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VIEWPOINT

Performance Metrics Required of Next-Generation Batteries to Make a Practical Electric Semi Truck

There is enormous interest around the development of an electric semi truck, and in order to understand the practical limitations imposed by the battery pack, a rigorous and thorough analysis considering battery metrics as well as vehicle design parameters is required. In this study, we find that an electric semi truck, such as the envisioned Tesla Semi, would be limited to a driving range well under 600 miles, a small payload capacity, and a prohibitively high cost. Enabling a longer driving range of 600 miles needed by the current standards of the trucking industry might require a transition to beyond Li-ion batteries.

In a recent TED talk,[1] Elon Musk discussed his vision for the transition to sustainable transportation, a sector which currently accounts for nearly one-third of the total greenhouse gas emissions.[2] A major discussion point following this talk has been the potential for Tesla Semi to revolutionize the trucking industry,[3−5] which is the source of about one-fourth of the emissions of the transportation sector while accounting for less than one-tenth of the total on-road vehicles.[6,7] This has led to enormous speculation, both among media and financial markets, on the cost and performance of the vehicle largely based on back-of-the-envelope estimates. Given the huge variability and limitations of such estimates, we feel compelled to carry out a rigorous study that accounts for the large uncertainties in crucial factors, such as the specific energy of the battery pack, vehicle weight, drag, and rolling resistance, and how the factors influence each other. On the basis of this analysis, we suggest a potential trajectory forward and targets for the required cost and specific energy of the battery pack to enable mass penetration in this sector; the implications of this analysis are summarized in Figure 1.

Vehicles like semi trucks fall under the "Class 8" category of the EPA standards, and the statistics and estimates for such vehicles can be found in a study by the National Academy.[8] The main value proposition of the trucking industry hinges on transporting a payload over a specified distance at a certain cost. On the basis of this aspect, we first address the limits of the range and payload capacity of heavy-duty trucks with current Li-ion battery technology with estimates for the cost of the pack. The uncertainty in each of these parameters is quantified based on the extensive data previously reported.[8,9] We then proceed to examine how each of these limitations would be alleviated with future and beyond Li-ion batteries.

The average annual distance traveled for a Class 8 vehicle is about 75 000 miles,[8] which translates to about 300−600 miles traveled per day assuming a daily driving time of 8−16 h throughout the year. The average payload carried by such vehicles for commodities from different industries is about 14 500 kg (16 US ton)[8] and can be as high as 20 000 kg (22 tons). The fully electric Tesla Semi would have to meet these performance requirements at a reasonable cost of operation in order to be a practical alternative to existing vehicles.

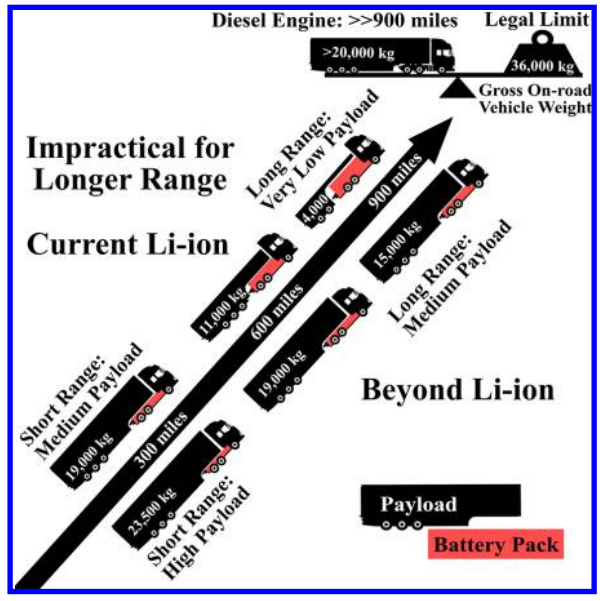

Figure 1. Summary of a comparison between current and beyond Li-ion batteries for electrifying semi trucks.

We begin our analysis with the estimation of the required battery pack energy based on the standard dynamic vehicle model, represented by the system of eqs 1−2

$$E_p = \left[\left(\frac{1}{2}\rho \cdot C_d \cdot A \cdot v_{rms}^3 + C_{rr} \cdot W_T \cdot g \cdot v + t_f \cdot W_T \cdot g \cdot v \cdot Z\right)/\eta_{bw} + \frac{1}{2} W_t \cdot v \cdot a\left(\frac{1}{\eta_{bw}} - \eta_{bw} \cdot \eta_{brk}\right)\right]\left(\frac{D}{v}\right) \quad (1)$$

where the pack energy, (E_p) depends on the energy utilized to overcome aerodynamic drag forces, frictional forces, the road gradient, and inertial forces. A significant fraction of the energy used to overcome inertial forces is recovered via regenerative braking when the vehicle is decelerating. The important parameters are the coefficient of drag (C_d), average velocity (v) and root-mean-square of the velocity (v_{rms}), the coefficient of rolling resistance (C_{rr}), the gross on-road vehicle weight (GVW) represented by (W_T) (includes the payload and battery pack), the road gradient Z, and the total time taken for a fixed driving range determined from $\frac{D}{v}$. The road gradient term is accounted

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for using the expression (Z = r/100), where r is the percentage road grade and (t_f) is the fraction of time the vehicle spends at a road grade of r%. We assume a road grade r of 1% and (t_f) of 15%. The other fixed parameters are ρ, the density of air (1.2 kg/m^3), g the acceleration due to gravity (9.8 m/s^2), A the frontal area of the vehicle (7.2 m^2), a the mean acceleration or deceleration of the vehicle (0.112 m/s^2). η_{bw} is the battery-to-wheels efficiency of ~85% which includes the battery discharge efficiency of 95% and a drivetrain efficiency of 90%. η_{brk} accounts for the efficiency of the brakes and is assumed to be 97%.

Class 8 vehicles currently have an average coefficient of drag (C_d) of 0.63,[8] with a projected value of 0.45[8] for future vehicles. The velocity profile data is obtained from the NREL DriveCAT database for heavy-duty trucks, and the mean and the root-mean-square values of driving velocity are based on a set of CARB HHDDT drive cycles namely the "Cruise and Composite" segments. The mean rolling resistance (C_{rr}) of truck tires is estimated to be 0.0063[8] with projections of as low as 0.0045[8] for future vehicles. The current average GVW is ~27 000 kg (30 tons),[8] but for our analysis we assume a fixed GVW of 36 000 kg (40 tons), which is the legal limit for Class 8 vehicles stipulated by the FHWA.[10]

The pack weight, W_P is given by, $W_P = \frac{E_P}{S_P f_{burden}}$, determined on the basis of a distribution of values for the specific energy S_P at the cell-level and a fixed value of 0.48 for the packing burden factor.[11] f_{burden} represents the weight for the thermal management systems, module hardware, battery jackets, and other noncell inactive materials used to assemble a practical battery pack. The specific energy (S_P) is considered with a mean value of 243 Wh/kg, which is equivalent to that of a Panasonic NCR18650B cell, and a maximum value of 300 Wh/kg for future Li-ion systems. Another distribution of specific energies is considered for the evaluation of beyond Li-ion systems, such as Li-metal coupled with an advanced cathode, Li−S, and Li−air, with a mean specific energy of 500Wh/kg at the cell level and a maximum value of 700 Wh/kg. It is worth pointing out that these are highly optimistic estimates, and current designs of these batteries provide specific energy far below the numbers used.[12] The maximum payload capacity for the vehicle (W_L) is given by

$$W_L = W_T - (W_P + W_V) \quad (2)$$

which is the weight that remains of the GVW after accounting for the weight of the pack (W_P) and the empty vehicle weight (W_V) with their respective distributions. The empty vehicle weight without the battery pack (W_V) is considered to be in the range of 6000−8000 kg,[8] based on existing estimates for diesel-powered vehicles without the weight of the engine.

Finally, the cost of the pack ($Cost_P$), given by $Cost_P = \frac{E_P}{Cost_{kWh}}$, is determined using the pack energy distribution obtained from eq 1 and a distribution of values for the cost per kilowatt-hour of the battery pack ($Cost_{kWh}$). The cost of the batteries based on prior work[9] is assumed to have a mean value of $190/kWh for Tesla battery packs and a maximum value of $350/kWh with a projected future value of $150/kWh. For beyond Li-ion batteries, we assume a mean cost of $120/kWh with a minimum value of $80/kWh.

Each of these parameters are cast as truncated Gaussian distributions (truncated within the limits of future projections and known maximum or minimum values), and a summary of this is listed in Table 1. Using the dynamic vehicle model and the pack cost determination equations, we perform a standard Monte Carlo simulation of all the possible outcomes based on the distributions of each variable. The simulations are performed for a driving range of 300, 600, and 900 miles. The resultant required pack energy can be seen in Figure 2(a), and for each driving range value, these uncertainties are propagated throughout the system of equations. In Figure 2(b−d), we can compare the parameters of pack weight, cost per pack, and the payload capacity between current Li-ion and beyond Li-ion (B-Li) batteries.

Table 1. Bounds and Mean Values of Variables

parameter	[bounds], mean
C_d	[0.45, 0.7], 0.63
C_{rr}	[0.0045, 0.01], 0.0063
W_T (1000 kg)	[27, 36], 32
W_V (1000 kg)	[7, 10], 8
v (m/s); (mph)	[16, 21], 19; [36, 47], 43
v_{rms} (m/s); (mph)	[19, 24], 22; [43, 54], 49
$Cost_{kWh}$ Li-ion ($/kWh)	[150, 300], 190
$Cost_{kWh}$ beyond Li-ion ($/kWh)	[80, 200], 120
S_P Li-ion (Wh/kg)	[220, 300], 243
S_P beyond Li-ion (Wh/kg)	[350, 700], 500

The resulting distribution for the energy consumption per unit distance, shown in Figure 2(a), is in the range of 2.2 and 2.9 kWh/mile and has a mean value of 2.6 kWh/mile or 65 Wh/ton-mile. This is an extremely efficient system in comparison to existing vehicles which have a mean estimated energy consumption of ~250 Wh/ton-mile or 155 ton-miles per gallon of diesel.[8] The mean values of the required pack size or pack energy (kWh) scale linearly with the distance and a massive 3100 kWh pack is needed for a range of 900 miles, nearly ~30 times the size of the battery packs in the Tesla Model S car. The values of the required energy consumption per mile and required pack size do not change with beyond Li-ion systems because they depend mainly on the gross vehicle weight and not the weight of the pack. Lower driving ranges of 300 and 600 miles require battery packs of 1000 and 2000 kWh respectively.

The weight of the pack required for each of the driving range values considered is shown in Figure 2(b). For 600 and 900 miles, we observe a mean pack weight of about 16 000 kg and 24 500 kg (18 and 27 tons), respectively. We observe an approximate one-third reduction in the pack weight after a transition from the most energy dense Li-ion battery with over 260 Wh/kg to a potental beyond Li-ion system with a specific energy of 350 Wh/kg. In terms of mean values, a range of 600 miles would require a battery pack that would weigh twice as much as the weight of the empty vehicle, but with batteries based on Li metal, Li−S, or Li−air, it would weigh only as much as the empty vehicle weight. The reduction in pack weight with beyond Li-ion systems would have a significant influence on the energy consumption of the vehicle, since the GVW of the vehicle would reduce drastically with the same payload. The influence of GVW on the energy consumption can be seen by examining the relation shown in eq 1.

The cost for the above-estimated pack size is shown in Figure 2(c), and we observe larger bounds around the cost of the battery packs for a longer driving range. The cost estimates use the uncertainties associated with the pack size and the cost per unit of energy ($/kWh). For current Li-ion systems, the cost of the pack is in the range of $160 000−$210 000 for a driving range of 300 miles, and with beyond Li-ion systems, the value could be lower than $100 000. For 600 miles, current Li-ion could cost as much

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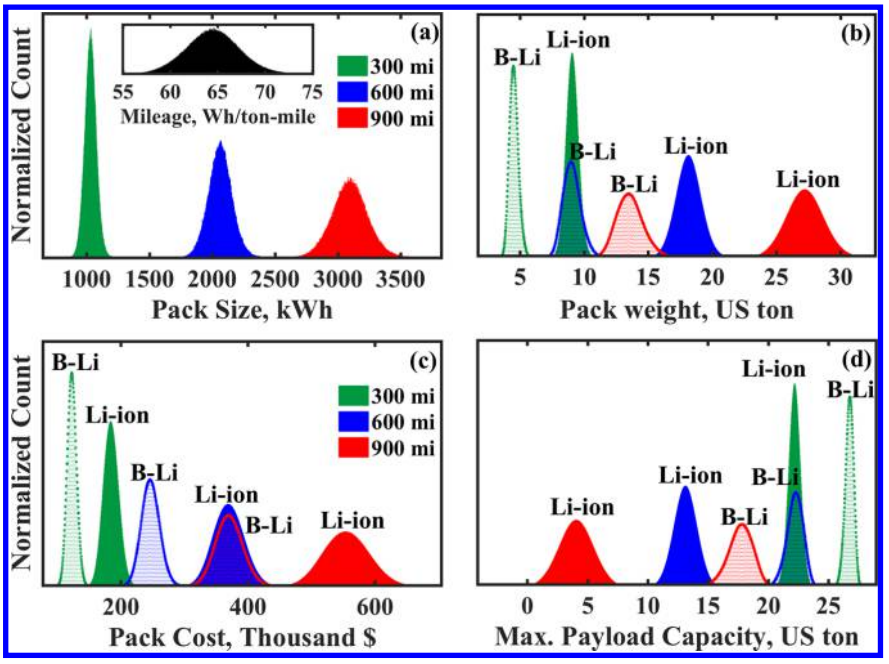

Figure 2. Estimated distributions of the required pack size, weight of the battery pack, cost of the pack, and maximum payload capacity for a fully electric Class 8 truck with driving ranges of 300, 600, and 900 miles. (a) The estimated pack size (in kWh) for various driving ranges, which is primarily determined by the gross vehicle weight. (b) The required pack weight for various driving ranges which is primarily determined by the specific energy, and we see that Li-ion based battery packs (mean cell level specific energy of 243 Wh/kg) are significantly heavier than potential beyond Li-ion systems (mean cell level specific energy of 500 Wh/kg). (c) The pack cost for various driving ranges, which is determined by the mean cost of the battery packs. Potential beyond Li-ion systems benefit from requiring a significantly smaller battery pack and higher energy in each cell. The cost of the battery pack is a major bottleneck. (d) The lower pack weight of beyond Li-ion systems directly results in an increased payload capacity, and the system would be practical for a long driving range of 600 miles. For reference, the current average payload carried by Class 8 trucks is 16 US Ton, and the legal limit for the GVW is 40 US Ton. We observe that the low specific energy of current Li-ion batteries renders a vehicle with a low payload capacity of under 10 US Ton for a driving range of 600 miles and higher.

The payload capacity of these vehicles is an important parameter for the trucking industry, and in a fully electric vehicle, the payload capacity would be reduced significantly because the battery pack weight forms a significant fraction of the gross vehicle weight.

as $400 000, but with a vehicle redesign to a low C_d of 0.45, a C_{rr} of less than 0.0045, the pack would cost $320 000 at $190/kWh, which is the current estimate for the price of a Tesla battery pack. The longest range considered of 900 miles would be commercially impractical, costing over $450 000. With a "beyond Li-ion" battery pack placed in a "well-designed" vehicle with optimal values of design parameters mentioned before, a 600-mile capable battery pack would cost $250 000, which is around 25% higher than the mean value of a current Li-ion battery pack capable of a short 300 mile range. It should be noted that each of these values is the cost of the battery pack alone, and the entire vehicle would include several other costs. For comparison, an equivalent diesel-powered vehicle would cost only $120 000, but a true comparison should include the operating costs of the vehicle and not only the initial costs in order to account for the difference in the price of electricity and fossil fuels as well as the significantly higher efficiency of electric drivetrains.

The payload capacity of these vehicles, as stated before, is an important parameter for the trucking industry, and in a fully electric vehicle, the payload capacity would be reduced significantly because the battery pack weight forms a significant fraction of the GVW. The estimates for the maximum payload capacity can be seen in Figure 2(d). For 600 miles, the vehicle would house about 11 000 kg (12 tons) of payload, which is about three-fourths of the current average payload carried by Class 8 trucks, 14 500 kg (16 tons) as mentioned before. For the same range, we could have a maximum payload of about 13 600 kg (15 tons) if the vehicle is designed with the lowest coefficient of drag, rolling resistance, and vehicle weight and the battery with the highest possible specific energy with current Li-ion systems. Another important observation is that a 600-mile capable battery pack would weigh over 16 000 kg (18 tons), which is much more than the available payload capacity of 12 tons. The weight of the battery pack in comparison to the payload carried provides the point for an interesting discussion, if the battery pack is much heavier than the payload, then it implies that a greater fraction of the energy consumed to move the vehicle is spent on moving the battery pack rather than the payload. Only at a shorter range of under 600 miles would the vehicle be practical considering the average required payload capacity of over 16 tons.

A key conclusion from this analysis is that, with current Li-ion batteries, we would have no meaningful payload capacity if we need a driving range of 900 miles since the battery pack and the vehicle weight together would account for nearly the entire GVW limit of 36 000 kg (40 tons). The payload capacity would increase significantly with a transition to beyond Li-ion systems, which show a mean payload capacity of 23 500, 20 000, and 16 300 kg (26, 22, and 18 tons) for 300, 600, and 900 miles respectively due to the much higher specific energy with a mean value of 500 Wh/kg equivalent to an advanced Li-ion or Li-S battery. The current

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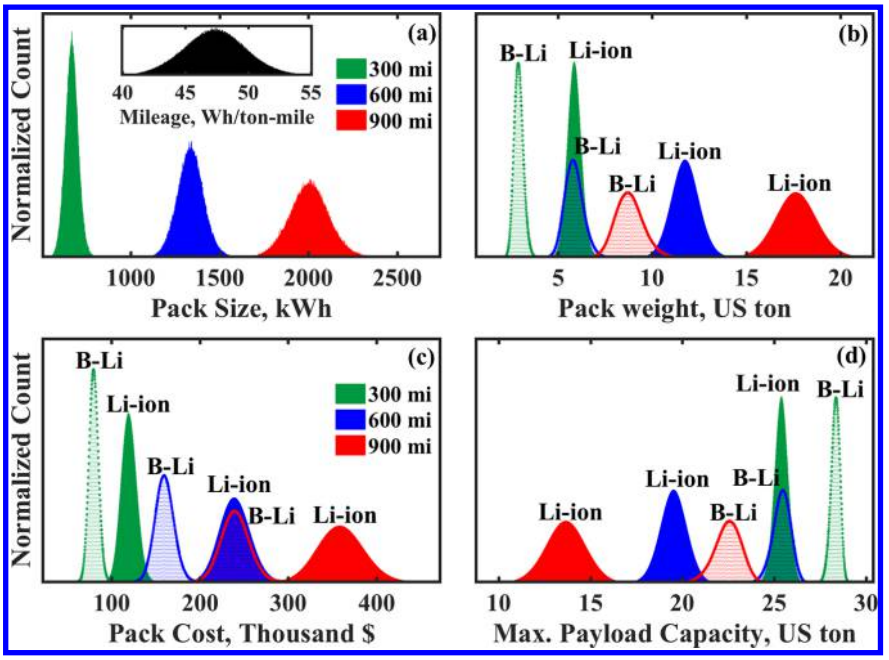

Figure 3. The figure shows the estimated distributions for the optimistic scenario, with no road gradient, a high battery-to-wheels efficiency, and a relaxed oversizing fraction. With the much lower energy consumption, the required pack size, shown in part (a), is more than 25% lower than the estimates in Figure 2(a). (b) The pack weight is over 12 tons for a driving range of over 600 miles but would be reduced to half the value with a battery pack based on beyond Li-ion batteries. (c) For the optimistic scenario, the pack would still cost over $200 000 for a driving range of 600 miles or higher. We also observe that the cost of a 900-mile capable beyond Li-ion pack would cost as much as a current Li-ion pack capable of 600 miles, similar to what is seen in Figure 2(c). (d) The lower pack weight of the optimistic scenario provides an additional payload capacity of up to 10 tons compared to Figure 2(d). At the same time it is important to point out that these optimistic parameters considered could be achieved for specific use-cases with a flat road, a highly efficient powertrain, and use-cases where only a fraction of the rated driving range is utilized implying a low depth-of-discharge.

required driving range close to 600 miles would have feasible payload capacity only with much higher specific energy, and current Li-ion batteries are clearly not suitable for longer driving range.

The results of the optimistic scenario considered are shown in Figure 3. With the high battery-to-wheels efficiency and no road gradient, the energy consumption is reduced to a range of 1.6 and 2.2 kWh/mile with a mean value of 1.9 kWh/mile or 47.5 Wh/ton-mile. The pack required, shown in Figure 3(a) is now reduced to 700, 1400, and 2000 kWh for 300, 600, and 900 miles respectively. The pack weight, in Figure 3(b) is consequently lower but still remains over 12 tons for a driving range of 600 miles or greater with current Li-ion batteries. The pack cost, in Figure 3(c) also remains at very high values, where the pack required for 600 and 900 miles costs over $250 000 and $350 000 respectively. In comparison to the payload capacity of the earlier scenario shown in Figure 2(d), the payload capacity of the optimistic scenario in Figure 3(d) is about 5 to 10 tons higher, depending on the driving range. The zero road grade assumption for the optimistic scenario reduces a significant amount of the energy consumption, but it is important to quantify this assumption which translates to ignoring an energy consumption increase of ~1.6r kWh for every mile traveled at a road grade of r %, for a GVW of 36 000 kg (40 tons). The ~1.6r kWh per mile quantity is derived from the road gradient term in eq 1.

Our analysis suggests that there are clear limitations in the cost and payload capacity for fully electric Class 8 trucks like the Tesla Semi, although the lower energy consumption of electric drivetrains remains a compelling motivating factor. With all of the parameters considered, as we attempt to design heavy-duty vehicles with a longer range the limitations of current Li-ion batteries are evidently magnified. Current Li-ion batteries would not be technically feasible solutions because of their lower specific energy values, and the longer driving range and higher payload capacity required by the trucking industry would be met only by beyond Li-ion solutions to the battery pack. Although there exists a large uncertainty in the cost of the battery pack due to the increased Li-ion production by the Tesla Gigafactory, the initial investment cost for the battery pack would be the most significant limiting factor when compared against the cost of existing diesel-powered vehicles. The targets needed for a driving range of 600 miles and to carry a payload of over 10 tons are a specific energy well in excess of 400 Wh/kg at the cell level costing less than $100/kWh along with a vehicle designed with a C_d of 0.45, a C_{rr} of under 0.005, and an empty vehicle weight of under 7000 kg. We end with a word of caution that autonomous driving could potentially play a crucial role in changing the landscape of the trucking industry, because a drastic change from the current known driving patterns could have significant impact on the energy and power requirements of the vehicle; an analysis of these effects is well beyond the scope of the present study.

With all of the parameters considered, as we attempt to design heavy-duty vehicles with a longer range the limitations of current Li-ion batteries are evidently magnified.

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We end with a word of caution that autonomous driving could potentially play a crucial role in changing the landscape of the trucking industry.

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Views expressed in this Viewpoint are those of the authors and not necessarily the views of the ACS.

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ABBREVIATIONS

TED	Technology, Entertainment, and Design conferences
EPA	Environmental Protection Agency
GVW	Gross vehicle weight
NREL	National Renewable Energy Laboratory
DriveCAT	Drive Cycle Analysis Tool
CARB HHDDT	California Air Resources Board - Heavy Heavy Duty Diesel Truck
FHWA	Federal Highway Administration

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