Potential Business Models for Recharging Infrastructure and their Implications for Plug-In Electric Vehicle Adoption

by

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Abstract

Plug-in Electric Vehicles are more efficient, have lower operating and maintenance costs, and emit fewer local air pollutants than conventional internal combustion engine vehicles. Despite these advantages, the customer adoption of plug-in electric vehicles has been slow due to their high purchase costs, limited driving range, and long recharging times. Construction of a ubiquitous network of high-power recharging stations has often been suggested as a solution to promote their adoption. Although many governments around the world are currently funding the construction of public recharging infrastructure, they cannot continue to provide support indefinitely. This necessitates a private sector-led effort to expand public recharging infrastructure for plug-in electric vehicles to become competitive with conventional vehicles. Unlike gasoline stations, public recharging infrastructure service fewer cars in a day, and hence, the traditional ancillary revenue based gasoline station business model will not be applicable. So, new, innovative business partnerships are required in the near term to support the construction of public recharging infrastructure until the demand from plug-in electric vehicles becomes significant enough to generate high revenues.

Using a System Dynamics modeling approach, we modeled and simulated the electromobility eco-system comprising of electric vehicles and various types of public recharging infrastructure to determine the factors that influence the infrastructure's financial viability. We then conceptualized two business models that affect these factors to improve the cash flow and net income of public recharging infrastructure. Data from literature was used to calibrate one of the two business models, and we were able to prove that public recharging infrastructure can be constructed in a profitable way if the provider partnered with a taxi fleet.

Once the business model was validated, we introduced it in the electromobility eco-system simulation to estimate its impact on the adoption of Battery Electric Vehicles. With the business model in action, the public recharging infrastructure expanded by 14% from earlier and resulted in a 7% increase in the adoption of plug-in battery electric vehicles by 2050.

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1. Introduction and Literature Review

1.1 Transition from conventional fuel vehicles to alternative fuel vehicles

Conventional gasoline vehicles have been around for about 125 years, and they have provided an affordable, reliable, and highly convenient mode of transport around the world. The internal combustion engines used in these vehicles typically use petroleum-derived fuels such as gasoline or diesel to generate energy by combusting them, resulting in harmful emissions such as nitrous oxides. Alternative fuel vehicles, on the other hand, are powered by non-petroleum fuels such as ethanol, compressed natural gas (CNG), liquefied natural gas (LNG), liquefied petroleum gas (LPG), hydrogen, and electricity. While the ethanol, CNG, LNG, and LPG vehicles use internal combustion to convert the fuels' energy into usable work, hydrogen and electrified vehicles don't use combustion and create zero pollution at the tailpipe.

The global automotive market is slowly transitioning from conventional fuel sources to alternative fuels due to the following reasons:

1. Energy Independence:

   Gasoline has often been used as a tool to exercise leverage over the geopolitical strategies of foreign countries, and a case in point is the 1973 Arab oil embargo which affected the US economy immensely (Office of the Historian, n.d.). For this reason, several countries around the world are shifting to alternative fuels that are available in plenty locally. For example, ethanol-based fuels dominate the Brazilian automotive market due to the high volume production of ethanol domestically (Belincanta, Alchorne, and Teixeira Da Silva 2016). It has been speculated that China is promoting electric vehicles in its domestic market to take advantage of its rich reserves of rare-earth metals.

2. Environmental Benefits:

   Governments around the world have been tightening their norms on greenhouse gas emissions (GHGs) due to the emissions' adverse climatic impacts (Hall, Cui, and Lutsey 2017). Alternative fuel powertrains such BEVs emit zero greenhouse gases during their operation, and have a significant potential to reduce total GHG emissions (Office of Energy Efficiency and Renewable Energy, n.d.). It has to be noted that the electricity used as fuel in BEVs usually has GHG emissions at its source, and unless the power generation shifts to using higher levels of renewable energy, there is a diminished potential to reducing GHG emissions from the light-duty vehicle fleet (Sandy Thomas 2012).

3. Economics:

   Alternative fuel vehicles such as PHEVs and BEVs are more energy-efficient than ICEVs due to their technology, and their operating costs are lower because electricity is often cheaper than gasoline for the same amount of energy. BEVs are also much simpler in vehicle architecture, resulting in fewer maintenance expenditures than ICEVs (Pavlenko, Slowik, and Lutsey 2019). Overall, alternative fuel technologies such as PHEVs and BEVs are economically attractive to potential buyers as long as the operating cost savings compensate for the higher purchase price.

4. Local Air and Noise Pollution:

   ICEVs emit pollutants such as nitrogen oxides that are formed during the combustion of gasoline or diesel within the engine. These pollutants cause smog in urban areas and have serious health consequences (Kim et al. 2004); in comparison, BEVs emit none of these harmful chemicals and help improve local air quality (Office of Energy Efficiency and Renewable Energy, n.d.). While PHEVs still emit NOx gases, they are more efficient than ICEVs and result in fewer NOx emissions (Skerlos and Winebrake 2010). Noise pollution is another hazard from ICEVs, whereas BEVs are much quieter during operation, and can help reduce noise pollution in urban areas (R, A, and D 2002).

Due to these reasons, we see a trend of light-duty vehicles shifting from conventional petroleum-based fuels to alternative fuel sources. We focus our work on the Battery Electric Vehicles (BEVs) because they are leading this transition to alternative fuel vehicles (Serradilla et al. 2017).

1.2 Battery Electric Vehicle Market in the US

The first BEVs made their appearance in the US market in the early 1900s with products such as the Rauch and Lang Carriage Company's Electric Car, and for a short period of time, they even outsold ICEVs (Richardson 2018). At that time, they were primarily used as taxicabs and delivery trucks, and were replacing horse-driven carriages for urban transport. Although they had a very limited range, it was sufficient for their intended purposes in urban transport. However, the availability of affordable ICEVs and the expansion of gasoline refueling infrastructure made them popular and eventually led to the demise of electric vehicles in the early 1910s (Matulka 2014).

In the 1970s, due to the oil crisis, there was a renewed interest in the development of electric cars, and several microcars with short driving ranges were developed and sold. However, these microcars were impractical for most drivers who commute long distances from suburban residences to jobs in downtown areas, and with the resolution of the oil crisis, the micro electric cars vanished from the market (Matulka 2014).

In the 1990s, the California Air Resources Board (CARB) enacted the ZEV (Zero-Emission Vehicle) mandate that required seven of the major automotive manufacturers to offer battery electric vehicles in California if they were to continue selling ICEVs there. This forced the auto manufacturers to design, develop, and market BEVs such as the GM EV-1 in the late 1990s. However, due to political backlash, the ZEV mandate was changed in 2003 to focus on the development of Fuel Cell Electric Vehicles, resulting in an abrupt end to the return of the BEVs.

In the early part of this decade (2010-), BEVs started becoming attractive again due to the advances in battery technology (specifically, the Li-ion technology), and the change in consumer attitudes towards environmentally cleaner vehicles. Products such as the Toyota Prius and the Tesla brand of BEVs have been instrumental in gaining positive consumer image for cleaner, "greener"[1], electrified vehicles. Although there is no BEV version of Toyota Prius, it is the first mass-adopted "green car" in the US, and the legacy of the Prius continues to gain consumer confidence in electrified vehicles (Matulka 2014). As of 2017, there are about 400,000 BEVs on the road in the US, while about 15 different BEV models are being sold by various manufacturers (International Energy Agency 2017).

1.3 Recharging Infrastructure: Types and Current Market in the US

The technical terminology for electric vehicle recharging infrastructure is electric vehicle supply equipment (EVSE), and it can be differentiated by the ownership of infrastructure and the power levels. The electric recharging infrastructure for plug-in electric vehicles (PEVs) is currently available in the following four types:

1. Home recharging:

   Typically, a wall plug or a dedicated Level 2[2] recharger (3.3 - 7 kW) installed at home; intended to recharge PEVs when parked for extended periods of time. As of 2018, almost 85% of PEV recharging occurs at home in the US (Office of Energy Efficiency and Renewable Energy 2018). With the recharging infrastructure network still in its infancy, the availability of home recharging provides BEV owners with a reliable fuel source that can cover 87% of Americans' daily travel needs (Needell et al. 2016). This is a feature that is not shared by other alternative fuels and offers a clear advantage for the proliferation of plug-in electric vehicles.

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[1] "Green cars" refer to the environmentally-friendly vehicles that have less destructive impact on the environment than conventional gasoline or diesel vehicles. An electric vehicle is not always green and is dependent on the fuel that is used for generating electricity; renewable sources are greener than fossil fuel sources such as coal.

[2] "Level" of recharging refers to the power level of recharging infrastructure; the higher the level, the more powerful is the recharging infrastructure and lesser is the recharging time. Since there is no common agreement/rule on what defines a particular "level", we use the vocabulary sparingly in this report.

2. Workplace recharging:

   Typically, a set of Level 2 rechargers (3.3 - 7 kW) installed at business center parking lots; intended to recharge PEVs when parked during the work hours. These stations are installed by employers and are typically open only to their employees. In some cases, the use of these rechargers may be free as an employee benefit to attract employees.

3. Public recharging:

   Typically, a set of Level 2 rechargers (3.3 - 7 kW) installed at shopping malls and parking lots; intended to recharge vehicles in 4 – 8 hours. In order to defray the fixed costs of parking real estate and electrical installation, the PEV owners are likely to pay a higher fare per kWh than home or workplace recharging. For example, the average price of electricity in the U.S. residences is roughly $0.12/kWh, while the use of a ChargePoint public recharging station costs between $0.19/kWh and $0.49/kWh (ChargePoint Inc. 2018).

4. Fast recharging:

   Typically, a set of Level 3 rechargers (25 kW and above) installed along the highways and potentially at malls and other public destinations. While fast recharging provides convenience with shorter recharging times over other options, it also comes with the highest fare per kWh due to high capital costs for the equipment and high electricity demand charges. For example, in Massachusetts, using a EVgo's CHAdeMO fast recharging station costs about $0.35/minute for a 50kW recharger which is equivalent to $0.42/kWh at peak charging power (EVgo 2018).

There are two more recharging methods emerging in the market, and they are aimed at increasing the convenience of PEV recharging.

5. Battery swapping:

   In a battery swapping station, the recharging process involves a complex robotic system that swaps a customer's depleted BEV battery with a fully charged one, and thereby, reduces the BEV "recharging" time to a few minutes. This level of service is comparable to that of a traditional gasoline refueling station. The number of batteries held in inventory in a battery swap station is dependent on the time it takes to swap a single battery, and the time to fully recharge a depleted battery using a Level 2 recharger inside the station. Battery swap technology was first piloted by an Israeli company called "Better Place" up until their bankruptcy in 2013. More recently, Chinese domestic electric vehicle manufacturers, NIO and BJEV, have begun building battery swapping stations in China (Bloomberg 2018; NIO Inc. 2018).

6. Wireless recharging:

   This technology has the ability to recharge a PEV through magnetic induction without the need to physically connect the car to a power source. Wireless recharging is possible when the vehicle is either stationary or being driven. This technology is currently at an early stage, and stationary wireless recharging is available only in a few 2019 car models such as the BMW 530e. In the more distant future, stationary wireless recharging may be an attractive option for autonomous electric vehicles to avoid the need for humans to plug in the vehicles (Bosshard, Member, and Kolar 2017).

Table 1 lists the major differentiating characteristics for the four popular recharging infrastructure options available today.

Table 1: Characteristics of Types of Electric Vehicle Recharging Infrastructure

	Home	**Workplace**	**Public**	**DC Fast**
Level	1	2*	2*	3+
Voltage (V)	120	240	240	480
Typical Max Current (A)	16, AC	80, AC	80, AC	125, DC
Maximum Power (kW)	1.9	3.3 - 19.2	3.3 - 19.2	22 - 150+
Miles/Hour of Charging**	2 - 5	10 - 20	10 - 20	150+
Unit Cost (2015 $)	300 - 1,500	300 - 1,500	400 - 6,500	10,000 - 40,000
Average Installation Cost (2015 $)	0 - 3,000	4,000	3,000	21,000

*Most Level 2 rechargers operate at 7.2 kW or below

**Assuming an average BEV driving efficiency of 3.15 miles/kWh (https://www.tesla.com/models)
Source: (International Energy Agency (IEA) 2018)

1.4 Stakeholder canvas of the Electromobility Industry

Based on (Madina, Zamora, and Zabala 2016), we explain the major actors in the electromobility eco-system encompassing BEVs and recharging infrastructure:

1. Vehicle and Component Manufacturers:

These include the automotive manufacturers who design, build, and sell Battery Electric Vehicles; and the battery manufacturers who conduct research, design, and construct battery cells according to the requirements of the auto manufacturer. The auto manufacturers' revenues are driven by the sales of the vehicles, although subscription-type revenue models are emerging in this industry (Edmunds 2018). Apart from the sales of components to new vehicles, the component manufacturers also earn revenues from the replacement parts market.

2. Recharging Infrastructure Stakeholders:

These include the Electric Vehicle Supply Equipment (EVSE) operators and Electric Vehicle Service Providers (EVSP). The EVSE operator owns and operates the public recharging stations whereas the EVSP acts as an intermediary between EVSE operators and BEV drivers. EVSP provides various services to BEV drivers such as searching and routing to the nearest available recharging stations, and making online payments. The EVSE operator's revenues are dependent on the utilization of recharging stations, whereas the EVSP's revenues are dependent on the number of BEV drivers using the EVSP's online platform.

3. Electric Utility Players:

These include the Transmission System Operator (TSO), Distribution System Operator (DSO), electricity retailers and producers. While the revenues of these stakeholders are driven by the power demand as well as the kWh units of electricity consumed by BEVs, the stakeholders also benefit from the opportunities to cut costs by using BEVs to balance the power demand throughout the day.

1.5 Review of pro-BEV policies around the world

In this section, we take a look at the best practices followed by various countries in promoting Battery Electric Vehicles in their respective local markets. In terms of number of vehicles, China is the world leader with 1.23 million BEVs operating on its roads (out of the total global stock of 3.1 million BEVs) (International Energy Agency (IEA) 2018). However, in terms of market share of new vehicles sold, Norway is the leading country with 39.2% of its market comprising BEVs, followed by Iceland at 11.7%, Sweden at 6.3%, China at 2.2%, Germany at 1.6%, US at 1.2%, and Japan at 1.0% (International Energy Agency (IEA) 2018). We take a closer look at pro-BEV policies in the above countries, and understand how these policies have promoted a relatively high BEV market share when compared to other countries. We have also studied the pro-BEV policies of the State of California in United States, because it has long been the pioneer of zero-emission vehicle policies.

Based on (Steen, Schelven, and Kotter 2015), we find that most of the governmental policy instruments in these countries involve either fiscal incentives such as income tax rebates and discounts for vehicle registration or organizational tools such as creating special purpose project management organizations entrusted with rolling out customer-facing initiatives. There is lesser importance given to legal and communication methods to promote BEV adoption. Most of the pro-BEV policies are promoted and sponsored by the national governments, with the exception of China where local governments are more active in promoting BEVs (Wan, Wang, and Sperling 2013).

Many of these policies in Europe are geared towards supporting the downstream of the vehicle supply chain, incentivizing consumers to purchase BEVs, and there has been fewer policies to support upstream initiatives such as funding new technology R&D or encouraging vehicle manufacturers to advance their production capabilities (Steen, Schelven, and Kotter 2015). In comparison, California's BEV policies are mostly aimed at upstream activities such as sponsoring the research and development of low-cost, high-energy density batteries, and creating sales tax exclusions for advanced manufacturing facilities.

On the recharging infrastructure front, most of the European policies are targeted at government-initiated construction of public recharging stations. On the other hand, California's policies are directed at incentivizing home recharging equipment. Research shows that most BEV recharging is conducted at home, and public recharging stations are only used during long-distance trips (Traut et al. 2013; Snyder 2012). So, the Californian policies may be more effective in increasing the adoption of BEVs.

2. Research Question and Scope

The core premise of this research is that there exists a co-evolution mechanism between the sales of Battery Electric Vehicles and the expansion of public recharging infrastructure. So, our first research question was to explore and understand the mechanism through which the co-evolution occurs, and the sensitivity of different variables contributing to this co-evolution.

Once we ascertained the most impactful variables, we carefully selected those that characterize the public recharging infrastructure. The reason to do this was to examine the recharging infrastructure side of the co-evolution in detail. The base model that we used was elaborate in its formulation regarding the vehicle powertrain selection, however, the representation of the recharging infrastructure was simplified. After adding important elements to the recharging infrastructure part of the model, we pursued our second research question of understanding the impact of infrastructural investment strategies on the construction of recharging infrastructure and their impact on the sales of BEVs.

The third and the final research question explored in this work was determining the factors that influence the financial viability of public recharging infrastructure, and creating innovative business models that could make public recharging infrastructure an attractive investment opportunity for private investors. We answered this question in two steps: First, we calculated the financial potential of each business model; then we estimated the spill-over effects of these business models on the sales of BEVs.

2.1 Scope of the research

The model used in our research was limited geographically to the United States of America, since the microeconomic model used in the vehicle powertrain selection process was calibrated for a representative US driver. The cars were aggregated based on their powertrain type, and a mid-size family sedan was used as the representative car for calibrating the purchase price, performance, and fuel efficiency. On the recharging infrastructure side, we do not look into the supply-side constraints of the electricity grid in this work. Although these constraints could arise at high levels of BEV adoption, we omitted them due to the limited adoption of BEVs even as further as 2050 (as deduced in the model).

2.2 Importance of the research

Lack of recharging infrastructure has often been cited as a barrier for mass-adoption of BEVs. Recharging infrastructure is not as ubiquitous as gasoline refueling stations due to the challenges in earning profits from the traditional gasoline station business model. However, if we could use innovative business models and earn profits from recharging infrastructure operations, the recharging infrastructure network will expand in scale and support mass adoption of BEVs, which then bring about benefits in pollution, energy efficiency, etc.

2.3 Contribution of the research

Most of the literature on the profitability of recharging infrastructure assumes that a certain number of BEVs exist in the market, and then calculates the levels of utilization required for the financial profitability of recharging infrastructure (Schroeder and Traber 2012; Madina, Zamora, and Zabala 2016). However, in our work, we have the ability to model the dynamic interaction between BEV sales and expansion of recharging infrastructure, and hence, we can study the relevance and importance of infrastructure business models at different stages of the market. This dynamic interaction between BEV sales and expansion of recharging infrastructure is much closer to reality than what other researchers have modeled, and captures unique insights about the behavior of these business models. Hence, we believe that this work is a significant contribution to this research area.

3. Methodology

There exists an established line of research on studying dynamic complexity surrounding the adoption of AFVs in the automotive industry by using the system dynamics methodology. In this study, we have expanded upon one of the most recent instance of it, the consumer vehicle choice Bass-type diffusion model developed by David Keith (Keith 2012). In this chapter, we explain the constructs of this legacy model and our modifications in three sections: Core endogenous structures of the system dynamics model, Model's inputs and outputs, and Modifications to the model.

3.1 Core Endogenous Structures of the System Dynamics Model

Figure 1 provides an overview of the decision-making logic built into the model. A fundamental building block of the model is a vehicle powertrain selection process, which uses a combination of two factors, "utility" and "familiarity", to determine the market share of various powertrains in the sales of new vehicles. At all times during the simulation period, the model maintains a measure of the number of vehicles of each powertrain in use, and this value is updated at every time period. This value increases with the sales of new vehicles of that powertrain, and decreases with the retirements of vehicles using that powertrain.

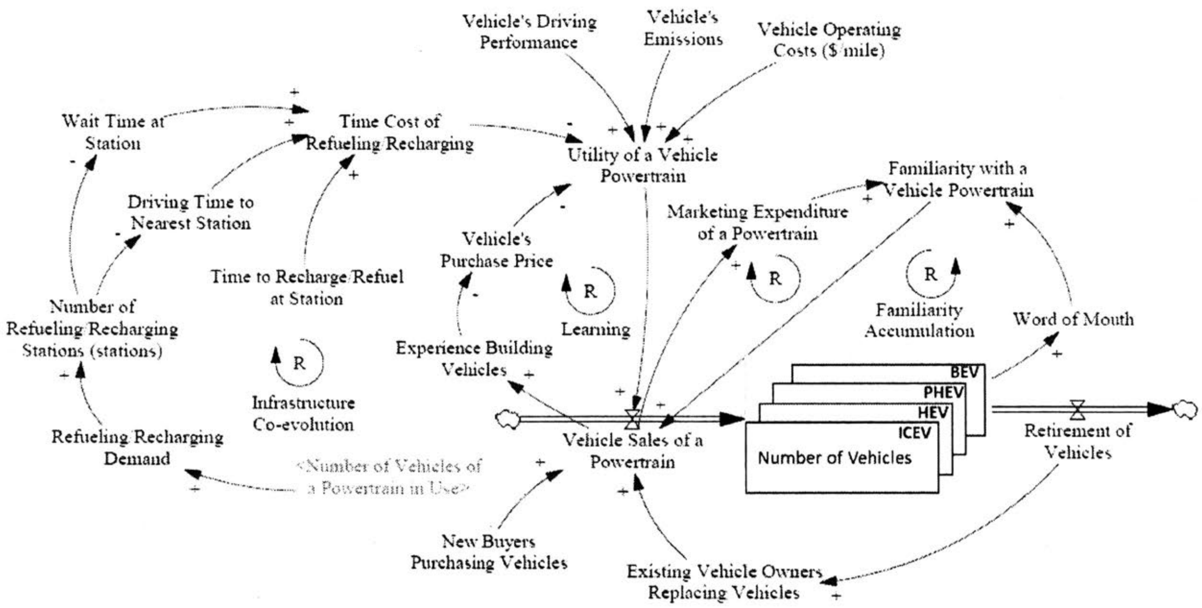
"Utility" of a powertrain is a microeconomic construct defined by how useful a powertrain is to a customer, and is calculated using various powertrain-specific parameters: vehicle price, operating cost, speed, acceleration, range, emissions, and refueling cost. "Familiarity" of a powertrain is determined by the customer's awareness of that powertrain's advantages over other powertrains, and is influenced by word-of-mouth from existing drivers as well as through marketing efforts by vehicle manufacturers.

Similar to the vehicle powertrain selection process, we also have a selection process for the expansion of refueling/recharging infrastructure where the decision-makers are investors and infrastructure providers. We use a combination of two metrics: "profitability" and "utilization" to model the attractiveness of each infrastructure type (e.g., gasoline, electricity). The infrastructure "profitability" is dependent on the profit margin on fuel, amount of fuel sold, and profits from ancillary sources. "Utilization" of an infrastructure type is dependent on the average demand for refueling/recharging at that infrastructure, the operating hours of the infrastructure, and the average time of refueling/recharging.

The model's value lies in its simulation of the non-linear interactions between different parts of the light-duty vehicle fleet and the infrastructure market. A significant portion of the dynamic complexity endogenous to the model can be explained using three decision feedback structures (loops). All three of these loops are labeled with an "R" to illustrate that they are reinforcing, resulting in growth (or decline) of the relevant variables. A reinforcing loop stands in contrast to a balancing loop in which the variables seek a stable equilibrium value.

The first feedback loop, "Infrastructure co-evolution", is pictured in Figure 2. This loop captures the interaction between sales of a particular powertrain and the expansion of the corresponding infrastructure. When the sales of a particular powertrain increases, the number of in-use vehicles of that powertrain increases, creating more demand for refueling infrastructure serving that powertrain. With more demand, investors are incentivized to build more refueling infrastructure, increasing the number of refueling stations in the market. With a higher number of refueling/recharging stations, it becomes faster and more convenient to refuel because the nearest recharging stations are closer than earlier. With this increased convenience, the utility of the powertrain grows relative to other powertrains, thereby, increasing the sales of the powertrain. This reinforcing loop can turn in the other direction too – i.e. if the sales of a vehicle powertrain slows down, it can lead to the fall of the corresponding refueling/recharging infrastructure serving that powertrain.

Figure 1: Overview of the System Dynamics Model



The second feedback loop, shown below in

Figure 3, is called "Familiarity Accumulation". This loop captures the relationship between the number of in-use and new vehicle sales of a particular powertrain, and the associated increase in consumer familiarity with that powertrain. When there are more consumers driving a particular powertrain, the effects of promotion by word of mouth increases. This loop also includes the effects of marketing, whose expenditure is modeled as a fraction of annual revenues from the sales of the powertrain. Both of these effects lead to a greater consumer familiarity with the powertrain. With a higher consumer familiarity, the sales of the powertrain increases, completing the "Familiarity Accumulation" reinforcing feedback loop shown in Figure 3.

Figure 2: Infrastructure Co-evolution - Reinforcing Loop

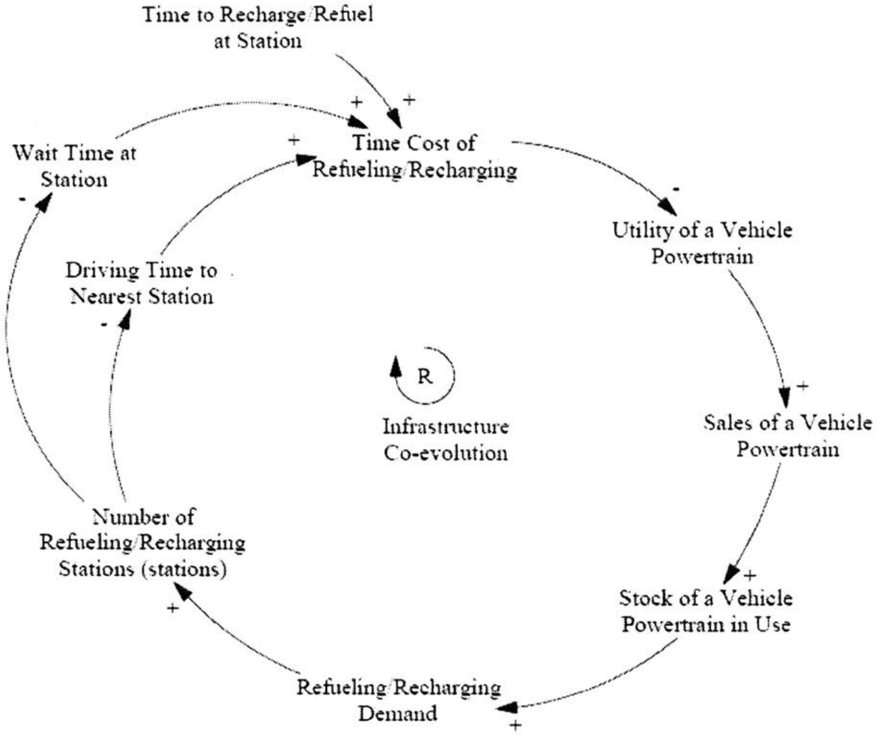
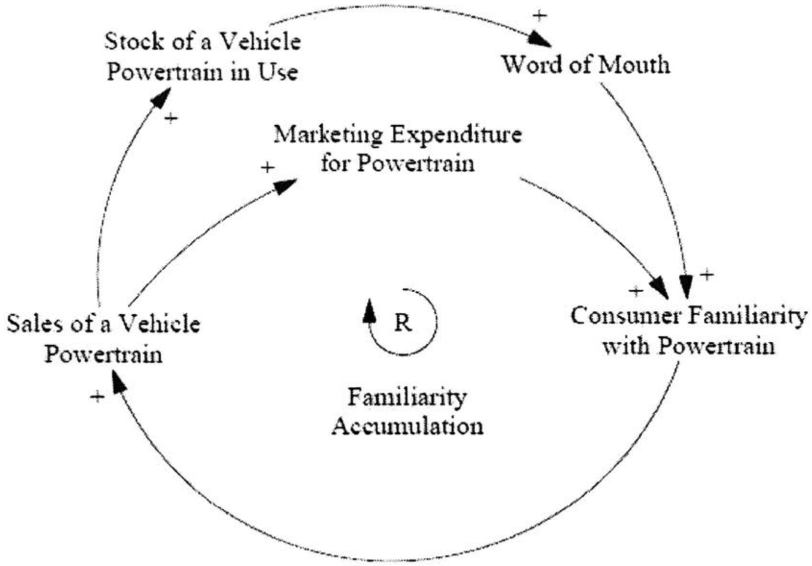
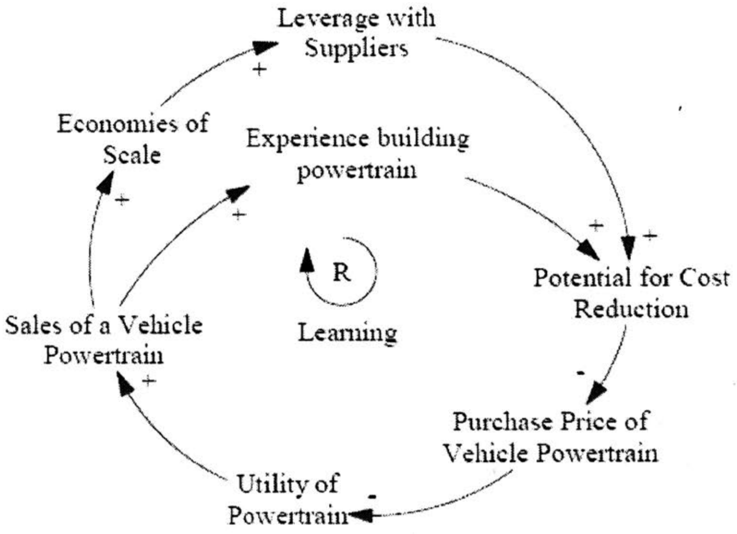


Figure 3: Familiarity Accumulation - Reinforcing Loop



The feedback loop between the sales of a powertrain and the technological advances in its attributes, based on economies of scale and process improvement, is captured in the third reinforcing loop called "Learning". This loop is pictured in Figure 4. When the sales of a particular powertrain increases, the vehicle manufacturer accumulates more experience building the powertrain. With experience comes improvements in efficiency, resulting in a lower purchase price for the vehicle. With a lower price, the powertrain becomes more attractive, and consequently, the sales of that vehicle powertrain increases. Thus, a reinforcing loop is formed between sales of a powertrain and its attractiveness to a potential customer. Apart from the manufacturing experience, there are also economies of scale associated with higher production volumes, which also results in reduced powertrain component costs. Learning effects also apply to other more specific technologies represented in the model including PEV batteries, fuel cell technology, and hydrogen production processes.

Figure 4: Learning - Reinforcing Loop



3.2 Model's Inputs and Outputs

Figure 5 presents the major inputs and outputs of the System Dynamics model. Note that this model is calibrated for the U.S. We represent the U.S. LDV market by calibrating the variables shown in Table 2, in addition to the microeconomic model that is used for powertrain choice.

Figure 5: Major Inputs and Outputs for the System Dynamics Model

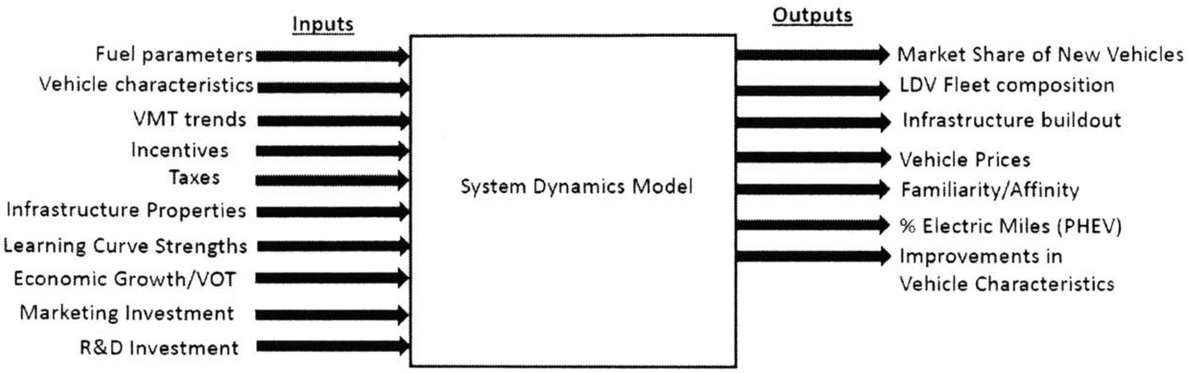


Table 2: Region-specific inputs in the System Dynamics model

Model Assumptions	**Value**	**Units**
Vehicle Lifetime	15	years
Value of Time	40	$/hour
Annual VMT	12,000	miles/year
LDV Fleet Growth Rate	0.7%	1/year
AFV Purchase Incentive Sunset Date	2030	year
Median Household Income (2018)	57,000	$/year
EV Home Charger Base Cost	1,000	$
% Energy Charged at Home - BEV	85%	-
Price Multiplier for Public Level 2 Charging	2	-
Percent of Households with Home Charging	70%	-

3.3 Modifications to the Model

3.3.1 Decision-making Structure for Infrastructure Choice

For Battery Electric Vehicles (BEVs), in reality, there are three recharging options: home recharging, public recharging, and fast recharging. In the base model, there were only two options: home and public recharging. So, we added an additional infrastructure type called "fast recharging".

We have assumed that 85% of all recharging (in terms of energy) is done at home, based on real-world data (Snyder 2012). The remaining 15% is shared between Level 2 public recharging stations and Level 3 Fast recharging stations. To determine how often a driver recharges at a Level 2 recharger vs. a Level 3 recharger, we first calculate the time cost of recharging at Level 2 and Level 3 rechargers and then use an inverse weighted average analysis. We use an inverse-weighted average method because the share of recharging done at each level is inversely proportional to the time cost incurred in recharging at that level. In the real world, the consumer choice may not be perfectly responsive to the time-cost of recharging and there may be some hysteresis built into the consumer's response; however, presently, the consumer reaction is assumed to be perfectly proportional to the time-cost of recharging.

To calculate the time cost of recharging at each level, we use the following four time components and then multiply their sum with the value of time for an average driver. Figure 6 summarizes the recharging cost calculations for each of the recharging infrastructure levels.

1. Driving to the nearest recharging station:

   The time it takes to drive to the nearest recharging station is the first component. It depends on the density of recharging stations of each level (in terms of stations per square area), the average speed of vehicle operation in a city/rural region, and the square-miles area of that region. We assume a uniform distribution of recharging and refueling stations all over the United States in this model.

2. Waiting at the recharging station to recharge:

   Once the driver reaches a recharging station, there may be a need to wait for a recharging spot. The waiting time is dependent on the average utilization of the recharging infrastructure. With a higher utilization, there is a higher probability of finding an occupied recharging station, thus incurring a higher wait cost. We use an exponential distribution of drivers arriving at the recharging station, and then calculate waiting time based on average utilization.

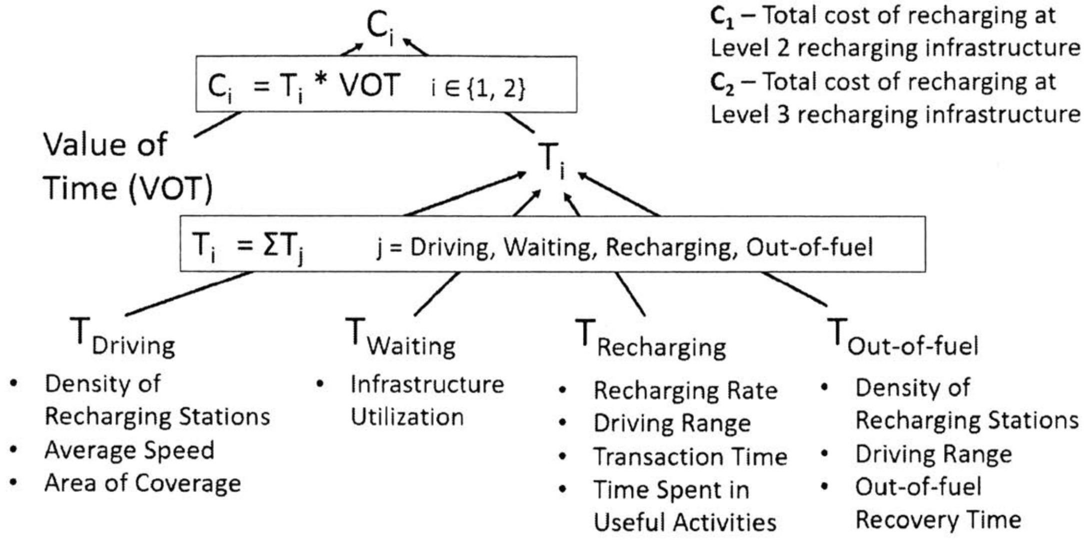
3. Recharging time at the recharging station:

   The recharging time is dependent on the power of the recharging station, the size of the battery in the vehicle, the transaction time for payment, and any useful activities that could be performed along with recharging so that the time burden is reduced for the driver. We assume that recharging happens linearly from 0% to 100% of the battery capacity, although in reality, the recharging trend line is linear only between 20% and 80% of the battery capacity. So, we underestimate the actual recharging time in our model.

4. Recovery time if the vehicle runs out of fuel:

   When a driver is searching for the nearest recharging station, there is a possibility that the vehicle may run out of fuel during the process. The probability of running out of fuel is dependent on the density of recharging stations and the driving range of the vehicle. If the vehicle runs out of fuel, there is also a recovery time associated with towing the vehicle back to the driver's home or the nearest recharging station. So, we combine the probability and the expected recovery time to determine the recovery time penalty that is then added to the cost burden of recharging at a particular level of infrastructure. We use a probability distribution for the calculation of running out of fuel.

Figure 6: Total Time Cost of Recharging at each Level of Recharging Infrastructure



3.3.2 Introduction of a new type of powertrain:

For the purpose of evaluating the second business model, we created a new powertrain class called Battery Electric Vehicles compatible with Battery Swapping Systems, or BEVBSS for short. While this powertrain resembles BEVs for the most part, there are two significant differences:

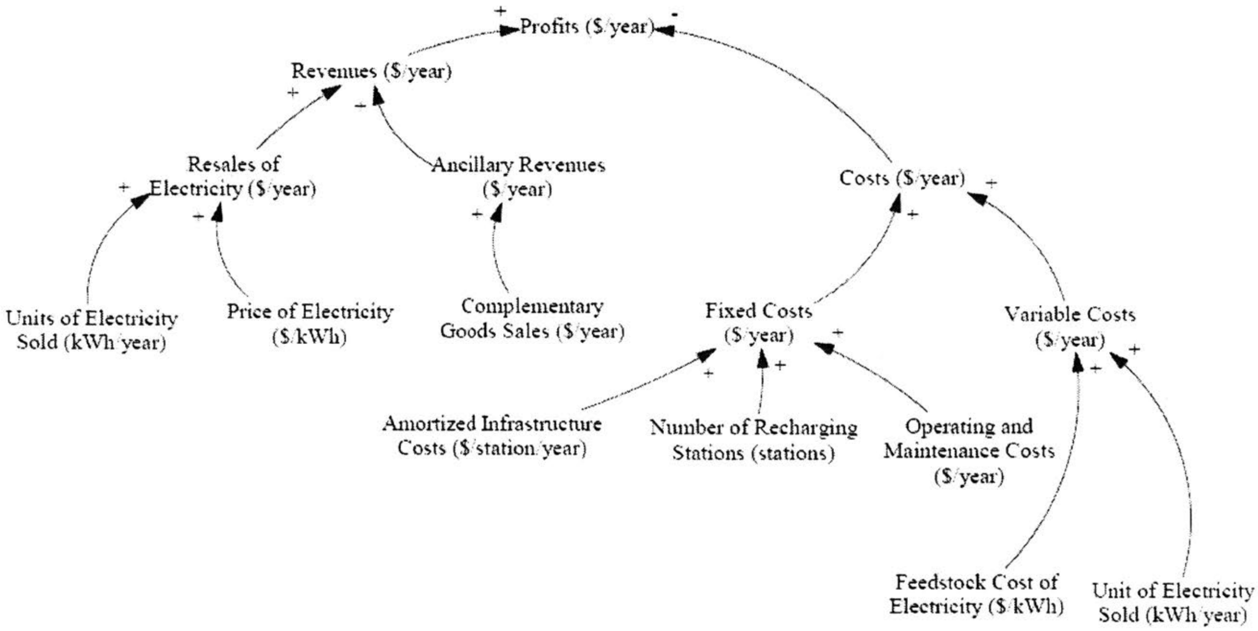
1. Purchase Price and Vehicle Operating Costs: The purchase price is lower than BEVs because the BEVBSS driver no longer owns the battery in the car, however, the vehicle operating costs are higher because an annual subscription fee is paid for using the battery lease service from the battery swap system provider.
2. Recharging Choice: Apart from home, Level 2, and Level 3 recharging stations, BEVBSS vehicles can also use Battery Swap Stations (BSS). This necessitated creating a new infrastructure choice model for BEVBSS drivers with a three-way choice between Level 2, Level 3, and BSS.

3.3.3 Formulation of Business Models:

To study the influence of business models for recharging infrastructure, we created new variables and added the relevant structures to the existing System Dynamics model.

To analyze the financial fundamentals of recharging infrastructure, we first laid out a profitability framework (as shown in Figure 7) in the System Dynamics model. We anticipate two major revenue streams for the infrastructure provider – resales of electricity to BEV drivers, and ancillary revenues from convenience stores, vending machines, and other services collocated with the recharging station. Some infrastructure providers are also using a subscription-based business model, in which case, a third revenue stream is added. On the costs side, there are two major costs: the capital expenditure required to build the network of recharging stations, and the cost of electricity that the infrastructure provider purchases from their utilities.

Figure 7: Profitability Framework for Recharging Infrastructure Provider



3.3.3.1 Business Model 1: Taxi Fleet Owner – Recharging Infrastructure Owner Partnership

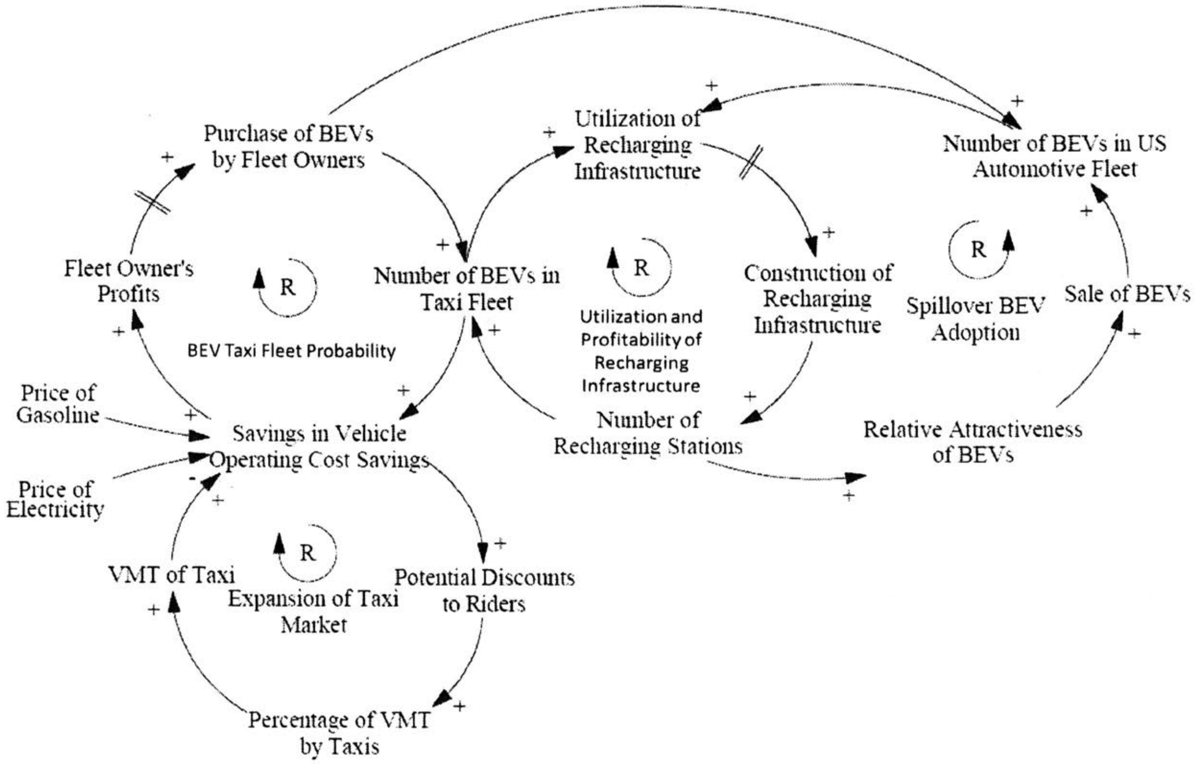
In this business model, a taxi fleet owner who currently operates a fleet of ICEVs converts the entire fleet to BEVs to capitalize on the lower operating costs of BEVs in comparison to ICEVs. The fleet owner also partners with a public recharging infrastructure provider to ensure that her BEV fleet has guaranteed access to recharging facilities. By partnering with the fleet owner, the recharging infrastructure provider achieves higher levels of utilization and reduced payback period for the capital investment in infrastructure. Table 3 shows a list of assumptions that we have used for the analysis of this business model. These numbers are based on (Pavlenko, Slowik, and Lutsey 2019) and (R Gogoana 2010), and are modified according to the specific characteristics of the recharging stations considered in this business model.

Table 3: Parameters for the Formulation of Business Model 1

Parameter	**Value**	**Units**
Capital Cost Of Recharging Station	50,000	$
Number Of Recharging Plugs Per Station	1	Plug
Power Of Fast Recharging Station	50 – 60	kW
Energy per charging event	27.5	kWh
Feedstock Cost Of Electricity	0.28	$/kWh
Life Of Infrastructure	15-20	Years
Life Of Taxi	5	Years
Range Of BEV Taxi	200	Miles
Battery of BEV Taxi	50	kW
Daily Driving Distance Of Taxi	250	Miles
Annual Driving Distance Of Taxi	70,000	Miles
Percent Of Home Recharging For BEV Taxi	60%*	-
ICEV Price (2018)	19,000	$
BEV Price (2018)	30,000	$
Taxes	10%	
ICEV Maintenance Costs	0.061	$/mile
BEV Maintenance Cost	0.026	$/mile
Opportunity Cost Of Taxi	22.9	$/hour
Labor Cost Of Taxi	15	$/hour
BEV Fast Recharging Frequency	0.5	1/day
ICEV Refueling Frequency	0.5	1/day
BEV Recharging Time	36	Minutes
ICEV Refueling Time	5	Minutes
Price Of Electricity At Home	0.13	$/kWh
Price Of Electricity At Fast Recharger Without Business Model 1	0.41	$/kWh
Price Of Electricity At Fast Recharger With Business Model 1	0.3	$/kWh

* Although we use 85% as the percentage of home recharging for private drivers, we use 60% home/off-duty recharging for taxi drivers because of their higher daily driving distance.

Figure 8: Causal Loop Diagram of Business Model 1



In the Business Model 1, there are four major reinforcing loops operating to maximize the impact of the business model, as shown in Figure 8.

1. BEV Taxi Fleet Probability:

   If the number of BEVs in the taxi fleet increases, the total vehicle operating costs (VOCs) will decrease for the fleet owner because BEVs are cheaper to operate than comparable ICEVs. With higher savings in VOCs, the fleet owner's operating profits increase, a part of which will then be invested (after some time delay) in the purchase of additional BEVs to replace the ICEVs in the fleet. This increases the number of BEVs in the fleet, and thus, a virtuous loop is formed.

2. Utilization and Profitability of Recharging Infrastructure:

   If the number of recharging stations increases, more areas will have access to recharging stations, giving flexibility to the taxi fleet owner to increase the number of BEVs in the taxi fleet. (These areas were earlier not accessible to BEVs due to the absence of recharging stations.) With a higher number of BEVs in the taxi fleet, the utilization of recharging infrastructure increases, making it attractive to invest and build more recharging infrastructure. However, it is important to note that there is often a delay in perceiving the increase in utilization and the decision to build more infrastructure. As more recharging stations are built, the number of recharging stations increases, resulting in a virtuous loop.

3. Expansion of Taxi Market:

   If the vehicle operating costs of the taxi fleet reduces due to the adoption of BEVs, some of the cost savings are passed on to riders, who are then more attracted to using taxis. This increases the annual vehicle miles traveled in taxis, and with higher miles logged, the higher are the savings in vehicle operating costs for the taxi fleet owner. Some of these savings are again passed on to the riders, resulting in a virtuous loop.

4. Spillover BEV Adoption:

   As the number of recharging stations increases, BEVs become more attractive for private use as the range anxiety is somewhat reduced. This increases the sales of BEVs, and the number of BEVs in the region increases. With a higher number of BEVs, the utilization of recharging infrastructure increases, incentivizing investors to build more recharging infrastructure. With more recharging infrastructure built, the number of recharging stations in the region increases, resulting in a virtuous loop.

3.3.3.2 Business Model 2: Battery Swap System Infrastructure Provider

In the second business model, a recharging infrastructure owner does two things: Own and lease a set of batteries to BEV drivers, and build and operate a network of battery swap stations (BSS). In the Business Model 2, there are two reinforcing loops maximizing the benefits of the business model, as shown in Figure 9.

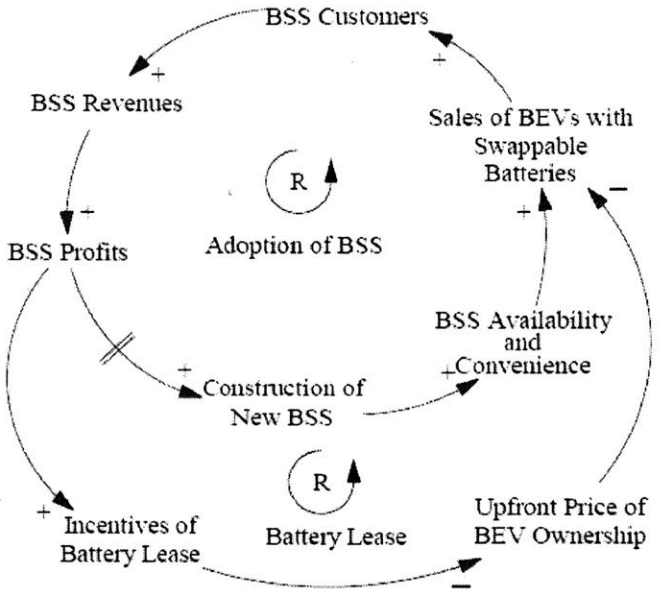
1. Adoption of Battery Swap Stations (BSS):

   This is a classic case of powertrain-infrastructure co-evolution explained earlier. When more BEVs capable of using Battery Swap Stations (BSS) are sold, there is more demand for BSS, attracting investors to build more BSS. With more BSS, BEVs become more useful and they also use BSS more often, resulting in higher sales for BEVs and higher utilization for BSS.

2. Battery Lease:

   When the number of BEVs leasing batteries increases, the BSS infrastructure owner's revenues increase. Apart from that, the BSS infrastructure owner also gains leverage over battery manufacturers (due to the scale of operation), resulting in better negotiation terms and cheaper prices for batteries. Some of this reduction in battery prices is passed onto potential lessees, thereby increasing the number of BEVs leasing batteries from the infrastructure owner. This creates a virtuous loop for the battery lease operation.

Figure 9: Causal Loop Diagram of Business Model 2



4. Results

In this section, we present our results from using the System Dynamics model explained above. First, we conducted a set of analysis to closely understand the co-evolution of sales of BEVs and proliferation of recharging infrastructure. Once we determined the major factors influencing the co-evolution, we delved into the analysis of financial viability of recharging infrastructure by using a set of causal loop diagrams. After identifying the major factors, we analyzed the viability of the business models presented in the methodology section. We also conducted an estimation of the increase in BEV adoption due to the implementation of these business models.

4.1 BEV – Recharging Infrastructure Co-evolution:

Generally, a powertrain type and its corresponding refueling/recharging infrastructure co-evolve as each side of the market strengthens; more vehicles of a certain powertrain increases the demand for the corresponding infrastructure, and as more infrastructure is built, it becomes more convenient to own vehicles that can use that infrastructure. Of course, some powertrain-infrastructure combinations could devolve as each side of the market weakens due to widespread adoption of alternative vehicle powertrain-infrastructure combinations. In order to understand the dynamics of co-evolution, we conducted our analysis in three parts:

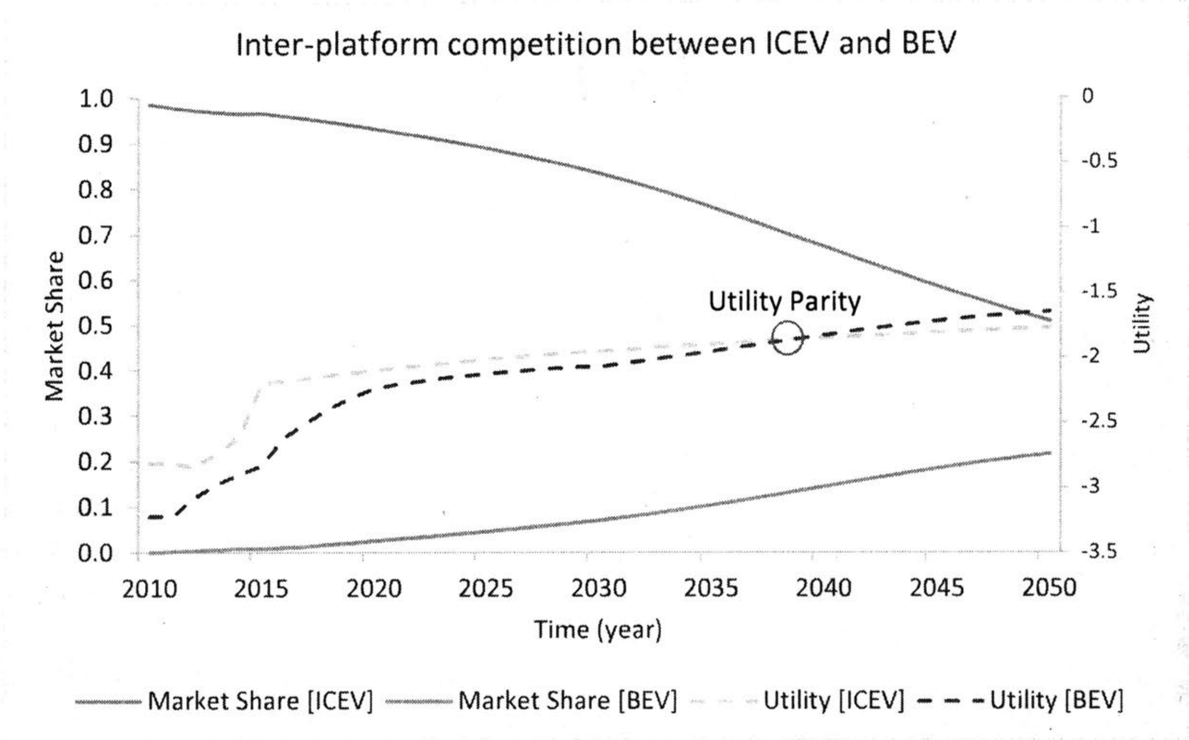
1. Inter-powertrain competition
2. Inter-infrastructure competition
3. Powertrain-Infrastructure interaction

4.1.1 Inter-powertrain competition

The various powertrains compete with one another for a potential customer based on the customer's perception of "utility" and their "familiarity" with different powertrains. As explained in the Methodology chapter, the "utility" of a powertrain is defined by how useful it is to the buyer, and is calculated using various parameters specific to each powertrain such as: vehicle price, operating cost, speed, acceleration, range, emissions, and the time cost incurred in searching for and refueling or recharging at a station. "Familiarity" of a powertrain is determined by the customer's awareness of that platform's advantages over other platforms, and is influenced by word-of-mouth and marketing efforts by manufacturers.

Figure 10 shows the competition between the powertrains of ICEVs and BEVs. While the utility of BEVs surpasses the utility of ICEVs around the year 2040 in our reference scenario, the switch in their actual market share lags by more than a decade due to the non-linearity in the growth of familiarity of BEVs.

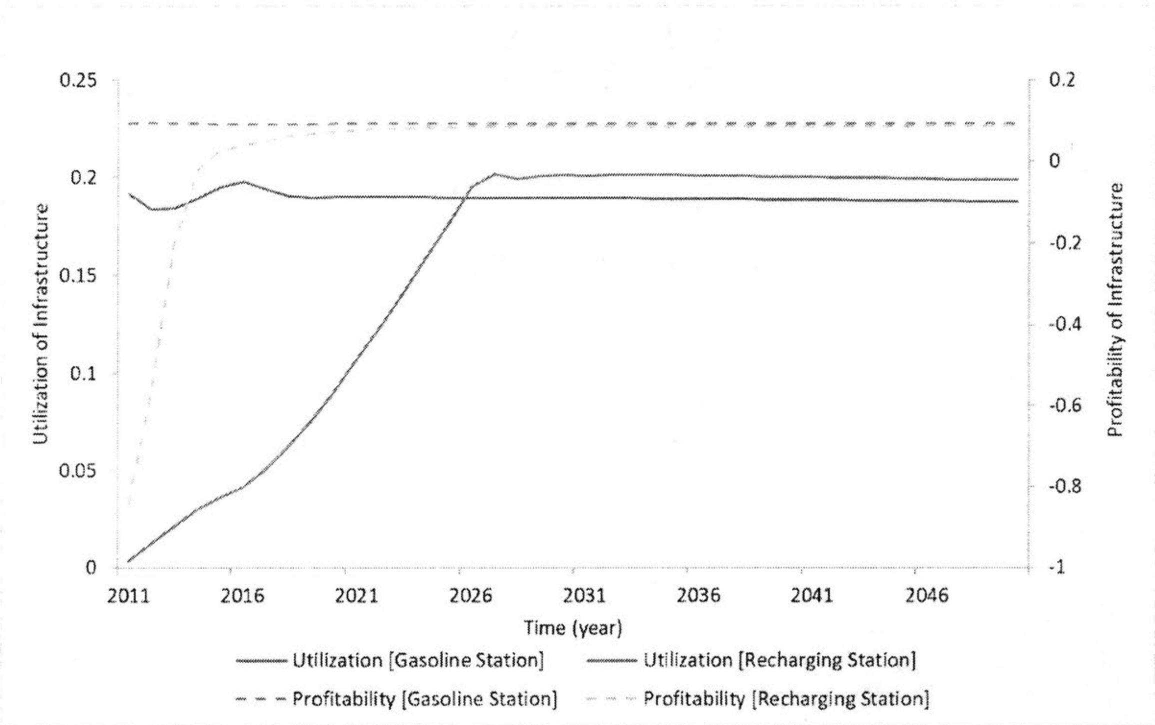
Figure 10: Comparison of Utility and Market Share of ICEV and BEV



4.1.2 Inter-infrastructure competition

Similar to the competition between different powertrains, the refueling and recharging infrastructures also compete with one another to attract investment and undergo network expansion by potential infrastructure providers. As explained in the Methodology chapter, the attractiveness of each refueling or recharging infrastructure type (e.g., gasoline, electricity, etc.) is determined by a combination of two metrics: "profitability" and "utilization". "Profitability" of an infrastructure type is dependent on the profit margin on fuel, amount of fuel sold, and profits from ancillary sources such as a convenience store. "Utilization" of an infrastructure type is dependent on the average distance to the refueling/recharging infrastructure, the operating hours of the infrastructure, and the average time of refueling/recharging. **Figure 11** shows the changes in "Profitability" and "Utilization" of gasoline refueling stations and public recharging stations over the simulation period. On the Y-axis in **Figure 11**, "utilization" can be interpreted as how busy the recharging station is on an average day, whereas "profitability" can be inferred as the profit margin that the recharging infrastructure owner earns for every unit of energy sold, after paying for the amortized capital expenditure.

Figure 11: Inter-infrastructure competition between Gasoline and Recharging Stations



It is important to note that the total number of refueling/recharging stations in the market changes dynamically as the market share of the corresponding vehicle powertrain changes. This is because when the market share of a particular powertrain increases, the demand for the corresponding infrastructure increases resulting in higher utilization and attracts investors to build more of that infrastructure. Hence, the inter-powertrain competition cascades down to inter-infrastructure competition as well. We show this cascading effect in **Figure 12** by plotting the changes in total number of refueling/recharging stations and the changes in market shares of ICEVs and BEVs over the simulation period.

4.1.3 Powertrain-infrastructure interaction

We use the example of interaction between BEV sales and proliferation of recharging infrastructure to demonstrate the powertrain-infrastructure interaction as shown in **Figure 13**. During the initial years of the simulation, we see that the BEV sales and the number of recharging stations are somewhat unrelated due to weak market factors that, if stronger, would promote co-evolution of BEVs and recharging infrastructure. However, in the latter years, we see a very strong correlation between BEV sales and the number of recharging stations.

Figure 12: Cascading Effect of Changes in Powertrain Market Shares to Changes in Number of Refueling/Recharging Stations

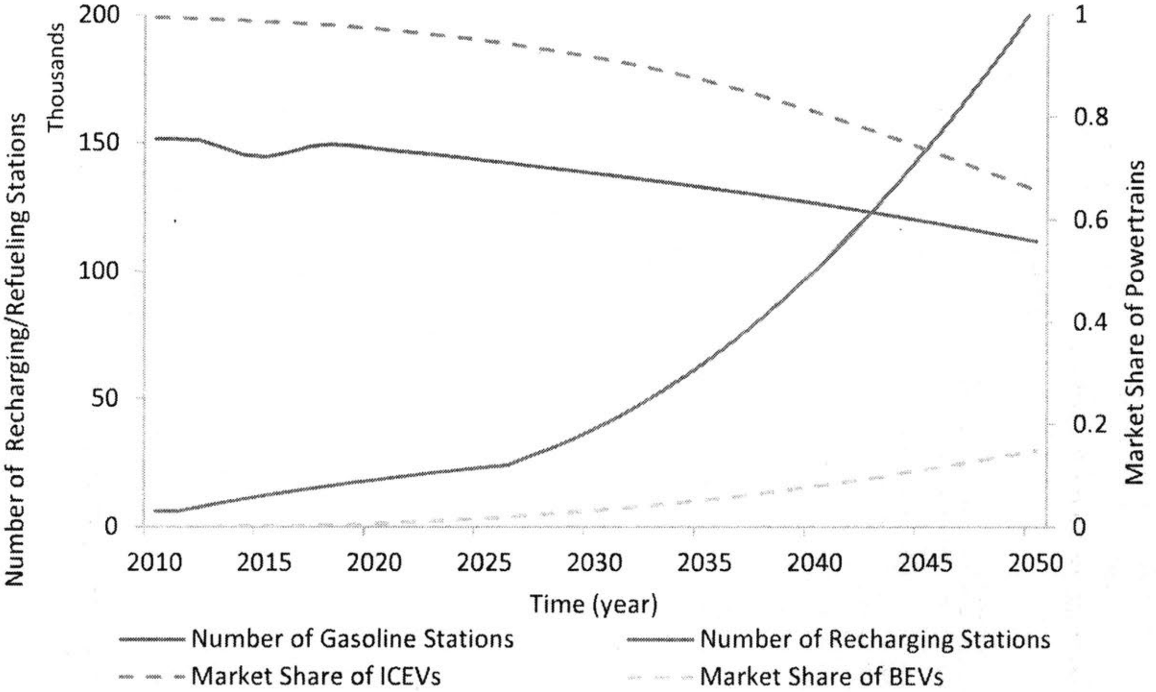
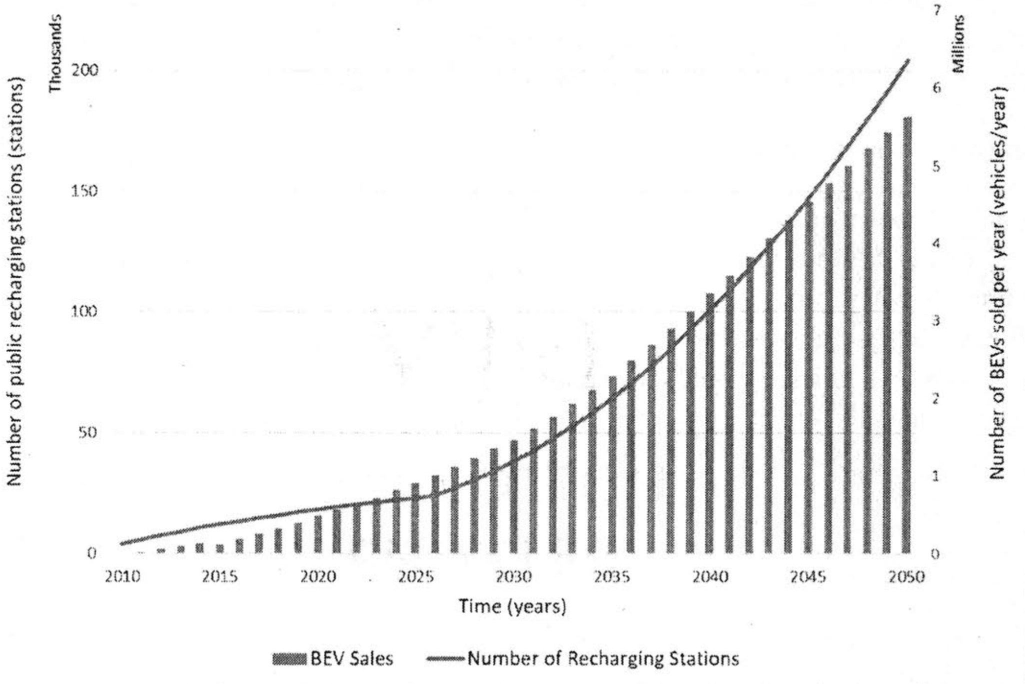


Figure 13: Co-evolution of BEV sales and public recharging infrastructure expansion



4.2 Financial Viability of Recharging Infrastructure

Until the BEV-recharging infrastructure co-evolution matures, we believe that continued government-initiated policy incentives (for vehicle and/or infrastructure) are required. However, several of the government incentives are currently being phased out – case in point, the BEV federal credit in the US is being phased out for automotive manufacturers who have sold 200,000 PEVs (InsideEVs, 2018). Initiatives from the private sector, especially on the infrastructure side, are required to sustain the acceleration of this co-evolution. However, attracting private sector investment in recharging infrastructure requires a clear economic rationale and financial viability.

In this section, we explore the factors that determine the financial viability of public recharging infrastructure, and the potential for investors to influence the co-evolution of BEV- electric recharging infrastructure. A major impediment preventing investors from constructing an expansive network of public recharging stations is the uncertainty in the profitability of infrastructure. Various studies (Schroeder and Traber 2012; Serradilla et al. 2017) show that public recharging infrastructure is hardly profitable at the early stages of the plug-in electric vehicle market, even though it is the most crucial stage for the expansion of the BEV market.

Using the Figure 7 presented in the Methodology chapter, we deduce the major risk factors influencing the financial viability of public recharging infrastructure:

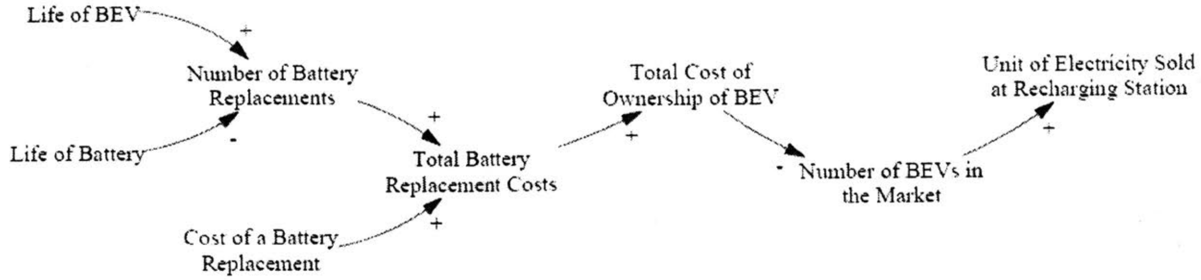
1. Battery Characteristics
2. Utilization of public recharging infrastructure
3. Recharging power of public recharging infrastructure

Figure 14, Figure 15, and Figure 16 illustrate the role and impact of these factors on the profitability of a recharging infrastructure, and how a potential infrastructural investor could influence these factors to improve their bottomline.

4.2.1 Battery characteristics

The impact of battery costs and lifetimes on the profitability of public recharging infrastructure is explained by the causal diagram shown in **Figure 14**. The cost of battery and its lifetime determine the battery replacement costs over the lifetime of a BEV. If the cost of battery could be reduced and the lifetime of battery prolonged, the total cost of ownership of a BEV would be lower, increasing BEV's utility and consequently, BEV sales. With a higher number of BEVs sold, the public recharging infrastructure can sell more electricity and earn more profits.

Figure 14: Impact of Battery Characteristics on Profitability of Recharging Infrastructure

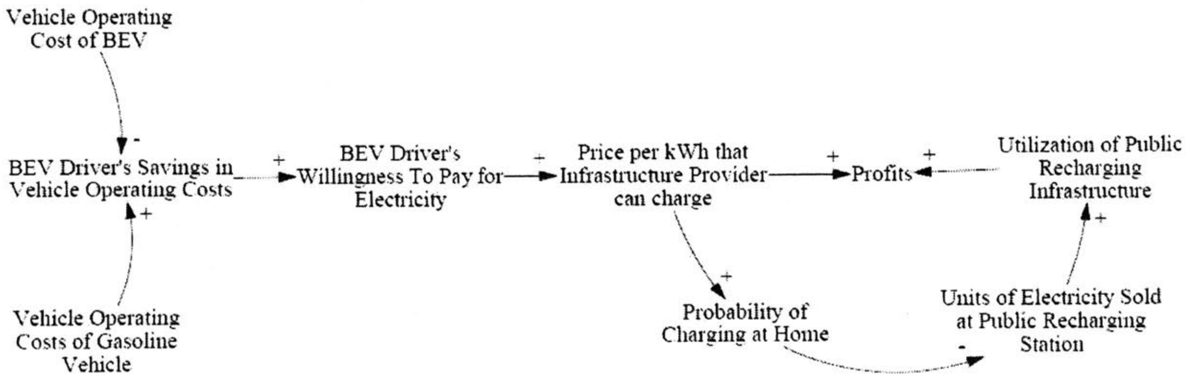


4.2.2 Utilization of public recharging infrastructure

Pricing of electricity is a double-edged sword; while higher price could increase revenues, it could also turn some customers away. Electricity can be sold at a higher profit margin if the gasoline prices are high because the savings in vehicle operating costs would be higher in such a case (for an ICEV driver who has replaced her ICEV with a BEV). However, home recharging is a reasonable alternative to public recharging, and BEV drivers may have a higher price sensitivity to public recharging than ICEV drivers have for gasoline refueling. If the utilization of public recharging infrastructure drops, the ability to recoup the higher upfront costs of infrastructure is reduced resulting in lower profits.

We use the causal diagram shown in **Figure 15** to analyze the interaction among pricing, infrastructure utilization, and share of home recharging in BEV recharging behaviors. At the left-hand side of **Figure 15**, the vehicle operating cost of a BEV and an ICEV represent the per-mile running costs for each of these powertrains. When a driver switches from an ICEV to a BEV, she benefits from the savings in operating costs if the BEV has a lower operating cost than an ICEV. Depending on the savings, the BEV driver may be willing to pay a higher fare for the public recharging infrastructure which then affects its profitability.

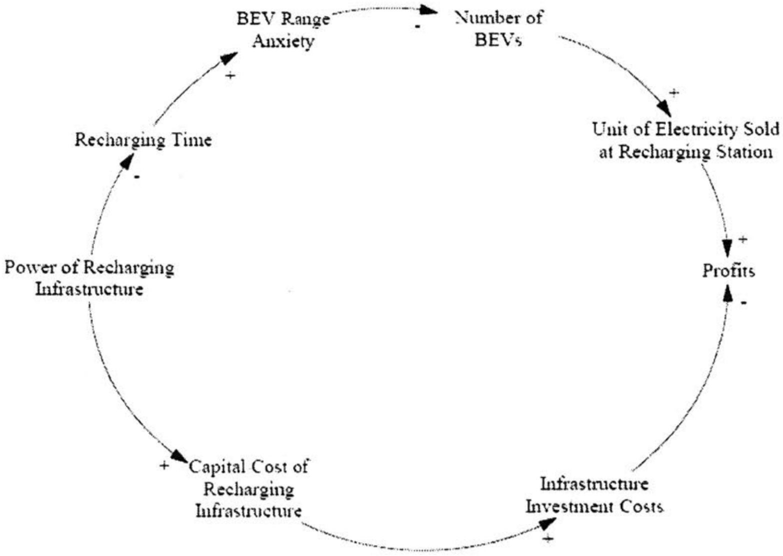
Figure 15: Impact of Pricing on Profitability of Recharging Infrastructure



4.2.3 Recharging power of public recharging infrastructure

Our preliminary studies showed that recharging power (and recharging time) is a key influencing variable in the adoption of BEVs, and hence, public recharging infrastructure should have high power levels. However, the implications of high recharging power on the profitability of recharging infrastructure is unclear, hence we use **Figure 16** to explore this question. A higher recharging power reduces the recharging time of BEVs, making them more attractive and increases the sales of BEVs. With more BEVs, the demand and utilization public recharging infrastructure increases, thereby increasing the revenues for infrastructure provider. However, a higher power recharging station is more expensive, incurring higher capital expenditure which would affect the bottom line for the infrastructure provider, if the utilization is below target levels.

Figure 16: Impact of Recharging Power on Profitability of Recharging Infrastructure



While the above factors in the electromobility ecosystem could be influenced by the strategies and policies of private and public organizations in the electromobility ecosystem, there are other factors that influence the evolution of the system but are not affected solely by it; for example, the provision of electricity at various geographical locations depends upon many factors beyond the electromobility ecosystem, but will directly affect the recharging infrastructure network.

Figure 17 provides a useful map of high-impact factors that influence the financial viability of public recharging infrastructure. We categorize these factors based on the level of control that a private investor exercises over them, and the directional impact of these factors on the financial viability of public recharging infrastructure. We used the System Dynamics model to arrive at these conclusions.

Of the four quadrants in **Figure 17**, the first quadrant represents the variables over which the recharging infrastructure provider has a high level of control, and by increasing the value of these variables, the provider can increase her profits. In the second quadrant are the variables that have a positive correlation with the profits for recharging infrastructure, however, they can't be influenced by the infrastructure provider. The third quadrant presents variables that have a negative correlation with profits and are also out of control for recharging infrastructure provider. In the fourth quadrant, we find those variables that can be controlled by the infrastructure provider, but their values have a negative correlation with the profits for infrastructure provider. So, the provider should reduce the value of variables in the fourth quadrant and increase the value of variables in the first quadrant, if she wants to improve the infrastructure's viability.

Figure 17: High-Impact Factors Influencing the Viability of Public Recharging Infrastructure

Level of Control Available to Recharging Infrastructure Provider

LOW → HIGH

Direction of Impact of an Increase in Factor's Value on Financial Viability of Recharging Infrastructure

	LOW	HIGH
POSITIVE	• Life of Battery • Price of Gasoline	• Utilization of Recharging Infrastructure • Life of Recharging Infrastructure
NEGATIVE	• Cost of Battery • BEV Fuel Efficiency • Average Annual Driving Distance of BEVs • Life of BEVs	• Power of Recharging Infrastructure

4.3 Analysis of Business Models for Public Recharging Infrastructure

In this section, we present our analysis on the Business Model 1: Taxi Fleet Owner – Recharging Infrastructure Owner Partnership which we introduced in the Methodology chapter. First, we look at the cost structure for the stakeholders in this business partnership and then estimate the spill-over effects of this business models on the sales of BEVs.

4.3.1 Cost Structure for Recharging Infrastructure Provider

For the recharging infrastructure provider, there are two major costs:

1. Capital Expenditure Costs – Although there is a lot of variability in the capital cost of Fast recharging, most sources indicate that $50,000 is a reasonable average for a single-plug Level III recharger (Pavlenko, Slowik, and Lutsey 2019; Schroeder and Traber 2012).
2. Electricity Costs – To understand the cost structure of the recharging infrastructure, we look at the fees that utilities companies charge. These fees are based on Connecticut Light and Power Company's Time of Day service charges for non-manufacturers, as documented in (R Gogoana 2010). There are two major classes of fees from the utility:
    a. Fixed Costs:

    i. Customer Service Charge – This is a monthly fee that is paid to the utility provider for locating a transformer close to the recharging infrastructure. Depending on the power of the transformer required, the service charge varies.
    ii. Distribution Demand Charge - This is the cost that is paid to the utility provider for reserving capacity and is dependent on the highest kVA that a customer consumes over a 30-minute period in the current and the preceding 11 months.
    iii. Production and Transmission Demand Charge – This is similar to the Distribution Demand Charge, and it is paid for electricity production and transmission. It is also dependent on the highest kVA that a customer consumes over a 30-minute period in the current and preceding 11 months.
b. Variable Costs:
    i. Generation Charge – This is the most substantial part of the variable costs, and is the cost incurred by the utility provider in producing electricity.
    ii. Miscellaneous charges – Several special fees are charged by utilities for various purposes such as Systems Benefit charge, Conservation charge, Renewable Energy charge, FMCC Delivery and Generation charges.

Based on (R Gogoana 2010), Table 4 lists the values of various charges at the Connecticut Light and Power Company for non-manufacturing operations. These fees are tailored to the power demands of the specific recharging infrastructure (a 50kW single-plug fast charger) that we are using in the analysis of this business model.

Table 4: Electricity Costs for Recharging Infrastructure

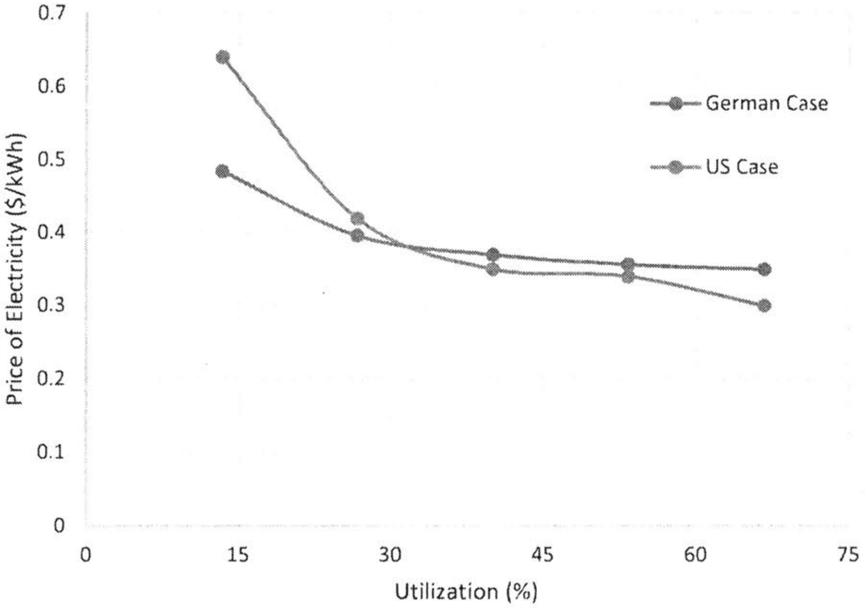
Type of Cost	Description of Cost	Flat fee	Per kVA	Per kWh	Units
Fixed	Customer Service Charge	1025			$/month
Fixed	Distribution Demand Charge		5.36		cents
Fixed	Production/Transmission Demand Charge		4.82		cents
Variable	Systems Benefit Charge			0.00135	$
Variable	Conservation Charge			0.003	$
Variable	Generation Charge (on-peak)			0.09433	$
Variable	Renewable Energy Charge			0.001	$
Variable	FMCC Delivery Charge			0.00602	$
Variable	FMCC Generation Charge			0.003	$

The variable costs for electricity from the table add up to $0.1087/kWh. The fixed costs are amortized over the total units of electricity consumed in a month. With low utilization, the amortized electricity costs are higher, and with high utilization, the amortized costs are lower. Likewise, the cost of the fast charging station must also be amortized over the number of kWh supplied.

For the recharging station to breakeven, the recharging network owner must set the recharging fee to cover the variable electric costs plus the amortized fixed electric costs plus the amortized station costs. Using two separate case studies for Germany (as documented in Schroeder and Traber, 2012) and the US (as documented in Gogoana, 2010), Figure 18 shows the interaction between the utilization of recharging infrastructure and the price of electricity per kWh for the recharging station to breakeven over its lifetime. As we can see in the Figure 18, at high levels of utilization (> 50%), an electricity price of $0.3 - $0.35/kWh is sufficient to breakeven for the infrastructure.

We have considered only one plug per recharging station in this analysis due to available data in (Schroeder and Traber 2012). However, theoretically, if a recharging station has multiple plugs, the fixed costs such as Customer Service Charge will be shared across the plugs resulting in lower per kWh costs for the recharging infrastructure provider. On the other hand, having multiple plugs per station may reduce the utilization of each plug; so, the additional plugs should be installed depending on the demand for recharging.

Figure 18: Utilization of Recharging Infrastructure vs. Price of Electricity



4.3.2 Cost Structure for Taxi Fleet Owner

For the taxi fleet owner, the major incentive to pursue this business arrangement is the lower total cost of ownership if the fleet vehicles were converted from ICEVs to BEVs. The total cost of ownership for a taxi fleet vehicle has five components based on the report from ICCT (Pavlenko, Slowik, and Lutsey 2019) and is shown in Table 5.

We calculate the total cost of ownership for one taxi fleet vehicle for the three following cases:

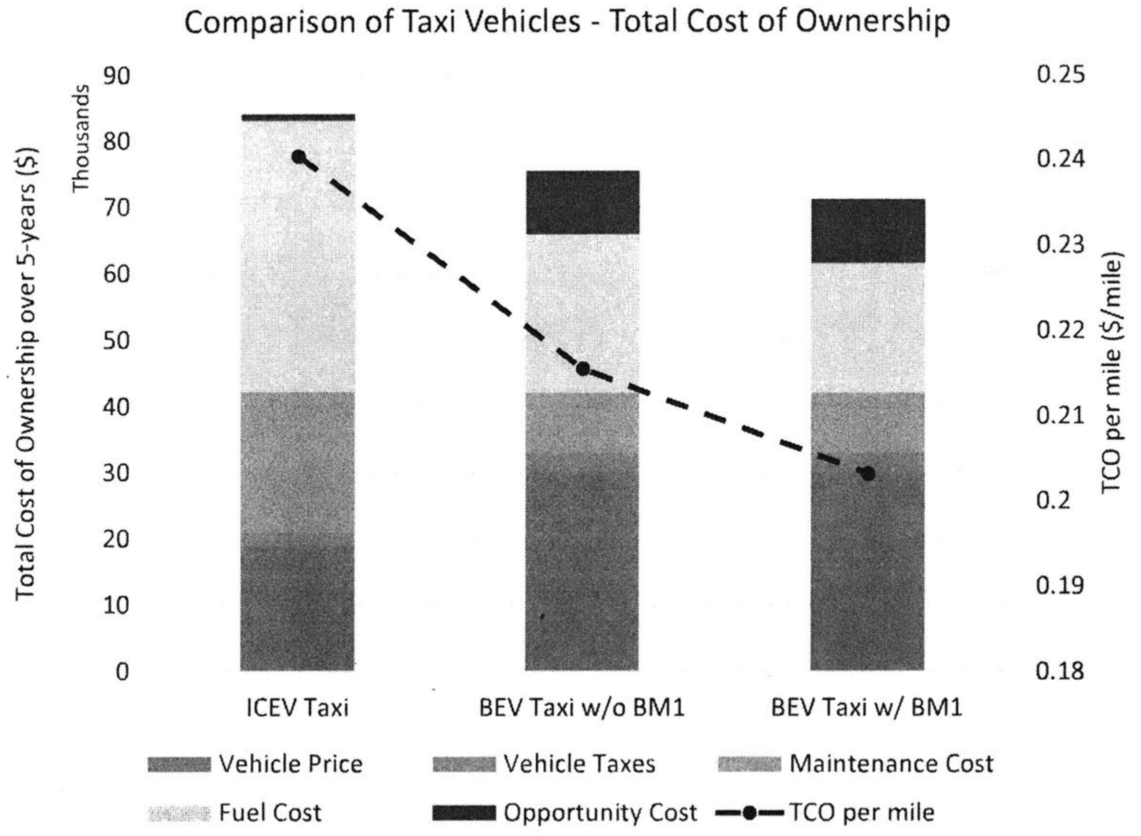
1. ICEV Taxi – a taxi using an internal combustion engine;
2. BEV Taxi w/o BM1 – a battery-electric vehicle taxi operating in the absence of the business arrangement;
3. BEV Taxi w/ BM1 – a battery-electric vehicle taxi operating in the presence of the business arrangement.

Note that the only difference between (2) and (3) above is in the price of electricity at fast recharging stations; with a business arrangement, the price of electricity is lower and the taxi fleet owner can save money in fuel costs. This difference is due to the mutual agreement which ensures that the recharging infrastructure owner charges a lower electricity cost in exchange for a guaranteed level of utilization. Figure 19 shows the total cost of ownership for a taxi fleet vehicle over its lifetime of 5 years for each of the three cases presented above.

Table 5: Cost Components for Total Cost of Ownership of a Taxi

Cost Component	**Description**	**Units**
Vehicle Price	Upfront investment made to purchase the vehicle	\$/vehicle
Vehicle Sales Taxes and Fees	Taxes paid for the purchase of the vehicle	\$/vehicle
Fuel Cost	Cost of fuel used in the operation of vehicle	\$/mile
Maintenance Cost	Routine service and repair costs for the upkeep of vehicle	\$/mile
Opportunity Cost	Revenues lost due to the unavailability of the vehicle	\$/hour

Figure 19: Total Cost of Ownership for a Taxi Fleet Vehicle



We see that the ICEV is better when it comes to Vehicle Price and Taxes due to its cheaper upfront cost, however, BEVs benefit from significantly reduced fuel costs. Another advantage for the BEV is in the maintenance costs where the BEVs, due to their simple powertrain with fewer parts, are much cheaper than an ICEV which has expenses in engine lubrication system, emission control systems, fuel systems, spark plugs, air filter, etc. Opportunity costs are higher for BEVs because of their longer recharging time. Overall, we see that the BEVs have a lower total cost of ownership than the ICEVs over the 5-year lifetime of a taxi. If we compare the two BEV cases – one with a business arrangement with an infrastructure provider and one without it, we see a lower fuel cost in the case of the business arrangement, resulting in a lower total cost of ownership. If we compare the per-mile ownership costs, we see about a 15-20% difference between the ICEV Taxi case at $0.24/mile and BEV Taxi with Business Model 1 case at $0.20/mile.

One of the major assumptions here is that the battery of the BEV doesn't have to be replaced during those 5-years and 350,000 miles of operation. The life of a battery is dependent on various factors such as – weather, recharging behavior, battery chemistry and temperature management system, and there is very little data on on-road BEVs' battery life. We have looked at two independent data sources – one from the Californian inter-city transportation provider Tesloop, and one from the Tesla Owners Group. While Tesloop's Model S had its battery replaced after 200,000 miles, several high-mileage Tesla BEVs in Europe are estimated to last over 500,000 miles before they reach a 20% degradation in battery capacity, based on their current levels of degradation (Tesloop 2017; Teslarati 2017). With the continuation improvement of battery technology, we expect the batteries to last longer than the current state-of-art. So, an assumption that the BEV taxi's battery doesn't have to be replaced over the 350,000 miles of operation seems plausible. The other major assumption is that we have excluded the potential resale value of the taxi fleet vehicles. Arguably, after 350,000 miles, these vehicles are at the end of their lifetime and will have only modest salvage values.

4.3.3 Real-life Examples of the Business Model

A real-life example of this partnership is emerging in China where Didi Chuxing, which offers ride-hailing mobility services, is building a network of recharging stations with Global Energy Interconnection Development and Cooperation Organization (Wire 2017). Such partnerships are expected to gain traction in the recharging infrastructure industry due to the mutual benefits for the ride-hailing business and the recharging station operators by ensuring adequate availability to support the fleet and reliable utilization of the charging stations.

Until the end of 2018, a mobility startup called Tesloop operated inter-city transportation services in Southern California using BEVs in its fleet exclusively. According to Tesloop, it saved an average of $0.05 per mile in vehicle operating costs, and $0.02 per mile in vehicle maintenance costs by using a Tesla Model S instead of a Lincoln Town Car (Tesloop 2017). However, the service has been recently suspended due to the lack of recharging infrastructure and permitting issues around seating capacity in a Tesloop vehicle (San Diego Union Tribune, 2018). The lesson learnt from Tesloop's case is that a reliable recharging network is pivotal for the operation of a large fleet of BEVs, and the Business Model 1 could solve the issue.

4.3.4 Spillover Effects of Business Model 1:

Our initial hypothesis was that with profitable business cases for recharging infrastructure, the infrastructure will be built to serve that market. This increase in the construction and availability of recharging infrastructure will then spur the sales of BEVs by reducing the range anxiety for BEV drivers. To test our hypothesis, we estimated the change in sales of BEVs due to the implementation of Business Model 1. Based on (Conway, Salon, and King 2018), we assume that 0.5% of the total annual VMT of the Light Duty Vehicle fleet is driven by taxis, and we assume all these taxis to adhere to Business Model 1.

Firstly, we simulated the impact of Business Model 1 on the availability of Fast recharging stations over the simulation period of the System Dynamics model as shown in Figure 20. When the Business Model 1 comes into action around the year 2018, we see a significant buildout of recharging stations due to the attractiveness of the business model, and the opportunities that come with it, making investors build more infrastructure. However, because of the limited size of the taxi market, the demand for fast recharging stations by taxi companies is capped. (We don't model of impact of cheaper taxi prices on the growth of the taxi market, but potentially, one could argue that the taxi market will expand if the operating costs and thus, the prices for taxi rides are lower. We already see this in the increased use of ride-hailing services such as Uber and Lyft (Conway, Salon, and King 2018)). In comparison to the case without Business Model 1, we see a 14% increase in the number of fast recharging stations at the end of simulation in 2050.

With the increase in the availability of recharging stations, the adoption of BEVs is also increased as shown in Figure 21. It is important to note that the availability of recharging stations during the early stages of the simulation helps drive the growth of BEVs which replace the retiring ICEVs earlier than the case without the Business Model. We see a 7% increase in the adoption of BEVs at the end of 2050 due to the presence of the Business Model 1. Thus, we see that the Business Model 1 has the potential to spur the BEV – Recharging Infrastructure market, and in a way that's attractive for relevant investors in BEV fleets and recharging infrastructure.

Figure 20: Proliferation of Fast Recharging Stations

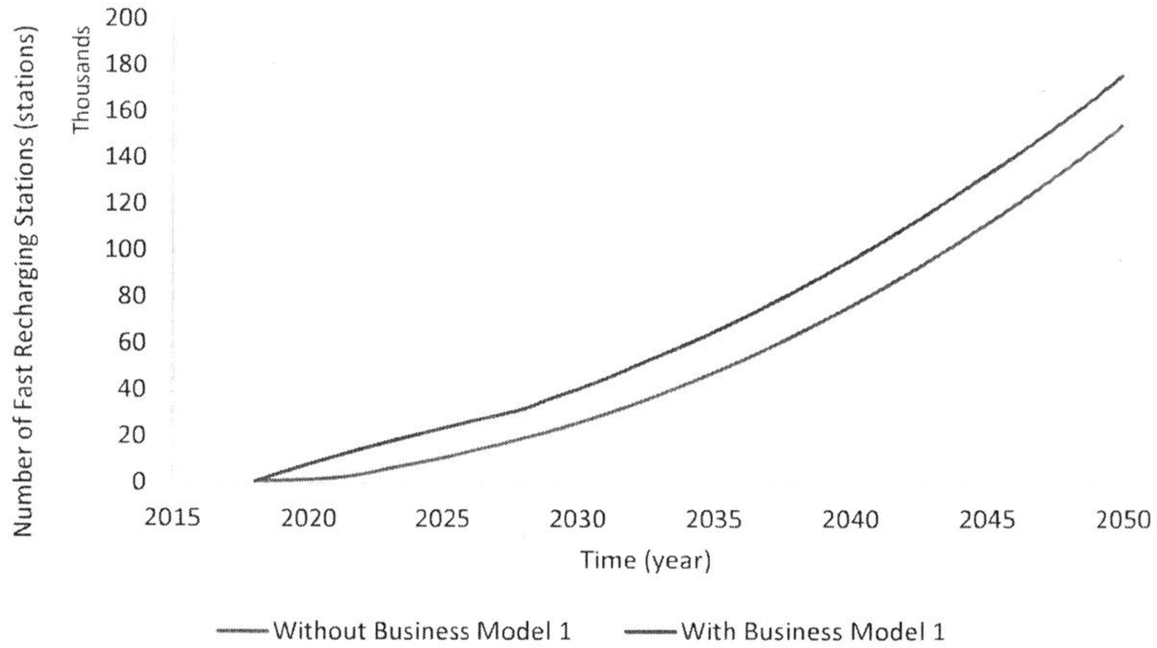
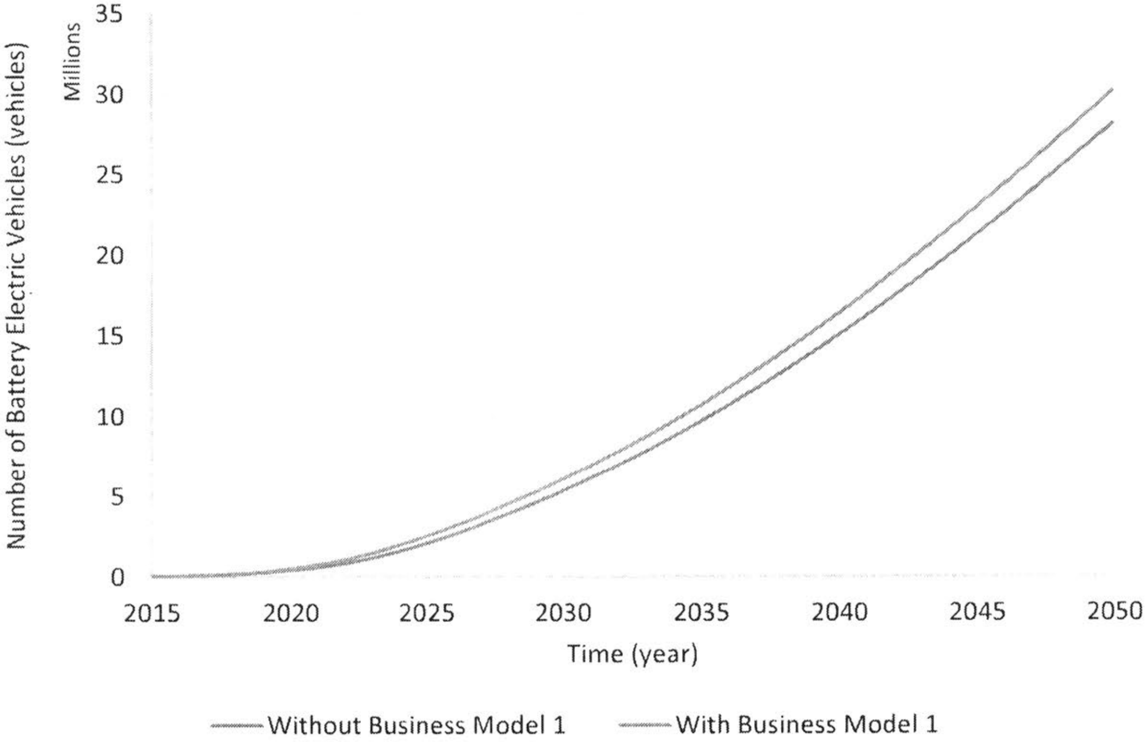


Figure 21: Adoption of Battery Electric Vehicles



5. Conclusion and Next Steps

We started our research by exploring the co-evolution between BEV sales and expansion of recharging infrastructure. We were able to understand and explain the co-evolution using the three-step process of inter-powertrain competition, inter-infrastructure competition, and powertrain-infrastructure interaction. We found that the co-evolution between BEVs and recharging infrastructure is weak during the early stages of the electromobility ecosystem, and external instruments are required to spur the construction of recharging infrastructure, if BEVs were to become competitive with ICEVs by 2040.

We then logically isolated the factors that affect the financial viability of recharging infrastructure into three categories: battery characteristics, utilization of recharging infrastructure, and recharging power of infrastructure. We analysed the level of control that a recharging infrastructure provider exercises over these factors, and narrowed down those factors with high level of control. We created a simplified map of high-impact factors that a recharging infrastructure provider can refer to and decide on actions improving the financial viability of recharging infrastructure.

Using this information about high-impact factors, we formulated two business models that can be used to construct recharging infrastructure profitably and at scale. We deduced that the taxi fleet owner – recharging infrastructure owner business partnership can benefit them both:

1. Taxi fleet owner – business model reduces operating cost of taxis by 15%;
2. Recharging infrastructure owner – business model provides the necessary utilization for recharging infrastructure to pay back its high capital cost and earn profits

We also found that this business model increased the availability of recharging infrastructure by 14% in the US-based simulation model. By increasing the availability of recharging infrastructure, the business model was able to increase the adoption of BEVs by 7% at the end of 2050.

Next Steps

Different business models are suited for different geographies. So, by expanding the model to include geography-specific characteristics will allow us to test the viability of various business models in different regions. We have assumed that there are no supply-side constraints in the electricity grid, but given that the transportation sector consumes more than 20% of the total fuel, if all LDVs were to become BEVs, there will be a significant additional demand on the electricity grid. Creating this feedback between sales of BEVs and supply constraints on the grid will add reality to the model. The model's powertrain choice is modeled using a stated-preference survey in California; recalibrating the microeconomic model for other parts of the country will better inform the scope of BEV adoption in the United States.

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7. Glossary of Terms:

ICEV – International Combustion Engine Vehicle

BEV – Battery Electric Vehicle

PHEV – Plug-in Hybrid Electric Vehicle

PEV – Plug-in Electric Vehicle (umbrella term for BEV and PHEV)

EVSE – Electric Vehicle Supply Equipment

EVSP – Electric Vehicle Service Provider

BM – Business Model

Appendix A: Model Code

We took David Keith's System Dynamics model documented in his thesis (Keith 2012), and made the additions explained in the Methodology section. Here, we present the model code for these additions.

Addition of Infrastructure:

In the base model, there was just one type of infrastructure called [PLUG] in the model code. This was calibrated to have a recharging power that adds 25 miles of driving range per hour of recharging. However, we disaggregated the recharging infrastructure into three types:

1. PLUG1 – Equivalent of Level II Public recharging stations
2. PLUG 2 – Equivalent of Level III Fast recharging stations
3. BSS – Battery Swap stations (added primarily for the purpose of Business Model work)

Addition of Powertrain:

In the base model, the Battery Electric Vehicle powertrain is called BEV. We added a new type of BEV called BEVBSS which refers to BEVs that can use Battery Swap stations. Normally, a BEV can't use such infrastructure due to limitations in vehicle construction and battery size.

Model Code for these additions:

```
a i  = A FUNCTION OF( ) ~~|
a i[Technology]=
        Platform Range i[Technology]
        ~       miles/vehicles
        ~               |

Actual Probability of Recharging at L2 and FAST[PLUG1]= INTEG (
        Change in Probability of Recharging[PLUG1],
                0.5) ~~|
Actual Probability of Recharging at L2 and FAST[PLUG2]= INTEG (
        Change in Probability of Recharging[PLUG2],
                0.5)
        ~       dmnl
        ~       The actual probability of recharging at Level 2 and FAST recharging \
                stations is captured in a stock to include the delay involved in a \
                consumer's response to changing attractiveness of Level 2 vs. FAST \
```

```
		recharging stations.
	|

Alpha=
	1
	~	dmnl
	~		|

Available Infrastructure f  = A FUNCTION OF( ) ~~|
Available Infrastructure f[Infrastructure]= INTEG (
	Infrastructure Aquisition Rate f[Infrastructure]-Infrastructure Exits f[Infrastructure\
		]+Exogenous Infrastructure f[Infrastructure
	],
		Initial Infrastructure Availability f[Infrastructure])
	~	stations
	~		|

Average Distance to Recharging Station[PLUG1]=
	SQRT(XIDZ(Mathematical Correction Term, Density of Recharging Stations[PLUG1]*Average
Distance Unit Correction\
		, 1e+20))/2 ~~|
Average Distance to Recharging Station[BSS]=
	SQRT(XIDZ(Mathematical Correction Term, Density of Recharging Stations[BSS]*Average Distance
Unit Correction\
		, 1e+20))/2 ~~|
Average Distance to Recharging Station[PLUG2]=
	SQRT(XIDZ(Mathematical Correction Term, Density of Recharging Stations[PLUG2]*Average
Distance Unit Correction\
		, 1e+20))/2
	~	miles/vehicles
	~	Specifically for the recharging choice decision between Level 2 public \
		recharging stations and FAST public recharging stations, we compute the \
		average distance to the nearest recharging station. This formulation is \
		the same as in View: Infrastructure - Fuel Search Cost. However, to avoid \
```

```
		cycling of calculations, we create a new variable.
	|

Average Distance Unit Correction=
	1
	~	vehicles*vehicles/stations
	~		|

Average Speed=
	40
	~	miles/hour
	~		|

Change in Probability of Recharging[PLUG1]=
	ZIDZ(Target Probability of Recharging at L2 and FAST[PLUG1]-Actual Probability of Recharging at
L2 and FAST\
		[PLUG1],Time parameter) ~~|
Change in Probability of Recharging[PLUG2]=
	ZIDZ(Target Probability of Recharging at L2 and FAST[PLUG2]-Actual Probability of Recharging at
L2 and FAST\
		[PLUG2],Time parameter)
	~	1/year
	~	The change in probability of recharging at Level 2 and FAST recharging \
		stations is captured in a flow to include the delay involved in a \
		consumer's response to changing attractiveness of Level 2 vs. FAST \
		recharging stations.
	|

Density of Recharging Stations[PLUG1]=
	Mathematical Correction Term*ZIDZ(Available Infrastructure f[PLUG1],US Area Square Miles\
		) ~~|
Density of Recharging Stations[PLUG2]=
	Mathematical Correction Term*ZIDZ(Available Infrastructure f[PLUG2],US Area Square Miles\
		) ~~|
```

```
Density of Recharging Stations[BSS]=
        ZIDZ(Available Infrastructure f[BSS],US Area Square Miles)
        ~       stations/(miles*miles)
        ~       Specifically for the recharging choice decision between Level 2 public \
                recharging stations and FAST public recharging stations, we compute the \
                density of recharging stations. This formulation is the same as in View: \
                Infrastructure - Fuel Search Cost. However, to avoid cycling of \
                calculations, we create a new variable.
        |

FE fixed i  = A FUNCTION OF( ) ~~|
FE fixed i[Technology]=
        FE i[Technology]
        ~       miles/GGE
        ~               |

Fuel Dispensing Rate r  = A FUNCTION OF( ) ~~|
Fuel Dispensing Rate r[GASPUMP]=
        600 ~~|
Fuel Dispensing Rate r[DIESELPUMP]=
        600 ~~|
Fuel Dispensing Rate r[BioPUMP]=
        600 ~~|
Fuel Dispensing Rate r[CNGPUMP]=
        400 ~~|
Fuel Dispensing Rate r[H2PUMP]=
        400 ~~|
Fuel Dispensing Rate r[BSS]=
        Battery i[BEVBSS]/(BEV Energy Efficiency*Average FE by Platform i[BEV]*Time to Swap Battery\
                ) ~~|
Fuel Dispensing Rate r[PLUG1]=
        Charge rate[PLUG1] ~~|
Fuel Dispensing Rate r[PLUG2]=
```

```
        Charge rate[PLUG2]
        ~       GGE/hour
        ~       GASOLINEFUEL,DIESELFUEL,BIOFUEL,CNGFUEL,H2FUEL,ELECTRICITY
        |

Infrastructure:
        GASPUMP,DIESELPUMP,BioPUMP, PLUG1, PLUG2,CNGPUMP,H2PUMP,BSS
        ~       stations
        ~       PLUG1 - Level 2 Recharging Station (low power), PLUG2 - FAST Recharging \
                Station (high power), BSS - Battery Swap System
        |

Infrastructure Utilization f  = A FUNCTION OF( -Available Infrastructure f) ~~|
Infrastructure Utilization f[Infrastructure]=
        MIN(0.95,IF THEN ELSE( Demand for Infrastructure f[Infrastructure]>0 , XIDZ( Demand for
Infrastructure f\
                [Infrastructure] , Available Infrastructure f[Infrastructure] , 0 ) , ZIDZ(Demand for
Infrastructure f\
                [Infrastructure],Available Infrastructure f[Infrastructure]) ))
        ~       dmnl
        ~               |

Mathematical Correction Term=
        1000
        ~       dmnl
        ~       Usage of this constant to remove some math errors generated by Vensim at \
                very low values (e-7 or below)
        |

Multiplier for Useful Activities Performed During Recharging=
        0.5
        ~       dmnl
        ~       We used a broad assumption that a certain percentage of total recharging \
                time (25% in this case) is used to perform useful activities. For a Level \
```

```
		2 rechargers that can take 4-6 hours, it could be a 1 hour shopping \
		activity. For a FAST recharger that can take 15 - 30 minutes, it could be \
		a coffee or toilet break.
	|

New Buffer i  = A FUNCTION OF( a i) ~~|
New Buffer i[Technology]=
	MIN(a i[Technology]*0.9, Distance to Station to Buffer i[Technology])
	~	miles/vehicles
	~		|

OOF Cost Recharging Decision[PLUG1]=
	Value of Time*"Out-of-Fuel Recovery Time"*Probability OOF Recharging Decision[PLUG1]\
		~~|
OOF Cost Recharging Decision[PLUG2]=
	Value of Time*"Out-of-Fuel Recovery Time"*Probability OOF Recharging Decision[PLUG2]\
		~~|
OOF Cost Recharging Decision[BSS]=
	Value of Time*"Out-of-Fuel Recovery Time"*Probability OOF Recharging Decision[BSS]
	~	$/vehicle
	~	Specifically for the recharging choice decision between Level 2 public \
		recharging stations and FAST public recharging stations, we compute the \
		cost of running out of fuel(i.e, time cost of recovering a vehicle that \
		has run out of charge when searching for recharging station). This \
		formulation is the same as in View: Infrastructure - Fuel Search Cost. \
		However, to avoid cycling of calculations, we create a new variable.
	|

"Out-of-Fuel Recovery Time"=
	5
	~	hour/vehicles
	~		|
```

```
PI=
	3.14159
	~	dmnl
	~		|

Probability OOF Recharging Decision[PLUG1]=
	EXP(-Density of Recharging Stations[PLUG1]*PI*New Buffer i[BEV]^2*Average Distance Unit Correction\
		/Mathematical Correction Term
	) ~~|
Probability OOF Recharging Decision[PLUG2]=
	EXP(-Density of Recharging Stations[PLUG2]*PI*New Buffer i[BEV]^2*Average Distance Unit Correction\
		/Mathematical Correction Term
) ~~|
Probability OOF Recharging Decision[BSS]=
	EXP(-Density of Recharging Stations[BSS]*PI*New Buffer i[BEVBSS]^2*Average Distance Unit Correction\
		/Mathematical Correction Term
)
	~	dmnl
	~	Specifically for the recharging choice decision between Level 2 public \
		recharging stations and FAST public recharging stations, we compute the \
		probability of running out of fuel when searching for recharging station. \
		This formulation is the same as in View: Infrastructure - Fuel Search \
		Cost. However, to avoid cycling of calculations, we create a new variable.
	|

Refueling Cost Recharging Decision[PLUG1]=
	Search Cost Recharging Decision[PLUG1]+OOF Cost Recharging Decision[PLUG1]+Service Cost Recharging Decision\
		[PLUG1]+Wait Cost Recharging Decision[PLUG1] ~~|
Refueling Cost Recharging Decision[PLUG2]=
	Search Cost Recharging Decision[PLUG2]+OOF Cost Recharging Decision[PLUG2]+Service Cost Recharging Decision\
```

```
		[PLUG2]+Wait Cost Recharging Decision[PLUG2]
	~	$/vehicle
	~	Specifically for the recharging choice decision between Level 2 public \
		recharging stations and FAST public recharging stations, we compute the \
		total time cost of recharging activity. This formulation is the same as in \
		View: Infrastructure - Fuel Search Cost. However, to avoid cycling of \
		calculations, we create a new variable.
	|

Search Cost Recharging Decision[PLUG1]=
	Value of Time*Average Distance to Recharging Station[PLUG1]/Average Speed ~~|
Search Cost Recharging Decision[PLUG2]=
	Value of Time*Average Distance to Recharging Station[PLUG2]/Average Speed ~~|
Search Cost Recharging Decision[BSS]=
	Value of Time*Average Distance to Recharging Station[BSS]/Average Speed
	~	$/vehicle
	~	Specifically for the recharging choice decision between Level 2 public \
		recharging stations and FAST public recharging stations, we compute the \
		search cost (i.e, time cost of searching for a recharging station). This \
		formulation is the same as in View: Infrastructure - Fuel Search Cost. \
		However, to avoid cycling of calculations, we create a new variable.
	|

Service Cost Recharging Decision[PLUG1]=
	MAX(0, Value of Time*(1-Multiplier for Useful Activities Performed During Recharging\
		)*(Transaction Time+(a i[BEV]-New Buffer i[BEV])/(Fuel Dispensing Rate r[PLUG1]*FE
fixed i\
		[BEV]))) ~~|
Service Cost Recharging Decision[BSS]=
	MAX(0, Value of Time*(1-Multiplier for Useful Activities Performed During Recharging\
		)*(Transaction Time+(a i[BEVBSS]-New Buffer i[BEVBSS])/(Fuel Dispensing Rate r[BSS]\
		*FE fixed i[BEVBSS
	]))) ~~|
```

```
Service Cost Recharging Decision[PLUG2]=
        MAX(0, Value of Time*(1-Multiplier for Useful Activities Performed During Recharging\
                )*(Transaction Time+(a i[BEV]-New Buffer i[BEV])/(Fuel Dispensing Rate r[PLUG2]*FE
fixed i\
                [BEV])))
        ~       $/vehicle
        ~       Specifically for the recharging choice decision between Level 2 public \
                recharging stations and FAST public recharging stations, we compute the \
                service cost (i.e, time cost of recharging plus transaction). This \
                formulation is the same as in View: Infrastructure - Fuel Search Cost. \
                However, to avoid cycling of calculations, we create a new variable. Note \
                that some part of the service time is compensated for by conducting useful \
                activities such as shopping or toilet break. We use a variable called \
                "Multiplier for Useful Activities" to account for the extent of \
                compensation.
        |

Target Probability of Recharging at L2 and FAST[PLUG1]=
        ZIDZ(Refueling Cost Recharging Decision[PLUG2],Refueling Cost Recharging Decision[PLUG1\
                ]+Refueling Cost Recharging Decision[PLUG2]) ~~|
Target Probability of Recharging at L2 and FAST[PLUG2]=
        ZIDZ(Refueling Cost Recharging Decision[PLUG1],Refueling Cost Recharging Decision[PLUG1\
                ]+Refueling Cost Recharging Decision[PLUG2])
        ~       dmnl
        ~       We used a weighted average formulation to calculate the target probability \
                of recharging at each of the Level 2 and Fast Recharging Stations. The \
                probability of recharging at a particular type of recharging station is \
                inversely proportional to the total time cost of recharging at that type \
                of station.
        |

Target Queue Time f[Infrastructure]=
        0.008
```

```
	~	hour/vehicles
	~		|

Target Utilization f[Infrastructure]=
	0.2
	~	dmnl
	~		|

Technology:
	GAS, HEV, PHEV, BEV, CNG ,Diesel,H2,Bio, BEVBSS
	~
	~		|

Time parameter=
	TIME STEP
	~	year
	~	This time parameter is used to model the delay in the system's response to \
		changes in attractivess of different recharging types.
	|

Transaction Time=
	0.0833
	~	hour/vehicle
	~	0.083333
	|

US Area Square Miles=
	3.79e+06
	~	miles*miles
	~		|

Value of Time=
	40
```

```
	~	$/hour
	~		|

Wait Cost Recharging Decision[PLUG1]=
	Value of Time*Target Queue Time f[PLUG1]*ZIDZ( ( XIDZ(1 , (1-Infrastructure Utilization f\
		[PLUG1])^Alpha, 0) - 1 ) , XIDZ( Target Utilization f[PLUG1] , (1 - Target Utilization f\
		[PLUG1]),0 ) ) ~~|
Wait Cost Recharging Decision[PLUG2]=
	Value of Time*Target Queue Time f[PLUG2]*ZIDZ( ( XIDZ(1 , (1-Infrastructure Utilization f\
		[PLUG2])^Alpha, 0) - 1 ) , XIDZ( Target Utilization f[PLUG2] , (1 - Target Utilization f\
		[PLUG2]),0 ) )
	~	$/vehicle
	~	Specifically for the recharging choice decision between Level 2 public \
		recharging stations and FAST public recharging stations, we compute the \
		wait cost (i.e, time cost of waiting for recharging). This formulation is \
		the same as in View: Infrastructure - Fuel Search Cost. However, to avoid \
		cycling of calculations, we create a new variable.
	|
```

Addition of Business Models:

We have added two business models whose formulations can be found below.

Business Model 1

```
Actual Number of BM1 Infrastructure= INTEG (
	Change in Size of BM1 Infrastructure-Infrastructure Exits,
		11000)
	~	stations
	~	The actual number of BM1 Infrastructure is captured in a stock variable. \
		It changes dynamically based on the changes in demand for BM1 \
		infrastructure. The inflow into the stock is the change in size of \
		required BM1 infrastructure, and the outflow is the retirement of \
		recharging stations.
	|

Actual Size of BM1 Fleet= INTEG (
```

```
	Change in Size of BM1 Fleet-Retirement of BM1 Fleet,
		190000)
	~	vehicles
	~	The actual size of the BM1 fleet is captured in a stock variable. It \
		changes dynamically based on the changes in demand for BM1 services. The \
		inflow into the stock is the change in size of BM1 fleet, and the outflow \
		is the retirement of vehicles in the BM1 fleet.
	|

Annual Energy Consumption of BM1 Fleet=
	Annual VMT of BM1 Fleet*BEV Energy Efficiency
	~	kW*hour
	~	We calculate the annual energy consumption of the entire BM1 fleet because \
		we want to calculate the net profits for the BM1 Infrastructure owner from \
		the electricity sales to BM1 fleet.
	|

Annual VMT of BM1 Fleet=
	IF THEN ELSE(Time>Start Year of BM1,Percentage of VMT by BM1 Fleet*Total Annual LDV VMT
in US Market
	,0)
	~	miles/year
	~	Since we assume that a percentage of US LDV VMT is captured by BM1, we \
		multiply the assumed percentage with total US LDV VMT to calculate the \
		total annual VMT driven by the entire BM1 fleet.
	|

Average Speed=
	40
	~	miles/hour
	~		|

Average Speed of BM1 Fleet Operation=
```

```
	20
	~	miles/hour
	~	This number was selected based on the daily VMT numbers we had from the \
		"Autonomous Vehicles" group of MITEI Mobility of Future. Daily VMT was \
		around 240 miles for a taxi in a major US city.
	|

BEV Energy Efficiency=
	0.28
	~	kW*hour/miles [0.2,0.5,0.05]
	~	0.25
	|

BM1 Fleet Driver Percentage Waiting Time=
	0.25
	~	dmnl
	~	This number was selected based on the daily VMT numbers we had from the \
		"Autonomous Vehicles" group of MITEI Mobility of Future. Daily VMT was \
		around 240 miles for a taxi in a major US city.
	|

BM1 Fleet Vehicle Lifetime=
	5
	~	years/vehicle [0,15,2]
	~	From Beijing data, we found that the average lifetime of a taxi is about 6 \
		years. This data is obtained from MITEI Mobility of Future's "Vehicles and \
		Fuels" workstream.
	|

Change in Size of BM1 Fleet=
	IF THEN ELSE(Time > Start Year of BM1, MAX(0,(ZIDZ((Target Size of BM1 Fleet-Actual Size of
BM1 Fleet\
		),Time to form perception of Demand))+Retirement of BM1 Fleet), 0)
```

```
	~	vehicles/year
	~	To match the "actual size of BM1 fleet" with "target size of BM1 fleet", \
		we use a flow variable called "Change in size of BM1 fleet" which is \
		calculated based on the delay it takes to recognize the change in demand \
		for BM1 fleet vehicles. The flow variable also compensates for the loss in \
		size of fleet due to retirement of vehicles.
	|

Change in Size of BM1 Infrastructure=
	MIN(SMOOTH((MAX(0,(Required Number of BM1 Infrastructure+Infrastructure Exits-Actual
Number of BM1 Infrastructure\
		)
	/(TIME STEP*64)
	))/Pumps per Station f
	[PLUG2],Time to form perception of Demand),Construction limit of Recharging Infrastructure\
		)
	~	stations/year
	~	To match the "Actual Number of BM1 Infrastructure" with "Required Number \
		of BM1 Infrastructure", we use a flow variable called "Change in Size of \
		BM1 Infrastructure" which is calculated based on the delay it takes to \
		recognize the change in demand for BM1 Infrastructure. The flow variable \
		also compensates for the loss in numbers of recharging infrastructures due \
		to their retirement.
	|

Charge rate  = A FUNCTION OF( ) ~~|
Charge rate[PLUG1]=
	Reference charge rate[PLUG1]*((1-Sensitivity of Charge Rate to Experience)+Sensitivity of
Charge Rate to Experience\
		*(Effect of Technical Progress on Charge Rate)) ~~|
Charge rate[PLUG2]=
	Reference charge rate[PLUG2]*((1-Sensitivity of Charge Rate to Experience)+Sensitivity of
Charge Rate to Experience\
		*(Effect of Technical Progress on Charge Rate))
```

```
	~	GGE/hour
	~	The charge rate is the reference rate modified by an effect of progress in \
		battery and charging technology.  The sensitivity parameter controls the \
		strength of the effect.
	|

Construction limit of Recharging Infrastructure=
	5e+10
	~	stations/year
	~	We limit the Maximum number of recharging stations that can be constructed \
		in an year to control the artificial spikes/modeling error.
	|

Cumulative Profits for BM1 Fleet Owner  = A FUNCTION OF( ) ~~|
Cumulative Profits for BM1 Fleet Owner= INTEG (
	Annual Profits for BM1 Fleet Owner,
		0)
	~	$
	~	We calculate the cumulative profits for BM1 Fleet owner by summing up the \
		annual profits. Note that this value is already discounted since the \
		inputs themselves are discounted. So, this value is the total profits in \
		terms of $ value at the start of BM1.
	|

Cumulative Profits for BM1 Infrastructure Owner  = A FUNCTION OF( ) ~~|
Cumulative Profits for BM1 Infrastructure Owner= INTEG (
	Total Annual Profits for BM1 Infrastructure Owner,
		0)
	~	$
	~	The cumulative profits for BM1 Infrastructure owner are calculated by \
		summing up the annual profits every year. Note that the annual profits are \
		discounted to a value at the start of BM1 (for example: 2015 in our case) \
		before being added to the cumulative number.
```

|

Daily Driving Distance BM1 Fleet Vehicle=

250

~ miles/day/vehicles [0,400,50]

~ We find this number to be 240 miles for a US taxi. We got this information from the \
MITEI Mobility of Future's Autonomous Vehicles workstream. It was also \
verified with the 400 km daily VMT of a taxi in Beijing.

Changed Dec 27, 2018: Average Speed of BM1 Fleet Operation*(1-BM1 Fleet \
Driver Percentage Waiting Time)*Hours of Operation of BM1 Fleet

|

Daily Energy Consumption of BM1 Fleet=

Daily Driving Distance BM1 Fleet Vehicle*BEV Energy Efficiency*Actual Size of BM1 Fleet

~ hour*kW/day

~ Computing daily energy consumption of BM1 fleet by dividing he annual \
energy consumption by the number of days in an year.

|

Daily Energy per BM1 car=

ZIDZ(Daily Energy Consumption of BM1 Fleet,Actual Size of BM1 Fleet)

~

~ |

Daily VMT of BM1 Fleet=

Annual VMT of BM1 Fleet/Days in a Year

~ miles/day

~ Dividing the annual VMT of BM1 Fleet by the number of days in an year to \
calculate the daily VMT of a BM1 fleet.

|

Days in a Year=

```
	365
	~	days/year
	~	Self-explanatory
	|

Fast Recharger Maximum Daily Energy Supply=
	Fast Recharging Station Power*Hours in a day*Units correction
	~	hour*kW/pumps/day
	~	Calculating the maximum energy that can be supplied by a fast recharging \
		pump in one day. It is calculated by multiplying the power of FAST \
		recharging station with the number of hours in a day.
	|

Fast Recharging Station Power=
	50
	~	kW [50,350,50]
	~	Since we define the recharging rate of FAST recharging stations in miles/hour, we \
		create this variable which converts the miles/hour number into kW terms.

		Changed 12/27: BEV Energy Efficiency*Charge rate[PLUG2]*FE by Platform by \
		Fuel ir[BEV,ELECTRICITY]
	|

FE by Platform by Fuel ir  = A FUNCTION OF( ) ~~|
FE by Platform by Fuel ir[Technology,Fuels]=
	IF THEN ELSE(Technology=PHEV :AND: Fuels=ELECTRICITY, Average FE by Platform i[BEV],\
		 Fuel Usage Matrix ir[Technology,Fuels]*Average FE by Platform i[Technology])
	~	miles/GGE
	~	IF THEN ELSE(Technology = BEV,Fuel Usage Matrix ir[Technology,Fuels] *Native units \
		to GGE Electricity
		/EE by Platform i[BEV] , IF THEN ELSE((Technology=PHEV :AND: Fuels = ELECTRICITY), \
		Fuel Usage Matrix ir
		[Technology,Fuels
```

```
		] *Native units to GGE Electricity/EE by Platform i[PHEV] , Fuel Usage Matrix \
		ir[Technology,Fuels]*
		Average FE by Platform i[Technology] ) )
	|

Fuels:
	GASOLINEFUEL,DIESELFUEL,BIOFUEL,CNGFUEL,H2FUEL,ELECTRICITY
	~	
	~		|

Hours in a day=
	24
	~	hours/day
	~	Self-explantory
	|

Hours of Operation of BM1 Fleet=
	16
	~	hours/vehicles
	~	This number was selected based on the daily VMT numbers we had from the \
		"Autonomous Vehicles" group of MITEI Mobility of Future. Daily VMT was \
		around 240 miles for a taxi in a major US city.
	|

Infrastructure:
	GASPUMP,DIESELPUMP,BioPUMP, PLUG1, PLUG2,CNGPUMP,H2PUMP,BSS
	~	stations
	~	PLUG1 - Level 2 Recharging Station (low power), PLUG2 - FAST Recharging \
		Station (high power), BSS - Battery Swap System
	|

Infrastructure Exits=
```

```
	IF THEN ELSE(Time>Start Year of BM1,Actual Number of BM1 Infrastructure/Infrastructure Life
f\
		[PLUG2],0)
	~	pumps/year
	~	The outflow representing the retirement of recharging stations from the \
		BM1 Infrastructure stock due to age, repair, etc. It is modeled as a \
		first-order outflow.
	|

Infrastructure Life f[Infrastructure]=
	20
	~	year [10,30,2]
	~		|

Initial BM1 Fleet Size=
	IF THEN ELSE(Time>Start Year of BM1,1e+06,0)
	~	vehicles [0,5e+06]
	~	We use 1M vehicles as the initial size of BM1 Fleet. This is based on the data that \
		there are 1M Uber vehicles on the road today.
		https://therideshareguy.com/how-many-uber-drivers-are-there/
	|

Initial Number of BM1 Infrastructure=
	IF THEN ELSE(Time>Start Year of BM1,50000,0)
	~	stations [0,100000]
	~	Since we have about 1M BM1 vehicles initially, we use a 1:20 ratio to \
		determing the initial number of BM1 Infrastructure. Note that we have 1 \
		pump per Fast recharging station.
	|

Installed Base i  = A FUNCTION OF( -Actual Size of BM1 Fleet) ~~|
Installed Base i[Technology]=
	IF THEN ELSE(Technology = BEV, Vehicles 0 to 4 years i[BEV]+Used Vehicles i[BEV]+Actual Size of
BM1 Fleet\
```

```
                , Vehicles 0 to 4 years i[Technology]+Used Vehicles i[Technology])
        ~       vehicles
        ~               |

Percentage of VMT by BM1 Fleet=
        IF THEN ELSE(Switch for Ramp up vs Steady BM1=1, Ramp up of BM1, Steady Share of BM1\
                )
        ~       dmnl
        ~       How much of the total VMT of LDV can the BM1 capture? The higher the \
                number, the higher will be the savings for the fleet owner. With higher \
                savings, the more will be the number of recharging stations built through \
                BM1 and its corresponding effect on BEV adoption.
        |

Pumps per Station f[Infrastructure]=
        8, 2, 2,3,1,2,2,1
        ~       pump / stations
        ~               |

Ramp up of BM1=
        RAMP(0.0005,2018,2028)
        ~       dmnl
        ~       In reality, BM1 is expected to capture the target % of VMT over a few years. So, a \
                ramp-up profile for BM1 makes practical sense, however, this change \
                confounds the effects of BM1 on other parts of the model. So, we also have \
                a steady share profile for BM1 to isolate the effects of BM1 from the \
                increase in modal share of BM1.

                IF THEN ELSE(Switch between BM1 Scenarios = 0, RAMP(0,2015,2025), IF THEN \
                ELSE(Switch between BM1 Scenarios=1,RAMP(0.0001
                ,2015,2025), IF THEN ELSE(Switch between BM1 Scenarios=2,RAMP(0.0005,2015,2025),
IF \
                THEN ELSE(Switch between BM1 Scenarios
```

```
		=3,RAMP(0.001,2015,2025),0))))
	|

Required Number of BM1 Infrastructure=
	IF THEN ELSE(Time>Start Year of BM1,Daily Energy Consumption of BM1 Fleet/(Fast Recharger
Maximum Daily Energy Supply
	*Target Utilization of BM1 Infrastructure),0)
	~	pumps
	~	If the daily energy demand of the BM1 fleet has to be met and at the \
		target utilization rate for recharging infrastructure, this is the minimum \
		number of FAST recharging pumps required.
	|

Retirement of BM1 Fleet=
	Actual Size of BM1 Fleet/BM1 Fleet Vehicle Lifetime
	~	vehicles/year
	~	The outflow representing the retirement of vehicles from the BM1 fleet due \
		to age, repair, accidents, etc. It is modeled as a first-order outflow.
	|

Start Year of BM1=
	2018
	~	dmnl [2015,2050,5]
	~	We assume that the BM1 starts in 2015.
	|

Steady Share of BM1=
	0.005
	~	dmnl [0,1,0.05]
	~	In reality, BM1 is expected to capture the target % of VMT over a few years. So, a \
		ramp-up profile for BM1 makes practical sense, however, such a profile has \
		two impacts -- one from BM1, and one from changing share of BM1. This \
		makes it hard to isolate the effects of BM1, so, we have a steady share \
```

```
		profile for BM1 to isolate the effects of BM1.
		
		Change 12/27: Instead of using BM1 Scenarios, we are going to have "Steady \
		Share of BM1" as an exogenous variable. IF THEN ELSE(Switch between BM1 \
		Scenarios=0, 0, IF THEN ELSE(Switch between BM1 Scenarios=1, 0.001, IF \
		THEN ELSE(Switch between BM1 Scenarios=2, 0.005, IF THEN ELSE(Switch \
		between BM1 Scenarios=3, 0.01,0))))
	|

Switch between BM1 Scenarios=
	1
	~	dmnl
	~	We define three scenarios for the scale of Business Model 1. This variable \
		is 0 when the Business Model is off. It is 1 for the least aggressive \
		scenario (0.1% all LDV VMT is captured by BM1), 2 for moderately \
		aggressive scenario (0.5% all LDV VMT is captured by BM1), 3 for most \
		aggressive scenario (1% all LDV VMT is captured by BM1). As of 2017, 0.5% \
		of all LDV trips are by for-hire vehicles - \
		https://www.mdpi.com/2413-8851/2/3/79. We have to find data on % of VMT \
		driven by for-hire vehicles as against personal vehicles.
	|

Switch for Ramp up vs Steady BM1=
	0
	~	dmnl
	~	0 for Steady Share of BM1, while 1 for Ramp Up of BM1.
		In reality, BM1 is expected to capture the target % of VMT over a few \
		years. So, a ramp-up profile for BM1 makes practical sense, however, this \
		change confounds the effects of BM1 on other parts of the model. So, we \
		also have a steady share profile for BM1 to isolate the effects of BM1 \
		from the increase in modal share of BM1.
	|
```

```
Target Size of BM1 Fleet=
	Daily VMT of BM1 Fleet/Daily Driving Distance BM1 Fleet Vehicle
	~	vehicles [0,5e+06]
	~	We calculate the target number of vehicles in the BM1 fleet by dividing \
		the daily VMT demand of the entire BM1 fleet by the daily VMT driven by a \
		single BM1 fleet vehicle.
	|

Target Utilization of BM1 Infrastructure=
	0.75
	~	dmnl [0,1,0.05]
	~	We use 25% as the target utilization for BM1's Fast recharging \
		infrastructure. The reason to select this number is to allow for \
		infrastructure use by non-BM1 vehicles. Having said that, this is a \
		subjective number, and a sensitivity analysis is required to gauge the \
		influence of this number on the financial viability of the Business Model.
	|

Technology:
	GAS, HEV, PHEV, BEV, CNG ,Diesel,H2,Bio, BEVBSS
	~
	~		|

Time to Form Cost Perception=
	1/12
	~	year
	~		|

Time to form perception of Demand=
	1
	~	year
	~	We use a subjective number of 1 year to model the delay in recognition of \
		changes in demand.
```

```
	|

Total Annual LDV VMT in US Market=
	SUM(Installed Base i[Technology!]*VMT per Year i[Technology!])
	~	miles/year
	~	Self-explanatory
	|

Total Installed Base=
	SUM(Installed Base i[Technology!])
	~	vehicles
	~		|

Total Profits from BM1 Partnership=
	Cumulative Profits for BM1 Fleet Owner+Cumulative Profits for BM1 Infrastructure Owner
	~	$ [0,?]
	~	We calculate the total profits from the ownership by summing up the \
		cumulative profits from each of the stakeholders - BM1 Infrastructure \
		Owner, and BM1 Fleet Owner. Note that this value is already discounted \
		since the inputs themselves are discounted. So, this value is the total \
		profits in terms of $ value at the start of BM1.
	|

Units correction=
	1
	~	1/pumps
	~	Self-explanatory
	|

Vehicle Lifetime=
	15
	~	year
	~		|
```

```
VMT per Year i  = A FUNCTION OF( ) ~~|
VMT per Year i[Technology]= INTEG (
        Change in VMT per Year i[Technology],
                Indicated VMT per Year i[Technology])
        ~       miles/vehicles/year
        ~       Initialized to the indicated value.
        |
 Actual Number of BM1 Infrastructure  = A FUNCTION OF( Change in Size of BM1 Infrastructure\
                ) ~~|
Actual Number of BM1 Infrastructure= INTEG (
        Change in Size of BM1 Infrastructure-Infrastructure Exits,
                11000)
        ~       stations
        ~       The actual number of BM1 Infrastructure is captured in a stock variable. \
                It changes dynamically based on the changes in demand for BM1 \
                infrastructure. The inflow into the stock is the change in size of \
                required BM1 infrastructure, and the outflow is the retirement of \
                recharging stations.
        |

Annual Capital Expenditure for BM1 Infrastructure Owner=
        MAX(0,Change in Size of BM1 Infrastructure*Infrastructure Life f[PLUG2]*Infrastructure Fixed
Costs Amortized over 20 years f\
                [PLUG2])
        ~       $/year
        ~       The Annual Capital Expenditure for the Infrastructure Owner depends on the \
                number of BM1 Infrastructure that is constructed in a certain year, and \
                the capital costs required to build a single BM1 Infrastructure. Note that \
                BM1 Infrastructure is all FAST recharging stations.
        |

Annual Energy Consumption of BM1 Fleet  = A FUNCTION OF( ) ~~|
```

```
Annual Energy Consumption of BM1 Fleet=
	Annual VMT of BM1 Fleet*BEV Energy Efficiency
	~	kW*hour
	~	We calculate the annual energy consumption of the entire BM1 fleet because \
		we want to calculate the net profits for the BM1 Infrastructure owner from \
		the electricity sales to BM1 fleet.
	|

Annual Operating Profits from Electricity Sales=
	Annual Energy Consumption of BM1 Fleet*Profit on Unit Electricity Sales
	~	$/year
	~	We calculate the annual operating profits for the BM1 Infrastructure Owner \
		(from electricity sales to BM1 fleet) by multiplying the profit every kWhr \
		of energy sold, and the energy sold annually to BM1 fleet.
	|

BM1 Fleet Driver Percentage Waiting Time=
	0.25
	~	dmnl
	~	This number was selected based on the daily VMT numbers we had from the \
		"Autonomous Vehicles" group of MITEI Mobility of Future. Daily VMT was \
		around 240 miles for a taxi in a major US city.
	|

Cents per Dollar=
	100
	~	cents/$
	~		|

Change in Size of BM1 Infrastructure  = A FUNCTION OF( -Actual Number of BM1 Infrastructure\
		,-TIME STEP,-Pumps per Station f) ~~|
Change in Size of BM1 Infrastructure=
```

```
	MIN(SMOOTH((MAX(0,(Required Number of BM1 Infrastructure+Infrastructure Exits-Actual
Number of BM1 Infrastructure\
		)
	/(TIME STEP*64)
	))/Pumps per Station f
	[PLUG2],Time to form perception of Demand),Construction limit of Recharging Infrastructure\
		)
	~	stations/year
	~	To match the "Actual Number of BM1 Infrastructure" with "Required Number \
		of BM1 Infrastructure", we use a flow variable called "Change in Size of \
		BM1 Infrastructure" which is calculated based on the delay it takes to \
		recognize the change in demand for BM1 Infrastructure. The flow variable \
		also compensates for the loss in numbers of recharging infrastructures due \
		to their retirement.
	|

Cumulative Profits for BM1 Infrastructure Owner= INTEG (
	Total Annual Profits for BM1 Infrastructure Owner,
		0)
	~	$
	~	The cumulative profits for BM1 Infrastructure owner are calculated by \
		summing up the annual profits every year. Note that the annual profits are \
		discounted to a value at the start of BM1 (for example: 2015 in our case) \
		before being added to the cumulative number.
	|

Discount Rate=
	0
	~	dmnl [0,1,0.01]
	~	Discount rate is a controversial term that is dependent on the specific \
		characteristics of the project, geographical location, etc. apart from \
		other factors. For a country with high inflation, a higher discount rate \
		is used and vice-versa. A higher discount rate for certain stakeholders \
```

```
		may be too low for a different set of stakeholders, so a consensus is \
		required across various stakeholders before a certain discount rate is \
		used for calculations. In this model, we will use Discount Rate to \
		calculate the "Internal Rate of Return" (IRR).
	|

Discounted Annual Costs for BM1 Infrastructure Owner=
	Annual Capital Expenditure for BM1 Infrastructure Owner/((1+Discount Rate)^(Time-Start Year
of BM1\
		))
	~	$/year
	~	For the purpose of calculating total costs for BM1 Infrastructure Owner, \
		we only include capital expenditure because we assume that the O&M costs \
		and feedstock costs are included in the pricing for electricity that is \
		sold to BM1 Fleet. So, the revenues from selling electricity cancels out \
		the O&M + Feedstock costs for electricity, while the variable called \
		"Profit on Unit Electricity Sales" captures the net profit from selling a \
		kWhr of electricity. Also, we discount the costs incurred at a future \
		point in time by using the parameter "Discount Rate".
	|

Discounted Annual Operating Profits for BM1 Infrastructure Owner=
	Annual Operating Profits from Electricity Sales/((1+Discount Rate)^(Time-Start Year of BM1\
		))
	~	$/year
	~	We take the annual operating profits for BM1 Infrastructure owner at every \
		time step in the simulation, and discount it to a value at the start time \
		of the BM1 using a "Discount Rate" variable. This is done to account for \
		the inflation of costs in the economy and to account for the opportunity \
		costs.
	|

Discounted Annual Savings for BM1 Fleet  = A FUNCTION OF( -Discount Rate,-Time,-Start Year of BM1\
```

```
		) ~~|
Discounted Annual Savings for BM1 Fleet=
	(Additional Annual Profits due to BEV conversion+Annual VOC Savings for BM1 Fleet Owner\
		)/((1+Discount Rate)^(Time-Start Year of BM1))
	~	$/year
	~	We take the annual vehicle operating cost savings for BM1 Fleet owner and \
		discount it to a value at the start of BM1 using the variable "Discount \
		Rate" to account for inflation and opportunity costs.
	|

Effective Price j[TechnologyTo]=
	MSRP j[TechnologyTo]-Vehicle Incentives j[TechnologyTo]+EV Home Charger Cost
j[TechnologyTo\
		]
	~	$/vehicles
	~		|

EV Home Charger Cost j[Technology]=
	0,0,1000,1000,0,0,0,0,1000
	~	$/vehicles
	~	(http://www.homedepot.com/p/Leviton-Evr-Green-400-40-Amp-Indoor-Outdoor-Ele\
		ctric-Vehicle-Charging-Station-410-EVB40-5PT/204126508?N=c3gj#.UXAcxLVjnYM \
		(Cost was 1099 as of 4/18/2013)
	|

Exogenous Gas Tax=
	0
	~	$/GGE
	~		|

Incentive Value BEV=
	7500-RAMP(750,2020,2030)
	~	$/vehicles [?,20000]
```

```
	~		|

Infrastructure:
	GASPUMP,DIESELPUMP,BioPUMP, PLUG1, PLUG2,CNGPUMP,H2PUMP,BSS
	~	stations
	~	PLUG1 - Level 2 Recharging Station (low power), PLUG2 - FAST Recharging \
		Station (high power), BSS - Battery Swap System
	|

Infrastructure Fixed Costs Amortized over 20 years f[Infrastructure]=
	10000,10000, 10000,250,2500 ,10000,10000,50000
	~	$/(year*stations)
	~	Assuming 5k for Level 2, and 50k for Level 3 recharger/plug. Check the \
		Excel "Infrastructure Data from References" for more information.
	|

Infrastructure Life f[Infrastructure]=
	20
	~	year [10,30,2]
	~		|

MSRP j  = A FUNCTION OF( ) ~~|
MSRP j[Technology]=
	IF THEN ELSE(Technology = BEV, (1+Markup)*Vehicle Cost i[Technology] - Manufacturer Subsidy 
i\
		[Technology]+Battery Replacement Costs, (1+Markup)*Vehicle Cost i[Technology] - 
Manufacturer Subsidy i\
		[Technology])
	~	$/vehicles
	~	IF THEN ELSE(Technology=BEV :AND: Time < Manufacturer's subsidy stop time \
		BEV, Manufacturer's Subsidy i[Technology], 0))
	|

Profit on Unit Electricity Sales=
```

```
	0.01
	~	$/(hour*kW) [0,0.5,0.05]
	~	It is assumed that the profit per kWh is fixed at a certain $ value, and \
		the price of electricity is varied as the feedstock costs and O&M costs of \
		electricity change to ensure that the profit margin (in $ terms) remains \
		the same.
	|

Pumps per Station f[Infrastructure]=
	8, 2, 2,3,1,2,2,1
	~	pump / stations
	~		|

Start Year of BM1=
	2018
	~	dmnl [2015,2050,5]
	~	We assume that the BM1 starts in 2015.
	|

Target Utilization of BM1 Infrastructure=
	0.75
	~	dmnl [0,1,0.05]
	~	We use 25% as the target utilization for BM1's Fast recharging \
		infrastructure. The reason to select this number is to allow for \
		infrastructure use by non-BM1 vehicles. Having said that, this is a \
		subjective number, and a sensitivity analysis is required to gauge the \
		influence of this number on the financial viability of the Business Model.
	|

Technology:
	GAS, HEV, PHEV, BEV, CNG ,Diesel,H2,Bio, BEVBSS
	~
	~		|
```

```
TechnologyTo:
        GAS, HEV,PHEV, BEV,Diesel,CNG,H2,Bio, BEVBSS
        ~
        ~               |

Total Annual Profits for BM1 Infrastructure Owner=
        (Discounted Annual Operating Profits for BM1 Infrastructure Owner-Discounted Annual Costs
for BM1 Infrastructure Owner\
                )
        ~       $/year
        ~       The total annual profits are calculated by subtracting the capital \
                expenditure every year from the annual operating profits obtained from \
                electricity sales to BM1 Fleet. The capital expenditure is incurred to \
                build recharging infrastructure to meet the excess demand from BM1 fleet's \
                expansion and also to replace retiring infrastructure.
        |

Total Costs for BM1 Infrastructure Owner= INTEG (
        Discounted Annual Costs for BM1 Infrastructure Owner,
                0)
        ~       $
        ~       The total costs are captured in a stock variable to represent the total \
                expenditure for the BM1 Infrastructure Owner over the simulation time \
                period. However, it has to be noted that O&M costs and feedstock costs are \
                excluded from this variable. Please read the comment on "Discounted Annual \
                Costs for BM1 Infrastructure Owner" to learn more.
        |

Total Operating Profits for BM1 Infrastructure Owner= INTEG (
        Discounted Annual Operating Profits for BM1 Infrastructure Owner,
                0)
        ~       $
```

```
        ~       The total operating profits are captured in a stock variable for the BM1 \
                Infrastructure Owner over the simulation time period.
        |

Vehicle Incentives j  = A FUNCTION OF( ) ~~|
Vehicle Incentives j[TechnologyTo]=
        Incentive Value j[TechnologyTo]*Incentive Active j[TechnologyTo]
        ~       $/vehicles
        ~       Incentive Value j[TechnologyTo]*Incentive Active j[TechnologyTo]
        |
Actual Size of BM1 Fleet  = A FUNCTION OF( Change in Size of BM1 Fleet) ~~|
Actual Size of BM1 Fleet= INTEG (
        Change in Size of BM1 Fleet-Retirement of BM1 Fleet,
                190000)
        ~       vehicles
        ~       The actual size of the BM1 fleet is captured in a stock variable. It \
                changes dynamically based on the changes in demand for BM1 services. The \
                inflow into the stock is the change in size of BM1 fleet, and the outflow \
                is the retirement of vehicles in the BM1 fleet.
        |

Additional Annual Profits due to BEV conversion=
        (Maintenance Days per Mile[GAS] - Maintenance Days per Mile[BEV])*Annual VMT of One BM1
Fleet Vehicle\
                *(Daily Driving Distance BM1 Fleet Vehicle
        *Profits per mile by taxis)*Actual Size of BM1 Fleet
        ~       $/year
        ~       Due to conversion to BEV, the taxis will be utilized more as they will \
                have fewer maintenance days. We try to estimate the profits that could be \
                earned for each of those maintenance days saved, and then estimate the \
                impact on annual profits for a single BM1 taxi.
        |
```

```
Annual BM1 Fleet Investment Cost =
	BEV Price Premium*Change in Size of BM1 Fleet
	~	$/year
	~	Since new vehicles are added to the BM1 fleet every year -- to replace \
		retiring vehicles as well as to meet increase in demand, capital \
		investment costs are incurred every year by the BM1 fleet owner.
	|

Annual Profits for BM1 Fleet Owner=
	(Discounted Annual Savings for BM1 Fleet-Discounted Annual BM1 Fleet Investment Costs\
		)
	~	$/year
	~	While BM1 Fleet Owner benefits from VOC savings by converting their fleet \
		from ICEV to BEV, they also incur capital expenditure in acquiring BEVs. \
		Hence, the annual profits for the BM1 Fleet Owner is calculated by \
		subtracting the annual capital expenditure from the annual savings. Note \
		that this value is already discounted  since the inputs themselves are \
		discounted.
	|

Annual VMT of BM1 Fleet  = A FUNCTION OF( -Time,-Start Year of BM1) ~~|
Annual VMT of BM1 Fleet=
	IF THEN ELSE(Time>Start Year of BM1,Percentage of VMT by BM1 Fleet*Total Annual LDV VMT
in US Market
	,0)
	~	miles/year
	~	Since we assume that a percentage of US LDV VMT is captured by BM1, we \
		multiply the assumed percentage with total US LDV VMT to calculate the \
		total annual VMT driven by the entire BM1 fleet.
	|

Annual VMT of One BM1 Fleet Vehicle=
	IF THEN ELSE(Time>Start Year of BM1,ZIDZ(Annual VMT of BM1 Fleet,Actual Size of BM1 Fleet\
```

```
        ),0)
    ~       miles/year/vehicle
    ~       We compute the actual VMT a single BM1 fleet vehicle drives by diving the \
            annual VMT driven by the BM1 fleet by the size of the fleet.
    |

Annual VOC Savings for BM1 Fleet Owner=
    VOC Savings*Annual VMT of BM1 Fleet/Cents per Dollar
    ~       $/year
    ~       We calculate the net savings per year for BM1 fleet owner by multiplying \
            the VOC savings per mile with the total miles driven annually by the BM1 \
            fleet.
    |

Average life of battery=
    100000
    ~       miles
    ~       We see product guarantees of 100,000 miles from OEMs selling BEVs. We \
            assume a 200,000 mile life for a BEV fleet vehicle's battery since the \
            recharging cycles for fleet vehicles are tightly controlled to optimize \
            for battery life.
    |

Battery Cost i  = A FUNCTION OF( ) ~~|
Battery Cost i[Technology]=
    (Battery i[Technology]*IF THEN ELSE(Switch for Learning vs Two Step Model,Unit Battery Cost
Learning Curve Based\
            [Technology
    ],Unit Battery Cost Two Step))*"Test Variable: Battery Cost"
    ~       $/vehicles
    ~               |

BEV Energy Efficiency=
```

0.28

~ kW*hour/miles [0.2,0.5,0.05]

~ 0.25

|

BEV Price Premium=

MSRP j[BEV]-MSRP j[GAS]+Total Battery Replacement Cost

~ $/vehicle

~ Apart from battery replacement costs, BEVs are also more expensive than \
ICEVs. So, when the BM1 fleet gets converted from ICEV to BEVs, an \
additional cost is incurred per vehicle.

|

BM1 Fleet Vehicle Lifetime=

5

~ years/vehicle [0,15,2]

~ From Beijing data, we found that the average lifetime of a taxi is about 6 \
years. This data is obtained from MITEI Mobility of Future's "Vehicles and \
Fuels" workstream.

|

BM1 Infrastructure Owner Profit per mile=

BEV Energy Efficiency*Profit on Unit Electricity Sales*Cents per Dollar

~ cents/miles

~ The feedstock costs of electricity are included in the Vehicle Operating \
Cost calculations, and we now calculate the profit margin (in $/mile \
terms) that the BM1 Infrastructure Owner charges the BM1 fleet.

|

Cents per Dollar=

100

~ cents/$

~ |

```
Change in Size of BM1 Fleet  = A FUNCTION OF( -Time,-Start Year of BM1,-Actual Size of BM1 Fleet\
		) ~~|
Change in Size of BM1 Fleet=
	IF THEN ELSE(Time > Start Year of BM1, MAX(0,(ZIDZ((Target Size of BM1 Fleet-Actual Size of
BM1 Fleet\
		),Time to form perception of Demand))+Retirement of BM1 Fleet), 0)
	~	vehicles/year
	~	To match the "actual size of BM1 fleet" with "target size of BM1 fleet", \
		we use a flow variable called "Change in size of BM1 fleet" which is \
		calculated based on the delay it takes to recognize the change in demand \
		for BM1 fleet vehicles. The flow variable also compensates for the loss in \
		size of fleet due to retirement of vehicles.
	|

Cumulative Profits for BM1 Fleet Owner= INTEG (
	Annual Profits for BM1 Fleet Owner,
		0)
	~	$
	~	We calculate the cumulative profits for BM1 Fleet owner by summing up the \
		annual profits. Note that this value is already discounted since the \
		inputs themselves are discounted. So, this value is the total profits in \
		terms of $ value at the start of BM1.
	|

Daily Driving Distance BM1 Fleet Vehicle=
	250
	~	miles/day/vehicles [0,400,50]
	~	We find this number to be 240 miles for a US taxi. We got this information from the \
		MITEI Mobility of Future's Autonomous Vehicles workstream. It was also \
		verified with the 400 km daily VMT of a taxi in Beijing.

		Changed Dec 27, 2018: Average Speed of BM1 Fleet Operation*(1-BM1 Fleet \
```

```
		Driver Percentage Waiting Time)*Hours of Operation of BM1 Fleet
	|

Discount Rate=
	0
	~	dmnl [0,1,0.01]
	~	Discount rate is a controversial term that is dependent on the specific \
		characteristics of the project, geographical location, etc. apart from \
		other factors. For a country with high inflation, a higher discount rate \
		is used and vice-versa. A higher discount rate for certain stakeholders \
		may be too low for a different set of stakeholders, so a consensus is \
		required across various stakeholders before a certain discount rate is \
		used for calculations. In this model, we will use Discount Rate to \
		calculate the "Internal Rate of Return" (IRR).
	|

Discounted Annual BM1 Fleet Investment Costs=
	Annual BM1 Fleet Investment Cost/((1+Discount Rate)^(Time-Start Year of BM1))
	~	$/year
	~	We take the annual vehicle operating cost savings for BM1 Fleet owner and \
		discount it to a value at the start of BM1 using the variable "Discount \
		Rate" to account for inflation and opportunity costs.
	|

Discounted Annual Savings for BM1 Fleet=
	(Additional Annual Profits due to BEV conversion+Annual VOC Savings for BM1 Fleet Owner\
		)/((1+Discount Rate)^(Time-Start Year of BM1))
	~	$/year
	~	We take the annual vehicle operating cost savings for BM1 Fleet owner and \
		discount it to a value at the start of BM1 using the variable "Discount \
		Rate" to account for inflation and opportunity costs.
	|
```

```
Maintenance Days per Mile[GAS]=
	112/300000 ~~|
Maintenance Days per Mile[BEV]=
	12/300000
	~	days/miles
	~	One of the advantages of BEV is the lower maintenance requirements, \
		specifically engine oil changes and drive train maintenance. Tesloop \
		estimates that their BEV had 12 days in service repair shop over 300k \
		miles while a comparable ICEV would have had 100-112 days in service \
		repair shop for the same distance. While they don't tell you the time it \
		took to reach 300k miles, we break it down into days/mile calculation. \
		Source: \
		https://www.tesloop.com/blog/2017/8/30/tesla-model-s-hits-300k-miles-with-l\
		ess-than-11k-maintenance-costs
	|

MSRP j  = A FUNCTION OF( ) ~~|
MSRP j[Technology]=
	IF THEN ELSE(Technology = BEV, (1+Markup)*Vehicle Cost i[Technology] - Manufacturer Subsidy
i\
		[Technology]+Battery Replacement Costs, (1+Markup)*Vehicle Cost i[Technology] -
Manufacturer Subsidy i\
		[Technology])
	~	$/vehicles
	~	IF THEN ELSE(Technology=BEV :AND: Time < Manufacturer's subsidy stop time \
		BEV, Manufacturer's Subsidy i[Technology], 0))
	|

Number of battery replacements=
	BM1 Fleet Vehicle Lifetime*Annual VMT of One BM1 Fleet Vehicle/Average life of battery
	~	1/vehicle
	~	We have two lifetimes for BEVs - one for the glider (vehicle chassis, \
		suspensions, drive systems, etc.) and one for the battery. While the \
		glider's lifetime is defined in years, the battery's lifetime is defined \
```

```
		in miles driven. We use this variable to calculate the number of times \
		battery will be replaced during one life-time of a BEV glider.
	|

Post BEV Fleet VOC=
	Vehicle Operating Cost in Cents i[BEV]+BM1 Infrastructure Owner Profit per mile
	~	cents/miles
	~	If the BM1 fleet is converted to BEVs, this will be the operating costs \
		for the vehicle on a per-mile basis. VOC - Vehicle Operating Costs.
	|

Pre BEV Fleet VOC=
	Vehicle Operating Cost in Cents i[GAS]
	~	cents/miles
	~	If the BM1 fleet had not converted to BEVs and continued to be ICEVs, this \
		will be the operating costs for the vehicle on a per-mile basis.VOC - \
		Vehicle Operating Costs.
	|

Profit on Unit Electricity Sales=
	0.01
	~	$/(hour*kW) [0,0.5,0.05]
	~	It is assumed that the profit per kWh is fixed at a certain $ value, and \
		the price of electricity is varied as the feedstock costs and O&M costs of \
		electricity change to ensure that the profit margin (in $ terms) remains \
		the same.
	|

Profits per mile by taxis=
	0.3
	~	$/mile
	~	We find that for every mile of taxi driven, the drivers earn a profit of 30 cents.
		Source: \
```

https://www.npr.org/sections/thetwo-way/2018/03/02/590168381/uber-lyft-driv\
ers-earning-a-median-profit-of-3-37-per-hour-study-says

|

Residual Value of Battery=

0.1

~ dmnl

~ We use 10% of MSRP of Battery as the residual value of the battery at the \
end of its life. We use the decimal value instead of using percentage \
numbers. In other words, 10% = 0.1.

|

Start Year of BM1=

2018

~ dmnl [2015,2050,5]

~ We assume that the BM1 starts in 2015.

|

Technology:

GAS, HEV, PHEV, BEV, CNG ,Diesel,H2,Bio, BEVBSS

~

~ |

Total Battery Replacement Cost=

0

~ $/vehicle

~ The total battery replacement cost over the lifetime of a BEV is \
calculated by multiplying the number of times the battery is replaced, and \
the cost of replacement everytime a battery is replaced.

|

Total Investment Costs= INTEG (

Discounted Annual BM1 Fleet Investment Costs,

```
		0)
	~	$
	~	We calculate the cumulative investment costs for BM1 Fleet owner by \
		summing up the annual investment cost. Note that this value is already \
		discounted since the inputs themselves are discounted. So, this value is \
		the total investment costs in terms of $ value at the start of BM1.
	|

Total Savings= INTEG (
	Discounted Annual Savings for BM1 Fleet,
		0)
	~	$
	~	We calculate the cumulative savings for BM1 Fleet owner by summing up the \
		annual savings. Note that this value is already discounted since the \
		inputs themselves are discounted. So, this value is the total savings in \
		terms of $ value at the start of BM1.
	|

Vehicle Operating Cost in Cents i  = A FUNCTION OF( -Cents per Dollar) ~~|
Vehicle Operating Cost in Cents i[Technology]=
	Vehicle Operating Cost i[Technology]*Cents per Dollar+Current VMT Tax
	~	cents/miles
	~		|

VOC Savings=
	Pre BEV Fleet VOC-Post BEV Fleet VOC
	~	cents/miles
	~	The basic concept of BM1 is that a taxi fleet will convert their fleet of \
		vehicles from IC engined vehicles to Battery Electric Vehicles, and \
		thereby, reduce their operating costs due to fuel cost savings (BEVs are \
		more energy efficient than ICEVs; Globally, electricity is usually cheaper \
		than gasoline for one unit of energy, though in the US, it is not really \
		so.) To calculate the reduction in operating costs, we calculate the \
```

```
		ICEV's operating cost per mile and BEV's operating cost per mile, and then \
		subtract the two numbers.
	|

Ancillary Revenues=
	0.2
	~	dmnl
	~		|

Ancillary Revenues Per Station  = A FUNCTION OF( -Subscription Fee per vehicle) ~~|
Ancillary Revenues Per Station[Infrastructure]=
	IF THEN ELSE(Infrastructure=BSS, ZIDZ((Subscription Fee per vehicle[BEVBSS]*Installed Base i\
		[BEVBSS]),Available Infrastructure f[BSS]),0)
	~	$/ year /stations
	~	The subscription fee paid by BEV owners for accessing battery swap \
		infrastructure is divided equally among all the battery swap stations and \
		added to the "Ancillary Revenues Per Station" for [BSS].
	|

BEVBSS Introduction Date=
	2015
	~	year
	~		|

BEVBSS Percent Home Charging=
	0.9
	~	
	~		|

Discount Rate=
	0
	~	dmnl [0,1,0.01]
	~	Discount rate is a controversial term that is dependent on the specific \
		characteristics of the project, geographical location, etc. apart from \
```

```
		other factors. For a country with high inflation, a higher discount rate \
		is used and vice-versa. A higher discount rate for certain stakeholders \
		may be too low for a different set of stakeholders, so a consensus is \
		required across various stakeholders before a certain discount rate is \
		used for calculations. In this model, we will use Discount Rate to \
		calculate the "Internal Rate of Return" (IRR).
	|

Discounted Profits[BSS]=
	Station Profit f[BSS]/((1+Discount Rate)^(Time-BEVBSS Introduction Date))
	~	$/station
	~	The station profits for BSS infrastructure are discounted by an \
		appropriate discount rate.
	|

Infrastructure:
	GASPUMP,DIESELPUMP,BioPUMP, PLUG1, PLUG2,CNGPUMP,H2PUMP,BSS
	~	stations
	~	PLUG1 - Level 2 Recharging Station (low power), PLUG2 - FAST Recharging \
		Station (high power), BSS - Battery Swap System
	|

Profits from BSS Station[BSS]= INTEG (
	Discounted Profits[BSS],
		0)
	~	$/station
	~	The discounted profits are then summed up over time to calculate the \
		"Stock" of profits accumulated at every BSS station.Note: We need to stop \
		the accumulation at the end of life for the infrastructure. We use 20 \
		years as the life of infrastructure currently.
	|

Station Profit f  = A FUNCTION OF( -Time,-Ancillary Revenues Per Station) ~~|
```

```
Station Profit f[GASPUMP]=
        IF THEN ELSE(Platform Introduction Date j[GAS]>Time,0,(Pump Operating Profits r[GASPUMP\
                ]*Pumps per Station f[GASPUMP])+Ancillary Revenues Per
Station[GASPUMP]+Infrastructure Incentive f\
                [GASPUMP]-Infrastructure Fixed Costs Amortized over 20 years f[GASPUMP]) ~~|
Station Profit f[CNGPUMP]=
        IF THEN ELSE(Platform Introduction Date j[CNG]>Time,0,(Pump Operating Profits r[CNGPUMP\
                ]*Pumps per Station f[CNGPUMP])+Ancillary Revenues Per
Station[CNGPUMP]+Infrastructure Incentive f\
                [CNGPUMP]-Infrastructure Fixed Costs Amortized over 20 years f[CNGPUMP]) ~~|
Station Profit f[H2PUMP]=
        IF THEN ELSE(Platform Introduction Date j[H2]>Time,0,(Pump Operating Profits r[H2PUMP\
                ]*Pumps per Station f[H2PUMP])+Ancillary Revenues Per
Station[H2PUMP]+Infrastructure Incentive f\
                [H2PUMP]-Infrastructure Fixed Costs Amortized over 20 years f[H2PUMP]) ~~|
Station Profit f[PLUG1]=
        IF THEN ELSE(EV Platform Earliest Introduction Year>Time,0,(Pump Operating Profits r\
                [PLUG1]*Pumps per Station f[PLUG1])+Ancillary Revenues Per
Station[PLUG1]+Infrastructure Incentive f\
                [PLUG1]-Infrastructure Fixed Costs Amortized over 20 years f[PLUG1]) ~~|
Station Profit f[DIESELPUMP]=
        IF THEN ELSE(Platform Introduction Date j[Diesel]>Time,0,(Pump Operating Profits
r[DIESELPUMP\
                ]*Pumps per Station f[DIESELPUMP])+Ancillary Revenues Per
Station[DIESELPUMP]+Infrastructure Incentive f\
                [DIESELPUMP]-Infrastructure Fixed Costs Amortized over 20 years f[DIESELPUMP]) ~~|
Station Profit f[BioPUMP]=
        IF THEN ELSE(Platform Introduction Date j[Bio]>Time,0,(Pump Operating Profits r[BioPUMP\
                ]*Pumps per Station f[BioPUMP])+Ancillary Revenues Per
Station[BioPUMP]+Infrastructure Incentive f\
                [BioPUMP]-Infrastructure Fixed Costs Amortized over 20 years f[BioPUMP]) ~~|
Station Profit f[BSS]=
        IF THEN ELSE(Platform Introduction Date j[BEVBSS]>Time,0,(Pump Operating Profits r[BSS\
                ]*Pumps per Station f[BSS])+Ancillary Revenues Per Station[BSS]+Infrastructure
Incentive f\
                [BSS]-Infrastructure Fixed Costs Amortized over 20 years f[BSS]) ~~|
```

```
Station Profit f[PLUG2]=
        IF THEN ELSE(EV Platform Earliest Introduction Year>Time,0,(Pump Operating Profits r\
                [PLUG2]*Pumps per Station f[PLUG2])+Ancillary Revenues Per
Station[PLUG2]+Infrastructure Incentive f\
                [PLUG2]-Infrastructure Fixed Costs Amortized over 20 years f[PLUG2])
        ~       $/(stations*year)
        ~               |

Subscription Fee per vehicle[BEVBSS]=
        200
        ~       $/vehicle/year
        ~       In the Business Model 3, we assume that a BEV owner pays an annual \
                subscription fee to access a Battery Swap station. According to current \
                assumptions, the owner will still pay for the energy cost of recharging \
                the battery, and the subscription fee only provides access to the battery \
                swap stations.
        |

Time to Swap Battery=
        0.083
        ~       hours
        ~       We assume a time of 5 minutes to swap out the depleted battery and insert \
                a fully charged battery.
        |
Actual Probability of Recharging Level 2 vs FAST vs BSS[PLUG1]= INTEG (
        Change in Probability of Recharging Level 2 vs FAST vs BSS[PLUG1],
                0.1) ~~|
Actual Probability of Recharging Level 2 vs FAST vs BSS[PLUG2]= INTEG (
        Change in Probability of Recharging Level 2 vs FAST vs BSS[PLUG2],
                0.1) ~~|
Actual Probability of Recharging Level 2 vs FAST vs BSS[BSS]= INTEG (
        Change in Probability of Recharging Level 2 vs FAST vs BSS[BSS],
                0.8)
```

```
	~
	~		|

Change in Probability of Recharging Level 2 vs FAST vs BSS[PLUG1]=
	ZIDZ(Target Probability of Recharging Level 2 vs FAST vs BSS[PLUG1]-Actual Probability of
Recharging Level 2 vs FAST vs BSS\
		[PLUG1],Time Constant) ~~|
Change in Probability of Recharging Level 2 vs FAST vs BSS[PLUG2]=
	ZIDZ(Target Probability of Recharging Level 2 vs FAST vs BSS[PLUG2]-Actual Probability of
Recharging Level 2 vs FAST vs BSS\
		[PLUG2],Time Constant) ~~|
Change in Probability of Recharging Level 2 vs FAST vs BSS[BSS]=
	ZIDZ(Target Probability of Recharging Level 2 vs FAST vs BSS[BSS]-Actual Probability of
Recharging Level 2 vs FAST vs BSS\
		[BSS],Time Constant)
	~	dmnl
	~	To dynamically adjust the "Actual Probability of Recharging at Level 2 vs \
		FAST vs BSS" such that it matches the "Target Probability of recharging at \
		Level 2 vs FAST vs BSS", we use this flow variable. We use a variable \
		called Time Constant to model the lag in the response of the system to the \
		changes in attractiveness of Level 2 vs FAST vs BSS.
	|

Full Refueling Cost i  = A FUNCTION OF( -Search Cost i,-Wait Cost i,-Service Cost i,-OOF Cost i\
		) ~~|
Full Refueling Cost i[GAS]=
	(Search Cost i[GASPUMP]+Wait Cost i[GASPUMP]+Service Cost i[GASPUMP]+OOF Cost
i[GASPUMP\
		])*Number of Refuels per Year i[
	GAS]*Platform Introduced j[GAS]*IF THEN ELSE(Refueling possibility i[GAS]=0, 2, 1) ~~|
Full Refueling Cost i[Diesel]=
	(Search Cost i[DIESELPUMP]+Wait Cost i[DIESELPUMP]+Service Cost i[DIESELPUMP]+OOF Cost i\
		[DIESELPUMP])*Number of Refuels per Year i
	[Diesel]*Platform Introduced j[Diesel]*IF THEN ELSE(Refueling possibility i[Diesel]=\
```

```
            0, 2, 1) ~~|
Full Refueling Cost i[H2]=
      (Search Cost i[H2PUMP]+Wait Cost i[H2PUMP]+Service Cost i[H2PUMP]+OOF Cost i[H2PUMP]\
            )*Number of Refuels per Year i[H2]*
      Platform Introduced j[H2]*IF THEN ELSE(Refueling possibility i[H2]=0, 2, 1) ~~|
Full Refueling Cost i[CNG]=
      (Search Cost i[CNGPUMP]+Wait Cost i[CNGPUMP]+Service Cost i[CNGPUMP]+OOF Cost
i[CNGPUMP\
            ])*Number of Refuels per Year i[
      CNG]*Platform Introduced j[CNG]*IF THEN ELSE(Refueling possibility i[CNG]=0, 2, 1) ~~|
Full Refueling Cost i[Bio]=
      (Search Cost i[BioPUMP]+Wait Cost i[BioPUMP]+Service Cost i[BioPUMP]+OOF Cost i[BioPUMP\
            ])*Number of Refuels per Year i[
      Bio]*Platform Introduced j[Bio]*IF THEN ELSE(Refueling possibility i[Bio]=0, 2, 1) ~~|
Full Refueling Cost i[HEV]=
      (Search Cost i[GASPUMP]+Wait Cost i[GASPUMP]+Service Cost i[GASPUMP]+OOF Cost
i[GASPUMP\
            ])*Number of Refuels per Year i[
      HEV]*Platform Introduced j[HEV]*IF THEN ELSE(Refueling possibility i[HEV]=0, 2, 1) ~~|
Full Refueling Cost i[BEV]=
      ((Search Cost i[PLUG1]+Wait Cost i[PLUG1]+Service Cost i[PLUG1]+OOF Cost i[PLUG1])*Number
of Refuels per Year i\
            [BEV]*Platform Introduced j [BEV]*IF THEN ELSE(Refueling possibility i[BEV]=0, 2, 1\
            )*Target Probability of Recharging at L2 and FAST[PLUG1])+((Search Cost i[PLUG2]+Wait
Cost i\
            [PLUG2]+Service Cost i[PLUG2]+OOF Cost i[PLUG2])*Number of Refuels per Year
i[BEV]*\
            Platform Introduced j
      [BEV]*IF THEN ELSE(Refueling possibility i[BEV]=0, 2, 1)*Target Probability of Recharging at L2
and FAST\
            [PLUG2]) ~~|
Full Refueling Cost i[BEVBSS]=
      ((Search Cost i[PLUG1]+Wait Cost i[PLUG1]+Service Cost i[PLUG1]+OOF Cost i[PLUG1])*Number
of Refuels per Year i\
            [BEVBSS]*Platform Introduced j [BEVBSS]*IF THEN ELSE(Refueling possibility i[BEVBSS\
```

```
                ]=0, 2, 1)*BSS Vehicle Charging Percentage[PLUG1])+((Search Cost i[PLUG2]+Wait Cost i\
                [PLUG2]+Service Cost i[PLUG2]+OOF Cost i[PLUG2])*Number of Refuels per Year
i[BEVBSS\
                ]*Platform Introduced j[BEVBSS]*IF THEN ELSE(Refueling possibility i[BEVBSS]=0, 2, \
                1)*BSS Vehicle Charging Percentage[PLUG2])+((Search Cost i[BSS]+Wait Cost
i[BSS]+Service Cost i\
                [BSS]+OOF Cost i[BSS])*Number of Refuels per Year i[BEVBSS]*Platform Introduced
j[BEVBSS\
                ]*IF THEN ELSE(Refueling possibility i[BEVBSS]=0, 2, 1)*BSS Vehicle Charging
Percentage\
                [BSS]) ~~|
Full Refueling Cost i[PHEV]=
        (Search Cost i[GASPUMP]+Wait Cost i[GASPUMP]+Service Cost i[GASPUMP]+OOF Cost
i[GASPUMP\
                ])*Number of Refuels per Year i[PHEV]*Platform Introduced j[PHEV]*IF THEN
ELSE(Refueling possibility i\
                [PHEV]=0, 2, 1)
        ~       $/(year*vehicles)
        ~       Search Cost i[Technology]+Wait Cost i[Technology]+Service Cost i[Technology]+OOF \
                Cost i[Technology]
                600,400,1300,2000,2000,800,2000,2000
        |

Infrastructure:
        GASPUMP,DIESELPUMP,BioPUMP, PLUG1, PLUG2,CNGPUMP,H2PUMP,BSS
        ~       stations
        ~       PLUG1 - Level 2 Recharging Station (low power), PLUG2 - FAST Recharging \
                Station (high power), BSS - Battery Swap System
        |

OOF Cost i  = A FUNCTION OF( ) ~~|
OOF Cost i[Infrastructure]=
        Value of Time*"Out-of-Fuel Recovery Time"*Probability OOF i[Infrastructure]
        ~       $/vehicle
        ~               |
```

```
Refueling Cost per Vehicle per Refuel[PLUG1]=
        OOF Cost i[PLUG1]+Search Cost i[PLUG1]+Service Cost i[PLUG1]+Wait Cost i[PLUG1] ~~|
Refueling Cost per Vehicle per Refuel[PLUG2]=
        OOF Cost i[PLUG2]+Search Cost i[PLUG2]+Service Cost i[PLUG2]+Wait Cost i[PLUG2] ~~|
Refueling Cost per Vehicle per Refuel[BSS]=
        OOF Cost i[BSS]+Search Cost i[BSS]+Service Cost i[BSS]+Wait Cost i[BSS]
        ~       $/vehicle/refuel
        ~       The refueling cost per vehicle per refuel is the time cost involved in a \
                refueling activity and is calculated by summing up the four components \
                involved: 1. The time cost of searching for a refueling station, 2. the \
                time cost of waiting to refuel at a refueling station, 3. the time cost of \
                refueling at a refueling station, 4. the cost of running out of fuel when \
                searching for a refueling station.
        |

Search Cost i  = A FUNCTION OF( ) ~~|
Search Cost i[GASPUMP]=
        2*ZIDZ(Value of Time*Average Distance to Station f[GASOLINEFUEL],Average Speed) ~~|
Search Cost i[DIESELPUMP]=
        2*ZIDZ(Value of Time*Average Distance to Station f[DIESELFUEL],Average Speed) ~~|
Search Cost i[BioPUMP]=
        2*ZIDZ(Value of Time*Average Distance to Station f[BIOFUEL],Average Speed) ~~|
Search Cost i[CNGPUMP]=
        2*ZIDZ(Value of Time*Average Distance to Station f[CNGFUEL],Average Speed) ~~|
Search Cost i[H2PUMP]=
        2*ZIDZ(Value of Time*Average Distance to Station f[H2FUEL],Average Speed) ~~|
Search Cost i[PLUG1]=
        2*Search Cost Recharging Decision[PLUG1] ~~|
Search Cost i[BSS]=
        2*Search Cost Recharging Decision[BSS] ~~|
Search Cost i[PLUG2]=
        2*Search Cost Recharging Decision[PLUG2]
```

```
        ~       $/vehicle
        ~       ZIDZ(Value of Time*SQRT(XIDZ(1, (ZIDZ(Available Infrastructure f[PLUG1]+Available \
                Infrastructure f[PLUG2]+Available Infrastructure f
                [BSS],US Area Square Miles))*Average Distance Unit Correction, \
                1e+20))/2,Average Speed)
        |

Service Cost i  = A FUNCTION OF( ) ~~|
Service Cost i[GASPUMP]=
        MAX(0, Value of Time*(Transaction Time+(a i[GAS]-New Buffer i[GAS])/(Fuel Dispensing Rate r\
                [GASPUMP]*FE fixed i
        [GAS])) - Offset of Service Cost by other useful activities i[GASPUMP]) ~~|
Service Cost i[DIESELPUMP]=
        MAX(0, Value of Time*(Transaction Time+(a i[Diesel]-New Buffer i[Diesel])/(Fuel Dispensing
Rate r\
                [DIESELPUMP]*FE fixed i
        [Diesel])) - Offset of Service Cost by other useful activities i[DIESELPUMP]) ~~|
Service Cost i[H2PUMP]=
        MAX(0, Value of Time*(Transaction Time+(a i[H2]-New Buffer i[H2])/(Fuel Dispensing Rate r\
                [H2PUMP]*FE fixed i
        [H2])) - Offset of Service Cost by other useful activities i[H2PUMP]) ~~|
Service Cost i[CNGPUMP]=
        MAX(0, Value of Time*(Transaction Time+(a i[CNG]-New Buffer i[CNG])/(Fuel Dispensing Rate r\
                [CNGPUMP]*FE fixed i
        [CNG])) - Offset of Service Cost by other useful activities i[CNGPUMP]) ~~|
Service Cost i[BioPUMP]=
        MAX(0, Value of Time*(Transaction Time+(a i[Bio]-New Buffer i[Bio])/(Fuel Dispensing Rate r\
                [BioPUMP]*FE fixed i
        [Bio])) - Offset of Service Cost by other useful activities i[BioPUMP]) ~~|
Service Cost i[PLUG1]=
        Service Cost Recharging Decision[PLUG1] ~~|
Service Cost i[PLUG2]=
        Service Cost Recharging Decision[PLUG2] ~~|
```

```
Service Cost i[BSS]=
        Service Cost Recharging Decision[BSS]
        ~       $/vehicle
        ~               |

Target Probability of Recharging Level 2 vs FAST vs BSS[PLUG1]=
        (1/Refueling Cost per Vehicle per Refuel[PLUG1])/((1/Refueling Cost per Vehicle per Refuel\
                [PLUG1])+(1/Refueling Cost per Vehicle per Refuel[PLUG2])+(1/Refueling Cost per
Vehicle per Refuel\
                [BSS])) ~~|
Target Probability of Recharging Level 2 vs FAST vs BSS[PLUG2]=
        (1/Refueling Cost per Vehicle per Refuel[PLUG2])/((1/Refueling Cost per Vehicle per Refuel\
                [PLUG1])+(1/Refueling Cost per Vehicle per Refuel[PLUG2])+(1/Refueling Cost per
Vehicle per Refuel\
                [BSS])) ~~|
Target Probability of Recharging Level 2 vs FAST vs BSS[BSS]=
        (1/Refueling Cost per Vehicle per Refuel[BSS])/((1/Refueling Cost per Vehicle per Refuel\
                [PLUG1])+(1/Refueling Cost per Vehicle per Refuel[PLUG2])+(1/Refueling Cost per
Vehicle per Refuel\
                [BSS]))
        ~
        ~       Since the probability of recharging changes dynamically based on the \
                changes in refueling cost at different infrastructures, we compute a \
                target probability for the user to recharge at Level 2 or FAST or Battery \
                swap station. We use a weighted average formulation to compute the target \
                probability of recharging at Level 2, FAST, and Battery swap station \
                infrastructure. Note that the target probability of recharging at a \
                specific type of infrastructure is inversely proportional to the refueling \
                cost at that infrastructure because the higher the refueling cost, the \
                less attractive is it.
        |

Time Constant=
        0.03125
```

```
	~	year
	~	We  use the same value as a TIME STEP = 0.03125 year to model the delay in \
		change of probability of charging at Level 2 vs FAST vs BSS infrastructure.
	|

Wait Cost i  = A FUNCTION OF( ) ~~|
Wait Cost i[Infrastructure]=
	Value of Time*Target Queue Time f[Infrastructure]*ZIDZ( ( XIDZ(1 , (1-Infrastructure Utilization
f\
		[Infrastructure])^Alpha, 0) - 1 ) , XIDZ
	( Target Utilization f[Infrastructure] , (1 - Target Utilization f[Infrastructure]),\
		0 ) )
	~	$/vehicle
	~		|
```

Appendix B: Model Parametization

All the model runs in this work are conducted on Vensim 7.3.5 DSS.

Simulation Control Parameters

FINAL TIME = 2050
Units: year

INITIAL TIME = 2000

Units: year

TIME STEP = 0.03125

Units: year

Integration type: EULER

The following tables present the main parameters used for the Figures 10, 11, 12, and 13:

Model Assumptions	Value	Units
Vehicle Lifetime	15	years
Value of Time	40	$/hour
Annual VMT	12,000	miles/year
LDV Fleet Growth Rate	0.7%	-
AFV Purchase Incentive Sunset Date	2030	year
Median Household Income (2018)	57,000	$/year
EV Home Charger Base Cost	1,000	$
% Energy charged at home- BEV	85%	-
Price Multiplier for Public Level 2 Charging	2	-
Percent of Households with Home Charging	70%	-

Parameter	ICEV	HEV	PHEV	BEV	FCEV	Units
Purchase Incentive*	0	0	4,000	7,500	7,500	$/vehicle
Vehicle MSRP (2018)	20,000	22,500	26,500	37,000	58,000	2018 $
Maximum Range (2018), ideal conditions	400	580	45 Electric, 460 gas	225 Electric	360	miles/refuel
New Vehicle Fuel Economy (2018)	32	55	124 electric 55 gas	124	75	miles/ GGE**

* These incentives ramp down to zero from 2020 to 2030

**Gallons of gas equivalent

Parameter	Gas Station	Level II Charging Stations	Level III Charging Stations	Units
Available Stations (2018)	160,000	16,000	1000	Number of Stations
Infrastructure Lifetime	20	20	20	Years
Pumps/Station	8	3	1	Pumps/Station
Fueling Time/Rate (2018)	5 minutes	25 kW	150kW	-
Fuel Price (2018)	2.87 $/gallon	21 cents/kWh	33 cents/kWh	-

System Dynamics Scenario Energy Prices	Price	Units
Retail Electricity (2030)	12.50	cents/kWh
Retail Electricity (2050)	13.80	cents/kWh
Retail Gasoline (2030)	2.90	$/gallon
Retail Gasoline (2050)	3.00	$/gallon

For Figures 18, 19, 20, 21, the following tables show the major variables and their values.

Type of Cost	Description of Cost	Flat fee	Per kVA	Per kWh	Units
Fixed	Customer Service Charge	1025			$/month
Fixed	Distribution Demand Charge		5.36		cents
Fixed	Production/Transmission Demand Charge		4.82		cents
Variable	Systems Benefit Charge			0.00135	$
Variable	Conservation Charge			0.003	$
Variable	Generation Charge (on-peak)			0.09433	$
Variable	Renewable Energy Charge			0.001	$
Variable	FMCC Delivery Charge			0.00602	$
Variable	FMCC Generation Charge			0.003	$

Parameter	**Value**	**Units**
Capital Cost Of Recharging Station	50,000	$
Number Of Recharging Plugs Per Station	1	Plug
Power Of Fast Recharging Station	50 – 60	kW
Energy per charging event	27.5	kWh
Feedstock Cost Of Electricity	0.28	$/kWh
Life Of Infrastructure	15-20	Years
Life Of Taxi	5	Years
Range Of BEV Taxi	200	Miles
Battery of BEV Taxi	50	kW
Daily Driving Distance Of Taxi	250	Miles
Annual Driving Distance Of Taxi	70,000	Miles
Percent Of Home Recharging For BEV Taxi	60%*	-
ICEV Price (2018)	19,000	$
BEV Price (2018)	30,000	$
Taxes	10%	
ICEV Maintenance Costs	0.061	$/mile
BEV Maintenance Cost	0.026	$/mile
Opportunity Cost Of Taxi	22.9	$/hour
Labor Cost Of Taxi	15	$/hour
BEV Fast Recharging Frequency	0.5	1/day
ICEV Refueling Frequency	0.5	1/day
BEV Recharging Time	36	Minutes
ICEV Refueling Time	5	Minutes
Price Of Electricity At Home	0.13	$/kWh
Price Of Electricity At Fast Recharger Without Business Model 1	0.41	$/kWh
Price Of Electricity At Fast Recharger With Business Model 1	0.3	$/kWh