Quantifying the Economic Case for Electric Semi-Trucks

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Abstract

There has been considerable interest in the electrification of freight transport, particularly heavy-duty trucks due to their potential to downscale greenhouse-gas (GHG) emissions from the transportation sector. However, there is uncertainty in the economic competitiveness of electric semi-trucks due to the substantial initial costs associated with the large battery packs required. In this work, we analyze the trade-off between the initial investment and the operating cost in realistic usage scenarios to compare a fleet of diesel semi-trucks and a fleet of 500-mile capable electric trucks. We define the payback period to be the time span required for the operational cost savings from electric trucks to break-even with the initial price differential between an electric and diesel truck. For the baseline scenario with 30\% of the fleet requiring battery pack replacements and an initial price differential of US$50,000, we estimate a payback period of \(\sim\)3 years or an odometer reading of about 200,000 miles. Based on the sensitivity analysis for the payback period, we find that the fraction of fleet requiring battery pack replacements is a crucial factor. If the replacement fraction reaches 100\%, the payback period could be as high as 5-6 years. We identify the price of electricity as the second most important variable, where an electricity price of US$0.14/kWh results in a payback period of about 5 years. Electric semi-trucks are expected to operate at much lower repair costs and the magnitude of savings thereof has a strong influence on the payback period as well. With increased penetration of autonomous vehicles, the annual mileage of semi-trucks could increase substantially which sways the case in favor of electric trucks, where an annual mileage of 120,000 miles brings the payback period down to about 2 years. Based on the outcomes of the several scenarios analyzed, there is an undeniable economic case for electric semi-trucks. Developing battery packs with longer cycle life, lower cost, higher specific energy and a careful consideration of other important variables would make this case even stronger.

Introduction

There is enormous interest around the electrification of Class 8 heavy-duty trucks following the unveiling of the Tesla Semi\textsuperscript{1} and accompanying announcements by several auto-and-truck manufacturers including Cummins, Daimler, BYD and Volvo.\textsuperscript{2-5} The importance of the trucking industry is highlighted by its share of the total freight shipments which is
about 65% by value and 68% by weight in the United States. At the same time, 24% of the greenhouse-gas (GHG) emissions from the transportation sector is due to the trucking industry. Batteries play a crucial role in enabling the transition to electric transportation which can mitigate GHG emissions along with improved efficiency of the fleet. In an earlier work, we analyzed the performance requirements of Li-ion batteries for electrifying class 8 semi-trucks. We demonstrated that semi-trucks would be limited to a driving range of under 600 miles if they were to carry the average Class 8 truck payload of about 16 US tons. We also highlighted the significantly higher costs incurred due to the large battery packs required. In a follow-up work, we quantified the potential for platooning to reduce the performance requirements of batteries and estimated a 15% reduction in the energy requirements. Both of these works were widely covered in the media and were largely consistent with the estimates that Tesla unveiled. A final missing piece is to quantify and compare the total and operational costs of electric and diesel semi-trucks in different realistic scenarios to explore the economic case for electric semi-trucks.

Class 8 semi-trucks have a typical lifetime mileage of around 1 million miles. The average annual mileage for the first two years of operation is over 100,000 miles. The average annual mileage for the semi-truck fleet in the U.S. is about 75,000 miles. Studies have shown that for a representative sample set of semi-trucks, about ~40% are known to travel much greater than 500 miles and an equal fraction travel between 100-500 miles per trip. In this work, we focus on the long-haul segment where we compare electric trucks with a range of 500 miles and with diesel trucks with a range of about 1000 miles.

The main cost categories for class 8 semi-trucks are the initial investment, operational costs and the periodic costs that occur due to the replacement of different components. A major advantage of using electric trucks is the significantly lower operational costs, which is primarily due to two factors: (i) increased energy efficiency for mobility and (ii) similar or lower cost per unit energy for electricity compared to diesel. Aside from the economic benefits of lower operational costs, as mentioned earlier, there are concerns regarding the size, cost and weight of the battery packs. Undoubtedly, there could be economic consequences of the potential reduction in payload carrying capacity because of the additional weight of the battery pack relative to diesel as a fuel. On the subject of the payload capacity, there are two possible scenarios commonly referred to as ‘cubing-out’ and ‘grossing-out’. Cubing-out refers to exceeding the volume limit of the trailer while grossing-out refers to reaching the gross-weight limit. The reduced payload carrying capacity of electric trucks naturally applies only to the grossing-out scenario. However, a significantly large fraction of fleets are known to cube-out or have a volume limitation on the payload and as a result, never gross-out. Based on this, throughout this analysis, we ignore the potential economic loss associated with trucks that grossing-out and plan to revisit this in future studies.

The central theme we address in this work is the trade-off between the initial investment and the operating cost in realistic usage scenarios. We estimate the payback period for an electric semi-truck in the same scenarios. Further, we analyze the economic benefits of techniques like platooning and how different variables influence the payback period through a sensitivity analysis. A compilation of each of the aforementioned aspects provides the foundation for evaluating the economic case for electric trucks. It is extremely important to understand and quantify metrics like the total cost of ownership and payback period which to inform and facilitate mainstream adoption of electric heavy-duty vehicles.
Figure 1: The energy consumption characteristics of a single truck with a drag coefficient of 0.4 and a platoon of three trucks under different conditions is shown in Part (a), with a road grade, (r), over a specified fraction of the total distance, (t_f). We estimate the energy consumption to be 2.05±0.32 kWh/mi over all the use cases considered. The drive cycles are shown in Figure (S2). The daily duty cycles applied to the battery pack comprises of driving for the given trip distance, charging, and rest amounting to a total 24-hours as shown in Figure (S3). Part (b) shows the estimates for the cycle life with all Cases (A to F) operating at the gross-weight limit. Case A and D represent 3 truck platoons with the Composite drive cycle under flat road conditions and a charging rate of 500 kW peak, representing the optimistic scenarios. Case B and E refer to single trucks with the Cruise drive cycle also under flat road conditions with fast charging with a peak power of 1.5 MW. Case C and F refer to single trucks with the Custom duty-cycle at a 1% road grade for a small fraction of the trip and fast charging, representing the pessimistic scenarios. As the odometer reading increases, the available range decreases monotonically while the rate of reduction is a function of the duty cycle. The optimistic use cases, with platooning and regular charging show a much higher cycle life than single trucks with fast charging. Considering the six cases, Part (b) shows that there is a high likelihood of battery packs reaching end-of-life before the lifetime of the truck.

Performance of Electric and Diesel Semi-Trucks

In an earlier work, we used a parameterized vehicle dynamics model to quantify the energy requirements of a class 8 semi-truck. The vehicle design parameters as well as the performance parameters of the battery pack form the primary inputs to such a model, described in Methods. In this work we utilize a similar model with a drag coefficient of 0.40±0.04, in order to account for highly optimized vehicle designs, a rolling resistance of 0.0075±0.002 and other parameters representative of a Class 8 semi-truck. Using these parameters in conjunction with realistic drive cycles shown in Figure (S2), we estimate that a well-designed electric semi-truck under full-load conditions would have an energy consumption of 2.05±0.32 kWh/mi or 51.25±8 Wh/ton-mile depending on the road conditions and the duty cycle, as summarized in Figure (1b). On the other hand, for conventional diesel trucks, fleets achieve an efficiency in the range of [6-8.5] mpg. Considering the energy content in
Figure 2: Comparison of the total cost of ownership per mile per truck for a diesel truck fleet and an electric truck fleet with a battery replacement fraction, (R_f), of 30%. For the baseline scenario, described in Table (1), the cost per mile for the diesel truck is about US$1.48±0.08/mile and that of the electric truck with R_f=30% is about US$1.22/mile. The cost per mile for R_f=0% is US$1.18±0.05/mile, and at R_f=100% it increases to US$1.3±0.05/mile. We observe a small region of overlap of the distributions for the most favorable cases for the diesel trucks and the most unfavorable cases for the electric trucks. Within this region electric trucks would not have a payback period.

diesel, this turns out to be about [4.45-6.3] kWh/mi.

Based on the results shown in Figure (1a), the battery pack required for a range of 500 miles would be ~1,000 kWh. Current estimates of the price of battery packs is about US$[180-220]/kWh\textsuperscript{21-23} while the cells of certain chemistries have been reported to have achieved prices below US$100/kWh.\textsuperscript{21} Some forecasts for the price of battery packs for the year 2020 are around US$125/kWh,\textsuperscript{22} and in such a time-frame, the battery packs for 500-mile electric trucks would cost about US$125,000 or lower. For a longer time-frame, the projections for the price of battery packs is about US$[90-120]/kWh.\textsuperscript{21}

For the case of electric semi-trucks, assuming 260 driving days in a year, based on the limits of the annual mileage, the daily distance traveled is between 270 and 400 miles. Considering the daily distance driven, along with the different drive cycles derived from CARB-HHDDT\textsuperscript{19} and the various road conditions, we obtain different duty-cycles that the battery pack is subjected to. We define regular charging for semi-trucks to entail 500 kW of peak power during charging and 1.5 MW for fast charging, each of which are implemented within a CC-CV protocol. Figure (1b) shows the cycle life estimates from the battery pack simulations. The simulations are performed on a full-pack model based on relatively high specific energy cells with NMC-622 (LiNi\textsubscript{0.6}Mn\textsubscript{0.2}Co\textsubscript{0.2}O\textsubscript{2}) cathode and Graphite anode. The details of the battery pack and the degradation model along with the cell specifications can be found in Methods and Supplementary Information. As seen in Figure (1b) the available range for all the cases apart from Case-A and Case-B reduces to under 400 miles before
the total distance traveled reaches 1 million miles. An available range of 400 miles also represents 80% of the initial capacity, generally considered the end-of-life criterion in electric vehicles. However, the trucks could be reassigned for use in shorter routes after the 80% of the initial capacity is reached. Platooning, represented by Case A and D where the energy consumption is reduced when coupled with lower charging rates is seen to improve the cycle life corroborating the results from our previous work where a different example semi-truck was studied. Across all the cases in Figure (1b), we can see that the use of fast charging with a peak power of 1.5 MW is seen to reduce the cycle life significantly as compared to the cases with regular charging. Figure (1b) shows that likelihood of the battery pack needing a replacement is high for all cases considered. Hence, in our baseline scenario, we include a fixed fraction of the fleet with battery pack replacements.

The end-of-life criteria for electric semi-trucks requires a careful consideration as trucks could be reassigned to routes according to the available range. Nearly all cases considered experienced a degradation in range to about 400 miles well before an odometer reading of 1 million miles is reached. However, it is likely that a re-balancing of the routes would ensure that only a few trucks will require battery replacements. We carry out a rigorous sensitivity analysis with respect to the battery replacement fraction that will be discussed later.

Economics of Electric and Diesel Semi-Trucks

In terms of economic variables, the general operational costs (General Op–Costs), common to both electric and diesel trucks include the cost of the cab, driver wages, insurance, tire replacements, and the cost of the permits and tolls, totally amounting to US$[0.76-0.81]/mi. Electric powertrains are expected to have much lower repairs compared to diesel powertrains which comprise of several moving components resulting in frequent maintenance costs. The cost of additional repairs incurred by diesel trucks is considered in the range of US$[0.15-0.16]/mi. The nominal price of diesel, based on known history and projections for a decade is about US$[2-4]/gal which is equivalent to about US$[0.05-0.11]/kWh. A discount rate of 3% is used throughout the framework. The price of electricity, based on the U.S. electricity market and potential improvements within the charging infrastructure is taken to be about US$[0.07-0.12]/kWh. Possible ‘demand charges’ due to charging at very high power is not explicitly considered but the reader is referred to the analysis on the price of electricity to understand the potential implications of demand charges. Each of the above-mentioned variables with their stipulated bounds is uniformly discretized within the bounds where each discrete value is assumed to have an equal probability of occurrence. The set of all possible outcomes based on the variables shown in Table (1) form the baseline scenario of the cost model.

The total operational costs of electric and diesel semi-trucks is shown in Figure (2) with their respective distributions. Under the baseline scenario, the cost per mile for diesel trucks turns out to be US$1.48±0.08/mile and that of electric trucks is about US$1.22/mile for a battery replacement fraction, (Rf), of 30%. The timeline for pack replacements is a minimum of ∼7 years and hence low battery pack prices of US$[90-120]/kWh are used. In the most favorable scenario for electric trucks, with low initial price differential, low electricity prices, high efficiency due to flat roads and/or platooning, the cost per mile could be as low as US$1/mile while a correspondingly favorable scenario for diesel trucks results in a cost of
Figure 3: Quantifying the sensitivity of the payback period to different variables. The variable under consideration is pinned to a constant value while the other variables remain at baseline values compiled in Table (1). The mean value of the payback period distribution in the baseline scenario, of 2.71 years is shown above. The sensitivity of the payback period to variables like the battery replacement fraction is extremely high, primarily due to the size and price of the battery packs that need to be replaced. The price of electricity has a significant impact on the payback period and high electricity prices could increase the payback period by about 75%. The sensitivity around E-Truck efficiency includes the case of platooning where energy consumption rates of $\sim 1.6 \text{ kWh/mi}$ can be achieved, although the payback period reduces by only 0.3 years.

US$1.3/mile. The distribution for electric trucks seen in Figure (2) is skewed because of the cases with battery pack replacements. As the pack replacement fraction increases, the mean cost per mile increases linearly to about US$1.3/mile at the limiting case $R_f=100\%$. This variation is visualized in Figure (S5,S6).

Payback Period

An important metric that needs to be studied within the framework discussed is the payback period. In the context of this study, we define the payback period as the time required for the cost savings from the operation of electric semi-trucks to break-even with the initial price differential between the electric and diesel truck. The payback period distribution obtained for the baseline scenario exhibits a mean value of $2.71\pm0.7$ years. The distribution for the payback period in the baseline scenario can be found in Figure (S4). The sensitivity of the payback period to several salient variables is compiled in Figure (3), where we can analyze the payback period both at the bounds of variables as well as the median value of range considered.

As seen in Figure (3), due to the size and price of battery packs, the fraction of cases that require battery pack replacements shows the highest sensitivity. The limiting scenarios of no replacement and $R_f=100\%$ show payback periods of 1.57 and 5.25 years respectively. A replacement fraction of about 50% results in a payback period of $\sim 3.5$ years. In terms
Table 1: Values of variables that define the baseline scenario to compute the total operational costs and payback period. General Op–Costs do not influence the payback period since they are equal for both diesel and electric trucks.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-Truck, Initial Price</td>
<td>US$150,000</td>
</tr>
<tr>
<td>E-Truck, Initial Price</td>
<td>US$200,000</td>
</tr>
<tr>
<td>Diesel Price</td>
<td>US$[2.21-4.19] / ga</td>
</tr>
<tr>
<td>Electricity Price</td>
<td>US$[0.07-0.12] / kWh</td>
</tr>
<tr>
<td>E-Truck, Efficiency</td>
<td>[1.7-2.3] kWh / mi</td>
</tr>
<tr>
<td>D-Truck, Efficiency</td>
<td>[6-8.5] mpg</td>
</tr>
<tr>
<td>D-Truck, Additional Repairs</td>
<td>US$[0.15-0.16] / mi</td>
</tr>
<tr>
<td>Annual Mileage</td>
<td>[80,000-100,000] mi</td>
</tr>
<tr>
<td>General Op–Costs</td>
<td>US$[0.76-0.81] / mi</td>
</tr>
<tr>
<td>Battery Pack Price</td>
<td>US$[90,120] / kWh</td>
</tr>
<tr>
<td>E-Truck, Battery Replacement</td>
<td>30% of the fleet</td>
</tr>
<tr>
<td>Discount Rate</td>
<td>3%</td>
</tr>
</tbody>
</table>

of the price of fuel (diesel or electricity), we observe that increasing the price of electricity from the baseline scenario to about US$0.14 / kWh nearly doubles the payback period. It is worth highlighting that the price of electricity in several locations within the United States is well-above US$0.14 / kWh and the large sensitivity exhibited is an important factor to consider for the charging infrastructure. This could effectively limit the locations where electric trucks can be utilized. Furthermore, the issue of ‘demand charging’ could arise due to the high power required to charge the battery packs which could significantly affect the price of electricity as well. Very low diesel prices would increase the payback period, although, the lower limit of US$2 / ga considered in Figure (3) is much lower than current projections and estimates. The economic case for electric trucks will be influenced to a much larger extent by the price of electricity than by the price of diesel, given the known projections for the possible fluctuations in the prices. A brief discussion on the comparison between electricity and diesel in terms of the price of per unit energy is compiled in the *Supplementary Information* with additional information is shown in Figure (S1).

Among other variables seen in Figure (3), the additional repairs required by diesel trucks, which account for under 10% of the cost per mile of diesel trucks, affects the payback significantly where a low cost of repairs for diesel trucks increases the payback period by about one year. The sensitivity of the payback period to the initial price differential shows a clear linear relationship and at a large price differential of US$80,000, we see a payback period of about 3.8 years. The annual mileage also influences the payback period to a significant extent. If the annual mileage is under 100,000 miles, the payback period would be extended, with a payback period of about 3.2 years at an annual mileage of 60,000 miles. On examining the payback period for the median value, we observe a non-linear relationship between the payback period and the annual mileage. In terms of energy efficiency, for a fixed set of road conditions, the potential variation in diesel truck efficiency affects the payback period to a larger extent than that of its electric counterpart. The electric efficiency variables considered include the scenario of platooning to reach energy consumption rates as low as 1.6 kWh / mi. While the higher efficiency of electric trucks results in a much lower cost per mile over the
lifetime of the truck, the payback period does not show a significant sensitivity towards the same.

It is worth noting that there are several other variables like changes in wages due to automation, tires with reduced wear-and-tear, reduced insurance costs etc., which affect the operational costs of electric and diesel trucks in a similar manner and hence, such variables do not influence the payback period. In addition, factors such as the charging infrastructure could add significant costs to the electric truck fleet, albeit, it could be argued that similar costs are not accounted for with the diesel trucks in terms of gas/ diesel stations. Extending this argument further, it might be imperative for OEMs or external entities to be responsible for the costs of the charging infrastructure in order to ensure an even-handed and favorable economic case for the electrification of semi-trucks. There is also an opportunity for distributed and renewable generation to provide electricity at a fixed cost since the current electricity market with the issues like demand charges mentioned previously can be resolved with fixed electricity prices.

Throughout this work, we consider vehicle designs with a low drag coefficient of around 0.4, and it should be noted that most semi-truck designs currently in the market have drag coefficients that are well-over 0.5. Enabling a range of about 500 miles for vehicle designs with high drag coefficients without sacrificing the payload capacity is possible only with very high specific energy battery packs. Higher drag coefficients result in higher energy consumption and require larger battery packs which effectively increase the initial price differential. A vignette on the trade-offs between vehicle design and specific energy for a fixed driving range and their effect on the payback period is compiled in the Supplementary Information and Figure (S4). If the drag coefficient is about 0.63, which is the current fleet average for the U.S., the mean payback period increases to about 8.45 years which is close to the lifetime of the truck itself, suggesting the vehicle design constraint for commercial viability.

Is there an Economic Case for Electric Trucks?
Across all the variables considered, the payback period is most sensitive to the battery pack replacement fraction which is due to the size and effectively the price of battery packs. This implies that for high-utilization applications like semi-trucks where the battery packs are used extensively, higher cycle life coupled with a lower purchase price of battery packs will play a crucial role in creating a favorable economic case. The next variable of importance is the price of electricity where the payback period could increase by about 2 years from the baseline scenario if the price of electricity reaches US$0.14/kWh. The variable that represents additional repairs for diesel trucks also has a significant impact on the payback period. If the repairs for diesel trucks are only US$0.05/mi higher than that of electric trucks, the payback period could increase by ~1.5 years from the baseline to ~4.2 years. Apart from the above-mentioned variables, most of the unfavorable scenarios result in a payback period of under 4 years. On the other hand, several favorable scenarios could result in a payback period of 2 years or lower.

In the overall analysis, it is evident that there exists a strong economic case for the adoption of electric heavy-duty commercial vehicles particularly for driving ranges of about
500 miles. In the premise of this work, we highlighted the importance of the trucking industry and also its considerable contribution to the greenhouse gas emissions. While it is crucial to accelerate the adoption of electric semi-trucks, it should also be noted that there are important factors like the price of battery packs, their cycle life and the price of electricity for charging, each of which should be carefully considered in order to ensure favorable economics. Also, a well-designed exterior with low energy consumption and a high specific energy battery pack will be key in enabling electric semi-trucks with a range of up to 500 miles. Increasing the driving range further without affecting the commercial viability would require higher specific energies and lower battery pack prices while other important factors mentioned previously remain favorable.
Abbreviations
CARB-HHDDT: California Air Resources Board-Heavy Heavy Duty Diesel Truck
D-Truck: Diesel Truck
E-Truck: Electric Truck (Range of 500 miles)
Op–Costs: Operational Costs
CC-CV: Constant Current-Constant Voltage
OEM: Original Equipment Manufacturer
mi: mile(s)
ga: gallon(s)

Methods

Vehicle Dynamics: The power demands of the electric semi-truck are estimated using a parametric relationship between the vehicle design parameters, the road conditions and the drive cycle in consideration, as shown by:

\[
P(t) = \left( \frac{1}{2} \rho_C d.A.v(t)^3 + C_{rr}.W_T.g.v(t) + t_f.W_T.g.v(t).Z + W_T.v(t).\frac{dv}{dt} \right) \frac{1}{\eta_{bw}} ,
\]

\[
P_{reg}(t) = \left( W_T.v(t).\frac{dv}{dt} \right) \eta_{bw}.\eta_{brk} ,
\]

The drive cycle provides information on the instantaneous speed, \(v(t)\), and the various drive cycles used in this study are shown in Figure (S2). Vehicle design parameters like the frontal area, \(A\), coefficient of rolling resistance, \(C_{rr}\), are obtained from current datasets of the fleet of Class 8 trucks in the U.S.\textsuperscript{16,18} The road gradient, \(Z\), and the fraction of the trip for which positive road gradients exist, \(t_f\), are fixed based on the case in consideration. The total weight of the truck, \(W_T\), is fixed at 80,000 lbs (\(~36,000\) kg) which is the gross-weight limit for Class 8 vehicles. The other variables include the battery-to-wheels efficiency, \(\eta_{bw}\), and the efficiency of the brakes, \(\eta_{brk}\). The regenerative power, \(P_{reg}(t)\), represents segments of deceleration. Charge rates at the regenerative segments is limited to 2C. The power load profile obtained from the above-mentioned relationships for a given case is then applied on the battery pack model to study the pack performance.

Battery Model: The battery pack is modeled within AutoLion-ST\textsuperscript{31} which uses a thermally coupled electrochemical battery model for each cell. The mathematical relationships for the Pseudo two-dimensional battery model used within the framework can be found elsewhere.\textsuperscript{32–34} The cells are assembled into the battery pack but no cell-to-cell variation is considered. The degradation model which accounts for the loss of Li-ions over cycling due to various parasitic processes is implemented as a sub-model within the battery pack model.\textsuperscript{35} The rate constants of the degradation reactions/processes are fit to a specific cell chemistry based on NMC-622 (LiNi\textsubscript{0.6}Mn\textsubscript{0.2}Co\textsubscript{0.2}O\textsubscript{2}) cathode and Graphite anode. Additional details on the degradation model can be found in the Supplementary Information.

Cost Model: Total operational costs including the fuel costs are calculated over the total lifetime distance traveled for each discrete value of the variables within the bounds from the baseline scenario. All the operational costs are expressed per unit distance. Using the values and bounds of the annual mileage, the annual cash flow distributions for each case are obtained. The present value factors are calculated using a fixed discount rate. Applying the present value factors on the annual cash flows and other investments, we obtain the levelized annual costs. Finally, the cost per unit distance (US$ per mile) distribution is obtained based on the same annual mileage values used to annualize cash flows for the respective cases.

The approximate timeline for the fixed costs related to battery pack replacements are estimated using the results of the cycle life simulations. The corresponding cash-flows for the battery replacement are converted to present values using the same discount rate. The fraction of cases that require replacement are randomly sampled from the cost per mile distribution to obtain the cost per mile distribution for a fixed replacement fraction. The effect of the battery pack replacement fraction on the cost per mile distribution is captured in the Figure (S5,S6).
The payback period, which is the time span over which the fuel savings from the electric semi-truck are able to recover the initial price differential, is studied using an approach similar to the cost per mile calculations. The sensitivity analysis for the payback is performed by fixing the variable in consideration while the rest of the variables remain at baseline scenario values.

Acknowledgements
The authors would like to thank Michael Cembalest and Zach Long at JP Morgan for the extremely helpful discussions about the assumptions in the cost model, Jake Christensen for general critique and insights on the work and Joshua Switkes for valuable comments on platooning and the performance of semi-trucks. The authors are also grateful for the inputs from Andreas Hintermarch at Daimler AG on the overall analysis. S.S. would like to thank Dilip Krishnamurthy for his inputs on data visualization.

S.S. and V.V. gratefully acknowledge support from the Technologies for Safe and Efficient Transportation University Transportation Center. S.S. and V.V. also thank the support from the Wilton E. Scott Institute for Energy Innovation at Carnegie Mellon University. V.V. gratefully acknowledges support from the Pennsylvania Infrastructure Technology Alliance, a partnership of Carnegie Mellon, Lehigh University, and the Commonwealth of Pennsylvania’s Department of Community and Economic Development (DCED).

References


(28) Posada, F.; Chambliss, S.; Blumberg, K. *ICCT White Paper 2016,*


Price of Electricity and Diesel:

One of the major advantages of electric powertrains is the higher efficiency. If we examine the cost of energy contained in the fuel itself, based on the energy density of diesel which translates to about 37.7 kWh/gal. Comparing the price of electricity and diesel using a common scale, we arrive at the comparison shown in Figure (S1).

Figure S1: A comparison of the nominal price of fuel per unit energy of diesel and electricity (transportation and industrial) with known projections\(^1\) is shown in Part (a). While the price per unit energy is very similar, the efficiency of the electric powertrain is several times higher than one powered by diesel. As shown in Part (b), for the baseline scenario consideration, if the price per unit energy of electricity and diesel and equal, it is about 2.5-4 times more expensive to power a diesel truck than a well-designed electric truck.
Realistic Use cases and Drive Cycles:

The drive cycles used to simulate the operation of semi-trucks as seen in Figure 1 are shown below in Figure (S2).

![Figure S2: The Composite, Cruise and Custom drive cycles used to study the performance of the electric semi-truck is shown over a small representative distance. The drive cycles are repeated over the total trip distance. The Composite and the Cruise drive cycles are segments of the CARB-HHDDT from NREL DriveCAT and the Custom drive cycle is based on the Cruise drive cycle without the acceleration from stop and deceleration to stop segments. The Custom drive cycle is representative of long-haul duty cycles where speed remains close to a mean value for most of the trip.](image)

Battery Modeling and Simulation:

The degradation processes are modeled within the battery pack model degradation sub-model shown below:

\[
\begin{align*}
    j_{SEI} &= -k_{o,SEI} \cdot c_{solvent}^s \cdot \exp\left[ -\frac{\alpha_{c,SEI} \cdot F \cdot (\phi_s - \phi_e - I \cdot R_{film} - U_{SEI})}{RT} \right] \\
    j_{PL} &= -i_{o,PL} \cdot \exp\left[ -\frac{\alpha_{c,PL} \cdot F \cdot (\phi_s - \phi_e - I \cdot R_{film})}{RT} \right] \\
    \frac{d\epsilon_{AM}}{dt} &= -k_{AMI} \cdot I_{total}
\end{align*}
\]

where the side currents for each of the degradation processes for Solid-Electrolyte Interphase (SEI), \( j_{SEI} \), for the Lithium plating, \( j_{PL} \), and the last rate equation captures the Active Material Isolation along with the total current, \( I \). The other constants from the degradation sub-model are the rate constants \( k_{o,SEI} = 1 \times 10^{-12} \text{ m/s} \), \( k_{AMI} = 2 \times 10^{-14} \text{ m/s} \) and the exchange current density, \( i_{o,PL} = 0.001 \text{A/m}^2 \). The \( \alpha \)'s are the cathodic transfer coefficients. \( c_{solvent}^s \), is the concentration of the solvent. The \( \phi \)'s are the potentials of the electrode and liquid phases. \( R_{film} \) is the resistance of the SEI layer.
Power Profiles:

The day-long load profiles generated using the vehicle dynamics model in conjunction with the drive cycles are shown in Figure S3. Cases A-C run for a distance of 270 miles while Cases D-F run for 400 miles. Case A and D are for 3 truck platoons with the Composite drive cycle, 500 kW charging in a flat road. Case B and E are single trucks under the Cruise drive cycle at a charging rate of 1.5 MW at flat road conditions as well. Case C and F are single trucks with the Custom duty-cycle at a 1% road grade and 1.5 MW fast charging.

Figure S3: The various power profiles corresponding to each of the cases used for estimating the cycle life of the battery pack as discussed in Figure 1(b). Each power profile spans 24 hours and is repeated to simulate the performance of the battery pack over its lifetime.
Vehicle Design Considerations:

The price of fuel (electricity and diesel) coupled with the efficiency of electric powertrains would always result in lower operational costs for electric trucks. However, an aerodynamically inefficient truck electric truck design would result in a higher energy consumption and require a larger battery pack for a fixed range. A larger required battery pack results in a higher initial price differential and the marginally higher operational costs together result in a much higher payback period distribution, as shown in Figure (S4). A mean payback period of 8.45 years which is very close to the lifetime of the truck itself. Also, it is worth noting that at a drag coefficient of 0.63, the battery pack would be extremely heavy and resulting in reduced payload capacity unless very high specific energy battery packs.

Figure S4: The exterior design and the effective drag coefficient of the electric semi-truck plays a crucial role in the economic case, where a lower drag coefficient which results in a lower energy consumption and effectively a smaller battery pack which in turn decreases the initial price differential. We identify a drag coefficient, $C_d$, of 0.63 to represent the threshold beyond which there is a very high probability of the payback period being higher than the lifetime of the trucks. Although, the case presented above stands for an electric truck with a range of 500 miles or over and a battery pack price in the range of $[90,120]/\text{kWh}$.

Battery Pack Replacement:

In order to account for the battery pack replacements, the fraction of cases that require replacement is randomly sampled from the ideal distribution with no replacement and replaced with another random sample with the same number of cases from the limiting distribution with all battery packs replaced. This process is captured in Figure (S5).
Figure S5: The extent to which the distributions are skewed by the replacement fraction is shown above. The mean value shows a steady increase with the increase in the battery pack replacement fraction as the distributions tend to become bi-modal in nature.

Figure S6: A comparison between the cost per mile of an electric semi-truck fleet and that of a diesel truck fleet is shown as a function of the battery pack replacement fraction. It can be seen that even under the limiting case of all trucks requiring a battery pack replacement, the mean cost per mile is less than the cost per mile of a diesel truck fleet.
References


Highlights:

- The economics of heavy-duty electric and diesel trucks is analyzed and compared.
- Payback period is estimated to be <3 years in the baseline scenario.
- There is an undeniable economic case for electric semi-trucks for all examined scenarios.
- Battery replacement costs and the price of electricity are the most crucial factors.

**eTOC Blurb:** Electric semi-trucks can transform freight transportation through reduced emissions and improved energy efficiency. The size and cost of the battery packs needed for semi-trucks have cast considerable doubts about the commercial viability of electric trucks. Here, we develop a robust performance and cost model to evaluate several metrics to quantify the merits of electric trucks. We find that there is a strong economic case for electric trucks, however, battery replacements and the price of electricity could alter the economics by a considerable extent.

**Context & Scale:** Approaches to electrify heavy-duty trucks have gained significant attention due to their potential to reduce emissions from the trucking industry along with a significant reduction in the net energy consumption of freight transport. While the operation of an electric powertrain is known to be more economical compared to diesel counterparts, the size and consequently the cost of the battery pack required for heavy-duty trucks raises uncertainty in the overall economic competitiveness of electric trucks. In this work, we analyze the initial investments and operational costs of electric and diesel semi-trucks to identify the most important factors that affect the viability and competitiveness of electric trucks. Based on robust performance and cost models, we find that there is a strong economic case for electric trucks. However, certain factors could significantly affect the economics like the cost of battery replacements, the price of electricity and the cost differential of repairs between electric and diesel.
Graphical Abstract:

- Electric
- Diesel
- 100% Battery Replacements
- 0% Battery Replacements
- High Electricity Prices
- Low Diesel Repairs
- BASELINE Platooning
- Payback Period (miles)
- Payback Period (years)