An Analysis on the Integration of Tesla Semis: The Mathworks Challenge

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Courtesy of tesla.com/semi

Executive Summary

As consumerism becomes more prominent in the United States, more vehicles with more efficient fuel sources are in increasing demand to meet the needs of the people. Electric vehicle companies such as Tesla have led innovations in developing electric semi trucks to compete with diesel semi trucks that are currently on the road. Major companies are looking at electric trucks as a viable replacement for diesel trucks. The task at hand is to construct a mathematical model to evaluate the efficiency of electric semi trucks if they replaced diesel semi trucks. First, the percentage of electric trucks is calculated to be 3.12%, 4.91%, and -11.26% in five, ten, and twenty years, respectively. Then, it is found that no additional charging stations would be needed along the routes of: San Antonio, TX to New Orleans, LA; San Francisco, CA to Los Angeles, CA; Boston, MA to Harrisburg, PA; Minneapolis, MN to Chicago, IL; and Jacksonville, MI to Washingtonm, DC to support the trucking industry if all vehicles were instead electric. Finally, it is found that San Antonio-New Orleans is the trucking corridor that should be developed first, because it had the smallest ratio of charging stations to area, followed closely by the corridor from Jacksonville, PA to Washington DC.

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Introduction

As innovations in battery efficiency and capacity of electric vehicles increase, so do their promise for replacing gasoline-based vehicles. Gasoline-based trucks are incredibly fuel efficient. Indeed, gasoline-based vehicles are responsible for over 12% of America's carbon emission[11]. Many companies are endeavoring to push for ambitious goals to convert their trucking to solely electric trucks. Over the years, the need for shipping and transport has increased. This need has been met in the past by increased use of diesel semi trucks. However, these trucks are very fuel inefficient, which means that this need can be filled by electric trucks.

The electric car company giant Tesla has revolutionized the car industry through their introduction of electric vehicles. The company is releasing a new electric semi in 2020[12]. Despite the benefits of switching to a cleaner energy source with better fuel efficiency, the roads have not been optimized with the ideal number of charging stations for an increase in electric trucks. Thus, there are many highways that can be targeted for development.

Our paper models possible changes in the electric truck industry: the percent of semis that are electric, the number of needed charging stations in a route, and priority of development for different routes.

This report analyzes the information of previous growth of electric cars as a model for the transition to electric semis. It then looks at the area to current stations ratio to create a model for the number additional stations needed and the ranking of the most important corridors to develop

Assumptions

1. The rate that Tesla semis replace diesel semis are the same as that of electric cars.

    Justification: Electric semis and electric cars will have similar properties and appeals because they are manufactured by the same company. They were also made with the same goal of moving to electric energy to increase energy cost efficiency, so consumers may see similar appeals in the electric semi as they do in the electric cars.

2. The number of charges per station is constant for all stations.

    Justification: Stations are made by the same company, so they share features. Every station can accommodate a certain number of cars and the number was assumed to be constant.

3. All reserved Tesla trucks will operate in the United States.

    Justification: Tesla is an American based company, and thus will probably release its models in the US. The companies also have large consumer bases in the US and would benefit from using the semis in the US.

4. Traffic distribution is constant overall and the density of stations in an area was constant.

    Justification: Traffic fluctuates throughout the day and across a highway, so to generalize the traffic information to anytime, it was assumed to be constant. Since the traffic was assumed to be constant, the stations were also assumed to be of uniform density per area to accommodate for the constant traffic.

5. Stations are on the side of the highway.

    Justification: There are many gas stations along major highways. This reduces the amount of energy spent searching for one along the route. Semis don't need to use extra energy in search of a place to refuel during a trip down a highway.

6. The charging stations are located at equidistant points throughout the routes.

    Justification: Clusters of charging stations distributed evenly throughout the United States.

Problem 1: Shape Up or Ship Out

The problem was to create a mathematical model of the percentage of electric semi trucks over 5, 10, and 20 years.

Method 1

The simplest way to approach this problem is to assume that the rate of semi replacement by electric vehicles is the same as the rate of car replacement by electric cars, and that the rate of purchase between cars and trucks would also remain proportionally the same. This function would approximate the amount of electric semi trucks as a function of time, though it would also ignore the qualities that may make the use and implementation of semis unique, such as its mainly commercial use, as opposed to the residential use of electric cars. Even so, the general factors that go into maintaining an electric vehicle as opposed to one powered with gasoline or diesel should be approximately the same.

From two separate data sets, the number of total plug-in electric vehicles and total light vehicle retail sales (including mostly cars) in the United States were taken from the years 2011 to 2017[5][8]. Then, using Excel, the closest regression equations were fit. For the electric vehicles, it was a power equation (see Equation 1.1), and for the total light vehicles, it was an exponential equation (see Equation 1.2). The former equation had an R^2 value of 0.9668, while the latter had an R^2 value of 0.9941. In both equations, the x variable represents the number.

$$num_{EV} = 2.0 \cdot 10^8 \cdot e^{0.0131 x_{EV}}$$

Equation 1.1

$$num_{tV} = -180917 \cdot {x_{tV}}^2 + 6 \cdot 10^6 \cdot x_{tV} - 3 \cdot 10^7$$

Equation 1.2

Using this, the numbers were calculated for five, ten, and twenty years. Then, the num_{EV} was divided by num_{tV} to get the percentage of semis in a particular year. The results are as follows: in 5 years, 3.12% will be semis, in 10 years, 4.91% will be semis. Putting it in 20 years into the model results in a negative solution (-11.26%). This seems irrational, but logically, it would still increase from here.

Method 2

The second method that was considered looked at took more variables into account, but ultimately was scrapped, due to how complicated it made our model. The amount of electric trucks was modeled as a logistical function that took time into account through the use of another variable, A, the quantified advantage of choosing an electric semi over a regular semi.

The logistic function was written as shown in Equation 1.3:

$$S_E = \frac{S_T[t]}{1+ke^{-bA}}$$

Equation 1.3

The variables $S_T[t]$, k, b, and A needed to be defined in order to get a function. Therefore, it was decided to have functions for $S_T[t]$ and A, and assume that b=1 (and have k account for any constant value of k), and then solve for k with the single point of (A, S_E) known, the current A with S_E modeled as the current requests for the Tesla electric semis.

A was modeled as a product of various advantage ratios, which keeps the importance of each ratio intact:

$$A_{total} = A_{annual\ costs} \cdot A_{initial\ costs} \cdot A_{charging\ time}$$

$$A_{total} = \frac{annual\ cost_{regular}}{annual\ cost_{electric}} \cdot \frac{initial\ cost_{regular}}{initial\ cost_{electric}} \cdot \frac{time_{regular}}{time_{electric}}$$

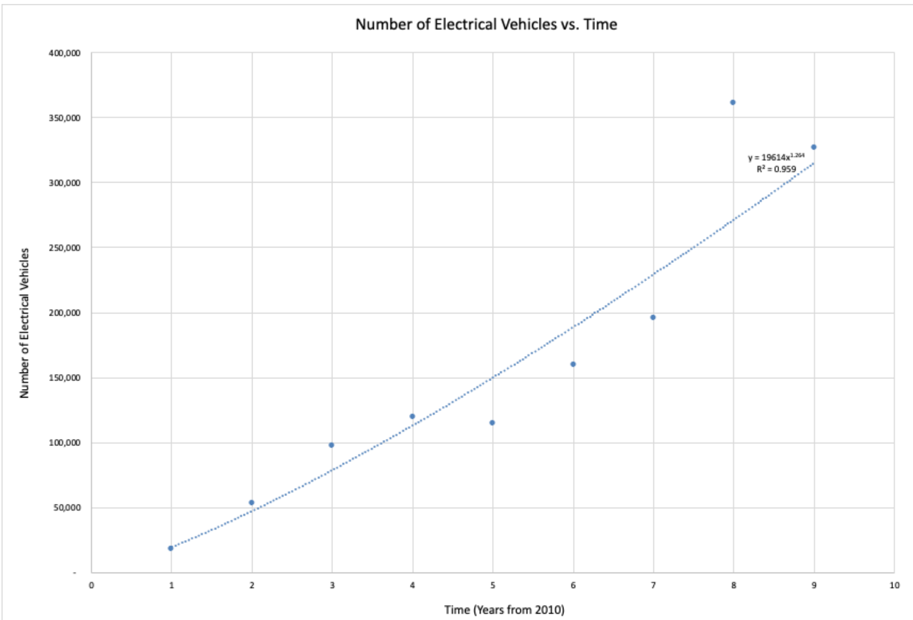
Equation 1.4

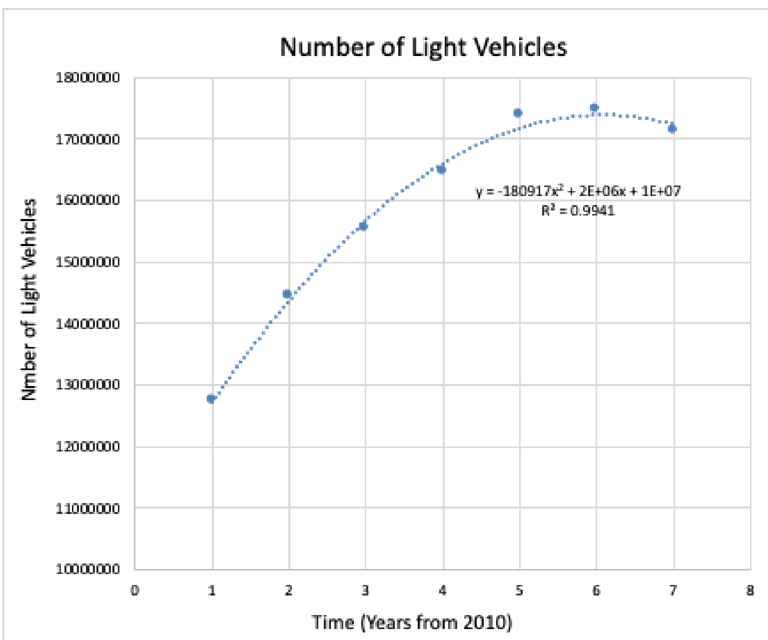
One of the problems with this method was that, even though we attempted to keep the importance of each ratio intact through multiplication, ratios that may be vastly different by nature, such as the time it takes to fully charge a vehicle, $A_{charging\ time}$, would greatly skew our A_{total} value. However, if this problem were to be solved, the flexibility of the A_{total} value means that multiple other factors could be taken into account, and the model could truly be centered around the specifics of semi trucks versus electric semi trucks, rather than be based on how electric cars have compared to regular cars.

Another problem with this approach is that our logistic function, as shown in Equation 1.3, had multiple unknown variables, but only a single point that we knew for sure, the current A_{total} value, as of 2020, and the amount of preorders for the Tesla semi, a truck that hasn't been released yet, and thus doesn't have reliable data for any other points in time. As such, though we could attempt to set b to 1, and thus only have to solve for k, we wouldn't have a truly customized function to our data set.

Solutions

Figure 1.1:





Our overall solution was that the percentage of electric trucks compared to that of regular trucks would be 3.12%, 4.91%, and -11.26% in five, ten, and twenty years, respectively. The first two percentages, 3.12% and 4.91%, seem reasonable estimates of what the percentage of electric cars could be in the next few years. However, the -11.26% that was found for the percentage of electric cars in the next twenty years seems unreasonable. This negative percentage could be indicative of a bug in the analysis of the data, something that would need to be looked at if this model were to be further extended.

Problem 2: In It for The Long Haul

This problem was to create a mathematical model to find the number of needed stations across a given route and how many chargers are sufficient at each station to ensure the current level of single-driver, long haul traffic would be supported if all trucks were electric.

Method

In order to find the number of needed electric-vehicle charging stations across a given route, the additional number of stations as a result of the new electric semi trucks was multiplied by the fraction of charging stations that are on the given route. To calculate the additional number of stations in the US, the total number of electric vehicles on the road had to be divided by the number of cars that can charge per station (number of outlets per charging station) and then subtracted by the current number of stations in the US. The total number of electric vehicles on the road includes the current number of electric cars plus the total number of semi trucks. The current number of electric cars had to be taken into consideration as they will occupy electrical outlets in a station. The total number of semi trucks is equal to the number of semis on the road plus the current reserved number of tesla semis. The total amount of stations that are needed can be quantified through Equation 2.1. The variable x_max signifies the maximum distance the truck driver can travel to reach the nearest electric-vehicle charging station. The x_max was kept at a constant value of 0.01 mi which is the width of the highway as per the assumption that a charging station must be on the side of the road. The variable x_route signifies the length of each given corridor from one city to another in the US. The product of x_route and x_max divided by the area of the US yields the fraction of stations that are on the path of the corridor. The overall number of additional stations was calculated by using the following formula:

$$N = Number\ of\ Additional\ Stations\ Needed$$
$$S_{Tot} = Total\ number\ of\ Semis\ in\ US$$
$$C_{Tot} = Total\ number\ of\ Electric\ and\ Hybrid\ Cars$$
$$S_{Stations} = Total\ Number\ of\ Current\ Stations\ in\ US$$
$$d = maximum\ distance\ from\ Route\ at\ which\ a\ station\ should\ be\ accessible\ (in\ miles)$$
$$R = length\ of\ route\ (in\ miles)$$
$$SA_{US} = Surface\ Area\ of\ the\ US$$
$$O_S = Outlets\ per\ station$$

$$N = \frac{\left(S_{Tot} + C_{Tot} - (O_S * S_{Station})\right) * d * R}{SA_{US}}$$

Equation 2.1

Below is a table of the constants and variables used in the solution:

Constants		
Number of Electric Cars in US	1.00E+06	cars
Number of Regular Semis	1.70E+06	semis
Number of Electric Semis in Reserve	425	semis
Number of Charging Stations	0.00E+00	stations
Surface Area of US	3.53E+06	mi^2
Number of Charging Outlets	57187	outlets
Number of Outlets per Station	2.8563508	outlets/station

Variables	
Distance of Route	411
Maximum Distance Travelled to Get Gas	0.01

Solutions

Overall, no route needed more than 1 additional charging station to ensure that all semis could drive through them. A table indicating the number of charging stations needed for each route is shown below:

Route	Distance	Number of Stations Needed
San Antonio to New Orleans	543	0.29
Minneapolis to Chicago	424	0.23
Jacksonville to Washington DC	706	0.38
Los Angeles to San Francisco	382	0.20
Boston to Harrisburg	411	0.22

Table: The number of charging stations required to charge all current semis for each route.

Although none of the routes are in immediate need of a charging station, San Antonio to New Orleans and Jacksonville to Washington DC need the most number of charging stations across the route. The San Antonio to New Orleans route requires 0.29 stations, while the Jacksonville to Washington DC requires 0.38 stations.

Problem 3: I Like to Move It, Move It

The problem was to make a model that determines which of the given routes had the most immediate concerns to develop electric semi charging stations.

Model

The main hurdle the team had to overcome when approaching this problem was developing a metric to assess the "importance" of adding charging stations to certain stations. The team decided on simulating trucks driving across the routes with a given route distance and a randomized initial battery state. The route would be given a success rate depending on whether they were able to make it through the route without dropping to 0 percent battery. The procedure to calculate the success rate of a given route was as follows:

1. Generate 1 million initial battery states for 1 million simulated trucks.
2. Divide the length of the route in miles by the number of charging stations present to calculate the length between two equidistant charging stations. The battery of the simulated truck decreased as the truck moved along the route.
3. Calculate the maximum number of miles that the simulated truck can travel given its initial batter state.
4. If the maximum number of miles that the simulated truck can travel is less than the length between two equidistant charging stations (ie. the simulated truck won't make it to the next station), label the truck as a "failure case."
5. The success rate then becomes:,

$$Success\ Rate = \frac{Number\ of\ Simulated\ Trucks - Number\ of\ Fails}{Number\ of\ Simulated\ Trucks}$$

where the number of simulated trucks was 1 million.

Solutions

1 million trucks were simulated for each of the five routes provided, and the success rates were calculated. The five routes simulated were:

1. San Antonio, TX to New Orleans, LA
2. San Francisco, CA to Los Angeles, CA
3. Boston, MA to Harrisburg, PA
4. Minneapolis, MN to Chicago, IL
5. Jacksonville, MI to Washington DC, MD

The success rates for each route were re-calculated for five trials.

All routes yielded a success rate greater than 99%, however there were some consistent discrepancies between the routes that allowed for a thorough analysis of what routes should be of prime interest when deciding on where to construct new charging stations. The average standard deviation of all routes was 4.62×10^{-3} %. This indicates that the simulations were precise in their success rate predictions. A table of the results of each trial for each route is shown below:

Success Rates over Trials for Each Route							
	Success Rate						
Route Name	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average	STDEV
	(%)	(%)	(%)	(%)	(%)	(%)	(%)
San Antonio to New Orleans	99.50	99.51	99.51	99.52	99.51	99.51	0.0061
Minneapolis to Chicago	99.78	99.78	99.78	99.78	99.78	99.78	0.0017
Jacksonville to Washington DC	99.65	99.67	99.66	99.65	99.66	99.66	0.0093
Los Angeles to San Francisco	99.93	99.93	99.92	99.92	99.93	99.92	0.0014
Boston to Harrisburg	99.86	99.87	99.86	99.86	99.86	99.86	0.0047

Table 2: The success rates for each route over each trial. The success rates were a function of the number of simulated trucks that failed to drive the full route without running out of battery.

An average of five trials' success rate for each route was plotted in a bar graph to better illustrate visually the routes most in need of additional charging stations. The resulting bar graph is illustrated below:

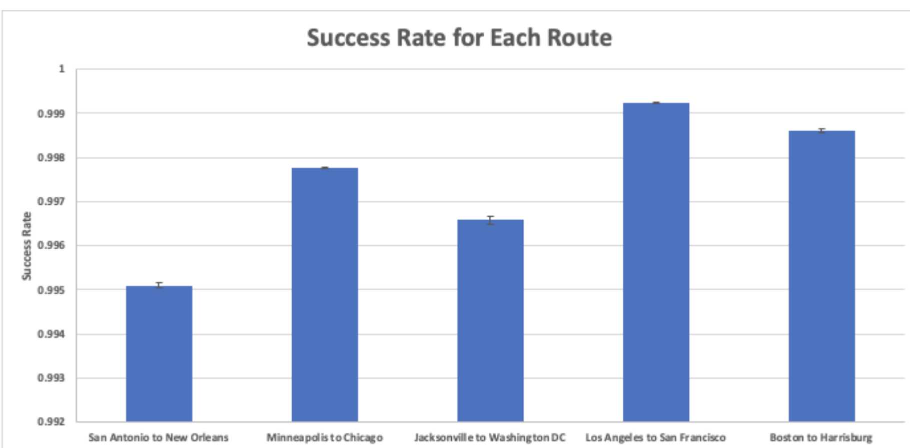


Figure 3: A graph of the average success rates for simulated trucks in each route.

The routes with the lowest average accuracy was the route from San Antonio to New Orleans, and then the route from Jacksonville to Washington, DC. The Los

Angeles to San Francisco had the highest success rate-- therefore, this route was not in immediate need for a new charging station. The most important contributor to the success rates for the routes was most likely the number of currently existing charging stations and the length of the route (in miles).

Discussion

Shape Up or Ship Out

The first method is extremely simple in concept, and is currently more reliable than the second, less developed method. The first method gives a good approximation for the increase in the percentage of electric vehicles, and works for most cases. However, the second method, though complex and currently not solvable, could be more useful, and more accurate, if its bugs were fixed. The second method also promises modularity and the ability to add various other variables as needed, a feature that is lacking in the first solution to the problem.

In It for the Long Haul

The method, used to find the number of charging stations needed for a specific route, first calculates the additional charging stations that will be needed based on the total number of electric cars and semi trucks and multiples this value by the fraction of charging stations that are on the path of a given corridor. The resulting model was considered for the third part of the problem.

I Like to Move It, Move It

The method used to solve this part of the problem uses a program that simulates how often trucks that go through the specific interstates can actually make it to the end of the interstate, given the changes in the initial battery states of the trucks. All routes had a success rate of upwards 99%. However, the San Antonio to New Orleans route and the Jacksonville to Washington DC route consistently had the lowest success rates out of all five routes. The average standard deviation of all routes was approximately 4.63×10^{-3}%.

Conclusions

Overall, the various models that were made satisfy the requirements to solve each problem. The first model gave values of a 3.12%, 4.91%, and -11.26% increase in the percentage of electric vehicles to that of regular vehicles over the course of five, ten, and twenty years, respectively. Though there was a negative increase in percentage after twenty years, which is contrary to what would be expected, and thus is probably indicative of a bug in the model, the initial two increases, 3.12% and 4.91%, are intuitive, and thus probably give a decent approximation for the ratio of electric vehicles to regular vehicles five and ten years from now.

The second model was used to calculate the number of additional charging stations required for a certain route. It concluded that no route had an immediate need for additional charging stations, though the San Antonio to New Orleans route and the Jacksonville to Washington DC route had the most need of the five given corridors. This was reaffirmed by the results of the third model.

The aim of the third model was to develop a metric and method to identify which routes were in most need for charging stations. A series of simulations of trucks driving through the routes was used to conclude that a truck will succeed in driving through all of the routes 99% of the time. However, the problem was to determine the routes which should be targeted for the addition of charging stations. The simulations developed for the third problem concluded again that the Jacksonville to Washington DC routes and the San Antonio to New Orleans routes were in most need for a charging station.

If more time were provided, these models could be extended to be more accurate and incorporate more data. For example, additional factors could be added for the growth rate of the electric vehicles in the first problem, the number of additional charging stations needed along specific routes could account for variations in regional density and voltage of each charging station, as well as whether or not the stations are special types, such as level 2 stations, or DCFCs.

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Appendix A

```
import random

################

# SUCCESS_RATE #

################

def success_rate(route_length, existing_stations=0, added_stations=1):
 '''
 This method calculates the success rate as a decimal for Problem 3.


 Parameters:
 ----------
 route_length (mi): The length of the corridor in miles.\n
 existing_stations: The number of stations along the corridor.\n
 added_stations: The number of stations that must be added\n
 to accomodate for the electric semi trucks.
 '''


 k = 0.1472474 # Simplified version of the constants used in model 2
 x_max =  0.01 # (mi). Specifies the maximum distance to reach the nearest
station.
 num_stations = added_stations + existing_stations
 data = []
 charge_states = [] # (%) list of random charge states
 next_dist = route_length / (1 + num_stations)
 fail = 0
 trials = 1000000
```

```
 battery_miles = 500 # (mi). The number of miles that the Tesla semi can
drive on a full charge.


 for i in range(trials):


     # Generate random charge state from 0 to 100% for the electric semi
trucks

     charge_state = random.randint(0,10000000)/10000000.0

     charge_states.append(charge_state)


     # Calculate the number of times the electric semi truck would have to
be charged

     pred_charge = x_max * route_length * charge_state * k

     data.append(pred_charge)


     if next_dist > (battery_miles * charge_state):

       fail += 1


 # The total number of trials subtracted by the number of fails yields the
number of successes. This number, divided by the total number of trials
yields the percent success rate.

 success_rate = (trials - fail) / trials

 return success_rate


# Prints the success rate for the given corridors as a decimal

print("SAN ANTONIO TX TO NEW ORLEANS LA:")

print("Success Rate:" , success_rate(543, added_stations = 0,
existing_stations = 219), "\n")
```

```
print("MINNEAPOLIS MN TO CHICAGO IL:")

print("Success Rate:" , success_rate(424, added_stations = 0,
existing_stations = 385), "\n")


print("JACKSONVILLE FL TO WASHINGTON DC:")

print("Success Rate:" , success_rate(706, added_stations = 0,
existing_stations = 406), "\n")


print("LOS ANGELES CA TO SAN FRANCISCO CA:")

print("Success Rate:" , success_rate(382, added_stations = 0,
existing_stations = 1005), "\n")


print("BOSTON MA TO HARRISBURG PA:")

print("Success Rate:" , success_rate(411, added_stations = 0,
existing_stations = 604), "\n")
```