Electric Semi Trucks and the Future of US Trucking

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March, 2020

1. Executive Summary

Land-based cargo transportation accounts for a significant portion of the United States' transportation industries and infrastructure. As part of that infrastructure, trucks are responsible for carrying significant portions of what is purchased or used for construction in the United States. This fact alone means that the trucking and transport industries are tremendously important for the US economy, and are a significant part of the US's ability to maintain its status as an economic superpower. [1] [6]

Like any industry, the trucking industry has components that both reinforce and undermine its efficiency. Because of its place as a structural backbone to major US businesses, the inefficiencies that plague the trucking industry can be felt throughout the US economy. One of these major inefficiencies for the trucking industry can be seen in the problem of fuel and its high price. Trucks are large, which means they have to use diesel fuel. The problem lies in the fact that the price of diesel is high, and fuel expenses make up a significant portion of spending, as well as limit the transport of goods due to the high cost [5] [6]. Enter the electric semi truck, a new innovative solution to the problem of diesel prices. In late 2020, production of electric semi trucks will begin. This could revolutionize the trucking industry by replacing the high-cost diesel trucks will lower cost electric alternatives.

For the first problem, we modeled the cost of purchasing and maintaining a single diesel truck using production, fuel, and maintenance rates. After this, we aggregated data to find the total number of diesels at any given time, based on the fact that diesel trucks last only 12 years. Together, this allowed us to generate an equation for the total cost for purchasing and maintaining a certain amount of diesel trucks which would allow us to predict future budgets for diesel trucks. Afterwards, we compared the costs of purchasing and maintaining electric vs. diesel trucks over time to see if and when one would be more profitable than the other. Electric trucks eventually came out on top, which led us to model the percent of trucks that would be electric in the future assuming that companies would always choose to buy as many electric trucks as they could underneath their previously calculated budget. After calculating the various aspects of replacement rates between diesel and electric semi trucks and applying an exponential regression, we found that after 5 years, 21% of trucks would be electric, after 10 years, it reached 51%, and after 20 years it leveled out at 73%. These values were accurate in so far as the supply of electric trucks remained at a constant rate from Tesla, which wasn't realistic given basic supply and demand relationships.

For the next part of the question, we had to first figure out where to place charging stations along the five corridors we were asked to test, as well as how many charging ports would have to be in each station. We approached the problem with the intent to minimize traffic and maximize the time efficiency by reducing time wasted waiting for charging stations to be available. By spacing

out charging stations based on the maximum distance a truck could travel before having to recharge, we minimized the number of charging stations necessary to support the number of trucks that traveled on each corridor by calculating the AAHTT for each corridor. To find how many charging ports were needed at each station, we multiplied the AAHTT by the number of hours it took to fully charge a battery according to our source (which was 2.2 hours) to find the total number of charging ports that had to be available for each station. After doing this work, we found not only the number of stations that were needed on each route, but also the cost of upgrading every corridor with the requisite number of stations. This data can be found in figures 5.3.2 and 5.3.3.

Finally, with the cost of upgrading each corridor calculated, we calculated the average monetary values of goods moved through each corridor. We found the net worth of goods transported across the corridors, and subsequently subtracted the costs of upgrading each corridor from the net value of goods transported through that route in order to find the preference rankings of each of the five corridors. Because the values of the corridors were high, and the costs comparatively low, the preference ratings ended up being the same as the highest-lowest values of the corridors. As such, the corridor that contributed the most to the economy (the San Francisco to LA corridor) was found to be the most suitable choice for upgrade.

2. Contents

3. Global Assumptions

- Corporations & companies seek to maximize profits and as such will choose the cheapest option for all cargo activities. In a market system, companies seek to maximize profits and will only change an operating process if the new alternative can save money.
- The lifetime of a semi truck is 12 years [1].
- There are only three types of semi trucks, classified by purpose: long haul, short haul, and regional haul. The only meaningful difference is the average miles traveled by each.
- Diesel prices will remain the same for the duration of the model ($3.17).
    - Justification: It is assumed that the price of diesel will remain the same for the duration of the models. Diesel prices are often related to economic or political circumstances that cannot be predicted. Factors like international conflicts, natural disasters, etc. all can radically change the price of diesel. Because such events have caused prices to change in the past, such as the 2008 Recession, it is assumed that none of these radical changes will occur and that diesel prices will remain the same. We assume that the national average for gas prices ($3.17) will therefore remain constant for the duration of the model. [5]
- Years consist of 261 work days [7].

4. Part 1: Shape up or ship out

4.1 Restatement of the Problem

The problem asks us to do the following:

- Calculate the replacement rate of diesel trucks with electric trucks based on production rate and annual diesel retirement rate.
- Calculate the cost benefits of transitioning from diesel to electric over time.
- Create a mathematical model to predict what percentage of semis will be electric 5, 10, and 20 years from 2020.

4.2 Assumptions

- It is assumed that all infrastructure necessary to transition to an electric semi truck fleet is already in place for companies seeking to transition.
    - Justification: Factoring in the cost of producing and operating necessities and producing all the infrastructure necessary to operate a fleet of semi trucks is a prerequisite for a full transition to electric trucks. As such, it is assumed that all infrastructure required for a transition to take place already exists.

- Production rates of diesel trucks reflect demand rather than manufacturing capability and stay around a constant rate.
- It is assumed that electric semi trucks will be purchased only as replacements for retiring diesel trucks.
    - Justification: The number of trucks in the US fleet is based on demand. Because it is assumed that corporations seek to reduce spending, they will elect to have the minimum number of trucks necessary to execute their services. As such, it is assumed that they will not mass purchase excess trucks or mass retire their fleet.
- It is assumed that cost factors, including grants, incentives, taxes, licenses, permits, tolls, liability, driver wages, etc. are constant/negligible.
    - Justification: Because licenses, permits, tolls, driver wages, etc. remain constant independently of whether diesel or electric semi trucks are in use, these costs are not calculated in terms of cost efficiency differences between electric and diesel trucks because they are constant and simply overlaid on top of the diesel-specific and electric-specific costs.
- Tesla will remain the only manufacturer of electric semi-trucks at a maximum rate of 100,000 per year
- The diesel or electric trucks purchased in a given year are immediately put to use at the beginning of that year.
- It is assumed that electric semi-trucks will have an average cost of $175,000.
    - Justification: As there is limited data on price points for electric semi-trucks, the cost has been determined to be around $175,000 based on the price of the Tesla semi-truck.

4.3 Developing the Model

We began our process by calculating the total money spent on purchasing and maintaining diesel trucks each year before electric trucks enter the market in order to give an idea of how much money all trucking companies in the United States are willing to spend on trucking expenses.

C_{DU} represents the money spent on maintaining/using diesel trucks every year (261 working days [2]) according to diesel prices [5], efficiency [1], maintenance [3], and usage [1]. This value is dependent on T_{DC}, the total number of diesel trucks in commission in that year.

$$C_{D_U} = \left(G_D \cdot E + M\right) \cdot U \cdot 261 \cdot T_{D_C}$$

$$= \left(\frac{\$\,3.17}{gal} \cdot \frac{gal}{5.98\ mi} + \frac{\$\,0.166}{mi}\right) \cdot (0.05 \cdot 164\ mi + 0.45 \cdot 300\ mi + 0.50 \cdot 457\ mi) \cdot 261 \cdot T_{D_C}$$

$$C_{D_U} = \$\,67{,}531.30 \cdot T_{D_C}$$

C_{DP} represents the money spent on purchasing diesel trucks every year. According to an article by Electrek, most diesel semi-trucks today cost around \$120,000 [11]. The total value is dependent on T_{DP}, the total number of diesel trucks produced in a year assuming all of them were purchased and immediately put into use:

$$C_{D_P} = \$\ 120,000 \cdot T_{D_P}$$

Given the number of Class 8 diesel regional ($T_{D:R,P}$) and long-haul($T_{D:L,P}$) trucks produced every year between 1999 and 2019 [13], the fact that diesel trucks typically last about 12 years [1], and the fact that regional and long-haul trucks make up 95% of all semi-trucks, the total number of short, regional, and long-haul trucks in commission (T_{DC}) in year t can be given by the sum of the number of regional and short haul trucks produced in each of the preceding 12 years increased by a factor of $\frac{100}{95}$:

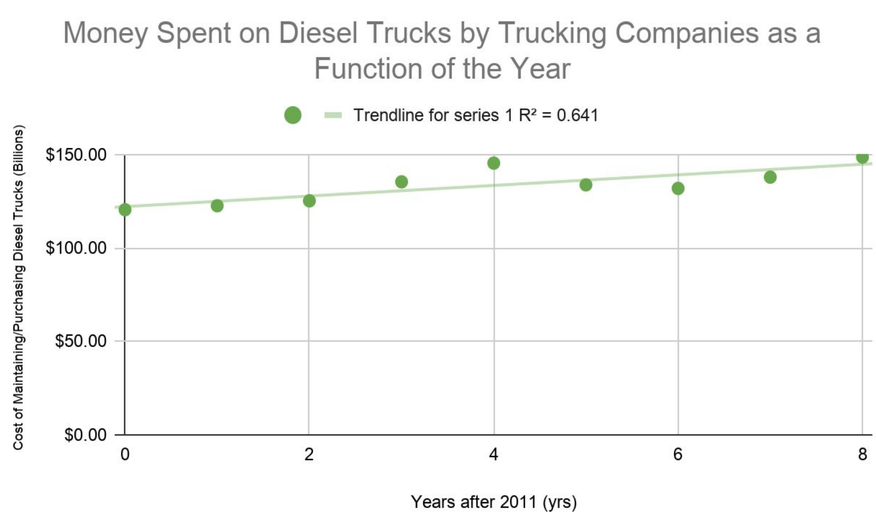
$$\left(T_{D:R_P} + T_{D:L_P}\right) \cdot \frac{100}{95} = T_{D_P}$$

$$\left(\sum_{n=0}^{11} T_{D_P}(t-n)\right) = T_{D_C}(t)$$

We now have enough information to calculate the amount of money spent on buying and maintaining diesel trucks in a given year post-2011 (since 12 preceding years of annual production values are needed):

$$C_D(t) = C_{D_P} + C_{D_U}$$

Plotting $C_D(t)$ from 2011 to 2019 and performing linear regressions yields the following:



The R^2 value 0.641 means 64.1% of the variability in the money that trucking companies spent on diesel trucks is explained by the relationship between the money spent on purchasing/maintaining diesel trucks and years after 2011. Coefficient correlation is equal to 0.80, meaning that we can reasonably model future expenditures with the equation

$$C_D(\tau) = 122.06 + 2.84\tau,$$

where $C(\tau)$ is money spent on diesel trucks billions and τ is the number of years since 2011.

To see whether an electrical semi would provide a cheaper and desirable alternative to traditional diesel trucks, we calculated how many years it would take for the prices to level out. We considered their purchasing cost and their fuel and operational/maintenance costs under the assumption that driver's salaries, permits, tolls, and other similar factors would remain constant and thus could be considered negligible. The average cost of an electric semi-truck was determined to be $175,000 and that of a diesel truck was on average $120,000 [1].

On average, the total cost of a diesel truck (C_{DT}) would be:

$$C_{DT}(t) = C_{DU}(t) + C_{DP} ,$$

where C_{DP} is the initial cost of purchase of a diesel truck ($120,000) and $C_{DU}(t)$ was the operational and maintenance costs of the truck over a given period of years, t, represented in the below equation

$$C_{DU}(t) = (G_D * E_D + M_D) * U * 261t$$

$$C_{DU}(t) = \$67,531.30t ,$$

where G_D is the average price of diesel, E_D was the efficiency of a diesel vehicle, M_D was the cost of maintenance, and U represented the miles driven by the vehicle, or usage. 261 days were used as a measure of how many days the truck is operational in a year, based on a five-day workweek.

The total cost of an electric semi-truck (C_{ET}) based on its average efficiency [1], average charging prices [8], maintenance [3], and usage [1], would be:

$$C_{ET}(t) = C_{EU}(t) + C_{EP} ,$$

where C_{EP} is the initial cost of purchase of a electric truck ($175,000) and $C_{DU}(t)$ was the operational and maintenance costs of the truck over a given period of years, t, represented in the below equation:

$$C_{EU}(t) = (G_E * E_E + M_E) * U * 261t$$

$$= (\frac{\$0.12kwH}{mi} * \frac{mi}{2kWh} + 0.8(0.166)) * (0.05 * 164mi/day + 0.45 * 300mi/day + 0.50 * 457mi/day)$$

$$* 261\ days * t$$

$$= \$18,704.24t$$

To determine when or if the electric semi trucks' expenses became less than those of the diesel trucks, we set equal the total costs of both as functions of time, t.

$$C_{DU}(t) + C_{DP} = C_{EU}(t) + C_{EP}$$

$$67,531.30t + 120{,}000 = 18704.24t + 175{,}000$$

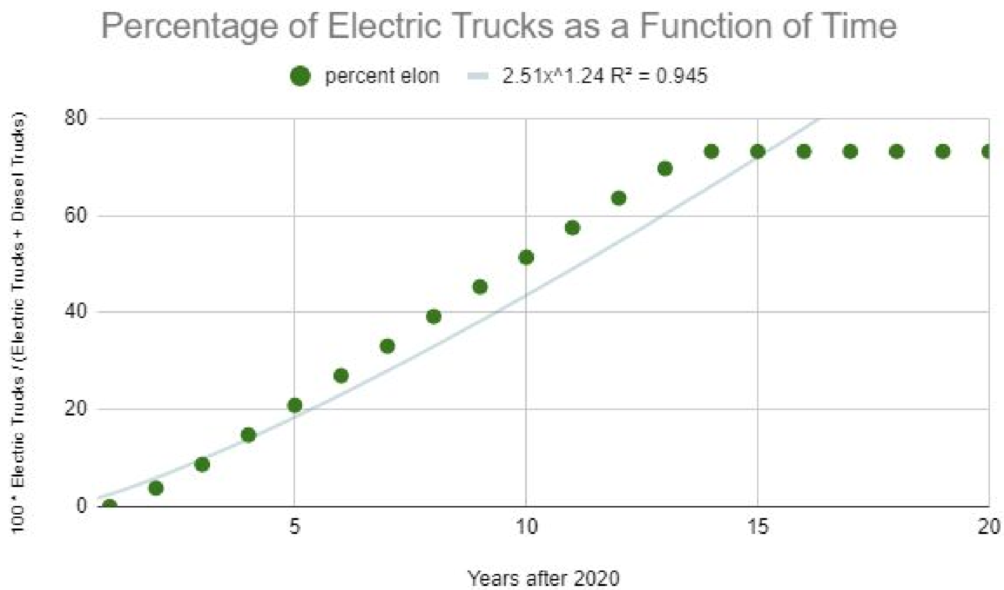
At t = 3.34 years, the total costs of the diesel truck surpass that of the electric truck and continue to grow at a faster rate.

Having shown electric trucks save more money in the long-term compared to diesel trucks, companies are assumed to (a) immediately buy as many electric trucks as possible to maximize long-term profits while (b) keeping their total expenditure under the amount they would have spent on diesel alone. (a) We assumed Tesla would be the only significant manufacturer of electric trucks at a rate of 100,000 per year [15], which would always be bought out first under the average yearly truck demand of 143,293 per year. Afterwards, the 43,283 trucks still needed would be bought as diesel trucks. (b) However, costs would only get as high as the company would have paid if it were exclusively buying diesel trucks that year, which was modeled before by $C_D(\tau)$:

$$C_D(\tau) = C_{E_P} + C_{E_U} + C_{D_P} + C_{D_U}$$

(Projected budget from diesel spendings) = (Cost of producing electric cars) + (Cost of maintaining electric cars) + (Cost of producing diesel cars) + (Cost of maintaining diesel cars)

Knowing the priority of what a company spends its money on, we were able to identify and graph the following relationship between the amount of electric and diesel trucks:



The R^2 value 0.945 means 95.5% of the variability in the percentage of electric trucks as a function of time is explained by the relationship between the equation, meaning that we can reasonably model future expenditures with the equation

$$P_E(\tau) = 2.51\tau^{2.14},$$

where $P_E(\tau)$ is percent of electric trucks in commission and τ is the number of years since 2020.

After calculating the various aspects of replacement rates between diesel and electric semi trucks, we found that after 5 years, 21% of trucks would be electric, after 10 years, it reached 51%, and after 20 years it leveled out at 73%.

4.4 Validity of the Model

Strengths:

- Our model addresses a variety of criteria, including the fuel cost, retirement rate, and purchasing cost to determine what percentage of electric trucks would make up the total truck force.
- The equation modeling total diesel trucks in a given year based on the average life-span of a truck and data on production rates,

$$\left(\sum_{n=0}^{11} T_{D_P}(t-n)\right) = T_{D_C}(t),$$

predicts that 1,826,022 diesel trucks will be in commission in 2019. This is about 6% less than the actual number of diesel trucks (1.7 million) in commission in 2019

- Our model relies heavily on prior data and utilizes that data to make projections for the future, lending to its credibility

Weaknesses:

- Our assumption that Tesla will be the only producer of electric trucks at a maximum of 100,000 per year is inaccurate because an increased demand due to cost efficiency would call for greater supply. Factoring this into our model would require an analysis of the barriers to entry in the electric truck market, participation of other companies in supplying trucks, and an increase Tesla's own output as the companies who bought electric trucks begin to profit and can afford more electric trucks.

5. Part 2: In it for the long haul

5.1: Restatement of the Problem

The problem asks us to do the following:

- Create a mathematical model that determines how many stations are needed along a given route and how many chargers are sufficient at each station to ensure the current level of single-driver haul traffic would be supported.
- Demonstrate how the model works by testing it on the following corridors
  - San Antonio, TX to/from New Orleans, LA
  - Minneapolis, MN, to/from Chicago, IL
  - Boston, MA, to/from Harrisburg, PA
  - Jacksonville, FL, to/from Washington, DC
  - Los Angeles, CA, to/from San Francisco, CA
- Find the cost of the construction of these stations.

5.2 Assumptions

- It is assumed that all of the trucks traveling along the major trucking routes are electric.
  - Justification: In order to make a full upgrade from diesel to electric trucks, US infrastructure must be able to support the current amount of trucks as electric trucks. This means that 1.7 million active trucks would have to be supported. As such, assuming all 1.7 million are electric ensures that no matter how many trucks are converted to electric, the USA's infrastructure will be able to support it.
- An electric truck can travel 400 miles before having to recharge.

   - Justification: A range of 300-500 miles has been given by Tesla, the company currently spearheading production of electric trucks. Because the mean between these two extremes is 400, it is assumed that the distance 400 miles on a full battery capacity is applicable to all electric trucks. [9]
- Batteries for all trucks are the same.
   - Justification: In order to simplify the process of purchasing chargers for trucks, it is assumed that all batteries are produced to the same specifications so as to ensure that chargers are universal. As a result of this assumption, all battery capacities and maximum distances are also the same. [12]
- The United States government will pay for all upgrades on trucking routes.
   - Justification: The trucking industry, as a crucial aspect of the US economy, relies on public services concerning roads. Because charging stations would be constructed on road-sides and public land, it is assumed that the government will agree to pay for the construction of charging stations so as to facilitate the upgrade of trucks. Further, if the construction of charging infrastructure is paid for by the government, it will not increase the total cost of upgrading corporate fleets in Part 1.
- Only DC (Level 3) superchargers will be built, each charger will cost $90,000, it takes 2.2 hours to charge a battery from 0 to 400 miles (capacity), and there will be no limit on space for each charging station
   - Justification: Because all trucks have the same batteries, and Level 1 and 2 chargers are slow, it is necessary to build DC chargers so as to ensure the efficiency of truck travel is not compromised by ridiculous charging times. Other level chargers could take hours or even days, which would compromise the ability of trucks to travel long distances in short times. As such, only DC chargers will be built. Further, according to data, DC chargers range between $15-90k in cost. We assume they will all cost $90,000 because we intend to use 1 MWh chargers (the fastest available). We also assume the information provided by Clipper Creek which says a DC charger can charge an electric vehicle from 0 to 90 miles in 30 minutes (which is equal to 0 to 400 miles in 2.2 hours) is a universal charging speed. Finally, we assume that charging stations will not be bound by lack of real estate. [10] [17]
- The path length of the corridors as dictated by Google Maps is the absolute length of each corridor.
- There are no additional costs in building the infrastructure of a charging station. The only cost is in the chargers themselves.

5.3 Developing the Model

Before starting, it was important to find the length of each corridor. Using google maps, we found the distances of the 5 corridors being tested. They are listed as follows:

- 544 miles (New Orleans to San Antonio)
- 408 miles (Minneanapolis to Chicago)
- 390 miles (Boston to Harrisburg)
- 706 miles (Washington to Jacksonville)
- 382 miles (San Francisco to LA)

With the corridor lengths established, we had to find out how many trucks were going to be on any of the given routes at a given time. In order to do this, we took the averages of the Annual Average Daily Truck Traffic (AADTT, a_d) on 10 segments of a highway (called s_1, s_2, etc. until s_{10})* and then divided it by 24 to find Average Annual Hourly Truck Traffic (AAHTT, a_h) for each highway. This can be represented by the equation: [14]

$$a_h = \frac{\left(\sum_{s=1}^{s=10} a_d\right)/10}{24}$$

$$\text{AAHTT} = (((s_1+s_2+s_3\ldots+s_{10}))/10)/24$$

After plugging the 5 test routes into this equation, we found the following AAHTT values for each highway, representing the number of trucks on the highway every hour for all working hours of the year. AAHTT values are rounded up to the nearest whole number.

Table 5.3.1: Average Annual Hourly Truck Traffic for each corridor

Route	**San Antonio- New Orleans [TR_1]**	**Minneapolis- Chicago [TR_2]**	**Boston- Harrisburg [TR_3]**	**Jacksonville- Washington [TR_4]**	**Los Angeles- San Francisco [TR_5]**
AAHTT	596	539	335	474	645

These numbers are important because they show how many trucks would need charging on each highway (assuming a full conversion to electric). In order to provide efficient servicing to these highways, the number of charging stations must be able to service the AAHTT number of trucks per hour. This leads to the next part of solving the problem, which is deciding where to place the stations on each highway. In order to decide station placement, the total length, D, of each corridor must also be known (D values are provided at the beginning of section 5.3).

If $D \geq 400$: Each endpoint in a truck route will have its own Charging Station (referred to as S_A and S_a, when the endpoints are A and a). In order to minimize time wasted charging, each station will be distanced 400 miles from the previous station so that trucks can travel their full maximum of 400 miles before reaching a charging station. This means S_B will be located 400 miles away from the starting point. Because each route is less than 800 miles in length, this causes the charging stations to loop back. This means that S_C will be distanced ($2D$-800) miles from the starting point, where D is the total length of the route. S_D then becomes distanced ($2D$-1200) miles from point A. Upon making the return trip (a full trip from A to a and back to A), trucks will then use S_A and then repeat their journeys. Using this system, trucks always maximize their energy and time by traveling the maximum possible before recharging, and then continuing post-recharge the maximum possible until they eventually return to their starting point and repeat the process. In order to allow this system to work on highways, it must be mirrored for both trucks traveling from point A to a as well as for trucks going from point a to A, which means that there will be charging stations spaced the same distances using point a as a reference instead of point A.

If $D < 400$: Using a similar system as for when $D \geq 400$, when S_A and S_a are located at points A and a, respectively, we found that after traveling 400 miles, a truck would be a distance of $2D$-400 from the starting point. Because the total length of the route is less than 400 miles, that means that only one charging station will have to be stopped at in order to complete the journey from A to a or from a to A. Once again, like in the previous condition, the situation for the charging stations bound to point A (S_A and S_B) are mirrored for point a.

Using these systems, for each route, there will be charging stations spaced at the following locations (labeled based on distance from A and a, depending on whether S is on the route from A to a, or a to A):

Table 5.3.2: Total number of stations in each corridor and distance from relative point A or a.

	TR_1	TR_2	TR_3	TR_4	TR_5
S_A	0 miles	0 miles	0 miles	0 miles	0 miles
S_B	400 miles	400 miles	380 miles	400 miles	364 miles
S_C	288 miles	16 miles	N/A	612 miles	N/A
S_D	N/A	N/A	N/A	212 miles	N/A

S_a	0 miles	0 miles	0 miles	0 miles	0 miles
S_b	400 miles	400 miles	380 miles	400 miles	364 miles
S_c	288 miles	16 miles	N/A	612 miles	N/A
S_d	N/A	N/A	N/A	212 miles	N/A
Total Stations	6	6	4	8	4

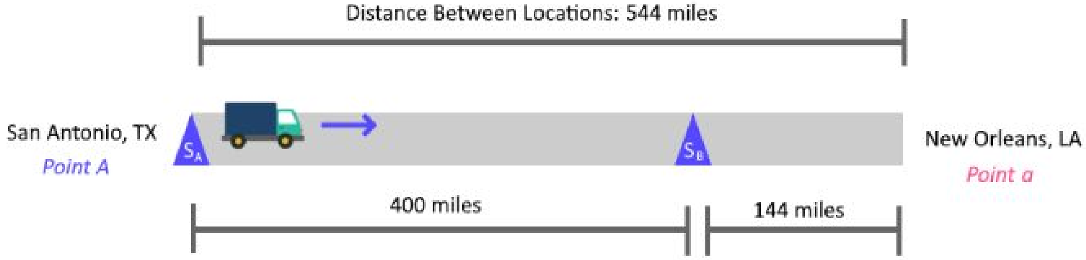


Figure 5.3.1: Truck moving from A to a, with charger S_A stationed 0 miles from A and supercharger S_B stationed 400 miles from A.

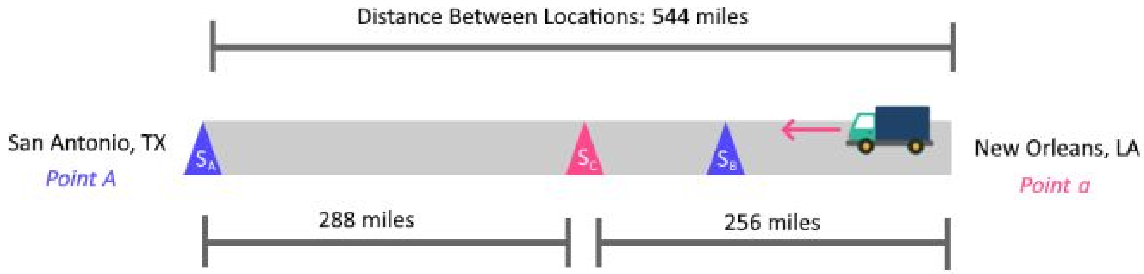


Figure 5.3.2: Truck returning from point a to A, with charger S_C stationed 288 miles from A.

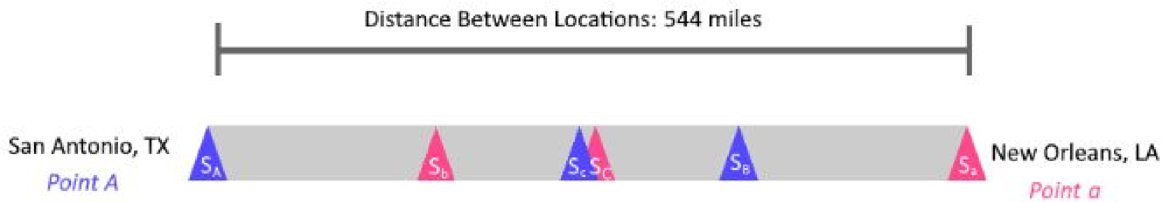


Figure 5.3.3: Placement of stations S_A, S_B, S_C, and counterparts S_a, S_b, S_c, where pink stations are on the side of the road originating from point a and blue originates from point A.

With the number of charging stations required for each route found, and with the total number of trucks per hour that need to be serviced known, it is now possible to calculate how many chargers need to be at each station and the total price of upgrading the 5 corridors. Each Level 3 charging port, being about the size of a person, will be placed at distances approximately 9 feet away from each other (the standard width of a parking space) so that trucks can park and charge at the stations. With each charging port costing $90,000, and having to construct enough ports at each station to service the AAHTT per hour for each highway, that means the total cost of buying and building DC charging ports can be represented by the equation:

$$T_C = (90,000) \cdot \left(n_{DC/S}\right) \cdot (S)$$

Where T_C is the total cost, $n_{DC/S}$ is the number of DC charging ports per station, and S is the number of stations for a specific route. Through this equation, the total cost of building enough charging ports to service the AAHTT per hour can be found for each highway, with each station equipped with a (2.2*AAHTT number) ($n_{DC/S}$ = 2.2*AAHTT) of charging ports, so that even if all trucks traveling a highway in one hour were to leave at the same time from the same place and arrive at charging points simultaneously, there would be no wait (where 2.2 equals the time it takes to charge a truck from 0 to 400 miles, and therefore the time a charging station will be occupied by one truck). Using the above equation, the total cost of upgrading each corridor can be found to be the following: [10]

Table 5.3.3: Total costs of buying and installing stations along the five corridors.

	TR_1	TR_2	TR_3	TR_4	TR_5
Upgrade Cost	$706.8 million	$640.3 million	$265.3 million	$750.8 million	$510.8 million
Total Cost:					$2.874 billion

To summarize the answers to the problem:

- Each station must have 2.2*(AAHTT) number of chargers, where AAHTT is dependent on traffic data for that route.
- The five corridors have the following numbers of stations:
  - San Antonio - New Orleans: 6
  - Minneapolis - Chicago: 6
  - Boston - Harrisburg: 4
  - Jacksonville - Washington DC: 8
  - San Francisco - LA: 4

5.4 Validity of the Model

Strengths

- Our model effectively deals with traffic. Using our staggered charging station placement, we can minimize traffic resulting from charging by ensuring that trucks only go to the charging stations they are supposed to go to. For example, a truck leaving point *A* would see minimal time wasted during the 2.2 hours it takes to charge as long as it proceeded directly to station S_B and did not stop along the way at station S_C, even though it's technically closer. The reason a trucker would not want to do this is because each station only has enough spots to handle a flow of traffic equal to 2.2*the hourly average of cars (AAHTT). Because of this, if trucks were to not follow their route by stopping at stations before they were supposed to, the number of trucks at a station would go above the maximum allowed for by the calculation and cause traffic jams and waiting for charging ports. However, if truckers *do* stay in line with their routes (from point *A* to S_B to point *B* to S_C, etc), then the total number of trucks at each charging station should not exceed the cap, which means that there would be minimal time wasted when arriving at a charging station. Because of the staggered placement of our charging stations, time efficiency is maximized.

Weaknesses

- We assumed all user batteries are identical and can/will be run down to depletion. This poses the risk of leaving worn down batteries stranded, so a more effective model would benefit from a wider sampling of electric truck batteries.
- Our model assumes that there is no additional cost required to construct the infrastructure of a charging station, as shown by the fact that some are built very close to each other because of the mirror. If there is a foundational cost, this might be an inefficient use of money, which leads to the next point:
- The costs produced by the model are very high. Having prioritized traffic and time efficiency over the cost, the final pricing for upgrading the 5 corridors comes out to be $2.874 billion, which is quite expensive. Partly due to the fact that Level 3 chargers are being exclusively used, and they are expensive, combined with the fact that at least a thousand charging ports are at every station, the upgrade plan is fairly expensive. However, an expensive plan is practically inevitable when proposing mass upgrades.
- Another weakness is that the method for spacing out the charging stations does not work when $200 > D$ or when $D > 800$. However, this problem can be fixed by generating a new set of equations for when such circumstances occur in a corridor, using the same strategy used to generate the sets of equations earlier for the placement of *S*. For when $200 > D$, these equations would result in there only being 2 stations at points *A* and *a*. For when $D > 800$, the solutions would require a different method of optimization..

6. Part 3: I like to move it, move it

6.1: Restatement of the Problem

The problem asks us to do the following:

- Find the net benefit of upgrading the 5 major trucking routes in terms of USD/year.
- Find the net cost of upgrading the 5 major trucking routes in terms of USD.
- Assign each of the 5 routes preference values based on the net benefit of upgrade minus total cost of upgrade.

6.2 Assumptions

- The average AADTT in part 2 is the universal daily number of trucks on each corridor.
  - Justification: The definition of the AADTT, being designed to measure the number of trucks on the road each day during a year, is the number of trucks on the road for a year.
- The value of the goods of every truck is constant
  - Justification: In order to calculate the net worth of each corridor, each truck will be assumed to be carrying the same value of goods, or an average of the values of the goods, which will be constant.
- It is assumed that all trucks on the corridors carry only 6 types of goods, which are clothing, produce, paper products, building materials, vehicles, and hazardous substances.
  - Justification: In order to calculate the average value of a truck, the goods carried by a truck must be limited so that the values of goods can be found and used to create the average truck value. Furthermore, it is assumed that the vast majority of construction products are wood and concrete. [19]
- Each truck carries 1,000 pounds of goods.
  - Justification: With semi trucks being able to carry up to 1,000 pounds of goods, and the assumption that companies that own trucks seek to maximize efficiency, it is assumed that trucks will be loaded with the maximum amount of goods possible so as to maximize the goods moved to spending ratio. [20]

6.3 Developing the Model

Using information from Part 2, we know the costs of buying and installing the Level 3 charging ports in each station. That data is as follows:

Table 6.3.1: Total costs of buying and installing stations along the five corridors.

	TR_1	TR_2	TR_3	TR_4	TR_5
Upgrade Cost	$706.8 million	$640.3 million	$265.3 million	$750.8 million	$510.8 million
Total Cost:					$2.874 billion

With the costs of upgrading each major corridor known, it is necessary to find the value of each truck on the corridor to determine the net value of the transportation of goods on each corridor. In order to do this, we take the value of 1,000 pounds of each of the 6 types (where P_1 is the value of 1 pound of the first type, P_2 is the value of 1 pound of the second type, etc.) of materials transported, add them, then divide by 6 to find the average value per 1,000 pounds of goods carried by a truck (V_{1000}) . To do this, we use the following equation:

$$V_{1000} = \frac{\left(P_1 \cdot 1000\right) + \left(P_2 \cdot 1000\right) \ldots + \left(P_6 \cdot 1000\right)}{6}$$

Further, we use the following for the values of P_1, P_2, etc. using sources from the internet as well as personal experience. For sources where there were multiple values for items, the averages were calculated and are shown below:

- Clothing: $1.49/lb [21]
- Produce: $2.67/lb [22]
- Paper Products: $10.86/lb [23]
- Building Materials: Wood $0.154/lb, Concrete $0.02/lb averaged to $0.078/lb [24]
- Vehicles: $114.8711/1 lb
- Hazardous Substances: $1.87/lb [25]

Using these values, we calculated that the value of 1000 pounds of goods, or the average value of goods carried by a truck in the United States is $21,724.85. With the average value of goods per truck now established, it is now possible to calculate the values of each of the 5 corridors by multiplying the value of goods:

$$ATR_V = (21724.85) \cdot (AADTT) \cdot 365$$

Where ATR_V is the annual truck route value, the AADTT is the AADTT as generated by the Mathworks challenge, and 365 is the number of days in the year. 365 is used instead of 261 (the working days) because AADTT is calculated based off of 365 and not 261. After using this equation, we find values for the corridors are as follows:

Table 6.3.2: Total values of goods of the five corridors

	TR_1	TR_2	TR_3	TR_4	TR_5
Value	\$133.4 billion	\$102.6 billion	\$63.8 billion	\$90.2 billion	\$122.8 billion
Total Value					\$492.7 billion

With the annual values of the goods carried on each corridor per year now established, it is possible to rank the corridors based on importance (value to the economy):

Table 6.3.3: Total values of goods of the five corridors

	TR_1	TR_2	TR_3	TR_4	TR_5
Value	2nd Place	3rd Place	5th Place	4th Place	1st Place

After ranking the corridors based on importance to the economy, all that is left to be done is subtract the cost of upgrading from the annual value for the year during which upgrades occur, which will show the net benefits and net losses from undergoing upgrades. When that is completed, each corridor will be assigned a priority ranking (1-5, where 1 is the most preferential and 5 is the least) on which should be upgraded first based on the net value for the first year. Corridors that still have the greatest net value will be prioritized in order to minimize upfront losses, as well as promote growth of electric trucking in those corridors, which will offset the cost of upgrading them.

Table 6.3.4: Total values of goods of the five corridors

	TR_1	TR_2	TR_3	TR_4	TR_5
Net Value	\$112.7 billion	\$101.9 billion	\$63.5 billion	\$89.5 billion	\$122.2 billion
Preference Rating	2	3	5	4	1

After assigning the preference values, it is clear that the preferences do not change after accounting for the cost of upgrading. The preferences would have remained the same if only net value had been accounted for instead of net value minus the cost of upgrades. However, although the preference values did not change, they have been created based on the value of corridors.
To summarize the answers to the problem:

- The five corridors should be upgraded in the following order:
    - San Francisco - LA
    - San Antonio - New Orleans:
    - Minneapolis - Chicago

- Jacksonville - Washington DC
- Boston - Harrisburg

6.4 Validity of the Model

Strengths

- The model's strength lies in its ability to produce the preference rating even though it has approximation problems with regards to truck values. Although the exact values of the trucking corridors cannot be relied upon for official purposes, they are effective estimates and make up an integral part of the preference ratings.

Weaknesses

- The model's weakness lies in its approximation of certain values regarding the value of goods in trucks. Although the assumptions make the data valid, in practice, the information would not be of any particular use due to its excessive approximations caused by the lack of any available data that could help to make superior approximations. Because of this, the final values of each corridor may not be completely accurate. However, they are accurate enough to be reliable to produce the preference rating.
- The significance of the upgrade costs on the preference rating was reduced to practically nothing due to the massive disparity between the values of the corridors and the costs of the upgrades. While this is problematic, in an economy as large as the US's, it can be attributed to the relative enormity of the US economy and trucking industry.

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*Note: The Minneanapolis-Chicago corridor only had 3 Segments available, so averages were calculated using only those 3 instead of a total of 10.