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Impact of technology progress and design choices on the techno economic feasibility of electric vehicles

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Executive Summary

Consumer adoption is steadily rising in US light duty segment, even though it is mostly among the affluent consumers. Tax incentives, environmental awareness, higher petroleum prices are among the factors drving this adoption. Commercial truck fleets are often guided by regulatory requirements and economic feasibility in their technology adoption plans. This study shows that medium duty electric trucks can achieve operational cost parity with diesel counterparts in the next 5 to 10 years. For long haul trucks, the ownership cost parity will be based on the design choices made by manufacturers. Short range trucks (150-200 miles) will be feasible in the near term even if penalties are imposed on charging time. As technology progresses longer range trucks will become more economical than incurring penalties for downtime associated with charging.

1 Abstract

Medium and heavy duty trucks contribute to 26% of the overall carbon emissions from the transportation sector[1], but has not experience the same enthusiastic adoption of the electric vehicles as we see in the light duty market. The Inflation reduction act of 2022 extends economic incentives of upto $40,000 to electric trucks signifying the importance assigned by US government to decarbonize commercial trucks. The act recorgnizes the need to continue the incentives for light duty vehicles, but refocuses the incentives to promote affordable electric vehicles. Argonne National Laboratory recently published a report evaluating over 30 vehicles types from the broad spectrum of cars and trucks in US maket, to evaluate the energy consumption, performance and ownership cost of convetional and advanced powertrains. This paper uses that report as reference and analyzes representative cars & trucks to discuss the impact of technology progress and design choices in achieving the economic viability of electric vehicles.

In this study, heavy duty trucks are represented by longhaul and regional haul trucks, as they are the major fuel consumers in ths market. Class 4 and 6 delivery trucks are chosen to represent medium duty trucks, as electric vehicles in those vocations are expected to achieve TCO parity in the near term. Not only that, last mile delivery applications are under regulatory pressures too to adopt cleaner vehicles.

To evaluate the potential cost and energy consumption of electric vehicles, the vehicles are simulated using Autonomie, a commercially available vehicle simulation tool. Component sizing approach used in this work ensures that the alternate powertrains can meet or exceed the performance & cargo carrying capacity of the diesel trucks they are replacing. For driving range requirements of BEVs, the worst daily driving requirement is identified from FleetDNA.

2 Approach

Economic feasibility is an important factor to achieve the wider adoption of electric vehicles. This study focus on how the technology progress expected in the next few dacdes and design choices can affect the techno-economic feasibility of EVs. Figure 1 shows the overview of the work described in this paper. Assumptions regarding technology progress is the key input for this work. The alternate powertrains are then defined in Autonomie[2]. For designing the future vehicles, component size estimates are needed. This is derived based on the vehicle sizing logic described in prior work[3].

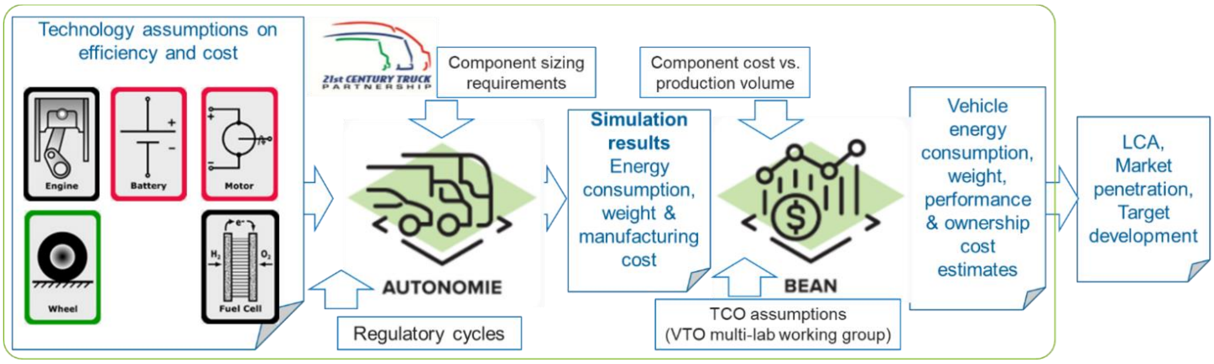

Figure 1. Overview of the process followed for this analysis

The basic premise in the sizing logic is that alternate powertrains can meet or exceed the performance and load carrying capabilities of the ICE powered trucks they are replacing. The results from vehicle simulation provides detailed energy consumption estimates over regulatory drive cycles. Vehicle manufacturing cost estimates are estimated based on the component sizing results and cost assumptions for each component technology. A retail price adjustment factor is applied on the manufacturing cost to estimate the vehicle price paid by the consumers. These factors are 1.5 and 1.2 for the cars and trucks respectively.

Based on vehicle price, energy costs and residual value of the vehicle after the service time, the total cost of ownership (TCO) is computed. Some of the factors such as wages for drivers, insurance etc are not considered in this study as we focus on the powertrain characteritics and the energy consumption.

2.1 Vehicle assumptions

The vehicles considered in this work spans all the whole breadth of cars and trucks in US market. Vehicles that contribute to nearly all of the gasoline consumed in light duty vehicles and over 85% of the fuel consumed in medium and heavy duty segment is simulated in this work.

Each vehicle is unique in its functional requirements. For light duty vehicles, most of the performance capabilities are widely published, but the capabilities that determine engine power requirements are rarely advertised for the heavier trucks. However, the engine power rating, transmission ratios, and curb weight are all available from OEMs. We estimated performance capabilities through simulations for each category of vehicle. Based on feedback from many of our industry partners, we identified the following parameters to enforce performance parity between conventional and more advanced powertrains:

1. 0- to 30-mph acceleration time
2. 0- to 60-mph acceleration time
3. Sustainable maximum speed at 6% grade
4. Driving range between refueling/recharging
5. Cargo & tow capability
6. Maximum cruising speed
7. Start/launch capability on grade
8. Maximum sustainable grade at highway cruising speed

By simulating conventional vehicle models over various test cycles, we determined the performance requirements for various types of vehicles. This is consistent with the claims OEMs have made through their websites and assuptions used for several projects with industry partners. Table 1 summarizes this for the short list of vehicles discussed in this paper.

Table 1. Summary of medium-and heavy-duty vehicle classes, functions, and performance requirements

Class	Purpose	0-30 mph (s)	0- 60 mph (s)	6% Grade Speed (mph)	Cruise Speed (mph)	Max. Speed (mph)	Cruise Grade (%)	Max grade at launch (%)	Daily driving range (mi)
4	StepVan	9	35	40	55	65	1.5	20	150
6	Box	14	40	45	65	70	1.5	20	150
8	Longhaul	18	80	30	65	70	1.25	15	500
8	Regional	18	80	30	50	70	1.25	15	250

2.2 Technology assumptions

All components are expected improve in cost and efficiency in the coming years, but the actual magnitude of the improvement is quite uncertain. US Dept of energy targets a high level of technology progress for the research work they fund, so we use that as our assumption for a 'high' level of technology progress. A business as usual scenario is also assumed where technology improvements are at a lower rate.

For this paper the most relevant technology progress is in batteries and in engines which are the main competitors in the medium and heavy duty market.

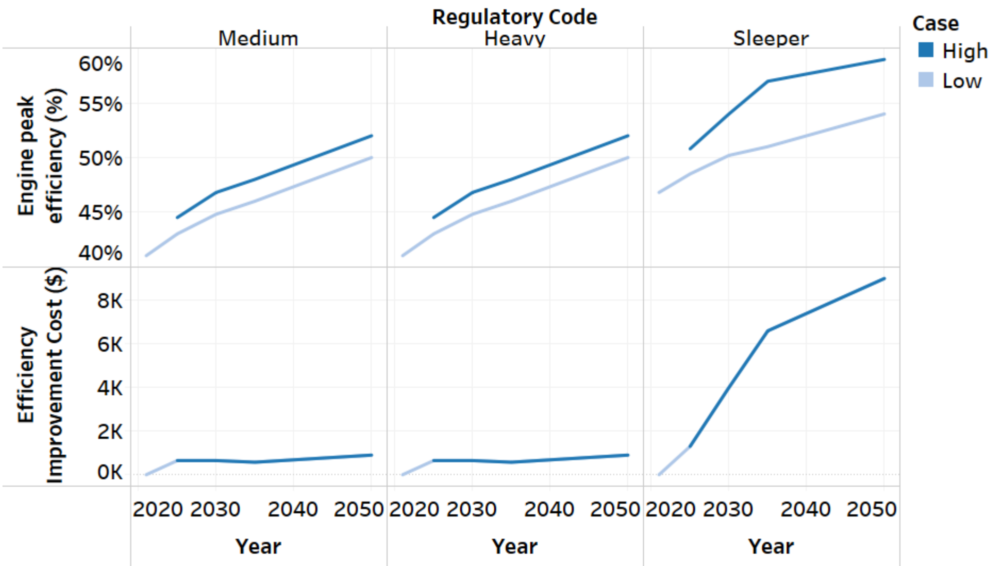

Figure 2. Efficiency and incremental cost estimates for medium and heavy-duty engines

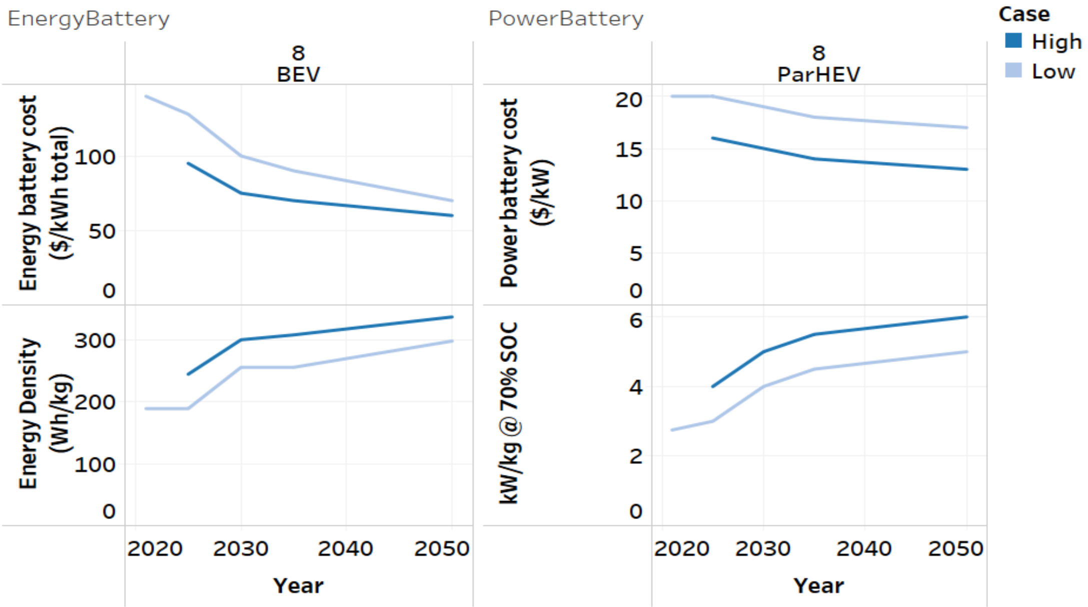

Figure 3. Battery assumptions for plug in hybrid and electric trucks (left) and charge sustaining hybrid trucks (right)

Vehicles are expected to improve in aerodynamics, rolling resistance and light weighting as well, but those improvements are expected to happen in both BEV and ICE powered vehicles.

Drive cycles

The EPA and NHTSA have issued compliance procedures for medium- and heavy-duty vehicles [4] that specify the three drive cycles that should be used to evaluate different operational conditions (Figure 1).

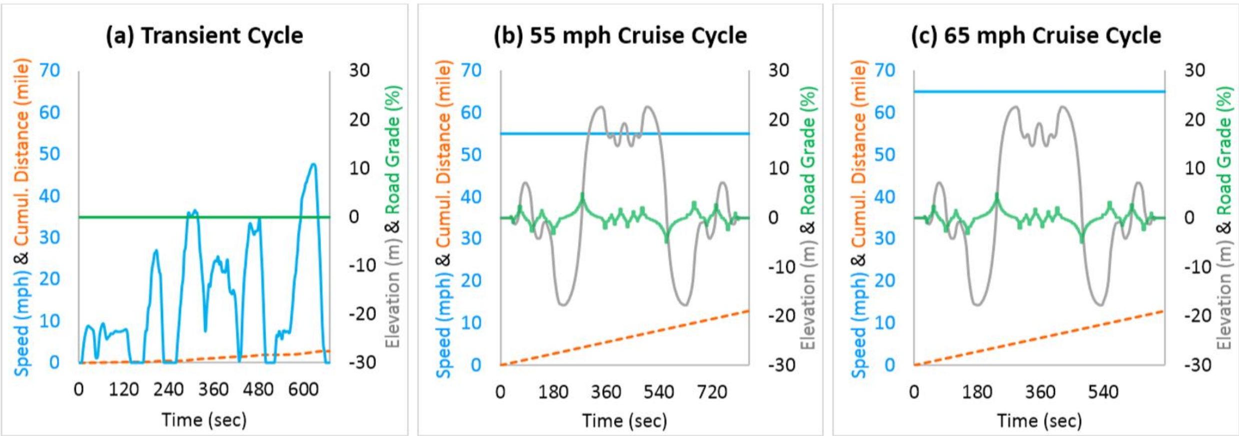

Figure 4. Drive cycles used for evaluating fuel consumption of medium and heavy-duty vehicles

The fuel economy observed in these cycles are weighted differently for each truck. The weighting used in this work is shown in Table 2

Table 2. Weight factors for three regulatory cycles to convert their fuel economy to vocation specific values

VMT Weightage for cycles		ARB Transient	EPA 55 cycle	EPA 65 cycle
Class 4 & 6 Delivery	Multi Purpose	54%	23%	23%

Class 8 Longhaul & Regional	Sleeper	5%	9%	86%

Comparsion of vehicles are made using a few different parameters. Initial purchase price, fuel economy and overall cost of ownership are usually viewed as factor affecting the vehicle adoption decisions. Figure 5 shows that BEVs could cost almost twice as much as the convetional truck in the near term. With improvements in battery cost, BEVs will achieve purchase price parity between 2030 and 2050 for various types of trucks.

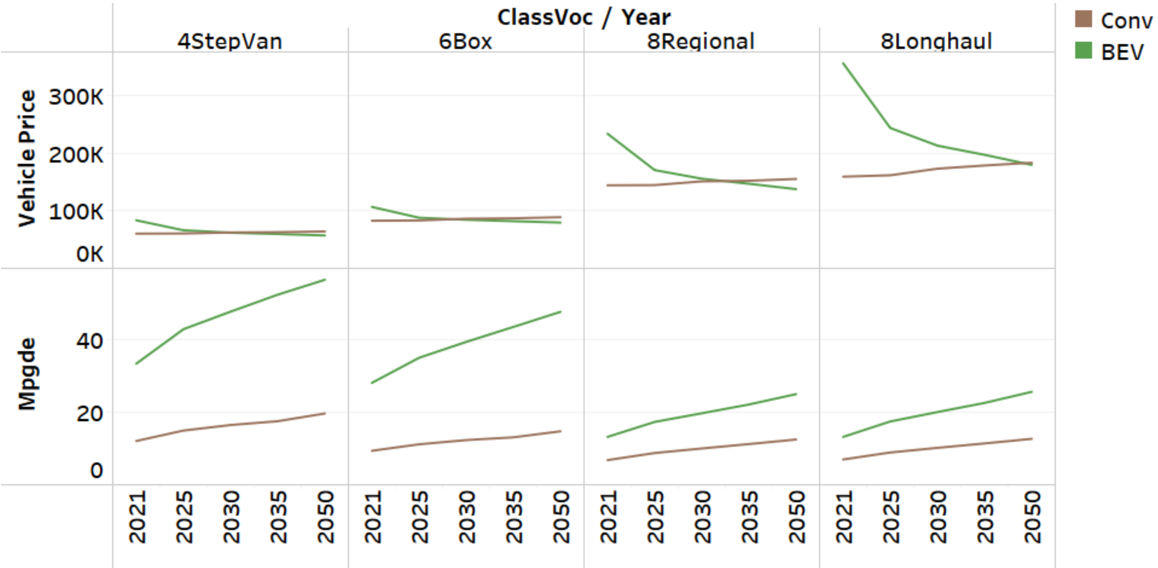

Figure 5. Vehicle price and fuel economy estimates for the convetional and electric trucks.

A simplified total cost of ownership analysis is shown in Figure 6. This simplified ownership cost metric is called levellised cost of driving (LCOD), and considers the vehicle purchase price, resale value and energy cost during operation. Wages, insurance, taxes, maintenance costs etc are not considered in this analysis as they are either the same between baseline vehicles and their more advanced competitors, or there is not enough data available to make assumptions on those factors.

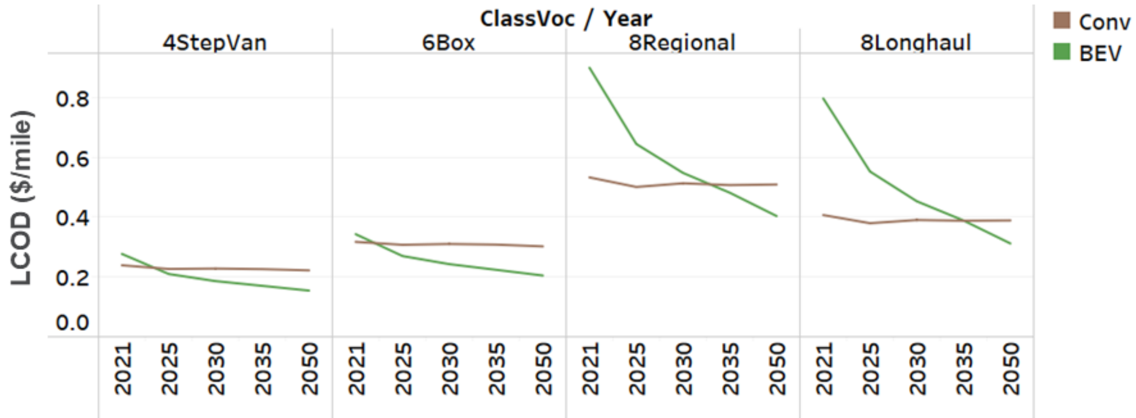

Figure 6. TCO comparison on BEVs and conventional trucks

LCOD analysis is done with a 15 year ownership period assumption for medium duty vehicles, as most delivery fleets own their trucks for their useful lifetime. For the regional and longhaul, the analysis is restricted to a 5 year service time.

For medium duty delivery trucks, we see that BEVs may have a lower total cost of ownership even now, if we restrict the analysis to vehicle price and energy costs. Diesel price estimates are taken from the Annual Energy Outlook 2021 report. The taxes associated with diesel are deducted from the price to derive a wholesale pre-tax cost for diesel, to make this comparable to the cost of electricity. The variation in diesel prices and taxes over time are shown in Figure 7.

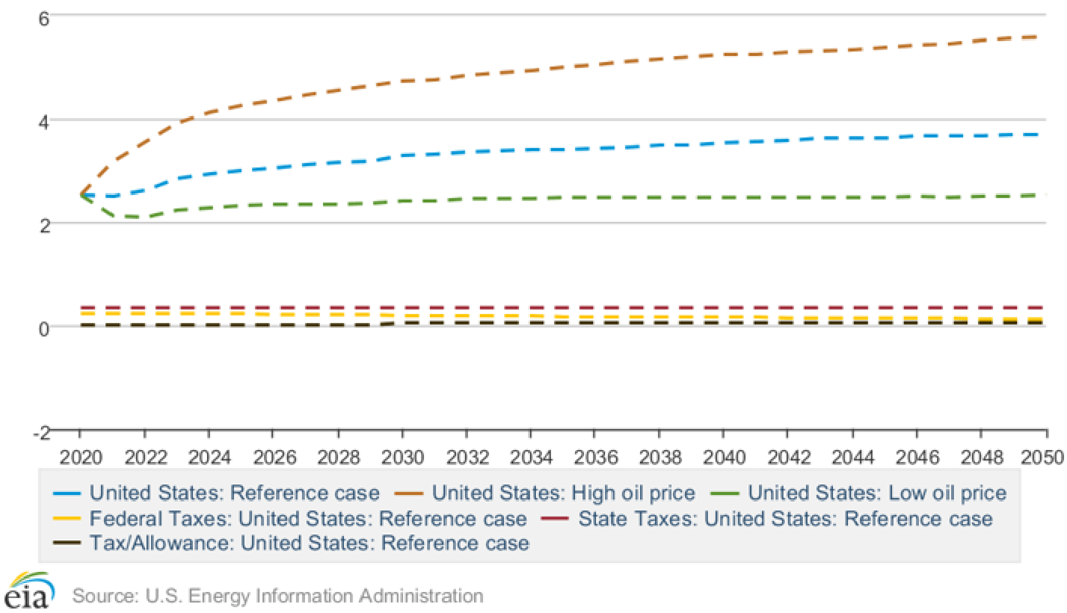

Figure 7 Projected diesel fuel prices from EIA Annual Energy Outlook 2021 (Taxes are subtracted from the end-user price to estimate the cost of diesel fuel)

There is an ongoing effort by DOE to quantify the break-even cost for high-power chargers for trucks. The relevant values were not publicly available at the time of this work, so an estimate was made for the charging costs for BEVs. For the initial years we assume a higher cost for electricity due to investment needed in setting up chargers. This cost is assumed to decrease over time as electric vehicles gain wider acceptance. The variation in electricty prices over time is shown in Figure 8Figure 7.

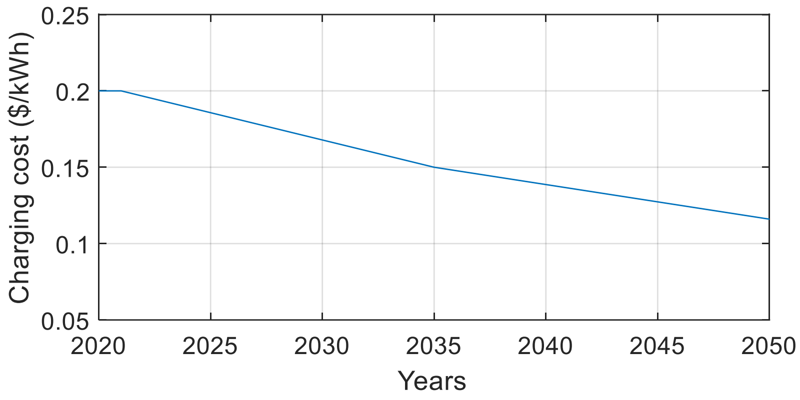

Figure 8. Assumed electricity cost for the next three decades

The initial purchase price estimate depends on the range requirements of the truck. Longer ragne trucks will need a bigger battery and will be more expensive. We are using 150 miles as the range for medium duty trucks in this work. While the average daily driving distance of trucks observed from FleetDNA database [9] is well within this range, we acknowledge that longer range BEVs may be needed to meet all the needs of the customers. This work considers explores such scenarios too by scaling the battery size of these vehicles.

Sensitivity of TCO to designed range of BEVs

Early adopters might be able to get shorter range BEVs and use them on routes that can be easily served by and electric truck. As per FleetDNA data, more than half of the daily trips for class4 and 6 delivery trucks are within 65 miles. The paper examines how BEVs will compete with diesel trucks if fleets could purchase electric trucks with driving ranges varying from 50 miles to 250 miles for medium duty trucks, and upto 750 miles for regional and long haul trucks.

The range choices considered for each truck type is shown in Table 3

Table 3. Range choices for electric trucks

	class	80th, 90th and 99th percentile ranges chosen based on FleetDNA			Default	Extended ragne.
Step Van	4	65	80	135	150	250
Box	6	50	65	135	150	250
Regional/Longhaul	8	120	150	250	500	750

For this study we assume that shorter and longer range variants of a BEV will differ only in the battery size and resultant additional curb weight. Having a larger battery can reduce the payload capacity, but the GVWR is assumed to remain unchanged. Since the motor power needed for a truck is designed based on the performance requirements at the maximum GVWR, that power rating is unaffected by battery size and range differences. Variation in battery energy, motor power and curb weight for a Longhaul trucks is shown in Figure 9. Similar differences will be there for medium duty trucks too, but we will examine the longhaul truck as an example in this paper for a detailed analysis.

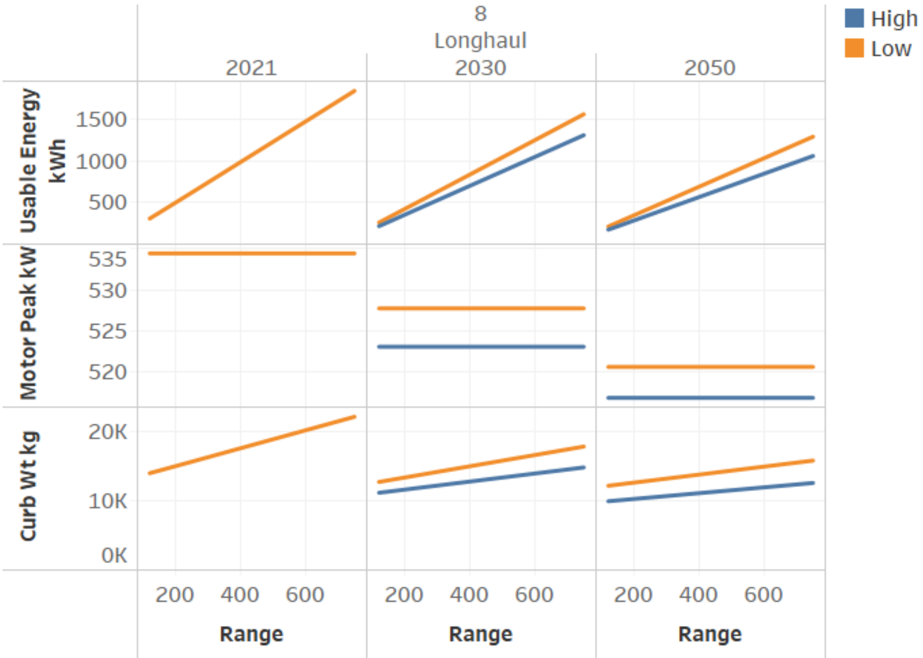

Figure 9. Variation in battery energy, motor power and curb weight of a class 8 longhaul truck when designed for ranges varying from 120 to 750 miles

Since the benefit of BEVs are mainly from the operational cost advantages and not from the purchase price benefits (in the near term), the most cost effective use for the BEV is to fully utlize the battery every day and charge it overnight at a depot where the fleets can rely on negotiated electric rates and optimum utilization of the charging facilities. This paper considers three scenarios where a mix of vehicles designed for different ranges are used in three different use cases.

Case 1: Trucks are used every day for the designed maximum daily driving range

Under this scenario, the daily vehicle miles travelled (VMT) is the designed range of the vehicle. This means a BEV sized for 150 miles, is driven only for 150 miles a day and a vehicles designed for 750 miles will be driven for 750 miles. This provides full utilization of the battery pack. The larger batteries in longer range vehicles are more expensive, but they can also provide higher operational cost savings from driving longer distances.

The Figure 10 shows that the initial purchase price of the vehicle more than doubles under the 2021 scenario when range is increased from 150 to 750 miles. Vehicles do suffer a small penalty in fuel economy as the longer ragne vehicles are heavier, but when we examine the LCOD, it is seen that longer range vehicles have lower $/mile value as the high initial cost is now distributed over more miles.

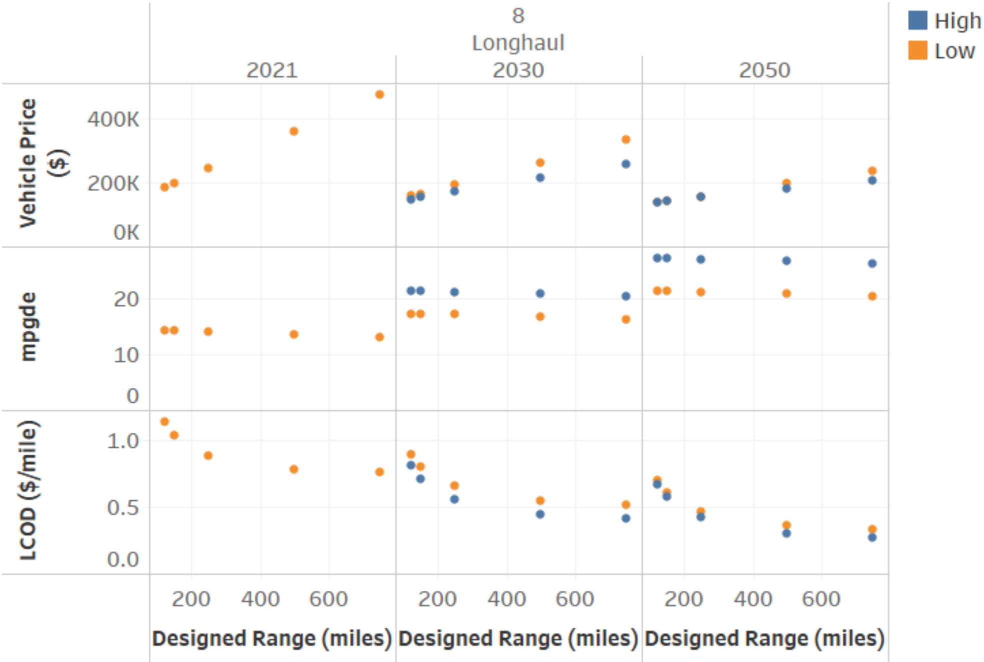

Figure 10. Variation in vehicle price, fuel economy and LCOD of a class 8 longhaul truck when designed for ranges varying from 120 to 750 miles

It should be noted that, this is a best case scenario for BEVs where the utilization of the battery is quite high. In a more practical scenario, fleets may have to pick a vehicle based on available choices, and the daily driving distances would be dependednt on their day to day business. Even under that restriction, fleets can choose short range vehicles and ensure that they are fully utilized. The next case examine in this paper describes such a scenario.

Case 2: Trucks are used every day for the 80th – 99th percentile daily driving distance without incurring penalties for mid shift charging.

This scenario examines the viability of the BEV when it is used for various daily driving ranges varying from 80th -99th percentile value of daily driving distances (150 - 750 miles). This scenario assumes that a 250 mile range vehicle that is used on a 750 mile daily driving scenario will be charged multiple times during the work day. The charging cost is as per the Figure 8, but no other additional penalty is applied for such charging events. This could be similar to charging the vehicle when it is at a loading dock, or during the lunch break or other mandatory breaks for the driver.

Vehicle price and fuel economy would be exacly same as what as shown in Figure 10, but LCOD calculation shows a different trend. In case of Figure 10, we saw that if the battery is fully utilized BEVs with longer ranges have lower LCOD than the short range vehicles. Figure 11 too shows the importance of the full utilization of the battery. In this case the VMT is varied from 150 miles/day to 750 miles/day for plots in each row. For each sub plot, the x axis shows the design range for the BEV. As the designed ragne increases, we see higher LCOD. The capital and operational expenses associated with longer range vehicles are higher but the denominator value (miles driven) remains the same in each sub plot.

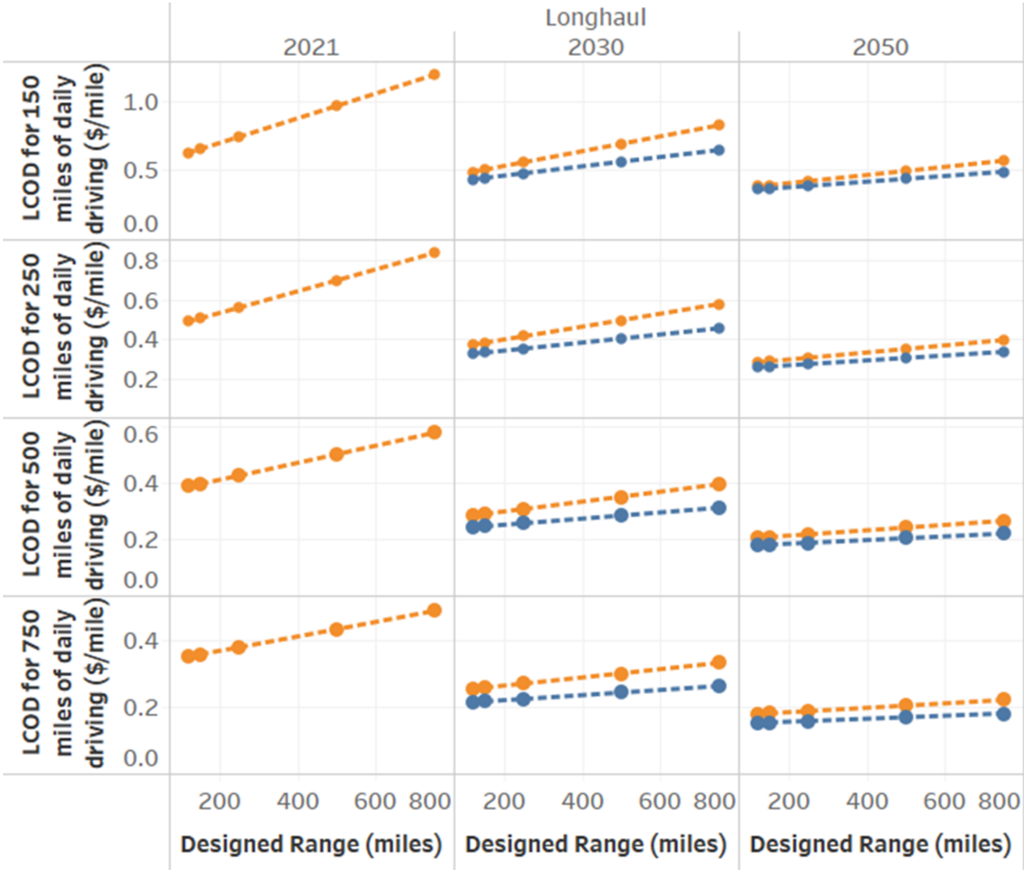

Figure 11. LCOD variation for BEVs designed for different ranges, and driven for different daily VMT

Case 3: Trucks are used every day for the 80th – 99th percentile daily driving distance. Penalties are imposed for charging at $75/hour.

The drivers for longhaul trucks are usually paid based on the miles driven, so a fair compensation is needed if they have to spend time charging the vehicle instead of driving them. In this third scenario, we consider a dwell time penalty of $75/hour for charging. Battery charging is assumed to take place at 3C rate, and for longhaul trucks this could be upto 1-3MW charge power depending on the battery size.

Considering the dwell time penalty as an operational expense shows that the shortest range truck is not the most cost effective one. The optimum choice now becomes a tradeoff between the higher initial price paid for a longer range truck and the higher operational expense for a short range truck. This shows that having a truck of about 200-250 miles range is an attractive choice, when we consider the present day battery prices ($140/kWh). For future years, as the battery price drops under $100/kWh by 2030, longer range BEVs (500 miles) become a more economic choice. In the long term, as battery prices as assumed to reach $60/kWh, it would be cheaper to invest in larger battery packs than incurring higher operational cost expenses due to down time related to charging.

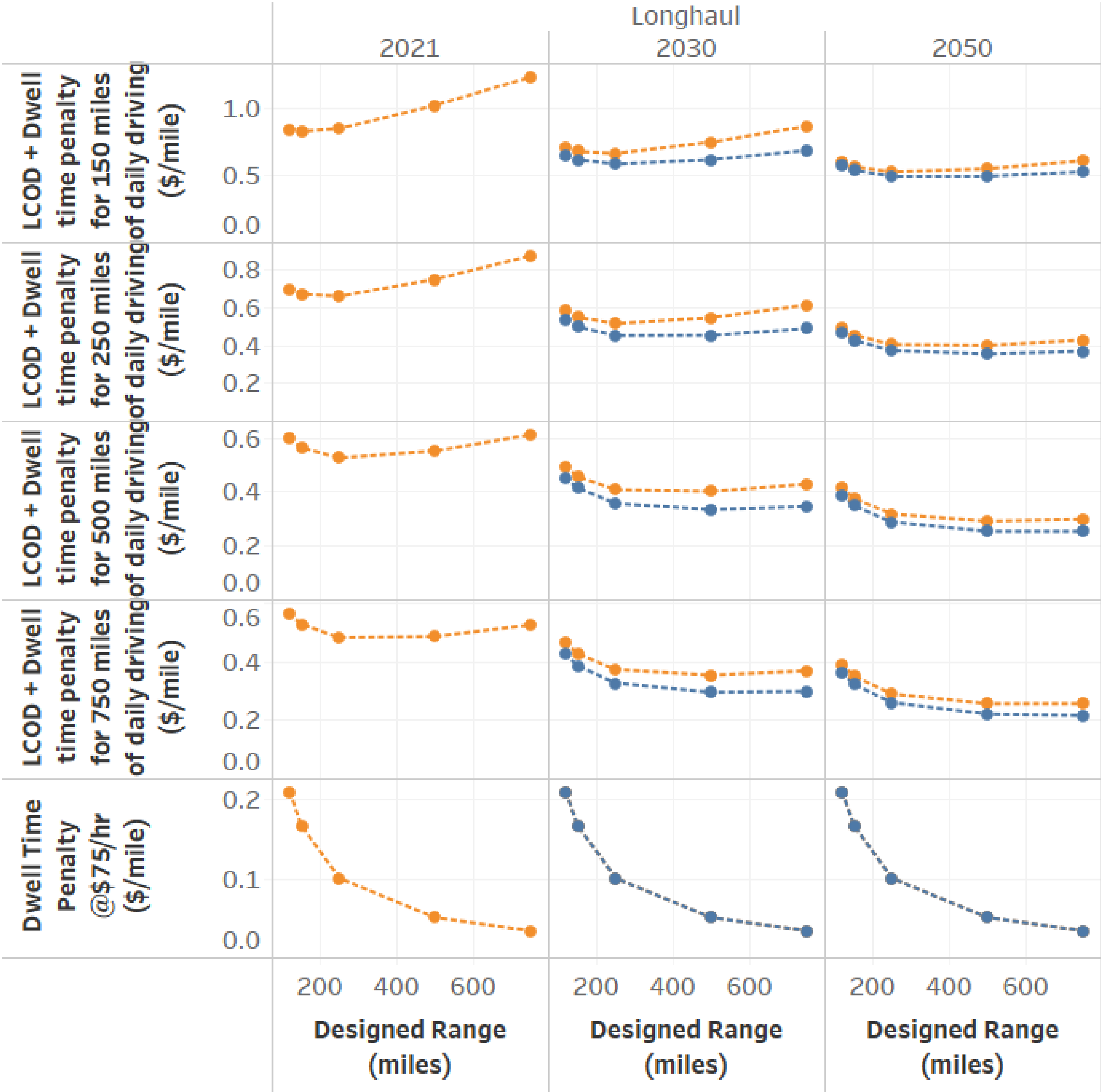

Figure 12. Levelised cost of driving (LCOD) for BEVs with different designed ragne, driven for varying daily driving distances

Medium duty truck cases were also examined as part of this work with different designed range and varying daily VMT. The trends are similar to what is shown for longhaul trucks. Since the drivers for MD delivery trucks are usually not paid based on the miles driven, the case 3 analysis is not applicable for those trucks. However having multiple charging events in a day could disrupt the business requirements for those applications, so fleets should examine their daily driving requirments and pick the minimum battery size that can meet their needs.

Conclusion

This paper shows that fleet managers should be judicious in picking the battery size they need for their fleets. Having a long range vehicle and using it on a few short trips is not an economically prudent way to use a BEV. It is necessary to use the BEV to the maximum extent possible to achieve the lowest ownership costs. In the near term, since battery costs are relatively high, it is more economical to opt a lower range vehicle and rely on mid shift charging even for longhaul applications. This approach is viable even if we consider a dwell time penalty of $75/hour for charging. This may limit the use cases for these trucks in the near term. However, as technology progresses, it is better to invest in larger batteries and rely on charging at planned predefined locations.

Impact of having multiple charging events in a day may adversely impact battery life. Argonne is in the process of interfacing the vehicle simulation model with a battery life estimation model. So, this aspect too will be considered in future TCO computation efforts.

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Presenter Biography

Ram Vijayagopal is the group manager for Vehicle Technology Assessment at Argonne National Laboratory. He is responsible for quantifying the energy saving potential of technologies using modelling and simulation. After working at Mahindra and Hitachi Automotive Systems, he joined Argonne National Laboratory as a research engineer.

He received his bachelor's degree in engineering from University of Kerala and a master's degree in engineering from University of Michigan. He has authored over 30 papers in the area of advanced vehicle technologies.