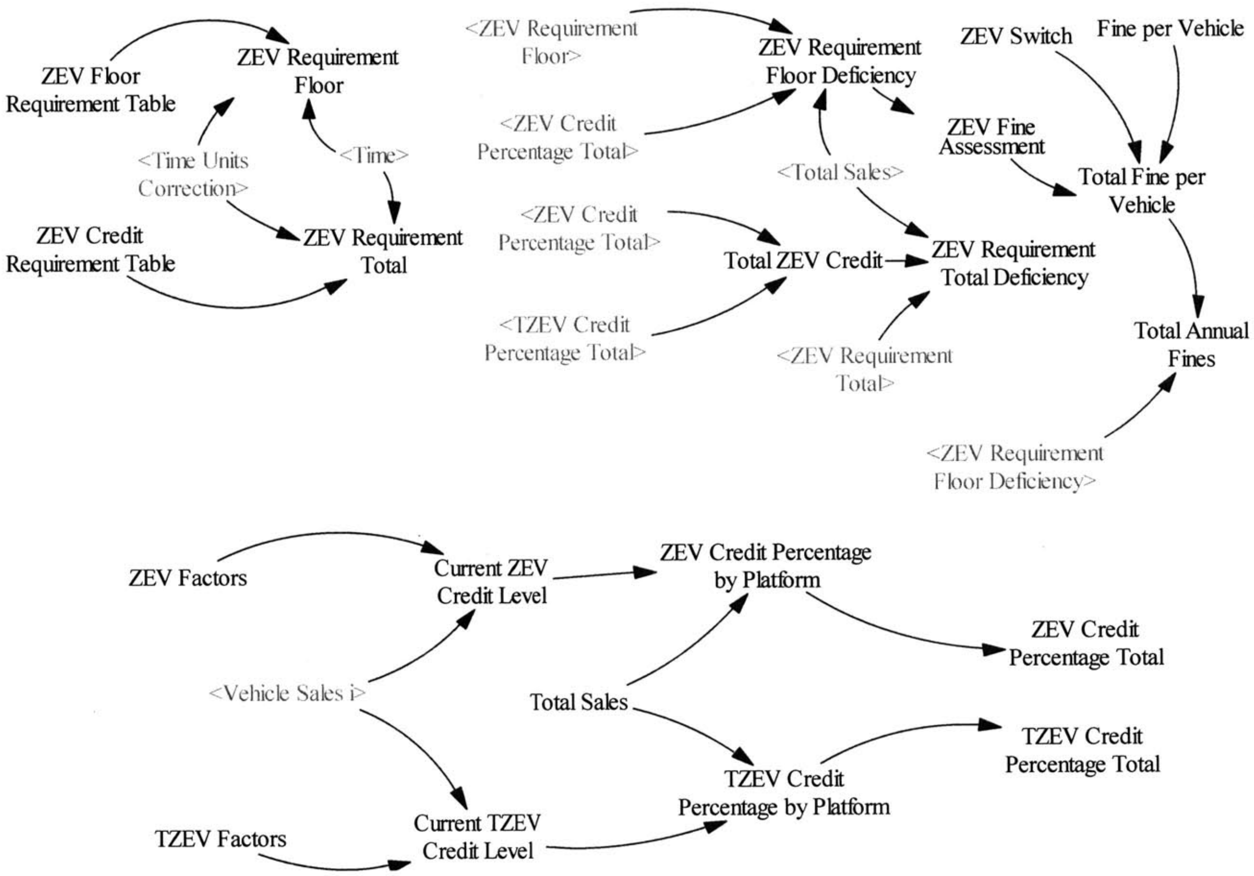
Ownership Cost and Purchase Price: Subsidizing the fuel or electricity of a vehicle has a much larger impact on adoption than subsidizing the vehicle purchase price. However, in the case of HFCVs, as the installed base grows and more consumers consider the vehicle, subsidizing hydrogen by any significant amount will become prohibitively costly. Accordingly, ramifications of such subsidy expirations must be considered.

8.3 Conclusion

California is the most proactive state in the U.S. when it comes to fostering improvements in vehicle FE and reducing GHG emissions. The ZEV Action Plan does not just encourage this trend, but mandates it by forcing the OEMs conform to the requirements if they wish to sell vehicles in the state. Other states are looking to adopt a similar mandate, which will only incentivize vehicle manufacturers to further invest in AFVs and other beneficial technologies.

While it is accepted that nearly all models are inevitably incorrect, there is significant value in the insights that can be gained from employing a robust model to analyze the subtleties of separate scenarios. The modeling process undertaken here allows us to account for the relative importance of the most significant HFCV commercialization barriers, and to assess measures that can mitigate them.

9.0 Appendix 1: ZEV Compliance Tracker Model



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