NORTH AMERICAN COUNCIL FOR FREIGHT EFFICIENCY

GUIDANCE REPORT:

Electric Trucks Where They Make Sense

ABSTRACT This report assesses the viability for North American Class 3 to 8 commercial battery electric vehicles (CBEVs) to help the industry understand the many arguments for and against them. These are very exciting times as the industry now sees daily news of electric truck developments. This report provides a foundation for understanding the key pro and con discussions of this rapidly evolving technology alternative to diesel powertrains. The study team engaged with the entire industry in generating the findings that are presented here. Thanks to all of those who contributed to this important work.

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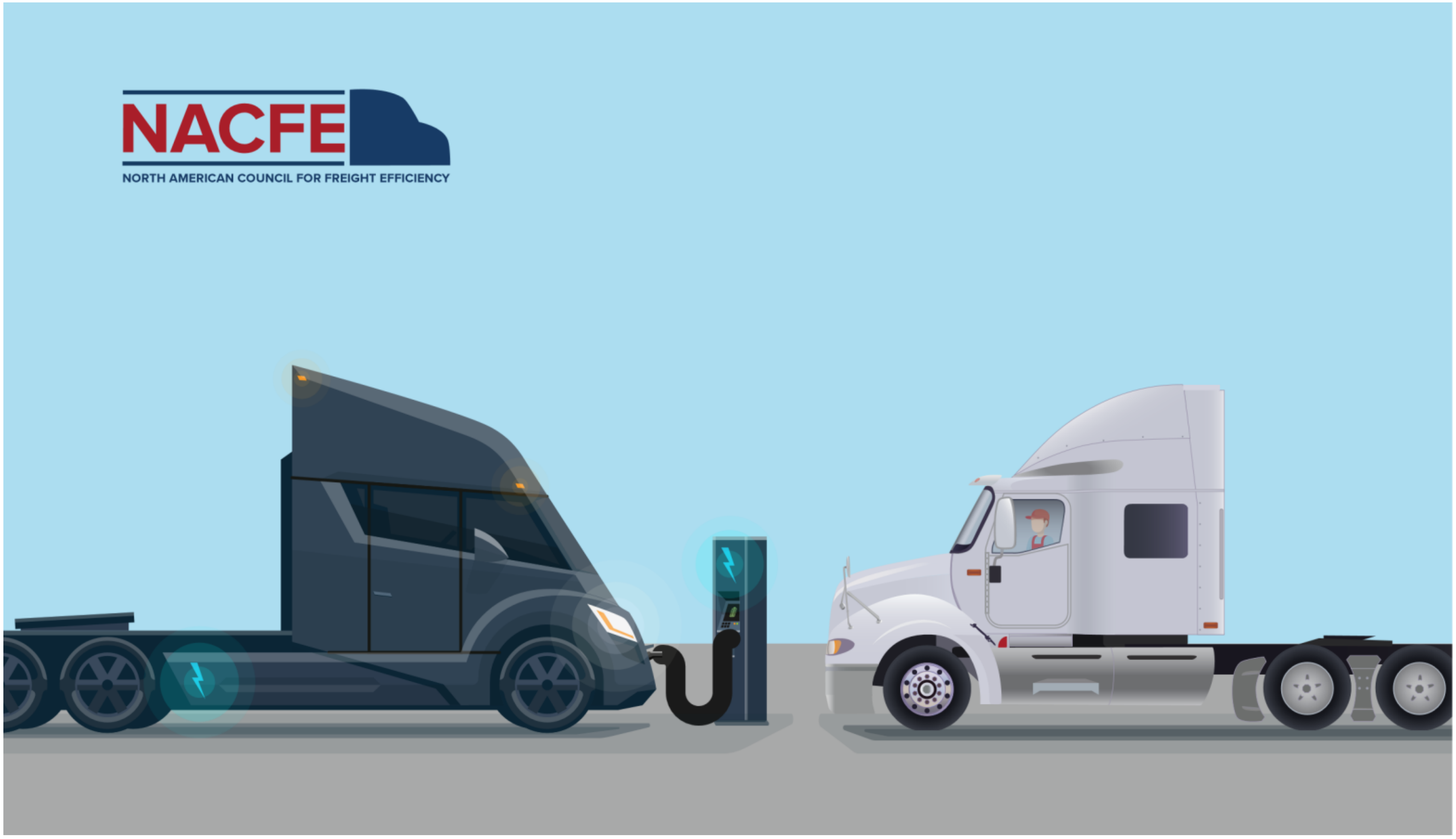


The North American Council for Freight Efficiency (NACFE) created this Guidance Report to provide perspective, insights, and resources on the complex topic of the viability of commercial battery electric vehicles (CBEVs), Classes 3 through 8. This report provides a foundation for understanding the key arguments for and against this rapidly evolving powertrain alternative. This report expands NACFE's role to include emerging new technologies that may not yet be available in production.

The fuel costs faced by the trucking industry are a significant part of the expense to operate a tractor-trailer in North America. Over the past decade fuel has been as high as $0.65 per mile driven and then dropped to $0.34 by 2016. At these two points, fuel costs accounted for 39% and 21% of the total cost of operating a commercial vehicle respectively. The price per gallon for diesel as of March 2018 has now risen to around $3.00 per gallon ($0.44 per mile) from the 2017 yearly average of $2.65.

In addition, the United States Environmental Protection Agency (US EPA) and the National Highway Traffic Safety Administration (NHTSA) have enacted greenhouse gas emissions regulations on commercial vehicles extended to 2027 that require manufacturers to develop and sell technologies to improve efficiency. These factors have driven fleets, manufacturers, and others to improve the efficiency of over-the-road tractor-trailers.

Fortunately, myriad technologies that can cost-effectively improve the fuel efficiency of Class 8 trucks are readily available on the market today. While the industry continues to increase the adoption levels of these technologies, industry stalwarts and new startups are aggressively developing revolutionary new products such as electric powertrains for trucks and technologies that continue to increase automated operation. To assist the industry in these efforts, the North American Council for Freight Efficiency (NACFE) is expanding its role with Guidance Reports—providing information on emerging new technologies that may not yet be available in production.

Widespread innovation and technological advances are producing technologies and practices that could affect decisive, revolutionary, and potentially disruptive opportunities across the transportation industry. As novel concepts, new applications, and original modes of behavior reach the market, fleets and manufacturers need information on the benefits, challenges, and risks so that everyone can profit in this evolving landscape. NACFE hopes that by fleet managers using its Guidance Reports in the months and years leading to launch, the first generation of production technologies will perform much better and offer better return on investments. This Guidance Report on electric trucks represents the first in a subset of reports being published on emerging technologies. Subsequent reports will focus on specific product offerings for market segments, duty cycles, and relevant technologies.

The goals of this Guidance Report are: (a) to present the viability of Class 3 through 8 commercial electric trucks, (b) to discuss the pros and cons of this evolving alternative to diesel powertrains, and (c) to provide industry with the quality information needed to make sound business decisions on this rapidly emerging technology.

ELECTRIC TRUCK ARGUMENTS

Battery electric vehicles for commercial applications are here today and are a growing alternative to traditional gasoline, diesel, alternative fuel, and hybrid powertrains. Opinions vary on whether this technology is a viable alternative to traditional powertrains; they are considered a threat by some and a promise by others. While considerable capital is being invested as a result of CBEVs, information is rife with biases and vested interests.

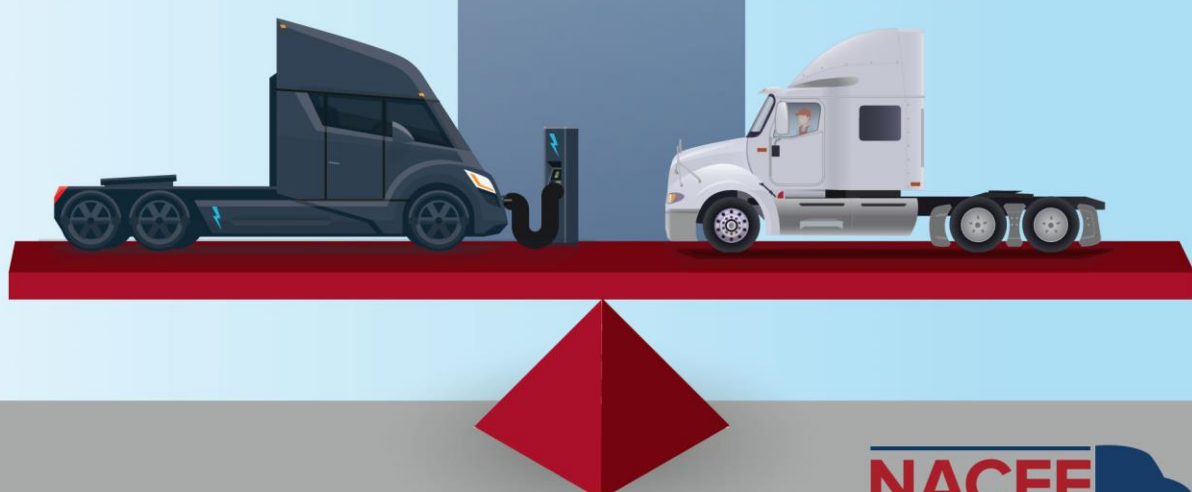
In research for this Guidance Report, NACFE identified some common arguments both for and against electric Class 3 through 8 commercial vehicles. The findings fall into several broad categories: weight, technology, cost, and charging/electric grid issues.

METHODOLOGIES

This report's conclusions were generated through interviews with fleets, manufacturers, and subject matter experts with first-hand experience with battery electric vehicles and grid infrastructure. Fourteen fleets responded to a survey that was used to better understand their needs and plans with respect to electric truck adoption. An extensive list of references was researched with the same diligence and thoughtful processes NACFE uses with its Technology Confidence Reports. The references and links are provided at the end of the full report for those interested in more detail.

10 ARGUMENTS
FOR AND AGAINST ELECTRIC TRUCKS

Argument FOR Electric Trucks	VS.	Argument AGAINST Electric Trucks
1 Commercial battery electric vehicle (CBEV) weight is not an issue	WEIGHT	1 Vehicle tare weight is too high to support my freight needs
2 CBEV technology is proven and here now	TECHNOLOGY	2 Technology is not ready
3 Maintenance will be less costly	TECHNOLOGY	3 Maintenance may not be less costly
4 CBEVs will last beyond 10 years	TECHNOLOGY	4 Vehicle life is too short
5 CBEVs will be competitively priced	COST	5 Vehicle purchase price is too high for a positive ROI
6 CBEVs will be less expensive to operate	COST	6 Vehicle operating costs are too great for positive ROI
7 CBEVs will command a premium at resale	COST	7 Vehicle residual value is questionable
8 Trust the market to provide CBEV charging solutions	CHARGING	8 Charging infrastructure is not ready
9 Trust the market to provide CBEV charging solutions	CHARGING	9 Charging Infrastructure is not fast enough
10 The grid and market will evolve with CBEVs	CHARGING	10 The electric grid cannot support growth in electric vehicles



NACFE's findings on these 10 arguments are discussed in detail in its Electric Truck Guidance Report

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This Guidance Report evaluates these positions and assesses the viability for North American Class 3 to 8 commercial battery electric vehicles to help the industry understand the many claims and rebuttals.

FINDINGS

NACFE's findings on these major positions on the extreme end of each argument are summarized below.

WEIGHT

Weight affects fuel economy. And the tare weight—the unladen weight—of the truck is important in determining the amount of freight it can legally carry. Many people worry that adding batteries to gain range in an electric truck will unacceptably reduce allowable freight, increasing the net vehicle operating costs so much that the comparison to a diesel is not attractive. Yet competitive vehicle tare weights are possible in all classes for many duty cycles. Diesel powertrains include fluids, emissions systems, exhaust systems, cooling systems, and mountings—all things that aren't included in CBEVs and that increase weight. Also, typical payloads in many applications are well below maximum GVWR. The combination of both of these factors allows for CBEV solutions with equivalent freight carrying capacity in many applications, but not all.

TECHNOLOGY

The rapid pace of improvements in battery technologies—increased capacity and decreased cost and weight—could spur increases in CBEV efficiency that likely cannot be matched by evolutionary changes to internal combustion engines. These competing technologies are at different points in maturing on their innovation S-curves, with the greater potential going to the newer CBEVs.

Reliability of the new CBEV technologies will improve through OEM experience with increasing numbers of vehicles on the road. The large OEMs will enter the market with production CBEVs providing long-term stability for fleets considering electric trucks.

Maintenance and service cost reduction is an open question at this time. The industry is still at the early stages of development where designs have not yet matured through significant field experience. Preliminary findings indicate that these costs are average or slightly better than typical internal combustion alternatives but could prove to be significantly better given the much simpler overall design of the CBEV. Feedback from medium-duty electric truck operators is that after separating out early failures, these vehicles over the long run do have lower maintenance costs versus diesel.

In regards to vehicle life, fleets, OEMs, and suppliers expect a Class 3 through 8 vehicle life of seven to 10 years before major refurbishing or salvage. The most common concern is the battery packs as charging of CBEV battery packs tends to reduce their capacity. The manufacturers expect the battery packs to be replaced when they reach 80% of their initial capacity. NACFE projects that batteries will likely exceed the seven to 10-year vehicle life.

COST

Cost is of course a critical factor in fleet technology decisions. The determination of net costs/benefits of CBEVs requires more effort than traditionally limited ROI calculations. Multiple factors need to be included, from straightforward costs such as grants, incentives, and taxes, to hard-to-quantify costs such as emissions credits, brand image, liability costs, disposal costs, indirect costs, driver/technician retention or attraction, potential customers, and other opportunity costs/benefits buried in overhead or ignored in traditional ROI calculations. Residual value and salvage value are also significant questions as there is no history at present. New business model innovations related to costing the delivery of energy to the vehicle also need to be included. Charging these trucks is not currently as available as gasoline or diesel refueling.

The industry is also developing alternatives to traditional purchasing or leasing which will factor into attaining positive ROI for CBEV investment. The battery system is the most expensive cost item. The trend over the last decade is expected to continue, with large reductions in cost and significant gains in performance. Diesel performance, in contrast, is unlikely to yield large gains in performance with reduced costs. Diesel powertrains, after a century of commercial vehicle development, are at a different point in maturation where gains are small and expensive, and complicated further by increased demand for emissions reduction.

Operating costs can be less for CBEVs because electric drives are more energy efficient than diesels and the reduction in diesel-based friction-sensitive mechanical systems such as pumps, valves, transmissions, and belts should reduce maintenance and servicing. However, vehicle residual value is still undetermined. Electric vehicles (cars and trucks) are still mostly within their first owner's use. The used electric vehicle is in its infancy. And Class 3 through 6 vehicles may not typically have a second life as the first owner may run them until they are scrapped. However, the value of electric motors and batteries in salvage may prove an advantage as they can be repurposed for non-vehicle uses and may have significant life left.

CHARGING/ELECTRIC GRID

CBEVs will increase demand on electricity and require improved demand management and storage and new electrical charging infrastructure. There are new business opportunities for charging infrastructure that may accelerate this, such as utilities or third parties providing the charging stations to factories and warehouses. Thus, the lack of current infrastructure is not a detriment to CBEV adoption, but rather an opportunity for market growth.

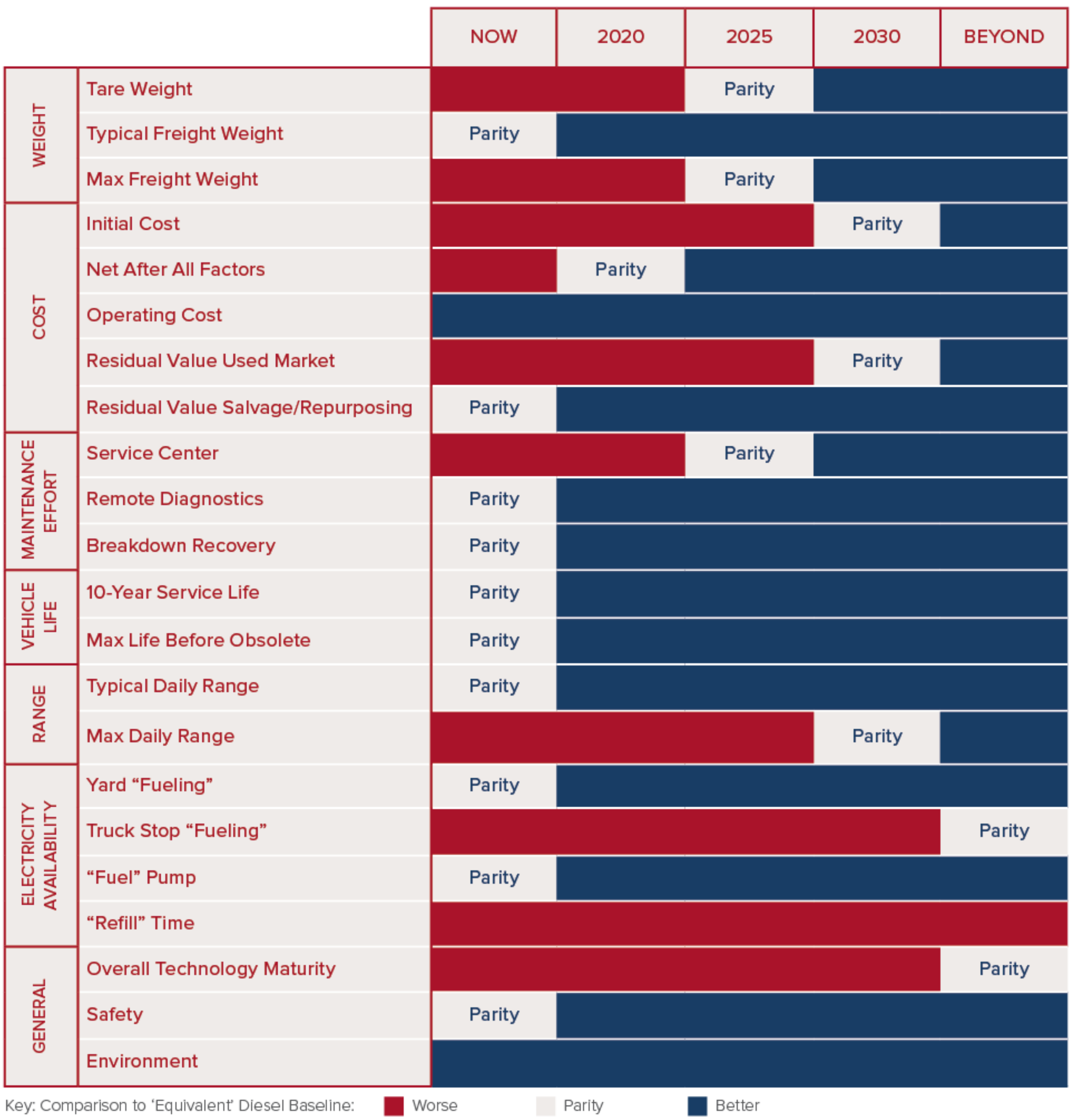
The speed needed for charging depends on each fleet's duty cycles and daily and weekly route scheduling. Many operations have defined cycles that permit off-cycle daily charging. While off-shift charging of vehicles is possible today with existing systems, the challenge is high-speed charging. CBEVs needing sub-30 minute charging speeds require high-capacity production charging systems that are currently only in the conceptual phase. Technically, these high-speed systems are thought to be feasible by a range of experts, but practicality is still a question for them. Fleets with well-defined one-driver shift A-B-A, or A-B-C-A type routes, for example, are well positioned to have base depot charging. Even fleets with routes between hubs, if range is sufficient, could have charging at both ends of the trip. Fleets with variable routes and no guaranteed return trips, will need growth in remote "public" charging capacity before considering replacing diesels with CBEVs. Hybrids may be needed where vehicles operate between and in zero-emissions zones.

The U.S. has energy production capacity for significant volumes of electric cars and trucks. Adding vehicle charging stations to a warehouse or factory is like adding a new line, a process utility companies regularly perform for commercial sites. High-rate charging expected for any sub-30 minute charging of commercial vehicles, does create a significant demand on the grid. Alternatives to mitigate this through leveling and storage systems are being considered.

PARITY BETWEEN CBEVS AND DIESELS

CBEV comparison to diesel powertrains is not a simple yes/no choice. There are multiple factors, time frames, and cost/benefits to consider. NACFE summarizes these multiple factors using parity, the point at which a CBEV is roughly equivalent to a diesel powertrain. The two charts below summarize NACFE's estimated time frame where parity is reached between these two powertrains. The first is for Class 3 through 6 segments, generally referred to as medium duty. The second is for Class 7 and 8 segments, heavy duty.

CLASS 3 THROUGH 6 CBEV PARITY VS. DIESEL SYSTEM (NACFE)



"Overall this is a very detailed report that will be valuable for the industry. It effectively discusses electric trucks in a way that is relevant to fleet managers and others who are interested in exploring the viability of this technology in the commercial vehicle market."

–Mike O'Connell, VP Supply Chain, Fleet & Sustainability, PepsiCo.

"There are many predictions about electrification. The reality is for the foreseeable future we will need a range of power solutions to provide fleets with the best opportunity for meeting their needs. NACFE sheds light on many of the complexities that will impact the rate of electrified power adoption in commercial trucks."

–Julie Furber, Executive Director, Electrified Power, Cummins Inc.

An example in how to interpret these charts is to look at the Class 3 through 6 weight. As stated in the report, battery capabilities and weight have evolved to the point that production CBEVs are available and capable of many medium-duty urban delivery services. These are where daily routes are in the 25 to 100 mile range, where load density cubes out, and where traffic stop-andgo conditions accentuate use of regenerative braking systems to recover energy. Parity exists today for typical daily range achievement. However, a diesel-fueled truck may have 30, 60, or more gallons in its fuel tank, meaning a potential daily range of hundreds of miles. While that truck only drives 25–100 miles per day, it could go much farther. Parity here requires advances in battery technology (e.g., energy density improvement and weight reduction). The report outlines that this improvement is occurring and significant change is expected in the next decade. So parity when max daily range is equivalent between similar capacity medium-duty urban delivery trucks is predicted in 2030.

This example highlights that electric truck viability is a series of trade-off discussions, not one single thumbs up or thumbs down.

CONCLUSIONS AND RECOMMENDATIONS

While CBEVs will not be a solution for every application or market, NACFE's research finds that commercial CBEVs will have an increasing role in freight transportation in Classes 3 through 8. The transition in specific market segments will be drawn out over decades, sharing space with traditional gasoline, diesel, and other alternative-fuel powertrains and also competing with other emerging technologies like fuel cells and hybrids. Thus, mixed fleets (including diesel, natural gas, hybrid, and CBEV products) optimized for specific routes and duty cycles will likely be the norm through 2050.

Early adopters will be in the urban delivery Class 3 through 6 segments where operations are characterized by fairly stable route definitions between 50 and 100 miles per day, loads tend to cube out, and vehicles run one shift per day and return to the same base location. Longer ranges and heavier weights in Classes 7 and 8 are possible in specific operations, but will not be viable in all roles. Particularly challenging will be long haul segments which need distributed infrastructure and payload capacity.

Electric trucks will succeed or fail under the intense spotlight of the marketplace. The evaluations we read daily in media and technical reports span the spectrum from overly optimistic proponents to overly pessimistic opponents. NACFE hopes this report provides a middle ground, where judgments include fact-based decisionmaking, active testing, and fleet experience.

"The explanation of arguments for and against CBEVs is a great way to explain where the opportunities and issues exist. The question of weight and freight carrying capacity was really compelling and presented in a balanced, logical manner."

–Mel Kirk, Chief Technology Officer, Ryder System, Inc.

THE FULL REPORT

The full report is available at www.nacfe.org and includes 204 references; a robust, current, relevant bibliography of Commercial BEV works; and 85 graphics, of which 31 are new. See the Table of Contents below for more information on the full report:

NACFE

The North American Council for Freight Efficiency (NACFE) is a nonprofit organization dedicated to doubling the freight efficiency of North American goods movement. NACFE operates as a nonprofit in order to provide an independent, unbiased research organization for the transformation of the transportation industry. Data is critical and NACFE is proving to help the industry with real-world information that fleets can use to take action. In 2014, NACFE collaborated with Carbon War Room, founded by Sir Richard Branson and now a part of RMI, to deliver tools and reports to improve trucking efficiency. These reports include a series of Confidence Reports that detail the solutions that exist, highlight the benefits and consequences of each, and deliver decision making tools for fleets, manufacturers, and others. As of early 2018, NACFE and RMI have completed 16 such reports covering nearly all the 85 technologies available. **www.nacfe.org**

ROCKY MOUNTAIN INSTITUTE

Rocky Mountain Institute (RMI)—an independent nonprofit founded in 1982—transforms global energy use to create a clean, prosperous, and secure low-carbon future. It engages businesses, communities, institutions, and entrepreneurs to accelerate the adoption of market-based solutions that cost effectively shift from fossil fuels to efficiency and renewables. RMI has offices in Basalt and Boulder, Colorado; New York City; Washington, D.C.; and Beijing. **www.rmi.org**

GET INVOLVED
Trucking Efficiency is an exciting opportunity for fleets, manufacturers, and other trucking industry stakeholders.

Learn more at: www.nacfe.org
Or contact: Mike Roeth at mike.roeth@nacfe.org

4 GUIDANCE REPORT OBJECTIVE

This report assesses the viability for North American Class 3 to 8 commercial battery electric vehicles (CBEVs) to help the industry understand the many claims or rebuttals. These are very exciting times as the industry now sees daily news of electric truck developments. This report provides a foundation for understanding the key pro and con discussions

The goal of this NACFE Guidance Report is to concisely present the viability of Class 3 through 8 commercial electric trucks; to discuss, in NACFE's unbiased way, the pros and cons of this evolving alternative to diesel powertrains; and to provide industry with the quality information needed to make sound business decisions on this rapidly emerging technology.

5 THE ELECTRIC TRUCK DIALOGUE

In research for this Guidance Report, NACFE identified some common themes/arguments both for and against electric Class 3 through 8 commercial vehicles.

The findings fall into several broad categories: weight issues, cost issues and charging/electric grid issues.

More specifically they are:

1. *Vehicle tare weight is too high to support my freight needs vs. CBEV weight is not an issue*
2. *Technology is not ready vs. CBEV technology is proven and here now*
3. *Charging infrastructure is not ready vs. trust the market to provide CBEV charging solutions*
4. *Charging Infrastructure is not fast enough vs. trust the market to provide CBEV charging solutions*
5. *The electric grid cannot support growth in electric vehicles vs. the grid and market will evolve with CBEVs*
6. *Maintenance will be more costly vs. maintenance may be less costly*
7. *Vehicle purchase price is too high for a positive ROI vs. CBEVs will be competitively priced*
8. *Vehicle operating costs are too great for positive ROI vs. CBEVs will be less expensive to operate*
9. *Vehicle residual value is questionable vs. CBEVs will command a premium at resale*
10. *Vehicle life is too short vs. CBEVs will last beyond 10 years*

NACFE's findings on these 10 major separate pairs of positions on the extreme end of each argument are summarized in Section 27, assessing each in an unbiased manner to ensure fleets are not hasty in accepting or rejecting the technology. Details of the research are in the body of the report along with an extensive reference list to aid the industry in better understanding the issues.

The Transportation Research Board of the National Academy of Sciences concluded in 2017 from interviews with fleets that "greater opportunities for benchmarking and collaborating with others in the industry were identified as ways to help carriers obtain better information about which technologies work and which do not. It was acknowledged that some limitations to obtaining and disseminating this type of information likely exist [43]."

It is in this vein that industry leaders, like Mike O'Connell at PepsiCo, stated, there is "no one right solution that fits all fleets [21]." Tim Proctor, of Cummins Inc., similarly reinforces Cummins wants to provide the "right product for every customer. There is no predetermined answer for them [21]."

Electric trucks will succeed or fail under the intense spotlight of the marketplace. The evaluations we read daily in media and technical reports span the spectrum from overly optimistic proponents to overly pessimistic opponents. Authors of these reports have a range of vested interests that can cloud objectivity. Readers also have their own biases that can color the interpretation of these reports. NACFE is committed to helping establish a middle ground on electric vehicle technology evaluation where judgments include fact-based decision-making, active testing and fleet experience.

Figure 1. The Electric Truck Opinion Spectrum (NACFE)

6 NACFE'S MISSION

NACFE's overriding principle in reporting on technologies is to provide an unbiased perspective. NACFE recognizes that it also has vested interests and an agenda. The mission of the North American Council for Freight Efficiency is simply to improve the efficiency of North American goods movement. NACFE pursues this goal in two ways: By improving the quality of the information flow and by highlighting successful adoption of technologies.

NACFE interviewed fleets, manufacturers, and subject matter experts with first-hand experience with CBEVs and grid infrastructure in preparing this report. An extensive list of references was researched with the same diligence and thoughtful processes NACFE uses with its Technology Confidence Reports. The references and links are provided at the end of this report for those pursuing more detail. This report is the first of several NACFE will issue on CBEVs and their associated technologies such as charging infrastructure. Subsequent reports will focus on specific product offerings for market segments, duty cycles and relevant technologies, including:

- Light Duty Delivery Truck (Class 3)
- Medium Duty Box Truck (Class 4-6)
- Heavy Duty City Tractor (Class 7/8)
- Heavy Duty Regional Tractor (Class 7/8)
- Heavy Duty Long Haul Tractor (Class 7/8)

7 Introduction To An Electric World

Technology has its roots in change. NACFE's Mike Roeth stated, "Engineers are always working on improvements." Advances are demanded by the commercial freight industry [21]. Electric Trucks are considered disruptive due to the potential to significantly change the status quo for commercial trucking operations. This discussion has been ongoing for over a century. An overview of electric truck history is available from the Institute of Electric and Electronic Engineers (IEEE) and a collection of images of early vehicles is available from CNET [1][2].

Much of the emotion clouding discussion of electric trucks stems from the multitude of possible visions of these vehicles. The Transportation Research Board of the National Academies noted from fleet interviews that "although several carriers expressed an interest in various powertrain technologies such as those used for hybrid and electric trucks, very few had operational experience with these technologies [43]." In the absence of direct experience, unknowns can be disproportionately weighted.

A key example is the common position that the lack of electric vehicle charging infrastructure on a scale necessary to support significant market adoption of electric trucks makes them unviable. It is relevant to note that Thomas Edison's first patent for the light bulb was filed in 1879 well before there was a North American power grid *(*US Patent 223,898*)*. Light bulb and electric motor technology ignited national development of new infrastructure to adapt society to the new technology rather than forcing the technology to fit poorly into the existing infrastructure. Figure 2 diagrams that the power grid infrastructure was demand driven based on success of the electric devices that needed it. This lag between product introduction and infrastructure investment has been repeated many times.

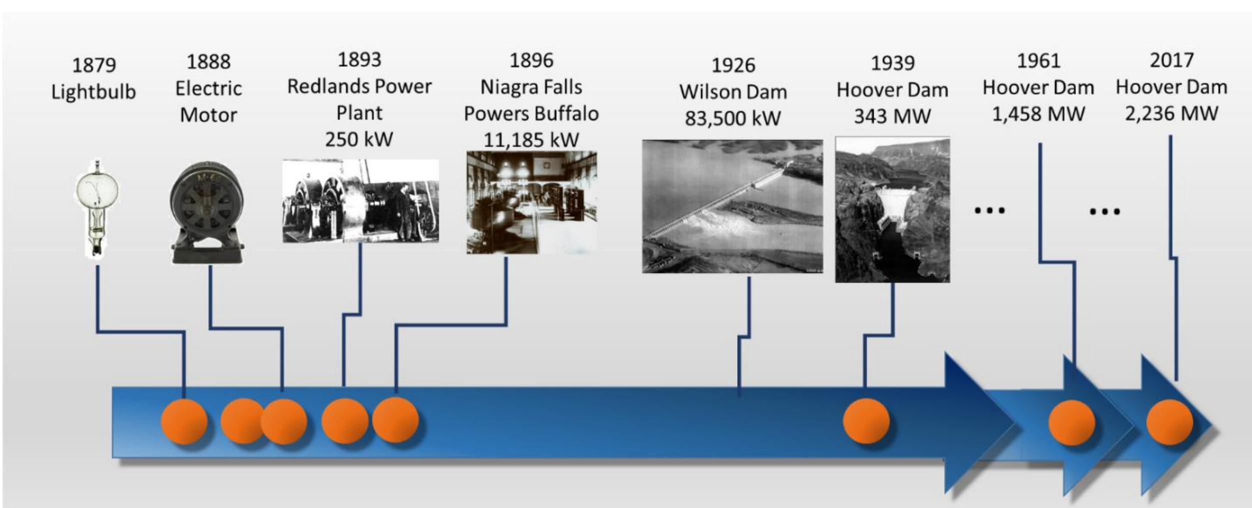


Figure 2. Infrastructure Follows Market Adoption of Revolutionary Technologies (NACFE)

A 2012 MIT Technology Review article predicted that “Tesla Motors’ first DC fast-charging station, halfway between San Francisco and Los Angeles, will allow drivers to add 150 miles of range to their electric cars in half an hour…But the impact of such charging stations will be limited by their high cost, and by the fact that fast-charging still takes far longer than it does to fill up a tank of gas.” The article speculated that “The cost of the (charging) technology could prove a major obstacle.” The report quotes a project manager at the Electric Power Research Institute that “Another challenge is the fact that utilities will often charge a hefty “demand charge” per month because of the high load these chargers can put on the grid… At least one DC fast-charging system charges $7 per charge.” The report continues “There are also reasons to doubt that electric vehicle owners will use fast chargers regularly.” A charging station manufacturer CEO stated in the report that he ”…doesn’t see such fast chargers becoming common.” “It’s not going to be a world where there’s DC everywhere and you’ve replaced gas stations [45].”

Fast forward to 2017, and Tesla has installed a national network of SuperCharger stations in North America and Europe, as shown in Figure 3 [50]. Tesla provides travellers charging power essentially free (within limits) for the life of their customers’ vehicles. They have produced and sold over 250,000 battery electric vehicles. While the capital investment and business mathmatics seems to confound accountants and investors, the engineering of creating this SuperCharger network and supporting a growing volume of user demand seems to have been proven technically feasible.

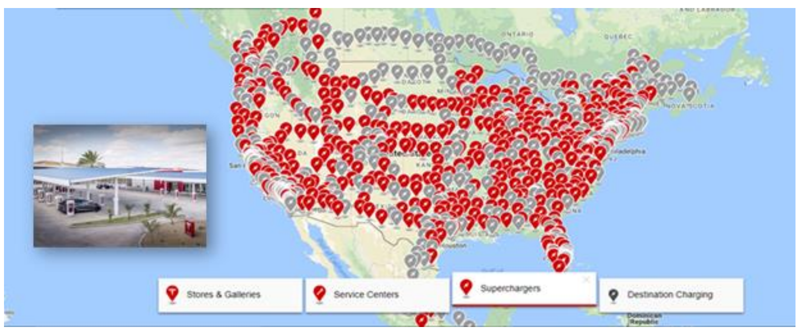


Figure 3. Tesla SuperCharger Stations (Tesla)[50]

8 Rationalizing Charging Trucks

The case for charging trucks is one of rationalizing scaling automotive experience and tailoring charging appropriately to duty cycles. Just as with cars, not all freight duty cycles require fast charging. Fleets currently already run vehicles under a variety of operational scenarios. For example, some make deliveries during daylight hours, others do so overnight, while others operate vehicles 24/7. Some have dedicated consistent routes, others are more random. The choice of charging scheme will vary for each of these scenarios. Furthermore, there may be future optimization of operations to adapt to the strengths and weaknesses of electric vehicle use. An example of shift charging is shown in Figure 4.

Figure 4. Example Shift Charging for Medium Duty Box Truck Cycle (HDT) [46]

The joint NACFE/ACT fleet survey conducted for this paper highlights in Figure 5 that over 75% of vehicles are operated on shift schedules where they are parked for more than six hours per day in the range of Class 3 to 8 segments.

Parked for ________ (in 24 hour day)	Light Duty Delivery Truck (Class 3)	Medium Duty Box Truck (Class 4-6)	Heavy Duty City Tractor (Class 7/8)	Heavy Duty Regional Tractor (Class 7/8)	Heavy Duty Long Haul (Class 7/ 8)
less than 1 hour	0%	0%	0%	1%	0%
from 1 to 2 hours	0%	0%	2%	4%	13%
from 3 to 4 hours	0%	0%	18%	15%	9%
from 5 to 6 hours	8%	0%	12%	10%	10%
from 7 to 8 hours	25%	50%	3%	14%	15%
Greater than 9 hours	67%	50%	65%	56%	54%

Figure 5. Vehicle Time Parked Per Day by Segment (NACFE/ACT Survey)

Drayage is an example. CALSTART estimated that a drayage Class 7 battery electric tractor would need a 100 mile range with safety margins. They scoped that the CBEV efficiency would average 2.5 kWh/mi. They estimated this would require up to 350 kWh of power. They projected a 2 hour charge per truck using a 150 kW charger. The charger would service six vehicles per day in their business case so would be operational 12 hours per day [4].

Urban delivery is another example. Cummins representatives, discussing their AEOS prototype CBEV, quoted by Forbes stated for "…a 100-mile range, the Cummins electric power train is being targeted at urban delivery vehicles (like a beer truck or food delivery truck) as well as for short haul trips in and around ports and other terminals. It can be recharged in about an hour at a 140 kWh charging station, and Cummins' goal is to get that down to 20 minutes by 2020, reducing down time for its business customers [33]."

Both these examples would employ chargers approximately the size of the latest Tesla SuperCharger for automotive use, shown in Figure 6. It is reasonable to simplistically project how ganging multiple Tesla SuperChargers might scale the technology for use for long haul Class 8 CBEVs.

Figure 6. Tesla Model S and SuperCharger Station (Tesla) [50]

The prototype Tesla Class 8 tractor unveiled in 2017 was projected as having a 500 mile range and could be charged in 30 minutes for 400 miles of range, with efficiency rated by Tesla at less than 2 kWh/mile [34]. A simplified estimate for the Tesla Class 8 tractor prototype present battery size might be 1,000 kWh.

The Tesla Model S, over the years since its introduction in 2012, has been equipped with a range of battery capacities, from 60 kWh to 100 kWh. Tesla's website states that "Superchargers in urban areas deliver a nearly consistent 72 kilowatts (kW) of power, even if another Tesla begins charging in an adjacent stall. This creates a predictable charging experience with an average Supercharging session lasting around 45-50 minutes in city centers [50]." Other sites are capable of 120 kW or more of power.

Charging math is Energy = Power x Time, as shown in Figure 7. Your home utility power bill charges you for kWh energy used, that is the power over time. That power originates from a variety of sources such as the Hoover Dam and is delivered to you typically through the national power grid.

Figure 7. Power & Energy References (NACFE) [47][48][49]

For example, there are 17 main turbines producing power at Hoover Dam. The most common unit's rated power is 132,735 kW. The total power output for the dam is rated at 2,235,608 kW [49]. The total energy ouptut is estimated at 4,400,000,000 kWh (or 4.4 TW). An average single family detached home in 2009 used about 13,159 kWh of energy in a year [47]. The average for all residential consumers in 2015 is about 10,816 kWh in a year [48].

Technical feasibility and practicality of fast charging a CBEV Semi Truck requires some background and perspective. Media sources and bloggers have equated charging the Tesla Semi Truck to powering so many homes versus what a diesel truck uses in fuel. This may not be particularly meaningful as a comparison because it rarely includes the same comparable evaluation of getting the diesel to the truck's fuel tank. There are also a variety of numbers used. For this report, data on home power use and Hoover Dam originates from the Energy Information Administration and the Bureau of Reclamation.

Evaluating, for the example, the Tesla Model S at an urban SuperCharger station, 72 kW x 50 minutes equates to 60 kWh of energy. This is approximately 166% of an average daily single family detached home energy use in 2009 from EIA data [47]. Charging at a rated 120 kW power level would get to the same battery charge level in 30 minutes but use the same total energy of 60kWh. A 350 kW charger would do 60kWh in 10 minutes. The total energy used would be the same in each of these three charging cases, only the speed of charging changes.

The example Tesla Class 8 prototype semi-truck equipped with 1,000 kWh of battery pack could require 1,600 kW power to charge for 400 miles of range in 30 minutes. This equates to ganging 23 72kW Superchargers in parallel in an urban situation. It would need 14 120kW rated Superchargers in non-urban scenario (Figure 8), and only five 350kW level Superchargers. Charging 800 kWh (for 400 miles range in 30 minutes charging) equates to 22 times the average daily single family detached home energy use in 2009. So charging a Class 8 CBEV is technically feasible today with adaptation of existing Supercharger technology.

Figure 8. Fourteen SuperChargers in Parallel could Charge 400 Miles Range in 30 minutes (NACFE adapted from Tesla graphics)

Evaluating these numbers for concurrently charging 10, 100 and 1,000 Tesla prototype Semi Trucks is shown in Figure 9. These scenarios would be for an individual truck stop (10) or various regional networks of truck stops (100 or 1,000 vehicles charging at the same time). Charging 1,000 CBEV Tesla Prototype example Semi trucks in this instance is then equivalent to the energy use of 22,190 average daily single family detached homes (from 2009 EIA data).

Charging Comparison					
Subject	Factor	Annual kWh	Daily kWh	% of Hoover Daily Average Output	Equivalent Number of Detached Homes Energy Use
Hoover Dam Output	Output	4,400,000,000	12,054,795	100%	
Residential Use	Ave Single Family Detached Home 2009	13,159	36	0.0003%	1
	Ave Residential Consumer 2015	10,816	30	0.0002%	
Tesla S Car Charging	One Tesla S Fast Charge Urban 72kW x 50 min		60	0.0005%	1.7
	One Tesla S Fast Charge 120kW x 30 min		60	0.0005%	1.7
	One Tesla S Fast Charge 350kW x 10 min		60	0.0005%	1.7
Tesla Semi Truck Charging	One Tesla Semi 400 mile Fast Charge		800	0.0066%	22
	10 Tesla Semi 400 mile Fast Charges		8,000	0.1%	222
	100 Tesla Semi 400 mile Fast Charges		80,000	0.7%	2,219
	1000 Tesla Semi 400 mile Fast Charges		800,000	6.6%	22,190

Figure 9. CBEV Charging Comparisons to Hoover Dam Output and Equivalent Number of Homes (NACFE)

The scale of the electric charging is only half of a comparison for the diesel truck replacement. The other half is what fueling a comparable diesel truck would mean expressed similarly in detached home equivalents.

9 Energy Content and Efficiency

The energy in different fuels, to begin this comparison, can be expressed in terms of Diesel Gallon Equivalent (DGE). There are various values published for how the energy in a gallon of diesel translates into electrical energy content. A value derived from the Department of Energy "Fuel Conversion Factors to Gasoline Equivelents" is that one gallon of diesel contains the same energy as 37.258 kWh of electricity [51]. Another DOE site lists the DGE as 37.64 kWh per gallon diesel [52]. A third site can derive 38.08 kWh per gallon diesel [53]. The National Fleet Management Association (NAFA) which uses data from Chevron can be used to derive a fourth value, 38.10 kWh per gallon diesel [54]. For the purposes of this paper, we'll use an energy content of 37.358 kWh per gallon diesel.

Energy equivalence is not the only story in comparing diesel to electricity. There are significant additional qualifiers. While the energy content of the fuel compares the available energy in the source, it does not reflect the efficiency of extracting that energy and putting it to use to move the vehicle down the road [52]. For that, a comparison of efficiency is needed.

The energy in diesel fuel is used by the truck in several ways. The energy efficiency of a modern heavy-duty diesel can range between 36% and 45% [154][57][58]. Figure 10 illustrates that the fuel energy is lost in heat transfer, exhaust, pumping, friction and auxiliaries. Additionally, "not all of the energy that is converted into work done on the piston makes it to the final engine shaft output. Some of the energy is used in overcoming engine friction at the bearings and piston-cylinder interface, some is used to pump air into the engine and exhaust gases out of the engine (pumping losses), and some is used to power engine auxiliaries and accessories (e.g., water pump, oil pump, fuel pump, cooling fan, alternator, power steering fluid pump, compressor for cabin air conditioning) [57]."

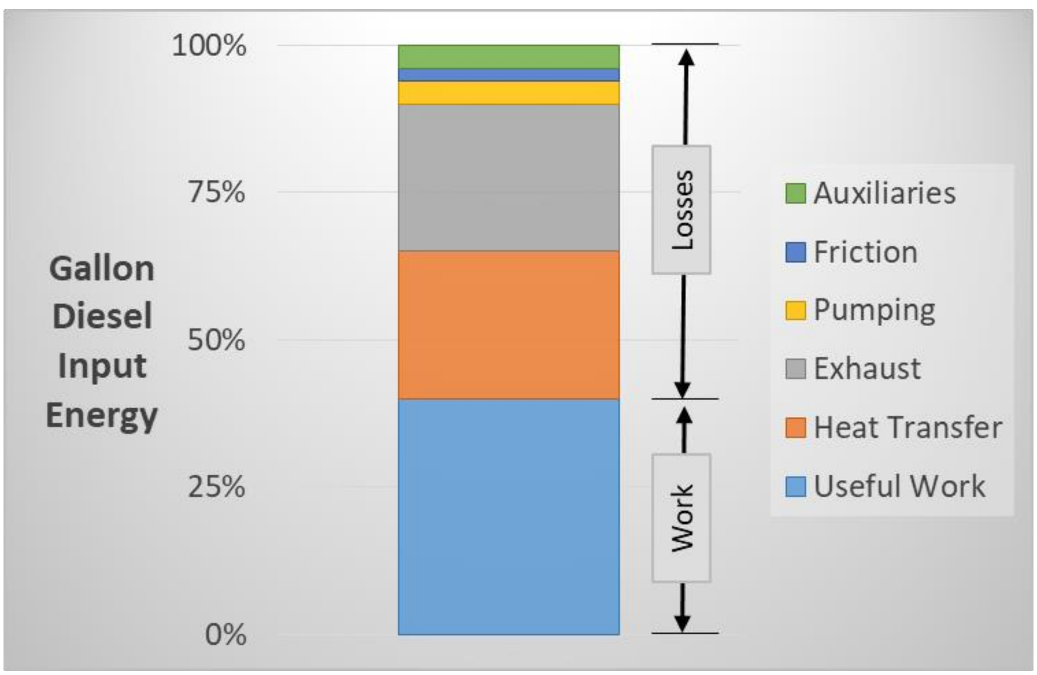


Figure 10. Where Energy Goes In A Gallon of Diesel (adapted from WVU) [57]

Cummins summarized analysis of 27 drive cycles over all seasons for Class 8 vehicles in their 2015 SuperTruck program merit review. Figure 11 shows ranges of losses for both Urban and Interstate cycles for Engine, Auxiliary Loads and Drivetrain [58].

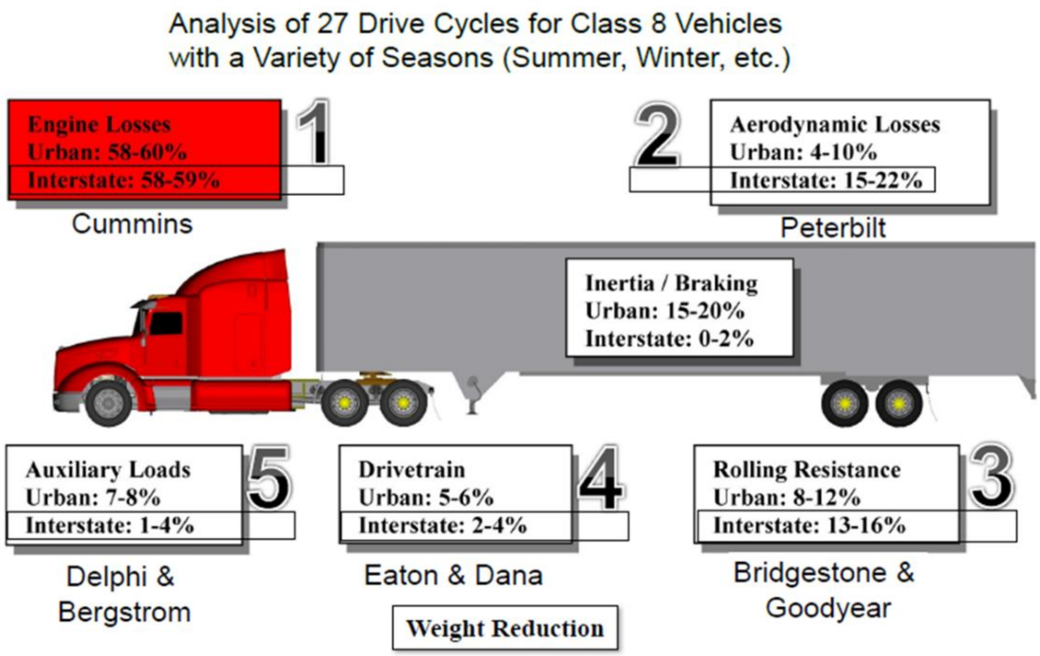


Figure 11. Where the Energy Goes for Typical Class 8 Cycles (Cummins) [58]

Volvo with West Virginia University in an ICCT study showed trends of diesel efficiency over time. Figure 12 illustrates the range of efficiency between the upper Peak Brake Thermal Efficiency line published by Greszler at the 2011 DEER Conference, and the lower West Virginia Univiersity FTP cycle lab results [57]. The graphs have inflection points related to major emissions rule implementations. In general, they show recent diesel efficiency ranges between 40% and 46%, depending on duty cycle.

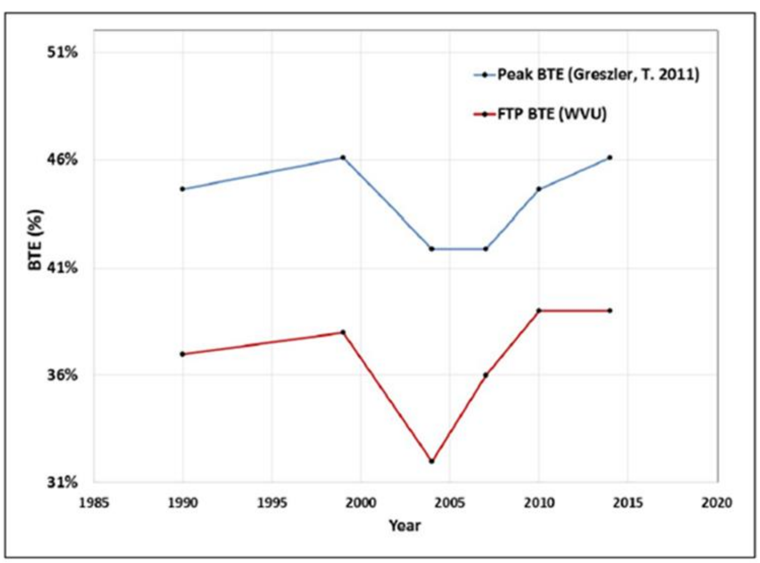


Figure 12. Historical Changes in Heavy Duty Engine Efficiency (WVU, Volvo, ICCT) [57]

Diesel fuel is then used to overcome the losses in the systems in the truck, and then to accelerate and maintain highway speeds against the aerodynamic and road friction forces, as illustrated in the Cummins evaluation in Figure 11. How the truck is configured and operated dictates its efficiency (for details, see NACFE's Determining Efficiency Confidence Report [61]). Modern diesel Class 8 trucks vary in average fuel economy from approximagely 5.9 mpg to over 7.1 mpg, as shown in Figure 13 from NACFE's 2017 Annual Fleet Fuel Study [40]. NACFE demonstrated in 2017's Run-On-Less event that currently available production trucks and trailers, outfitted with production fuel savings technologies and driven by well trained drivers, could exceed 10 mpg [179].

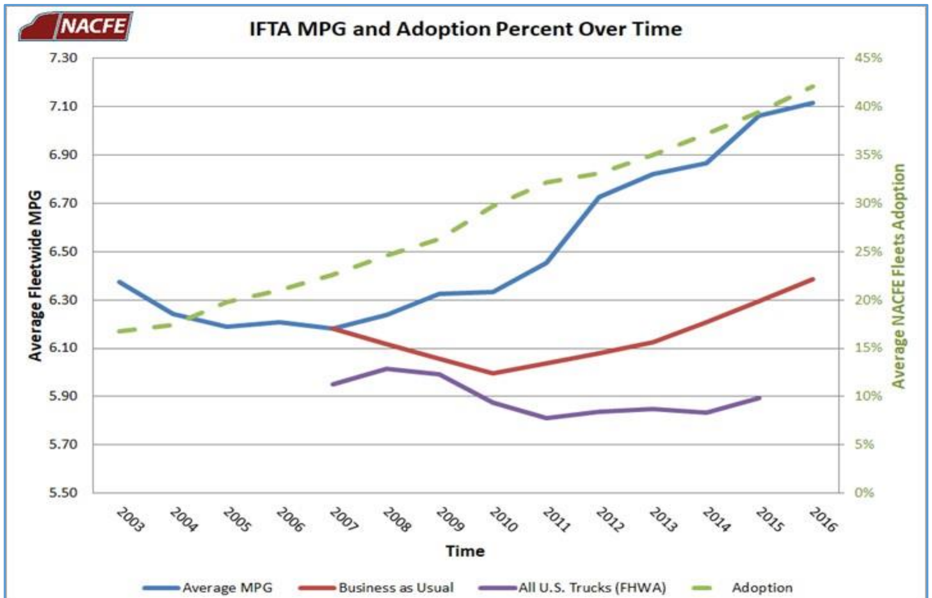


Figure 2: Average Fleet-wide Fuel Economy over Time

Figure 13. Average Fleet-Wide Fuel Economy over Time (NACFE) [40]

If a current truck averages 7 mpg on diesel over a 400 mile range, then that truck is using 57 gallons of fuel. The raw energy content of that 57 gallons of fuel equates to 2,129 kWh. This is equivalent to the energy to power 59 average daily single family detached homes in 2009. Multiplying by 10, 100 and 1,000 creates this direct comparison as tabulated in Figure 14. This is an apples-to-apples comparison using the home energy use as the metric. It shows electric is more efficient than diesel.

Number of Trucks	Class 8 at 400 Miles Range		Equivalent Number of Average Daily Single Family Detached Home Energy Use in 2009	
	BEV kWh	Diesel kWh	BEV kWh	Diesel kWh
1	800	2,129	22	59
10	8,000	21,290	222	591
100	80,000	212,900	2,219	5,905
1,000	800,000	2,129,000	22,190	59,054

Figure 14. Apples-to-Apples Comparison of Energy Use in Equivalent Housing Units (NACFE)

10 DEFINE SCOPE OF COMPARISON

Comparable evalution of diesel trucks to electric trucks requires drawing the lines on where to make the comparisons. A truck driver pulls up to a truck stop and pumps fuel into his vehicle. This "fuel" can be diesel or electricity. The driver pays for the "fuel" and leaves. The diesel pump, or electric charger, at a truck stop is an effective, common point of comparison for vehicles. These comparisons are termed "tank –to-wheel" comparisons conveying the energy efficiency comparison is just of the vehicle itself, as shown in Figure 15 [59][92].

Another perspective on energy use efficiency encompasses the entire production system. A gallon of diesel starts from a well site, is transported to a refinery (via trucks, pipelines, ships, trains, etc.) is refined, then transported to the truck stop (again, via trucks, pipelines, ships, trains, etc.) where the pump can dispense it into the truck's fuel tank. Electricity starts from a power source that is making use of some potential energy to create power (coal fired plant, natural gas fired plant, nuclear plant, hydroelectric dam, solar farm, wind turbine farm, geothermal facility, etc.). All these conversion sites generally transmit the energy to the truck stop via the shared electricity grid.

There are many variables and factors to consider in comparing total system efficiency between diesel and electricity. These comparisons have been labeled as "well-to-wheel" type comparisons, conveying they are all-inclusive of the processes that extract the potential energy and deliver it to moving the truck, outlined in Figure 15 [56][92].

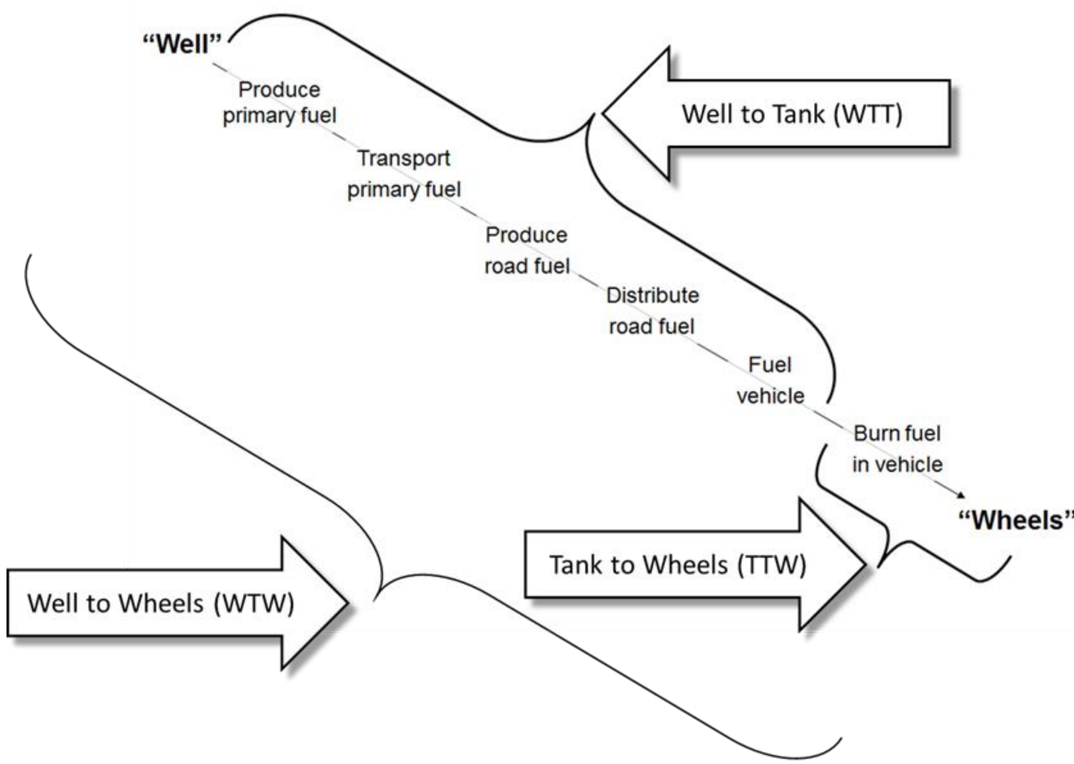


Figure 15. Graphic representation of Well-to-Wheels Analysis (modified from EU) [92]

The "well-to-wheel" comparisons tend to over-complicate the comparison of diesel and electric trucks with complex questions on the capital costs and capital recovery of installing the infrastructure to get the energy to the point of use. The reality is that few fleet owners need to consider the past capital costs invested to get diesel fuel to the truck stop fuel pump. They do not consider the cost of maintaining the SuperTanker, or the cost of the fracking well site operation, or the cost of the freight train hauling tankers to the refinery, or the cost of the refinery itself, or the pipelines, storage and distribution systems, or even the cost of the truck stop itself. They pay a per gallon fee for the diesel at the pump. That gallon of diesel incorporates the cost of producing and delivering the fuel to the pump. The U.S. Department of Energy constantly monitors these costs, shown in Figure 16, and estimates the component costs of diesel fuel production, delivery and marketing (included is what the market forces permit for profit making) [60].

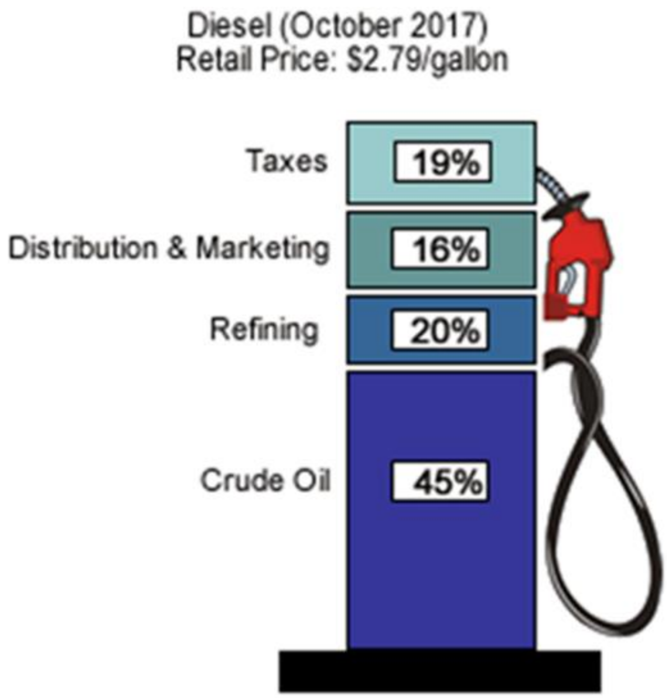


Figure 16 What We Pay for Diesel (EIA) [60]

Similarly, the cost of electricity you pay for at your home or business amortizes the cost of the production, maintenance, capital recovery, delivery, marketing, etc. in a single statement. The cost at an electric truck stop encompasses all these factors along with what the market will permit for profit. The Department of Energy tracks the electricity retail pricing. The graph in Figure 17, shows the retail prices since 2002 vary between 7 cents per kWh for industrial use and as high as 13 cents per kWh for residential [61]. As with your home utility bill and also with purchasing diesel, there are likely additional tax charges and fees tied to this number, so the values shown in the EIA graph are not directly comparable to the diesel fuel, but are indicative of market trends and a sense of energy pricing scale.

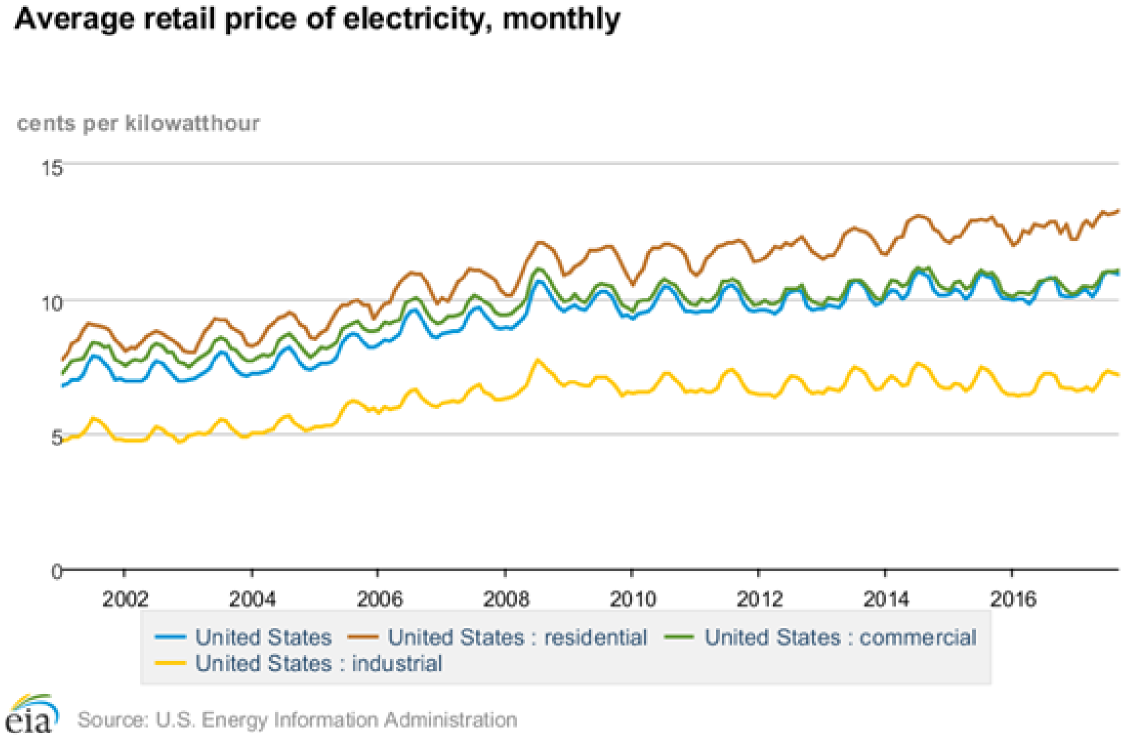


Figure 17. Average Monthly Retail Price of Electricity By User Type (EIA) [61]

EIA tracks average retail cost of diesel fuel on regional and national bases. EIA estimates that the average price of diesel fuel in October 2017 was $2.79/gal [60]. The raw energy content cost comparison at today's market prices slightly favors diesel over electricity.

Diesel Costs $0.075/kWh

Electricity Costs $0.07 –$ 0.13/kWh

Factoring in truck efficiencies (for a diesel, for example, at 7 mpg and electric truck, and for a CBEV, for example, described as 2 kWh/mi), and put them in consistent units (recall that the raw energy content of 1 gallon of diesel fuel is 37.358 kWh) shows that a diesel truck is less efficient at converting on-board energy into movement than a battery electric truck. The electric truck is 62% more efficient than the 7 mpg diesel. Parity, where diesel truck energy use equals 2 kWh/mi electric truck energy use would be if a diesel truck could average 18.5 mpg.

Diesel Truck 0.19 mi/kWh

Battery Electric Truck 0.50 mi/kWh

The equivalent kWh energy for diesel values are tabulated in Figure 18 for a range of diesel mpg efficiencies.

Diesel MPG	Diesel mi/kWh
5	0.13
6	0.16
7	0.19
8	0.21
9	0.24
10	0.27
11	0.29
12	0.32
18.5	0.50

Figure 18. Diesel Truck Efficiencies Expressed in kWh (NACFE)

Well-to-wheel comparisons are important for strategic planning. Comparing the net cost of diesel vehicles to battery electric vehicles is important for companies making capital investment decisions on production and delivery systems. However, they are not relevant to the individual or fleet vehicle for vehicle performance comparisons because the market usually prices all those factors into the “at-pump” price for both diesel and electric vehicles. This is a pump-to-wheel comparison, and perhaps the primary point of comparison for fleets.

Demand and supply will continue to dictate “at pump” pricing whether gallons of diesel or kWh of electricity. The “at pump” pricing will be the primary visible metric of vehicle use cost, as it is today. The more complex energy delivery infrastructure costs are expected to be reflected in the “at pump” pricing. Sufficient demand creates investment in capacity and efficiency improvement. Those investment costs are to a degree offset by market pricing competition and innovations.

CBEVs will increase demand on electricity. Grid capacity will need to be improved. Demand management, storage and production will need to evolve. What impact all these forces have on market pricing of electricity and diesel is challenging to predict.

Similarly, factoring in emissions and GHG ramifications is important to strategic planning. However, those are not all that relevant to individual or fleet vehicle-to-vehicle comparisons, because, the cost and ramifications of emissions should be factored into the net cost experienced at the pump and in the purchasing price of vehicles for vehicle operators. The fact that they are not equitably accounted for in cost of fuel or vehicles is an on-going industry challenge, and at the heart of market and legislative efforts to develop carbon and other emission credit trading systems, incentives and grants. Those strategic issues are largely outside the scope of this report. This report focuses on the factors controllable by fleets and vehicle manufacturers. The fleets see (a) the net cost of purchasing a vehicle, (b) the net operating cost over the period of ownership, and (c) the net redisual value recovered in resale or disposal of the used vehicle.

Infrastructure costs are relevant to fleets where they choose to outfit their own facilities with fueling or servicing capabilities. Whether installing a diesel fuel pump system or an electric charging station, the fleet must make appropriate return-on-investment calculations.

For diesel, factors to consider would include total gallons in storage, through-put rate (how many trucks can fuel at a time), safety and environmental costs over the life of the tanks, etc. A factor not usually discussed in evaluations is the speed of pumping the diesel fuel, as speed of delivery is not usually a significant cost factor in considering fuel station pumps.

For electric charging, however, the speed of charging takes on added significance. A fleet that operates a day time operation might have one or two shifts available over night to charge at a slower, potentially less costy rate. A 24 hour delivery operation wanting to keep assets moving most of the time would require fast charging capability that may carry premium costs. There are other alternatives between these overnight charging and fast charging. A fleet could, for example, choose to have some extra tractor capacity, so that some tractors might charge at a slower full shift rate – in the same way that fleets operate an excess of trailers with three or four trailers for every tractor to deal with demand shifts.

11 WEIGHT

Miles per kWh and miles per gallon are not the only story for truck efficiency comparison. The purpose of a truck is to move paying freight. U.S. highway laws restrict the maximum weight of vehicles and restrict possible configurations. The tare weight, the unladen weight, of the truck is important in determining the amount of freight it can legally carry. However, not all trucks operate at maximum weight. The nature of freight is that most freight carried by 53 ft. dry van trailers tends to “cube out” before reaching maxium weight. Trucks operate at a variety of freight weights over the course of their use. They can operate empty (known as “dead heading”). They can start a multi-stop trip at one weight and change weights at every stop. They can carry high density packages or low density ones. Some always carry less than a truck load. Its natural to want to simplify weight discussion to a single maximum allowable weight of 80,000 lb. GVWR. The truth is that trucks see an entire spectrum of weights. Some vocations value weight reduction differently than others. For example, a beverage hauler likely aims to operate at 80,000 lbs. because the load is very dense. Someone shipping bulky lightweight furniture likely sees typical operating weights below 60,000 lbs. Others that provide expedited delivery and charge a premium for rapid delivery, may operate below 50,000 lbs. GVWR.

11.1 TYPICAL FREIGHT WEIGHT

Three curves, Figure 19, Figure 20 and Figure 21, showing typical distributions of gross vehicle weights are summarized average vehicle weights in SAE 2016-01-8020, Fuel and Freight Efficiency - Past, Present and Future Perspectives [63]. All three show GVWs across a wide spectrum with a typical bi-modal distribution.

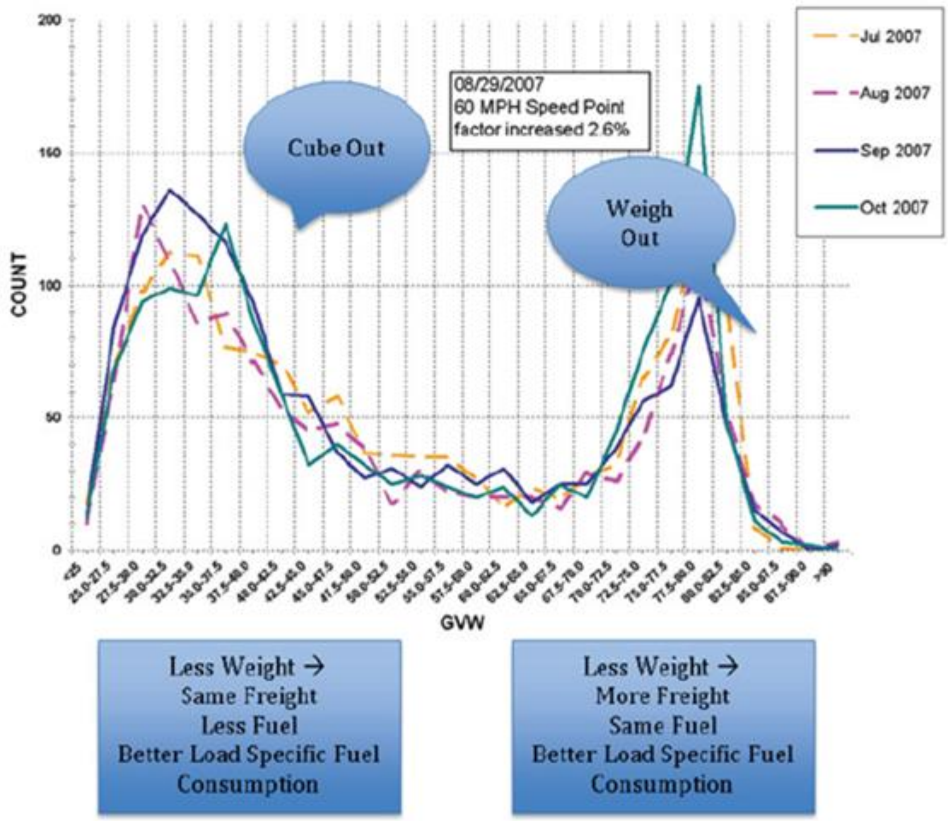


Figure 19. Bimodal distribution of truck gross vehicle weight for five axle vehicles from Weigh-in-Motion data (Quinley)[64]

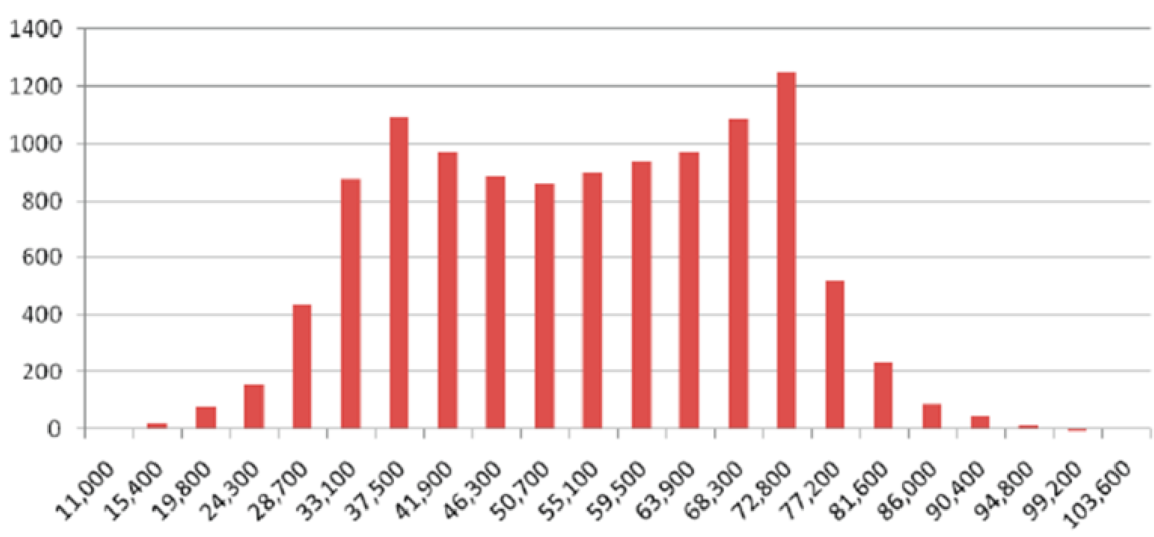


Figure 20. Truck weight distribution from 2008 weigh-in-motion (New West Technologies) [64]

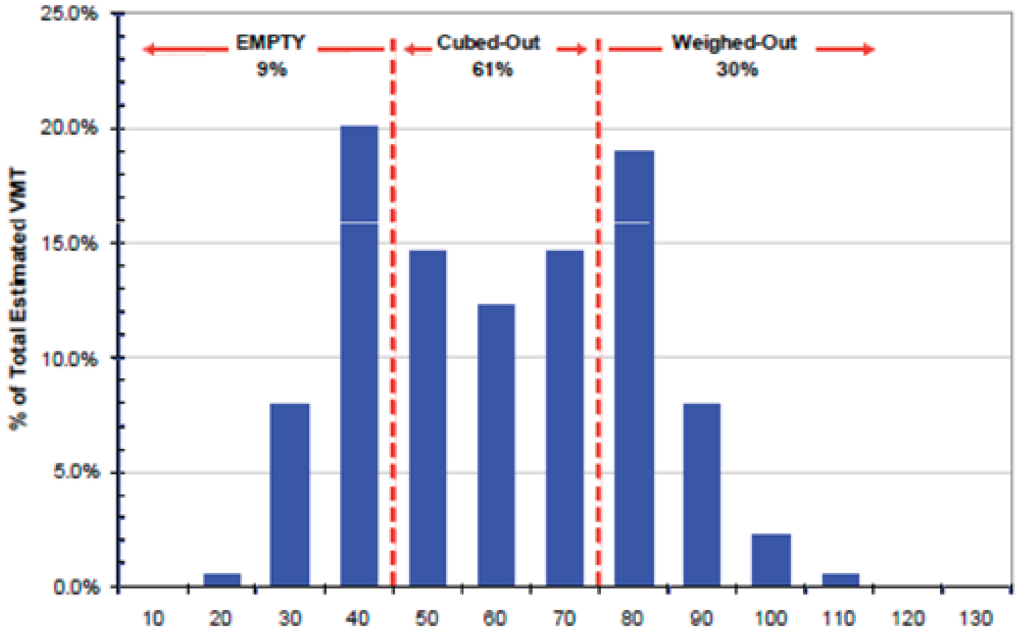


Figure 21. Truck weight distribution from 2009 (M.J. Bradley & Associates) [63]]

An average estimated from the U.S. Census 2002 Vehicle Inventory & Use Survey (last year available) is approximately 63,500 lb. GVW [64]. Average values in the U.S. have increased more recently as shippers and fleets strive to get greater freight density in trailers as shown in a National Resource Canada review in Figure 22 and the American Trucking Associations recent Truck Tonnage Index in Figure 23 [65][66].

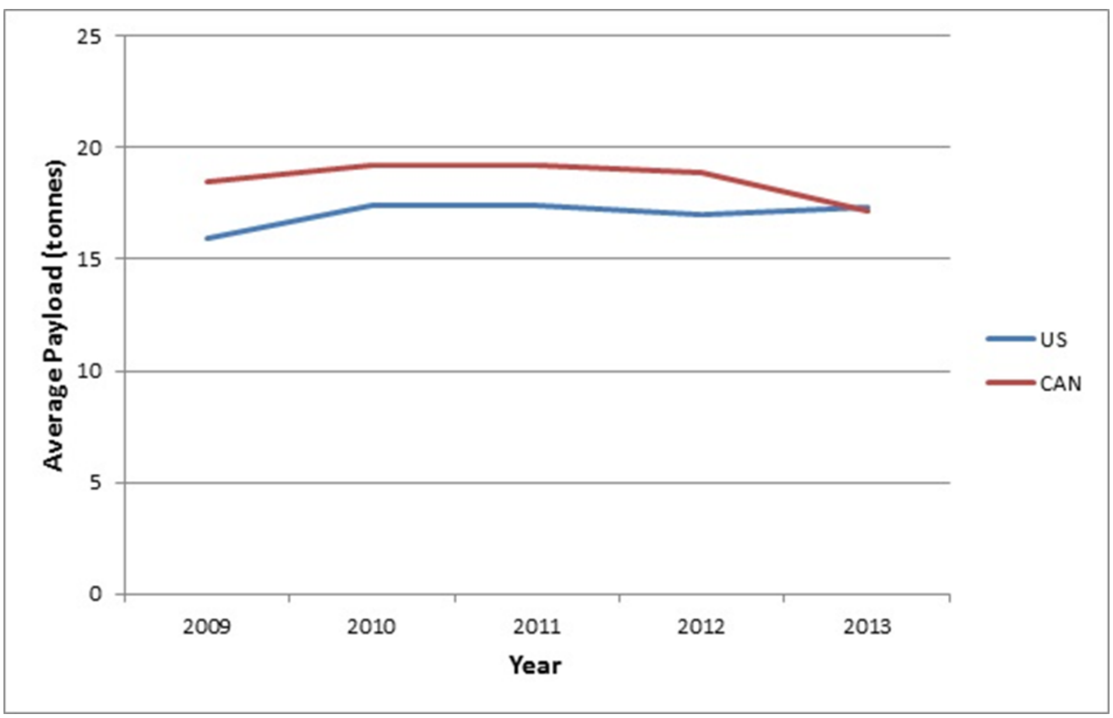


Figure 22. U.S. & Canada Average Payload (NRCan) (note: 1 Tonne = 1.1023 Ton) [65]

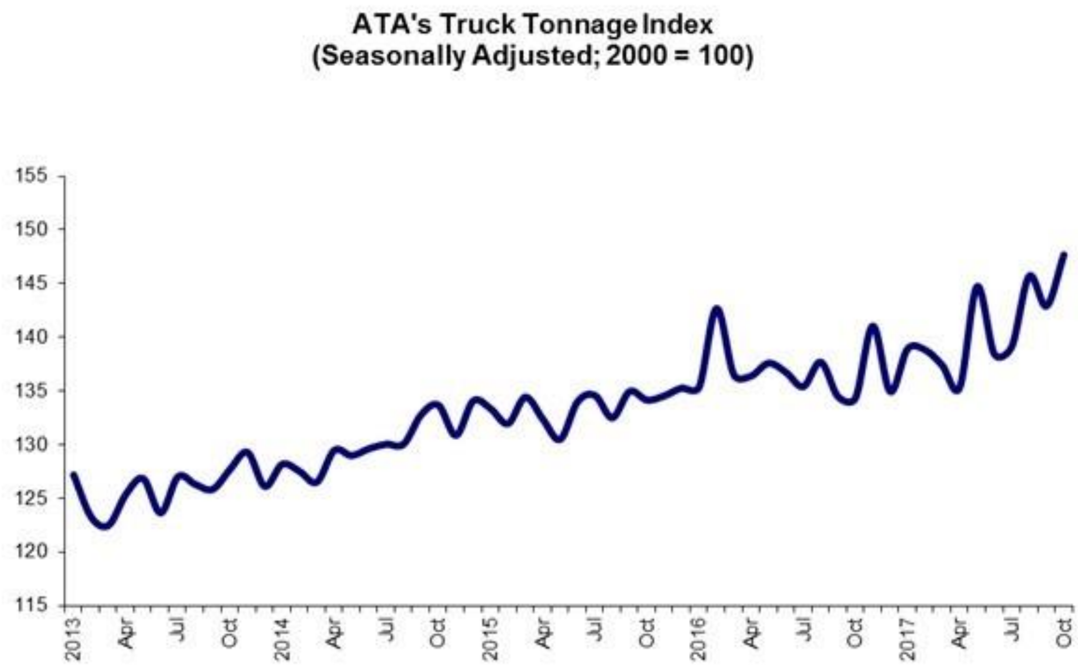


Figure 23. ATA Truck Tonnage Index (ATA HDT) [66]

11.2 Weight Reduction

The unladen weight of both the tractor and trailer is important to fleet operations because the fuel used to move the vehicle is paid for by the freight that is carried. OEMs constantly are seeking weight reductions for their vehicles. An overview of opportunities can be found in the NACFE Confidence Report on Lightweighting [149].

Weight does effect fuel economy. Mihelic summarized in SAE 2016-01-8020 that the ”NAS reported that tests by NESCCA/ICCT in 2009 showed a 65,000 lb. GVW tractor/trailer had 5.96 mpg in an on-highway duty cycle with some grade change. When run at 80,000 lb. GVW, the unit had 5.4 mpg. The NAS listed several reported results for weight sensitivity for fuel economy varying from 0.1% per 1,000 lb. to 2.4% depending on grades, speeds, traffic, etc. In the same time period, TMC in RP 1112 used 0.0375 mpg per 1,000 lb. [63].” Reducing a tractor's weight by 1,000 lbs. is approximately 1/20th reduction (~5%) of the weight of a sleeper equipped diesel tractor. A 1,000 lb. reduction is approximately 1/14 (~7%) of the weight of a current steel trailer.

Current tractors and trailers have seen decades of weight refinement. OEMs and fleets negotiate over tens of pounds or less weight reduction. Large savings like 1,000 lbs. typically require substantial changes to lighter weight, more expensive materials. A ~14,000 lb. mostly steel 53 ft. van trailer with steel dual wheels might save 2,000 lbs. by using aluminum in place of the steel and including other weight savings like moving to wide base aluminum singles and lighter weight suspensions. It might save 3,000 lbs. by replacing the body steel with carbon fiber composite. Costs for the trailer in each case carry significant premiums, so while the lightweighting technology is available, the market penetration has been gradual [93][94][95][96]. Savings on the scale of 1,000 lbs. on a current SmartWay designated diesel tractor are unlikely without significant changes in vehicle performance needs. A study on European trucks estimated that the cost-effective weight reduction possible by 2020 for the entire range of vehicle types fell between 3% and 5% against 2015 baselines as tabulated in Figure 24 [87].

Vehicle type	2020	2025	2030	2040	2050
Average Truck	**4.1%**	**7.4%**	**8.6%**	**9.8%**	**10.2%**
Urban	4.4%	8.4%	10.3%	11.5%	11.8%
Utility	3.7%	4.0%	4.6%	4.6%	4.6%
Regional	4.9%	8.6%	9.9%	10.1%	10.2%
Construction	3.8%	8.2%	9.9%	12.0%	13.5%
Long Haul	4.1%	7.6%	8.0%	10.1%	10.6%
Average Bus	**2.8%**	**4.2%**	**5.4%**	**5.1%**	**10.5%**
Bus	3.5%	7.1%	8.0%	8.0%	20.5%
Coach	2.3%	2.4%	3.8%	3.3%	4.2%

Figure 24. Calculated cost-effective weight reduction potential (%) versus 2015 baseline vehicles (Ricardo) [87].

If fleets are reluctant to value weight reductions on the scale of 1,000 lbs. through more costly body material choices, how sensitive are they to vehicle overall weight? Clearly there is always a trade-off between capital investment in equipment and the payback period and return on that investment. For some fleets that consistently operate at the 80,000 lb. limit, any weight savings translates into more paying freight, but the fuel economy is always the same because the total vehicle weight is a constant 80,000 lb.

Fleets that see a range of gross vehicle weights can get better fuel economy through weight savings, but they may not be willing to pay a premium to get them because the return is considered too small or too long to be desireable. It is this market segment that battery electric trucks may fit, because of the signficant differences in energy costs between electricity and diesel and efficiency differences.

11.3 Batteries and Weight

A key point in the electric truck discussions is that batteries are heavy. The concern is that adding batteries to gain range might unacceptably reduce allowable freight or that adding the weight will make the net vehicle operating costs increase such that the comparison to a diesel is not attractive. Evaluating these two concerns requires understanding the net weight effects of an electric vehicle drive train versus a comparable diesel.

11.3.1 Comparing Anatomy of Electric and Diesel Trucks

Daimler's Jim Bevan simplistically compared the basic anatomy between a typical diesel commercial vehicle and a battery electric one at the 2017 American Trucking Associations (ATA) Technology & Maintenance Council (TMC) Fall Meeting as shown in Figure 25 [15]. The ATA TMC has issued a paper titled Electric Truck and Bus Charging Infrastructure and Electric Vehicle Terminology containing a view of an electric truck in Figure 26 [17].

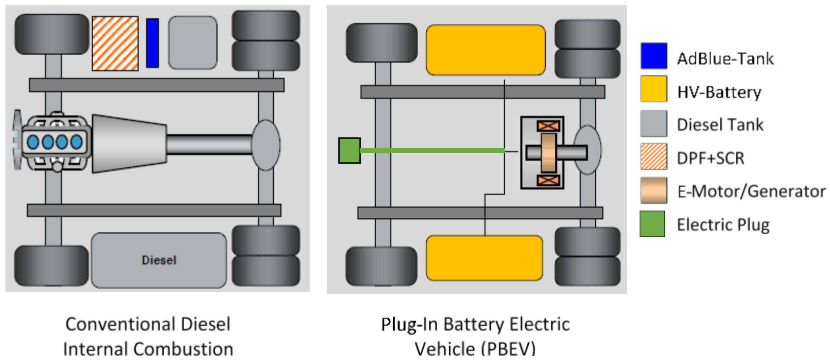


Figure 25. Powertrain Comparison Diesel vs. Plug-In Electric (Modified from Daimler's Jim Bevan ATA TMC 2017 Fall Presentation) [15]

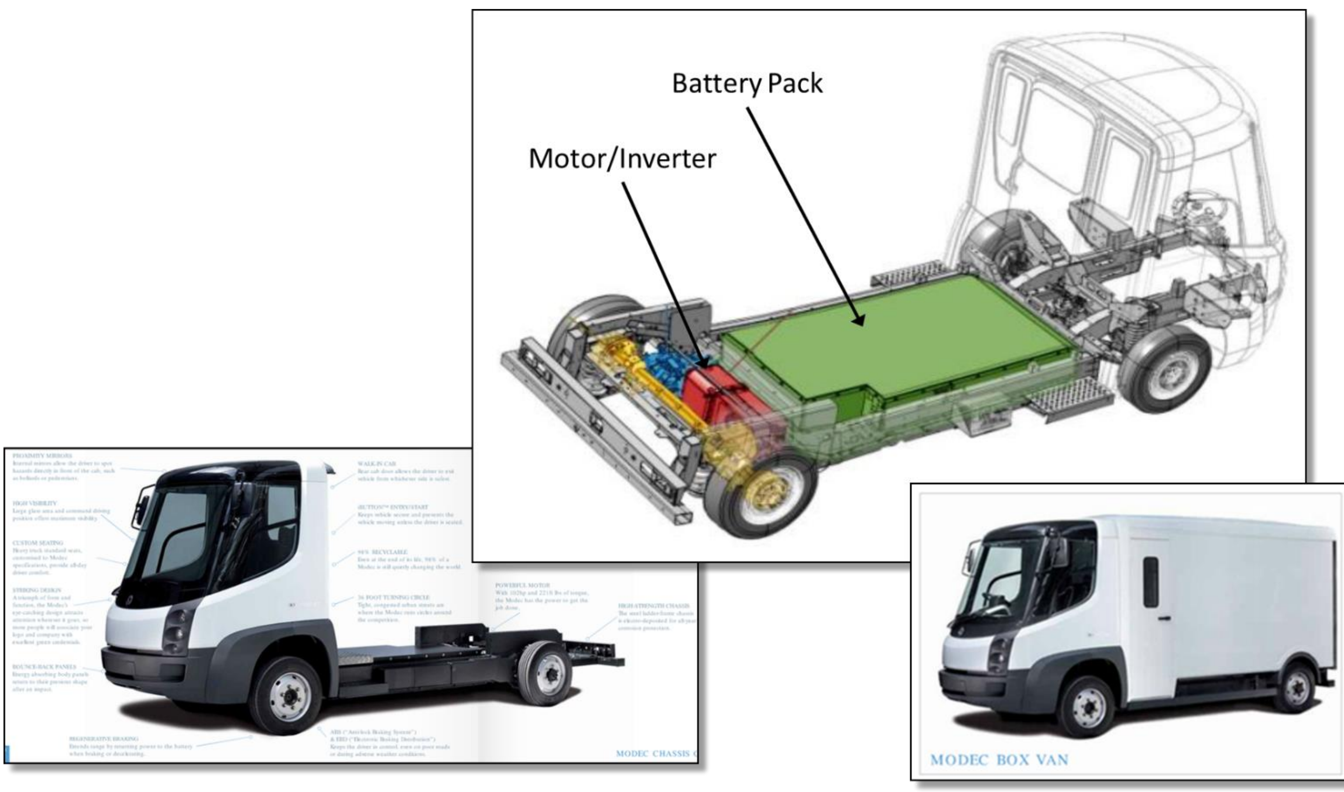


Figure 26. Class 3 Plug-In Electric Powertrain (adapted from TMC and MODEC) [17][147]

Daimler introduced an electric truck prototype at the 2016 Hanover truck show illustrated in Figure 27 [74]. The vehicle places the batteries between the chassis rails. Motors are located in the wheel end, a configuration not shown in Bevan's simple electric truck example, but proposed also in the Tesla Semi prototype.

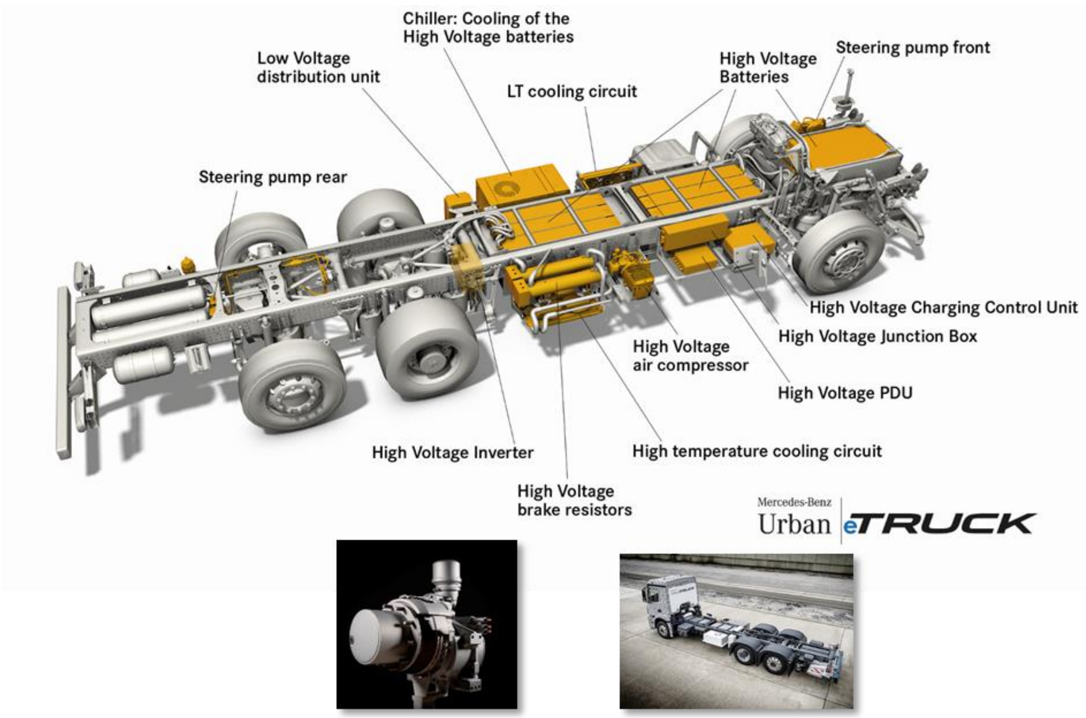


Figure 27. Example Prototype Electric Truck Chassis with Liquid Cooled Traction Wheel End Motors Equipped with Disc Brakes (Mercedes-Benz) [74]

A comparable diesel truck would have an engine, transmission, drive shaft, transaxle and cooling module, as shown in the example Figure 28 shows [75].

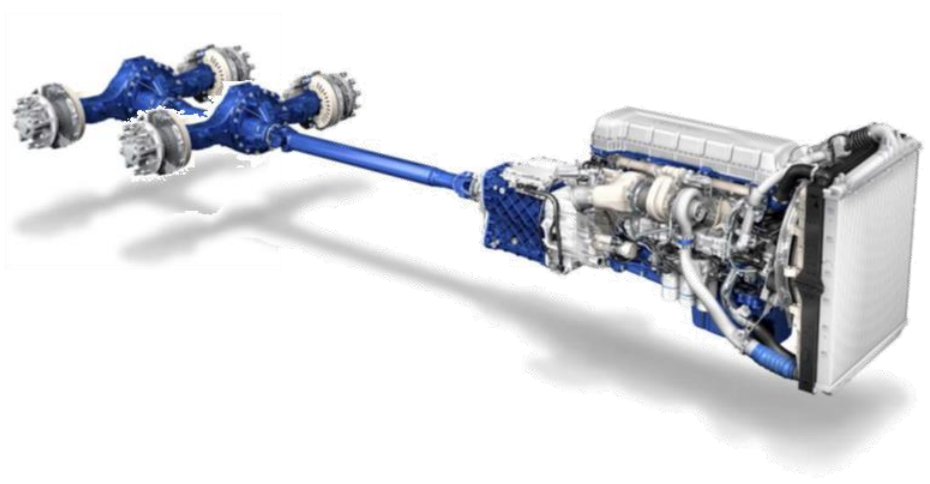


Figure 28. Example Diesel Powertrain (adapted from Volvo) [75]

In addition to the drivetrain, the vehicle has an exhaust system including an emission system, typically two fuel tanks, a battery box (with 3 or 4 batteries), and all the associated bracketry, as can be seen in Figure 29.

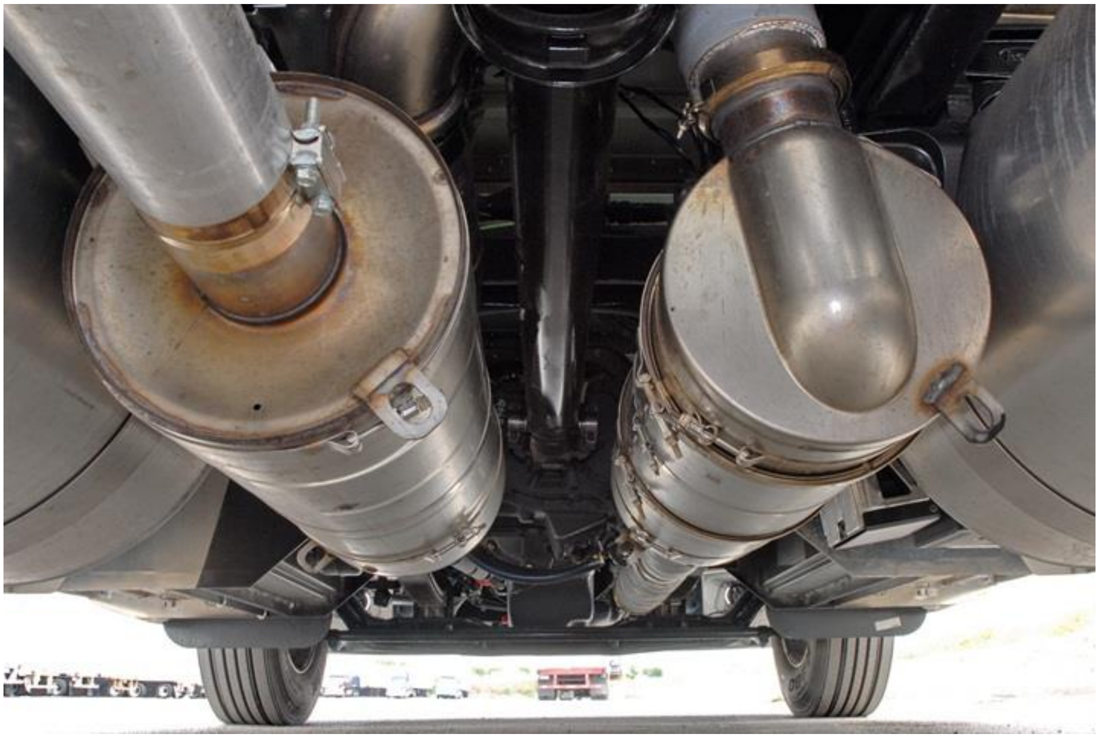


Figure 29. Typical Under Chassis of a Diesel Truck (Park) [76]

11.3.2 Weight of Fluids

Diesel trucks have significant weight in fluids. The heavy truck engine cooling system may have a 12 gal capacity. Engine coolant varies in density based on type. Cummins lists a variety of densities around 9 lb/gal. This example equates to 108 lb. of coolant.

Diesel fuel weighs approximately 7.2 lb/gallon. A Class 8 tractor with two 120-gallon tanks is carrying a maximum of 1,728 lbs. of fuel. Fuel decreases during travel. The exact average weight of these fluids during a trip depends on the duty cycle. Assuming a driver goes 500 miles per day averaging 7 mpg equates to 71 gallons used per day. He would have to refuel after about three days travel. Driving two more days that week he would average 148 gal during the week and fuel weight would range between a maximum of 1,728 lbs. down to a minimum of 194 lbs., with a weekly average of 1,065 lb. An electric truck's batteries do not change weight with mileage.

The required DEF emissions fluid in a diesel truck is approximately 9.1 lb/gal. Tank size varies by fuel tank size and may be sized between 9 and 27 gallons. The DEF tank in a typical on-highway long haul tractor may be a 23-gallon tank where the fluid weighs a maximum of 209 lbs. This also varies during trips.

Engine oil capacity varies by engine manufacturer and model. Information in 2011 from Detroit Diesel puts total engine oil capacity between 46.5 qts. and 49.0 qts. for the DD13, DD15 and DD16 line of engines [78]. Engine oil density varies around 7.2 lb/gal. So a 49 qt. capacity equates to approximately 88 lb of engine oil.

The transmission also has fluids. A Freightliner Cascadia 2016 owner's manual states transmission capacities that vary between 8 qts. and 18.0 qs.t depending on model [79]. Eaton's lubrication guide has similar values [80]. A typical capacity might be 13 qts. for a 10-speed transmission. This is approximately 92 lbs. of transmission fluid.

The rear axles have lubricants as well, that in total for a tandem rear axle may total 26 qts. equaling approximately 186 lbs.

The fluid weights inherent in a typical Class 8 tractor are summarized in Figure 30. A typical on-highway tractor has fluid weights that vary between 1,100 and 2,600 lbs. during travel. These would be replaced on a battery electric truck.

Fluid	Approximate Weight (lb)
Coolant	108
Fuel	194 to 1728
DEF	209
Engine Oil	88
Transmission Oil	92
Rear Axle Oil	186
Total	Max 2,411 lb Min 877 lb

Figure 30. Example Weight of Fluids in a Class 8 Tractor (NACFE)

11.3.3 Major Vehicle Components

Weights of individual components of tractors can be difficult to sum up correctly from available catalog data. Top-level breakdowns published can similarly be misleading as what is and isn't included in sub-groups is rarely detailed. A review of published and private literature was used here to estimate typical diesel truck subsystem weights [67][85][86][87]. These are accurate enough to discuss the approximate scale of diesel systems that would not be found on a battery electric vehicle. Each vehicle has its own tare weights. This is not intended to reflect all vehicles. It is just one example to illustrate that approximately 7,800 lbs. are related to diesel engine functions on some Class 8 on-highway tractors, and this includes approximately 2,600 lbs. of fluids required for operation.

Diesel Truck Subsystem	Approximate Weight (lb)
Engine & Related	2,300
Transmission & Related	810
Driveshaft Parts	230
Fuel Tank & Related	200
Rear Tandem Axle	1,200
Exhaust/Emission Systems	480
Diesel Fuel (full)	1,728
DEF	209
12V Batteries (3)	180
Cooling System	310
Other Brackets, Mounts, Cables, Components	200
Total Diesel Related	7,847

Figure 31. Example Diesel Related Systems for Class 8 Tractor (NACFE)

11.3.4 Average Vehicle Weights

The EPA estimated for the 2011 GHG Phase 1 rules that average weight for high roof sleeper tractors was 19,000 lbs., and average trailer tare weight was 13,500 lbs. for 53 ft. dry van trailers. These are listed in the 2011 EPA GEM Model User Guide. They also established a typical average freight weight of 38,000 lbs., so that the total average high roof sleeper vehicle weight was 70,500 lbs. representing the entire class of on-highway, high roof sleepers [81][82][83][84]. EPA stated, "The payloads were developed from Federal Highway statistics based on the averaging the payloads for the weight classes of represented within each vehicle category."

A more recent 2016 analysis by Carrigan and Ray of typical gross vehicle weights evaluated five different sources for vehicle weight information. They said, "Heavy vehicle weights were assessed by examining five different databases: (1) the Vehicle Travel Information System (VTIS), (2) the NAS heavy vehicle fuel consumption study, (3) the FHWA Vehicle Inventory and Use Survey (VIUS), (4) the Mechanistic-Empirical Pavement Design Guide (MEPDG) and (5) NCHRP Report 683 WIM data [85]." The authors concluded, "While all the data is fairly similar it is certainly not identical. Each different data source includes its own assumptions and definitions such that there are nuances between all the different data sources [85]." This report describes vehicles using FHWA Vehicle Classifications shown in Figure 32.

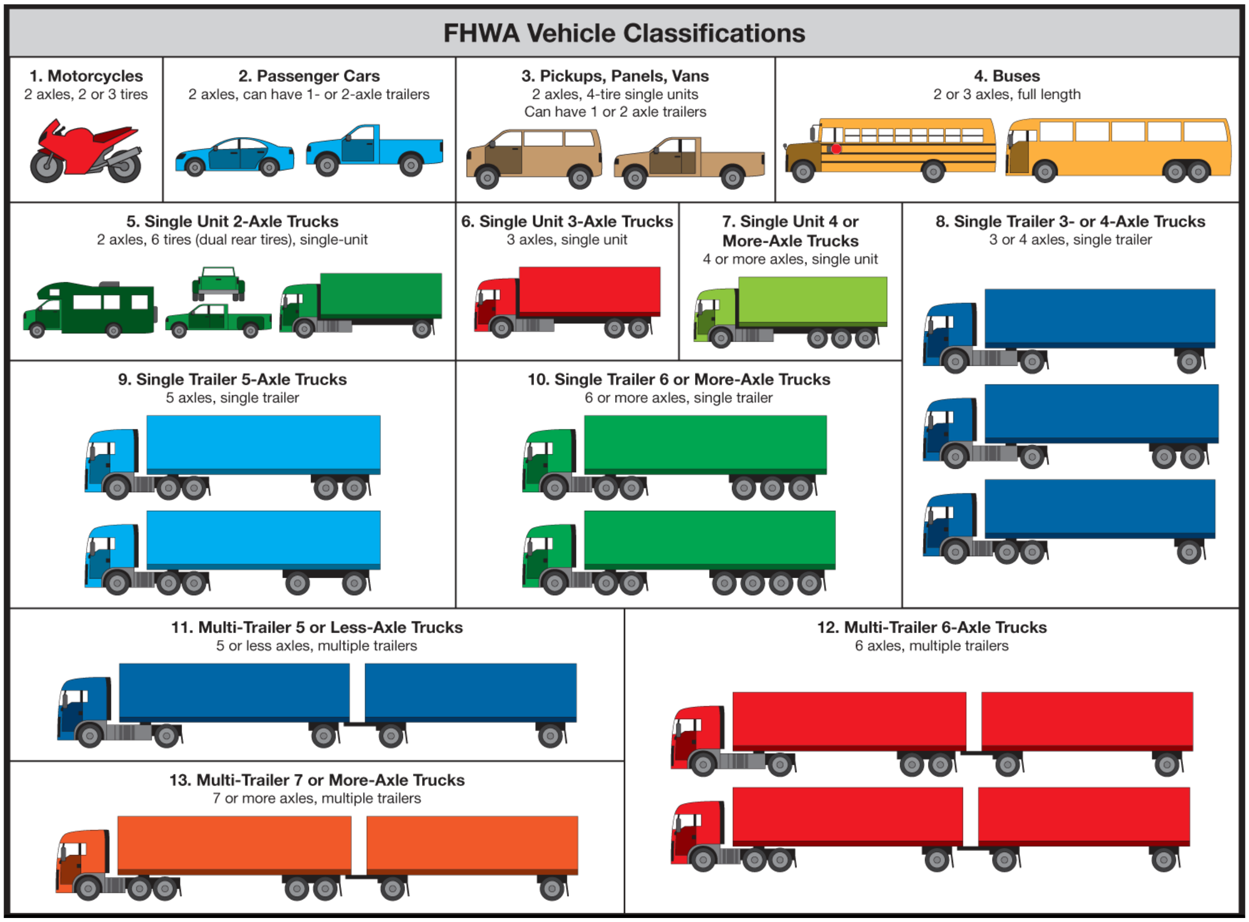


Figure 32. FHWA Vehicle Classifications (TXDOT) [85]

Carrigan and Ray summarized their evaluation of these five sources for selected regions, so are subsets of the total available data. For Class 8, they show in Figure 33, similar to other studies, that vehicles see a wide range of weights ranging from approximately 28,000 lbs. GVW to, and slightly beyond the 80,000 lbs. GVW. Keep in mind that some vehicle options are excluded from the maximum weight restrictions, such as APUs. Also, vehicles do travel overweight – which is why states audit and fine for these instances. Carrigan and Ray also noted that there are significant volumes of vehicles that operate in FHWA Class 9 and 10 in some regions where these are allowed, with weights up to approximately 118,000 lbs. [85]. The 90th percentile shown for four data sets falls below 55,000 GVW. The 95th percentile falls below 65,000 lbs. GVW for these four example data sets.

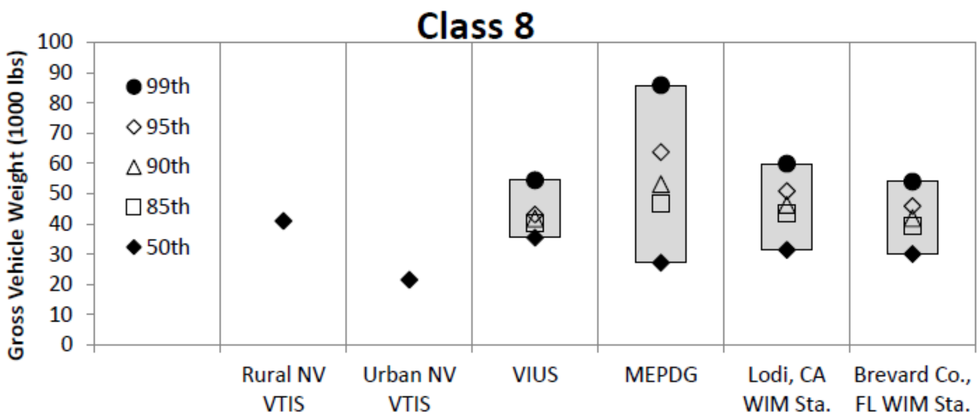


Figure 33. Gross Vehicle Weights (Carrigan & Ray) [85]

While 80,000 lbs. GVW is a convenient weight level to use in discussions, it is not representative of the majority of actual Class 8 vehicles being driven on U.S. roads where actual loads may be between 55,000 to 65,000 lbs. GVW for Class 8 trucks. The same holds true for other classes of trucks, which may operate below their maximum allowed weights. This is a critical point in considering suitability of electric trucks as alternatives to diesel units. Right sizing the evaluation of electric vehicles to the actual fleet duty cycles is important.

11.3.5 Class 8 CBEV Battery Weight

It is assumed that an electric Class 8 tractor will be pulling the same trailers as the diesel units, at least in the near term. Removing all the diesel-related systems from the Class 8 tractor could reduce vehicle weight by greater than 7,000 lbs. Cummins AEOS prototype was able to offset the added weight of the electric drive train (batteries, motors and mountings) to achieve parity for a 100-mile range Class 7 tractor. Consider an example 500-mile range Class 8 tractor using wheel end motors as prototyped by both Mercedes Benz and Tesla. The 400 miles of additional mileage range is achieved primarily through adding battery capacity, assuming space on the chassis can be found. All other systems remain largely unchanged. This is similar to adding diesel fuel tank capacity to extend range on a tractor; all other truck systems remain largely unchanged.

Regarding battery performance units, some clarification is needed. Power density is a science term used to describe battery electrical power per unit of mass or volume. Units are typically kWh/kg or kWh/l. The fleet focus is typically on mass, not volume of batteries. Specific power is the inverse of that value, mass divided by power, typically expressed as kg/kWh. In the U.S., colloquially, it's common to see batteries described in units of lb/kWh. This technically mixes measurement systems, something that your science teacher would fault you for. It is U.S. weight (a unit of force not mass) per SI system power, and expresses a weight-to-power value. In the U.S., trucks carry pounds of freight weight. Furthermore, vehicle GVWR, the gross vehicle weight rating, is expressed in pounds of weight. Battery electrical power in kWh per pound of battery weight expresses a power-to-weight ratio for comparison purposes. Expressing the inverse of that, weight-to-power, emphasizes that battery weight is important in terms of freight capacity, so is a common simplification used in this report.

Battery weight-to-power can be estimated from Mercedes Benz in their 2016 prototype (24 lb/kWh) [74]. CALSTART/DELFT estimated in their 2014 feasibility studies that current capability is at 22 lb/kWh and future capability is projected to reach 4.5 lb/kWh [3][4]. The National Academies in 2015 report on automotive EV batteries converted to lb/kWh estimates "best-case (low rate), practically achievable" potential future values for a variety of EV battery technologies between 2.7 and 5 lb/kWh [73].

Frito Lays' Smith Electric Class 5 delivery trucks from 2011 have weight-to-power of 25 lb/kWh (according to details from A123, the originally battery maker in 2011). The 48V battery pack in the Proterra electric buses have in 2017 achieved 13.7 lb/kWh for production vehicles [41]. NACFE interviews conducted with vehicle system manufacturers and fleet operates indicate confidence that this trend in battery weight-to-power improvement will continue at a steep rate for the next decade. The Department of Energy's funded research into battery improvements is reported on annually as documented in annual progress reports for energy storage and advanced batteries [114][115].

The Department of Energy states in their 2016 progress report, "Current battery technology performs far below its theoretical limits. For example, in the near term, even with existing lithium-ion technology, there is an opportunity to more than double the battery pack energy density (from 125 Wh/kg to 250 Wh/kg) by using new high-capacity cathode materials, higher voltage electrolytes, and high capacity silicon or tin-based intermetallic alloys to replace graphite anodes [115]."

Battery weight required for a specific duty cycle is then a moving target for the future. Working through an example, assume battery efficiency of 2 kWh/mi; then adding 400 miles range requires an estimated 800 kWh of additional battery capacity. At CALSTART/DELFT's 2014 value of 22 lb/kWh, the added weight for the range would be 17,600 lbs. Using Proterrra's 2017 value of 13.7 lb/kWh, the added weight for range would be 10,960 lbs. Using the NAS projected future batteries at 5 lb/kWh, the additional 400 miles of range equates to adding 4,000 lbs. of battery. These example trends are summarized in Figure 34.

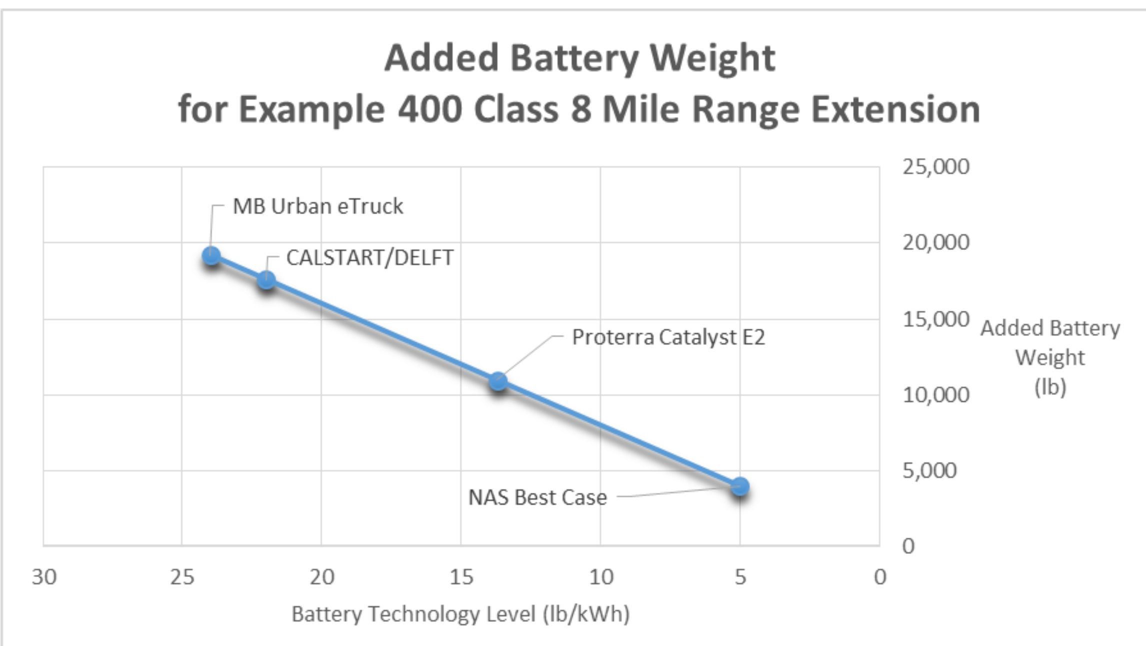


Figure 34. Added Battery Weight for Example 400 Mile Class 8 Range Extension (NACFE)

If OEMs can produce GVW vehicle weight parity for vehicles at 100 mile range comparing battery electric vehicles to diesel as Cummins AEOS has prototyped, then adding 400 miles of range today might use 17,600 lbs. of freight capacity, and in the future, perhaps as little as 4,000 lbs. of freight capacity.

EPA estimated a representative Class 8 high roof sleeper truck weighs 19,000 lbs. The trailer tare EPA estimates is 13,500 lbs. This configuration has 47,500 lbs. of freight potential. A 80,000 lb. GVW rated Class 8 battery electric vehicle equipped with Proterra E2 type batteries, might be limited today to carrying 36,540 lbs. of freight for a vehicle capable of 500 mile range.

The U.S. built BYD production Class 8 Model T9 day cab CBEV is advertised as having a tare weight of 23,589 lbs., with a range of 92 miles and GCWR up to 120,000 lbs. [155]. At 80,000 GVWR and towing a 13,500 lb. tare trailer, freight weight possible equates to 42,911 lbs. for 92 miles range.

EPA's estimate of average payload is 38,000 lbs. Carrigan and Ray's evaluation suggests slightly lower values are common. If EPA's typical Class 8 high roof sleeper has a loaded GVW of 70,500 lbs. carrying 38,000 lbs. of freight, then Carrigan and Ray's data suggests 95% of payloads are less than 33,000 lbs.

A joint NACFE and ACT fleet survey of fleets conducted for this report shows that for three Class 7/8 segments, the fleets contacted estimated that 50% or more of loads were below 39,500 lbs. of freight as shown in Figure 35.

Daily Portion of Fleet _____ (of max allowed GVWR)	Typical Vehicle Daily Weight Range (lb)	Daily Freight (lb)	Heavy Duty City Tractor (Class 7/8)	Heavy Duty Regional Tractor (Class 7/8)	Heavy Duty Long Haul (Class 7/ 8)
Between 90% to 100%	72,000 to 80,000	39,500 to 47,500	51%	43%	44%
Beween 80% to 90%	64,000 to 72,000	31,500 to 39,500	37%	20%	23%
Beween 70% to 80%	56,000 to 64,000	23,500 to 31,500	8%	10%	9%
Beween 60% to 70%	48,000 to 56,000	15,500 to 23,500	3%	10%	10%
Beween 50% to 60%	40,000 to 48,000	7,500 to 15,500	1%	11%	13%
Less Than 50%	Less Than 40,000	0 to 7,500	0%	6%	2%

Figure 35. Daily Freight Carried NACFE/ACT Fleet Survey (NACFE)

This report concludes that a 500 mile range CBEV Class 8 vehicle may be viable with respect to freight carried using current technology batteries, for perhaps 50% to 95% of 53 ft. van trailer loads. If the technology advances projected by the National Academy of Science on energy density occur, then a CBEV Class 8 may be suitable for all but the routes running near 80,000 lbs. GVW.

The joint NACFE/ACT fleet survey outcomes were consistent with published resources in finding that 98% of light- and medium-duty (Classes 3 through 6) vehicles daily travel is between 50 and 150 miles. Urban heavy-duty (Class 7/8) was distributed across all the daily mileage ranges. Heavy-duty regional had 70% over 300 miles per day and heavy-duty long haul had 73% over 400 miles/day. The survey results are tabulated in Figure 36.

These findings highlight that 100 to 150 maximum daily ranges for commercial battery electric vehicles match well with expected Class 3 to 6 duty cycles.

The findings show that for heavy-duty urban delivery, there is a wide range of duty cycles, daily ranges and freight weights. Vehicles for this segment likely have significant differences in option content optimized for specific sub-segments and fleet specific duty cycles. For example, one fleet may have routes where the driver makes multiple store deliveries from the same trailer, while others may drop entire trailers at one store. One-size-fits-all truck specifications likely are not optimum for the variety of end uses, but work for specific duty cycles. Heavy-duty regional and heavy-duty long haul in the NACFE/ACT fleet survey tend to have longer range and heavier freight weight requirements as tabulated in Figure 35 and Figure 36.

Daily Range (miles)	Light Duty Delivery Truck (Class 3)	Medium Duty Box Truck (Class 4-6)	Heavy Duty City Tractor (Class 7/8)	Heavy Duty Regional Tractor (Class 7/8)	Heavy Duty Long Haul (Class 7/ 8)
Less than 50 miles per day	43%	38%	5%	0%	0%
between 50 to 100 miles per day	30%	33%	16%	3%	1%
Between 100 to 150 miles per day	25%	25%	10%	3%	0%
Between 150 to 200 miles per day	2%	3%	6%	3%	1%
Between 200 to 250 miles per day	0%	0%	8%	6%	3%
Between 250 to 300 miles per day	0%	0%	15%	15%	10%
Between 300 to 350 miles per day	0%	0%	14%	8%	5%
Between 350 to 400 miles per day	0%	0%	2%	14%	7%
Between 400 to 450 miles per day	0%	0%	9%	26%	28%
Greater than 450 miles per day	0%	0%	15%	22%	46%

Figure 36. Typical Daily Range Requirements by Segment (NACFE/ACT Fleet Survey)

11.3.6 Class 3 through 6 CBEV Weight

The medium-duty segment now has commercially available production offerings including the Mitsubishi Fuso eCanter, the Chanje V8070, the BYD T5 and T7, Workhorse eGen and other OEMs have announced they are working on new products [152][153][174][175][176]. Fleets like Ryder, FedEx, UPS, DHL, and others are investing in these medium-duty vehicles. The reasons for this interest are offered up by two competing CBEV CEOs.

Justin Palmer, the CEO of Mitsubishi Fuso Truck of America, stated in a Fleet Owner article, "In the long view, I believe personally that the entire [commercial truck] industry is going there – going electric, going autonomous, offering new solutions that are more than just owning trucks, owning the hardware," The article summarized Palmer's thoughts that, "the urban delivery segment is 'leading the way' when it comes to those trends (– especially in electrification, as electric propulsion '"suits and fits' those much more 'short range' delivery needs [175]."

Similarly, Bryan Hansel, the CEO of Chanje, and former CEO of Smith Electric Vehicles, was summarized as stating "…fleets in last-mile delivery need to be looking at such electric trucks if they want to be competitive in the near future, with electric power offering a much lower cost per mile in the long run vs. diesel trucks. Reduced fuel costs, simplified maintenance, less driver fatigue and 'green' corporate image all are advantages… [174]."

ICCT reported similar conclusions from multiple researchers stating, "Based on the research literature, plug-in electric vehicles are being considered for a number of applications in the medium- and heavy-duty sectors. Electric vehicles' high efficiency, generally 3 to 4 times more efficient than diesel and natural gas engines, results in a reduction in primary energy use and greenhouse gas emissions (e.g., Chandler, Espino, & O'Dea, 2016). These vehicles are most suited for applications with short ranges and duty cycles that can take advantage of regenerative braking and where required electric battery packs sizes are lower (CARB, 2015b). An analysis of duty cycles suggests urban delivery vans and delivery trucks, refuse trucks, and drayage trucks as targets for electrification (Kelly, 2016) [127]."

The present maturity of battery energy density puts medium-duty CBEVs on a par with competing diesel powertrains for Class 3 through 6 segments in shorter-range urban delivery duty cycles. These segments have daily range requirements from 50 to 150 miles. At these ranges the weight of current technology batteries does not significantly limit load capacity for many routes. Taking the weight and range issue off the table allows other attributes of CBEVs to win over fleets and drivers.

Direct comparisons of identical diesel powered models with battery electric ones is challenging. There are few manufacturers that make both in the same model. Also, the magnitude of changes between the two powertrains affect nearly the entire vehicle configuration. The Mitsubishi Fuso Model 180 and eCanter are not identically equipped, but are similar enough they can serve to illustrate differences in weight and payload capacity from a review of their published spec sheets. The eCanter is capable of "a range of 60 to 80 miles, with advanced charging capabilities of one-to-two hours via a DC fast-charge option [152]." The FE180 has a 30 gal. tank and an optional second 33 gal. tank. At a conservative 8 mpg with just the 30 gal. tank, that would be 240 miles range. Actual mpgs are probably above 12 mpg.

The table in Figure 37 and Figure 38 document specification differences between the FE180 Diesel and the somewhat similar eCanter Battery Electric vehicle.

Factor	FE180 Diesel	eCanter Battery Electric
Weight Rating GVWR	17,995 lb	15,995 lb
Curb Weight	5,505 lb (est.)	6,615 lb (est.)
Body/Payload Est. Max.	12,490 lb	9,380 lb
Wheelbase	Several including 151.6"	151.6"
Overall Length (cab/chassis)	Several including 246.3"	245.5"
Useable Cab to Rear Axle	Several including 122.6"	122.6"
Axle Capacity (Front/Rear)	6,835 lb, 13,230 lb	6,390 lb / 12,700 lb

Figure 37. Diesel and Battery Electric Comparison (from Mitsubishi Fuso data) [152]

FE180 Diesel

WEIGHT RATINGS	GVWR/GCWR	17,995 lb./25,710 lb.				
	GAWR (front/rear)	6,390 lb./12,700 lb.				
CURB WEIGHT	Base model	5,505 lb. (est.)				
BODY/PAYLOAD	Estimated max.	12,490 lb. (see dealer for details)				
DIMENSIONS	Wheelbase	110.2" (C)	133.9" (E)	151.6" (G)	169.3" (H)	187.0" (K)
	Overall length (cab/chassis)	204.9"	228.5"	246.3"	264.0"	281.7"
	Usable cab to rear axle	81.2"	104.9"	122.6"	140.3"	158.0"
	Min and max body sizes	10' to 20' (22' with FUSO review/approval)				
ENGINE	Model	FUSO 4P10-T5 Diesel				
	Type	DOHC, 4-cylinder, 4-stroke cycle, water-cooled, turbocharged, intercooled diesel with 4 valves per cylinder, with high-efficiency electrically-engaged cooling fan				
	Displacement	183 cu. in. (3.0 L) Electronically controlled DPF/SCR system with OBD				
	Max. output (SAE, gross)	161 hp @ 3,400 rpm				
	Max. torque (SAE, gross)	295 lb.-ft. @ 1,300 rpm				
BATTERY	Type/Capacity	Two 12-volt, maintenance-free/750 CCA				
AIR CLEANER	Type	Dry paper element with snorkel				
TRANSMISSION	Standard	M038S6 DUONIC® 6-speed dual-clutch automatic				
AXLE CAPACITY	Front/Rear	6,835 lb./13,230 lb.				
FINAL REDUCTION GEAR	Type	Single-reduction hypoid				
	Ratio	6.166				
TOP SPEED, EST.	Diff	71 mph				
TURNING DIAMETER	Minimum, by wheelbase	34.1'	40.0'	44.6'	49.5'	54.1'
TIRES (PREMIUM)	Configuration	Single front, dual rear				
	Size/Type	215/75R17.5 12PR LR:F hwy front/traction rear				

eCanter Battery Electric

WEIGHT RATINGS	GVWR/GCWR	15,995 lb.
CURB WEIGHT	Base model	6,615 lb. (est.)
BODY/PAYLOAD	Estimated max.	9,380 lb. (see dealer for details)
DIMENSIONS	Wheelbase	151.6" (E)
	Overall length (cab/chassis)	245.5"
	Usable cab to rear axle	122.6"
BATTERY	Type/Capacity	Six Mercedes-Benz liquid-cooled, 360V, 82.8 kWh lithium-ion
AXLE CAPACITY	Front/Rear	6,390 lb./12,700 lb.
TURNING DIAMETER	Minimum, by wheelbase	44.6'
TIRES (PREMIUM)	Size/Type	215/75R17.5
WHEELS	Size/Configuration	17.5" x 6"/6-lug
STEERING	Type	Ball-nut type with electric-hydraulic power boost
	Adjustments	Tilt/telescoping steering column with steering lock
SUSPENSION	Front	Laminated leaf springs with shock absorbers and stabilizer bar
	Rear	Laminated leaf springs with shock absorbers
FRAME	Type	Ladder/tapered
	Section modulus	7.08 cu. in. per rail
	Yield strength	56,565 psi
	RBM per rail	400,410 lb.-in.
	Height/Width	35.8"/33.5"
CONVENIENCE / ASSURANCE	Cruise control	Standard (programmable)
	Entry	Keyless, with driver/assistant door lock control
	Radio	Clarion AM/FM/CD, hands-free Bluetooth® (optional)
	Air conditioning	Standard factory-installed

Figure 38. Spec Sheets Comparing FE180 Diesel and eCanter (Mitsubishi Fuso) [152][180]

The difference in GVWR of the FE180 and eCanter is 2,000 lbs. Curb weight is 1,110 lbs. heavier for the eCanter. Last mile deliverers like UPS, FedEx, and DHL likely cube out their cargo before weight limits are an issue. Others like Frito-Lay, have less dense cargo so are not at risk of exceeding weight limits. Medium-duty fleets that move densely packed loads, like beverages, are very sensitive to weight limitations. CBEVs are better suited to some duty cycles and loads.

The tremendous range differential in the diesel and the battery electric versions of this vehicle suggests that the medium-duty diesel is often carrying 100 to 200 lbs. of non-freight weight in extra fuel than needed for a day's route. That excess range capacity is a fleet choice, a trade-off on fill-up frequency versus weight sensitivity. It suggests that a few hundred pounds of excess fuel some days may be acceptable to fleets in one-shift operations versus requiring daily fueling time. Where operations slip seat trucks, the focus is on keeping the trucks moving maximizing asset utilization, so once-weekly fueling is a logical trade-off against carrying extra fuel.

Fleets that have announced orders for production medium-duty CBEVs have factored in vehicle tare weight and load capacity, and found they have margin without changing their duty cycles and routes. This acceptable tradeoff is demonstrated in the NREL Frito-Lay Smith Newton testing where the Newton performed as a one-for-one replacement of a diesel powered Navistar 4200 and 4700 trucks [72].

12 TIME

Two key factors for fleets is how much labor is spent in fueling/charging their vehicles, and how much time their vehicle assets are sitting idle not moving freight.

12.1 OPERATOR TIME AT PUMP VS. TIME AT CHARGER

On comparable routes over a week's time, the medium-duty diesel might only fill up once. A heavy-duty vehicle might fill up twice. The battery electric vehicle would be charging once daily. The rate of filling a diesel fuel tank is estimated by NACFE to be about 20-gallons per minute actually pumping, plus a few minutes dealing with keypad entry and billing. Extra time may be involved when adding a DEF fill. One example NACFE found of a typical diesel truck fuel station filled 114 gallons in 5 minutes, a rate of 22 gallons per minute [177]. Charging a CBEV at a terminal charging station requires about the same level of effort as putting a fuel pump nozzle into a fuel tank. A driver would wait for diesel fueling to complete, then put the nozzle back on the pump. In electric charging, the driver or service tech, would move to other tasks while the vehicle charged. The net labor time difference between a once-a-week fuel stop and a once nightly charging over a week seems minimal.

12.2 Vehicle Charging Times

Fleets operate vehicles in a variety of utilization modes. Some have single shift operations where the vehicle is not moving for long periods. Others have dual drive, or team driver, operations where the vehicle is rarely at rest. A similar variation is slip seating, where drivers are swapped out at shift changes and the vehicles keeps moving. The type of operation dictates the time available for charging.

Long haul applications may fully deplete batteries between charges, while shorter urban delivery application may only partially deplete batteries between charges. The type of operation also dictates the depth of charge required, which factors into the time available for charging.

Operations that have high daily vehicle utilization rates will require fast charging for battery electric vehicles to be competitive. “Fast Charging” is a relative term to each fleet’s operation. A dual driver, long haul operation implies the vehicle needs deep recharging on a scale of 30 minutes or less to be competitive with similar diesel operations. Modes that use slip seating of drivers likely require deep recharging on a scale of 2 hours or less to be competitive with equivalent diesel use. Operations with one shift of driving likely can take advantage of more moderate charging times on the scale of 4 to 8 hours, and depth of recharge is likely much less.

All these modes have technically viable battery electric vehicle solutions. The practicality of each depends on many factors. The present state of battery and charging technology suggests that urban delivery, single-shift medium-duty operations are currently the best opportunity for commercial CBEVs in the trade-off of technical viability and practicality [127].

13 Duty Cycles - More Than Range & Weight

As with diesel trucks, the fuel efficiency, or rather energy use efficiency, is very dependent on the actual duty cycles. Advertised potential range estimates for CBEVs generally have a number of assumptions and qualifiers that may or may not be listed. For example, stating a loaded truck has a 100 or 500-mile range without stating the duty cycle is insufficient to relate to a fleet’s specific needs.

There are a number of defined duty cycles in use by researchers, industry and regulators. Stating performance with respect to any of these published duty cycles can reduce confusion and provide a basis for applicability to a specific fleet.

A summary of duty cycles for emissions evaluations for light- to heavy-duty vehicles for both the U.S. and the world is found at DieselNet [70]. The list has approximately 50 different cycles identified. This is not all-inclusive. There are many other cycles and fleets may use their own cycles built from auditing their own operations. The EPA selected and combined subsets of cycles for use in the 2011 Green House Gas Emissions Modeling (GEM), analysis software that medium- and heavy-duty commercial truck OEMs use to report on compliance, as shown in Figure 39 [81]. EPA explained the selections in their Regulatory Impact Analysis (RIA) and responses to questions about the RIA [82][84].

Table 4: Drive Cycle Weighting

CATEGORY	CLASS 8 SLEEPER CAB TRACTORS	CLASS 7/8 DAY CAB TRACTORS	CLASS 2b-8 VOCATIONAL VEHICLES
ARB Transient	5%	19%	42%
55 mph Cruise	9%	17%	21%
65 mph Cruise	86%	64%	37%

Figure 39. Duty Cycles Used By EPA in Phase I GHG GEM Modeling Software (EPA) [81]

In 2016's Phase 2 GHG rules, EPA expanded the use of the three duty cycles for the GEM 2 version of the software [90]. "The Phase 2 rulemaking … predefines three drive cycles including a transient cycle and two cruise speed cycles. The transient mode is defined by California Air Resources Board (CARB) in its Highway Heavy-Duty Diesel Transient (HHDDT) cycle. The cruise speed cycles are represented by two nominally constant speed 65 mph and 55 mph cycles, each with varying road grade [90]." These cycles are as shown in Figure 40, consistent with Phase 1 GEM for typical on-highway Class 8 sleeper cabs and Class 7/8 day cabs. Figure 41 tabulates duty cycle weighting for other non-vocational Class 7 and 8 sleepers and day cabs.

EPA Phase 2 GEM Model Combination Modeling Parameters		Regulatory Subcategory					
		Class 8 Combination, Sleeper Cab			Class 8 Combination, Day Cab		
Factor	Roof Height	High Roof	Mid Roof	Low Roof	High Roof	Mid Roof	Low Roof
	Total Weight (kg)	31,978	30,277	30,390	31,297	29,529	29,710
	Total Weight (lb)	70,499	66,749	66,998	68,998	65,100	65,499
	Number of Axles	5			5		
	Payload (tons)	19			19		
Drive Cycle Weighti	CARB HHDDT	0.05			0.19		
	GEM 55 mph	0.09			0.17		
	GEM 65 mph	0.86			0.64		

Figure 40. EPA Phase 2 Typical on Highway Duty Cycles (created from EPA data) [90]

EPA Phase 2 GEM Model Combination Modeling Parameters		Regulatory Subcategory									
		Heavy Haul Class 8 Combination (All Cabs)	Class 7 Combination, Day Cab			Heavy Class 8 Combination, Sleeper Cab			Heavy Class 8 Combination, Day Cab		
Factor	Roof Height	All Roof Heights	High Roof	Mid Roof	Low Roof	High Roof	Mid Roof	Low Roof	High Roof	Mid Roof	Low Roof
	Total Weight (kg)	53,750	22,679	20,910	21,091	53,750	52,049	52,162	53,069	51,301	51,482
	Total Weight (lb)	118,498	49,999	46,099	46,498	118,498	114,748	114,998	116,997	113,099	113,498
	Number of Axles	5	4			5			5		
	Payload (tons)	43	12.5			43			43		
Drive Cycle Weighting	CARB HHDDT	0.19	0.19			0.05			0.19		
	GEM 55 mph	0.17	0.17			0.09			0.17		
	GEM 65 mph	0.64	0.64			0.86			0.64		

Figure 41. EPA Phase 2 Other Non-Vocational Class 7 & 8 Duty Cycles (created from EPA data) [90]

EPA also includes vocational vehicles with combinations of additional duty cycles based on use, defined as Regional, Multi-purpose and Urban. EPA stated, "For vocational vehicles two additional idle cycles are utilized, one simulating parked idling operation and the other idling in traffic. Each regulatory subcategory is assigned a specific set of drive cycle weightings," as summarized in Figure 42 [90].

EPA Phase 2 GEM Model Vocational Modeling Parameters		Regulatory Subcategory								
		HHD (Class 8)			MHD (Class 6-7)			LHD (Class 2b-5)		
		Regional	Multi-Purpose	Urban	Regional	Multi-Purpose	Urban	Regional	Multi-Purpose	Urban
Factor	Total weight (kg)	19,051			11,408			7,257		
	Total weight (lb)	42,000			25,150			15,999		
	CdA (m2)	6.86			5.40			3.40		
	Payload (tons)	7.50			5.60			2.85		
Drive Cycle Weighting	ARB Transient Drive Cycle Weighting	0.20	0.54	0.90	0.20	0.54	0.92	0.20	0.54	0.92
	GEM 55 mph Drive Cycle Weighting	0.24	0.23	0.10	0.24	0.29	0.08	0.24	0.29	0.08
	GEM 65 mph Drive Cycle Weighting	0.56	0.23	0.00	0.56	0.17	0.00	0.56	0.17	0.00
	Parked Idle Cycle Weighting	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	Drive Idle Cycle Weighting	0.00	0.17	0.15	0.00	0.17	0.15	0.00	0.17	0.15
	Non-Idle Cycle Weighting	0.75	0.58	0.60	0.75	0.58	0.60	0.75	0.58	0.60

Figure 42. EPA Phase 2 Duty Cycles - Vocational Modeling Parameters (created from EPA data) [90]

EPA also specified cycles for specific custom vocational vehicles as shown in Figure 43 [90].

Custom Chassis Subcategory	GEM Simulated Vehicle
Emergency Vehicles	HHD Urban
Cement Mixers and Other Mixed Use Applications	HHD Urban
Refuse Vehicles	HHD Urban
Coach Buses	HHD Regional
Transit Bus, Other Bus and Drayage Tractors	HHD Urban
Motor Homes	MHD Regional
School Bus	MHD Urban

Figure 43. EPA Phase 2 Vocational Custom Chassis Duty Cycles (EPA) [90]

Still other sources exist for duty cycle modeling. The U.S. National Renewable Energy Laboratory (NREL) maintains the Fleet DNA database which they describe as a "…clearinghouse of commercial fleet vehicle operating data that helps vehicle manufacturers and developers optimize vehicle designs and helps fleet managers choose advanced technologies for their fleets. This online tool provides data summaries and visualizations similar to real-world 'genetics' for medium- and heavy-duty commercial fleet vehicles operating in a variety of vocations [68]." Three examples of this Fleet DNA duty cycle speed data are shown in Figure 44. The images are Daily Average Driving Speed vs. Distance for Delivery Vans (left), Delivery Trucks (center) and Class 8 Tractors (right) [109][110][111]. The vocations of the Class 7 and 8 tractors in the Fleet DNA database as of December 2018 are listed by NREL as beverage delivery, food delivery and local delivery – there are no units classified as "long haul" vocation. The second Figure 45 shows the distribution of distances at speeds for these three types of vehicles. These graphs illustrate that delivery vans see much slower speeds and ranges than delivery trucks. Delivery trucks similarly see much different driving speeds and distances than Class 8 tractors. Each presents significantly different challenges and opportunities for diesel or electric powertrains and their drivers.

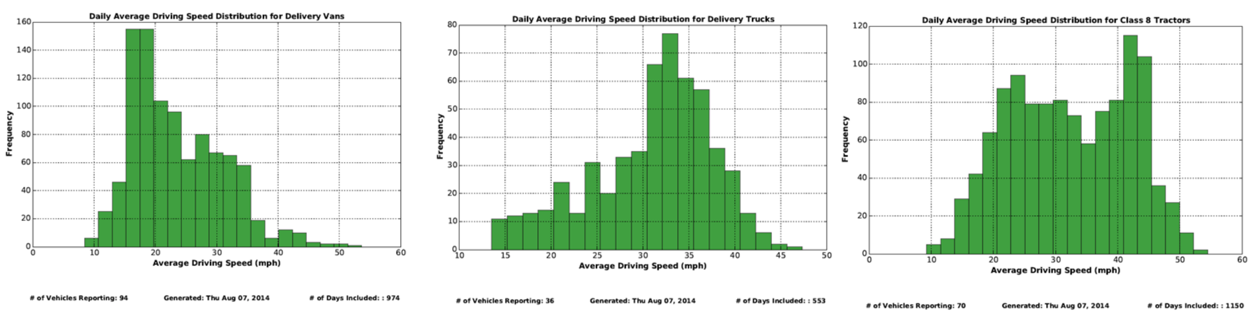


Figure 44. Example Duty Cycle Speeds from Fleet DNA Database (NREL) [109][110][111]

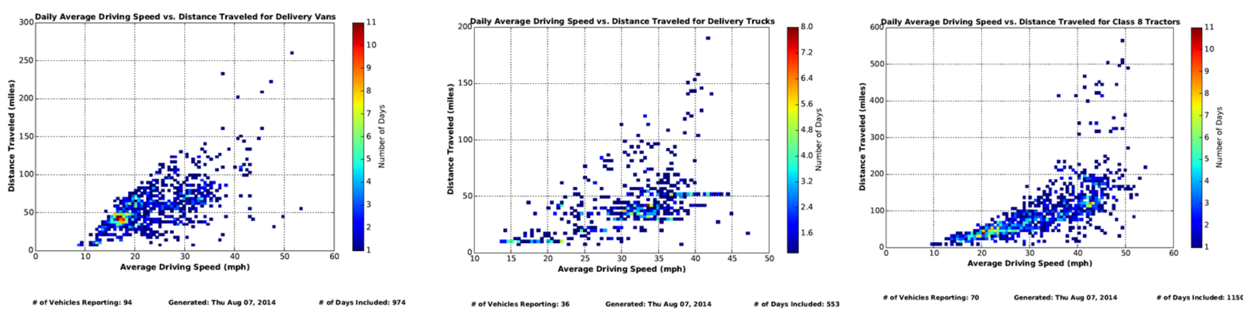


Figure 45. Example Duty Cycle Range at Speeds from Fleet DNA Database (NREL) [109][110][111]

Advertising on electric vehicle performance should include reference to the duty cycle on which that performance is based. When it doesn't, fleets should request this detail. The DieselNet list, the EPA GHG 2 cycles, the NREL Fleet DNA database, and others are all possible sources for duty cycles from which to choose as a starting point. The fleet's actual duty cycles may vary from these composite values. Fleets wanting a more refined estimate of performance may need to provide manufacturers with their specific fleet's duty cycles.

Ultimately, a pilot test with comparison vehicles running side-by-side in daily operations may be needed to substantiate performance. An example of this type of CBEV evaluation was done by NREL in their 2016 "Field Evaluation of Medium-Duty Plug-in Electric Delivery Trucks [89]." The study summarized PepsiCo's Frito-Lay North America (FNLA) Division's fleet side-by-side testing of the Smith Newton electric Class 5 delivery truck versus comparable diesels. The test used 10 Smith Newtons and a comparison fleet of 9 diesel International 4400's and 1 gasoline Hino 238. The vehicles were equipped with data loggers. They were tracked over the same 17-day period, April into May of 2014. The vehicles were based from Frito-Lay's Federal Way facility, a suburb of Seattle, Washington [89].

Frito-Lay found that their average daily driving time for both electric and diesel units was just 1.5 hours, as the drivers spent time at each location handling stocking, customer interfacing, and other non-driving tasks. Distances travelled daily were statistically distributed as shown in Figure 46 [89]. The majority of electric vehicle runs were less than 45 miles per day.

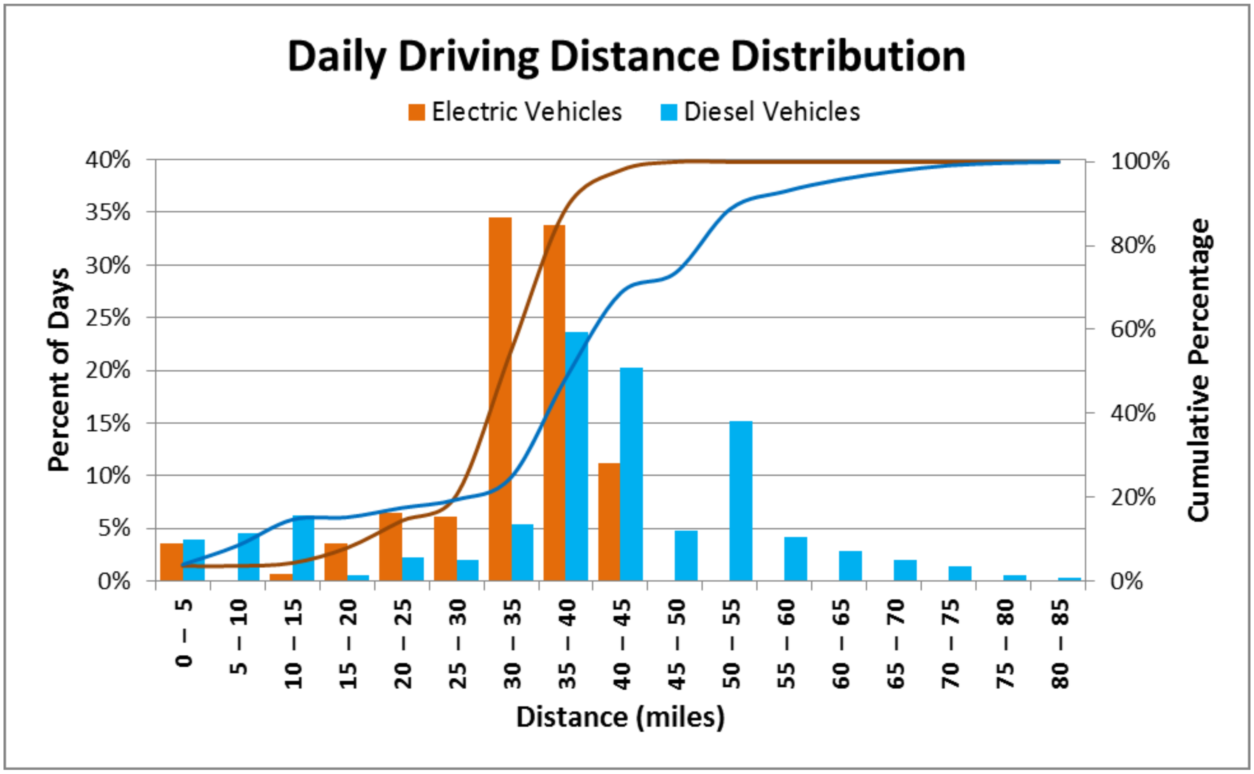


Figure 46. Average daily driving for Smith Newton CBEV and Comparison Diesel Trucks (NREL) [89]

The Smith Newton vehicles were second-generation vehicles "…configured as Class 6 delivery trucks with an 80-kilowatt-hour (kWh) lithium iron phosphate (LiFePO4) battery pack manufactured by A123 Systems. Gross vehicle weight rating was 22,028 lbs. with payload capacity of 9,750 lbs. [89]." The vehicles were speed limited not to exceed 50 mph. Both the diesel and electric trucks averaged 20 to 25 mph over the delivery routes. Figure 47 shows the Smith CBEV and the comparison Navistar diesel units.

Figure 47. Smith Newton and Navistar 4400 Comparison Vehicles (NREL) [89]

In this example, NREL concluded, "The FLNA delivery duty cycle closely matched the capabilities of Smith EVs [89]." This example shows that a fleet's specific regional duty cycle can be significantly different than any aggregated national average cycles.

This study noted that during the testing the Smith EVs were operating below rated kWh energy capacity. NREL concluded that, "79% of EV trips required less than 55 kWh of the available 80 kWh [89]." NREL suggested that, "FLNA fleet managers could improve their operational efficiency by dispatching the EVs on routes closer to their maximum range to maximize the electrification advantage [89]." This highlights that forcing CBEVs into existing duty cycles can artificially limit their potential. The new technology may permit rethinking operations to better tune them to the capabilities of the CBEVs rather than forcing the CBEVs to duplicate the diesel duty cycles.

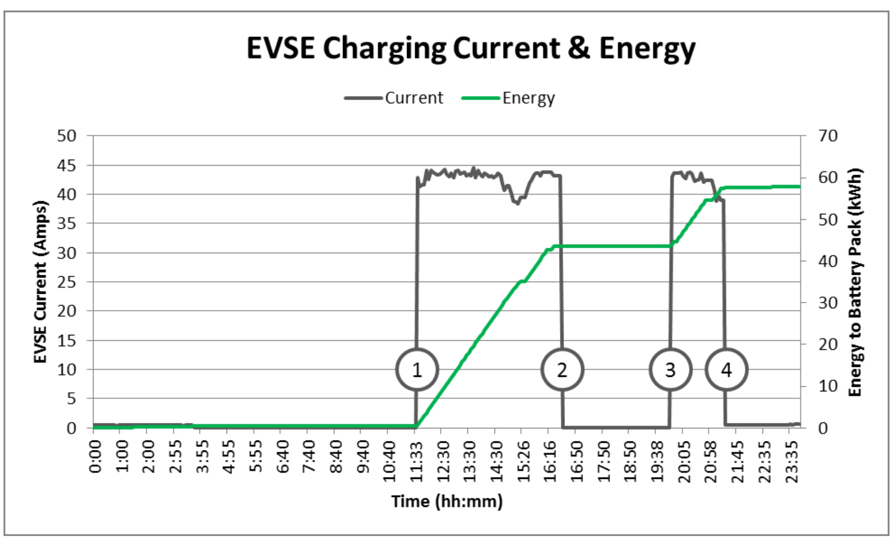
14 Fueling and Charging

The duty cycle for a diesel engine requires, at some point, that the vehicle get fueled. Fueling is a short and a relatively infrequent weekly event for many diesel-powered vehicles. Not so with electric trucks. The Smith EVs in the NREL Frito-Lay test, for example, required daily recharging. Effective comparisons of diesel and electric vehicle duty cycles needs to be done on a 24-hour and possibly a 7-day week basis, not just over a single day's driving miles. Diesel fuel tanks and electric batteries also are not always empty when arriving at the "pump."

Illustrating these points, NREL reported that prior to daily recharging, "…the battery pack state of charge (SOC) for this 10-vehicle EV fleet is on average 42%, requiring an average of 6.1 hours of charging to recharge the battery to 100% SOC [89]." Charging was done using 10 on-site charging stations installed specifically for these vehicles. The system required an on-site power supply including a new transformer, load panel, main disconnect and monitoring equipment panel. The infrastructure is shown in Figure 48.

Figure 48. Ten Charging Stations and Facility Power Supply (NREL) [89]

The operators chose a two-step charging approach where the delivery van would charge for a period of time, then move to a loading dock to be filled, then returned to the charging station to fully charge. A typical 24-hour charging history for one vehicle is shown in Figure 49.



Graph Key:
(1) Vehicle returns from route and is plugged in.
(2) Vehicle is unplugged and moved to loading dock to be reloaded for following day's route.
(3) Vehicle is returned to original parking spot and plugged back in.
(4) Vehicle reaches full SOC and stops charging.

Figure 49. Typical 24-hour Charging History for A Smith EV in NREL Test (NREL) [89]

During the NREL FLNA test, the 24-hour duty cycle "starts with the vehicle out on the route making deliveries, then around 11:30 a.m., the vehicle returns to the depot and is plugged in for recharging. At some point before the vehicle leaves for the next day of deliveries, it is moved a short distance to the main facility's loading dock for loading of the next day's goods. After the vehicle is loaded, it is returned to the charging station and plugged in again where it remains until the next morning. [89]."

A factor to note in this example for comparison to diesel is that the choice of charging method had charging occurring during daytime hours subject to premium electricity demand pricing. Another factor is that the operation was tuned so that the driver might have no labor or time associated with charging or freight loading, as these tasks may be done by other on-site personnel. This may be similar to facilities where diesel fueling and freight loading is handled on-site prior to the driver's shift.

15 Electricity Pricing

The time of day at which a diesel truck fuels generally does not affect the price of fuel. Demand pricing, as it is termed, does impact the price of electricity. Electricity pricing can be subject to instantaneous price changes. This pricing variability has many contributing factors, and can vary dramatically by region based on the composition of the local energy grid's generating capacity. For example, spot pricing for electricity in Southern California is heavily influenced by less costly solar and wind generation with peaks during daylight hours. Pricing can actually be below zero during day shifts and may rise during night times [97]. In other regions were power generation is from hydroelectric dams, daily generating capacity may be more uniform over a 24-hour period, but pricing depends in part on seasonal rainfall and the extent of stored water. In regions where coal and natural gas dominate power generation, daily energy pricing depends on market price fluctuations of those fuel sources. The nature of the national power grid is that the power you use may be generated in another region, making it more difficult to predict market pricing. The graph in Figure 50 shows how 24-hour pricing varied averaged over the first quarter of 2016 for California's Independent System Operators [97]. An overview of the complexity of energy pricing for an example state, Ohio, can be found in a Cleveland State University paper, "Understanding Electricity Markets in Ohio [98]."

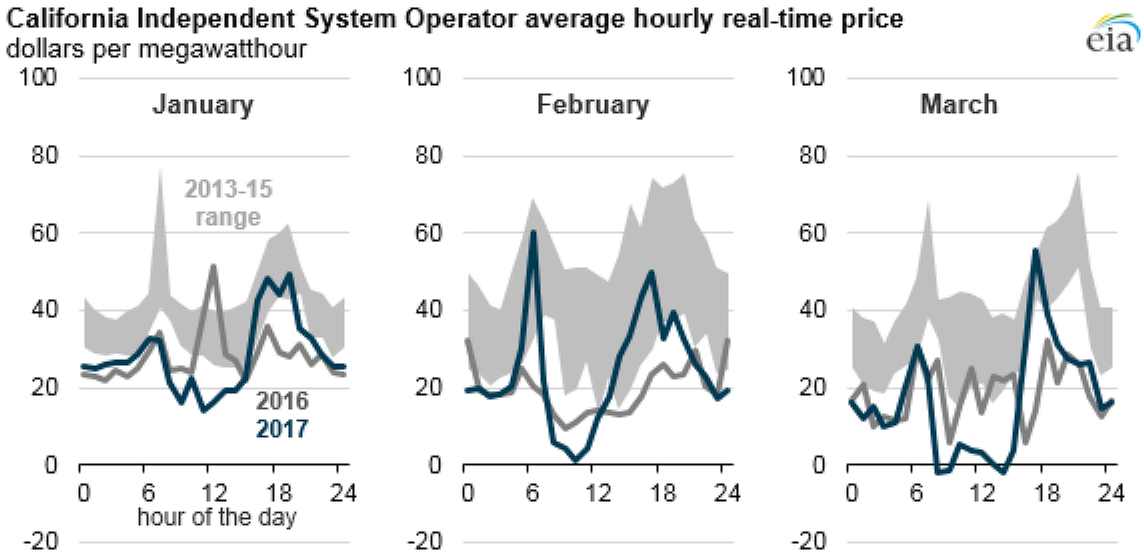


Figure 50. Example Hourly Pricing in California (EIA/LCG Consulting) [97]

The California hourly graphs for the 1Q2016 reflect a period with very limited current electric vehicle penetration versus internal combustion engine vehicles. As CBEV market penetration increases, these patterns will change to reflect the additional demand for electricity. The Society of Automotive Engineers International conducted a webinar on the predicted effects in "Preparing the Energy Grid for Electrified and Autonomous Vehicles [101]." Representatives from Mercedes Benz and the National Renewable Energy Laboratory provided details on electrical consumption pattern changes due to CBEV vehicle market growth [99][100]. The presenters highlighted that leveling energy demand was critical to successful CBEV growth. This leveling, they proposed, could be done through use of local energy storage systems that charged during off-peak periods, and then were used to charge the CBEVs on-demand.

The Energy Storage Association outlines that growth in energy storage systems is critical to stabilizing demand and supply for the future grid in their 2017 "35x25 A Vision for Energy Storage" whitepaper [102]. They predict that energy storage systems have the potential of reducing the net cost of energy to users through balancing the time of day that energy is produced with the time when peak demand occurs. Rocky Mountain Institute has also discussed the need for storage capacity at vehicle charging stations to level demand and supply capability in its 2017 "From Gas to Grid" whitepaper [25]. This is somewhat comparable to how diesel fuel stations store fuel on-site for their pumps to balance their fuel delivery schedules with timing of consumer demand.

Alternatively, businesses could revise their operations, to some extent, to tailor CBEV charging directly from the grid during off peak periods. The change in demand patterns will open the solution space for innovations in storage and distribution of electricity to contain cost growth of CBEV operation. RMI suggests that market demand pricing models might change consumer charging if "…operators were to expose customers to time-varying retail pricing that reflects their time-varying wholesale electricity costs [25]."

Electricity supply will evolve with demand. Bloomberg's Liam Denning discussed an example of infrastructure development opportunity , "In theory, electrifying America's light-duty vehicle fleet would boost power demand overall by roughly one-fifth. The prospect of roughly 20 percent growth in a century-old industry that's been flat-lining on demand for a decade is so alluring it's almost scary. And, in fact, it is -- because adding even a portion of that much demand to the grid takes more than a little planning and coordination." [24]

Rocky Mountain Institute report, From Gas to Grid, projects, "Under some reasonable assumptions, there could be 2.9 million EVs on the road in the U.S. within five years, bringing over 11,000 GWh of load to the U.S. power grid, or about $1.5 billion in annual electricity sales. That would constitute a nontrivial load that utilities would need to accommodate well within their current planning horizons, and would almost certainly be the largest growth sector in the U.S. electricity market for the foreseeable future." [25]

Early CBEV low volume electric truck operators will, of necessity, however have to largely adapt to existing electrical power infrastructure and business routines. In the NREL Frito-Lay example, Frito-Lay did install charging stations for these vehicles at an estimated average cost of $22,000 per station (across multiple locations) [89]. The charging operations at the Federal Way Washington site occurred during peak electrical power pricing. This was felt acceptable for the evaluation period as it was consistent with normal delivery schedules and driver routines. The NREL report states, "The researchers found a significant increase in the overall facility peak power load (approximately 70kW to 110 kW) and energy requirements with the introduction of the EVs." However the authors concluded, "…the peak demand charges are comparatively low in the Pacific Northwest and were not found to be high enough to justify the integration of onsite solar and managed EV charging at this location."

Large operations, or cooperative agreements between smaller operators, may be able to negotiate pricing agreements with utilities that may largely remove them from the hour-to-hour demand pricing. There may also be incentives, grants, tax breaks or other offsets to the electricity demand pricing.

16 Grid Readiness and Market Penetration Realities

Market pressures to change the electric grid system related to any increase in market share for commercial battery electric vehicles may be fairly gradual. There are, today, roughly 2.5 million Class 8 commercial vehicles in use in the U.S. In 2014, the best production year between 2012 and 2017, the trucking OEMs produced approximately 200,000 new Class 8 trucks, 49,000 Class 7, 47,000 Class 6, and 305,000 Class 3, 4 and 5 combined [113]. Trucks tend to have long useful lives with minimum expectations of 10 years. The graph in Figure 51 illustrates, for example, that even if every new Class 8 vehicle produced by OEMs was a CBEV, it would take in excess of 15 years to fully replace the existing fleet with today's production capacity [112]. The growth in demand for and capacity to produce commercial battery electric vehicles may follow a traditional S-Curve as shown in Figure 52. This reflects slow fleet adoption in the early years of new technology, followed by rapid acceptance in later years. These two graphs illustrate that commercial battery electric vehicles market penetration may take years, giving infrastructure necessary lead time to evolve as demand grows. There may be exceptions to this trend, such as where regulators mandate rapid turnover of vehicle population in specific regions like Southern California.

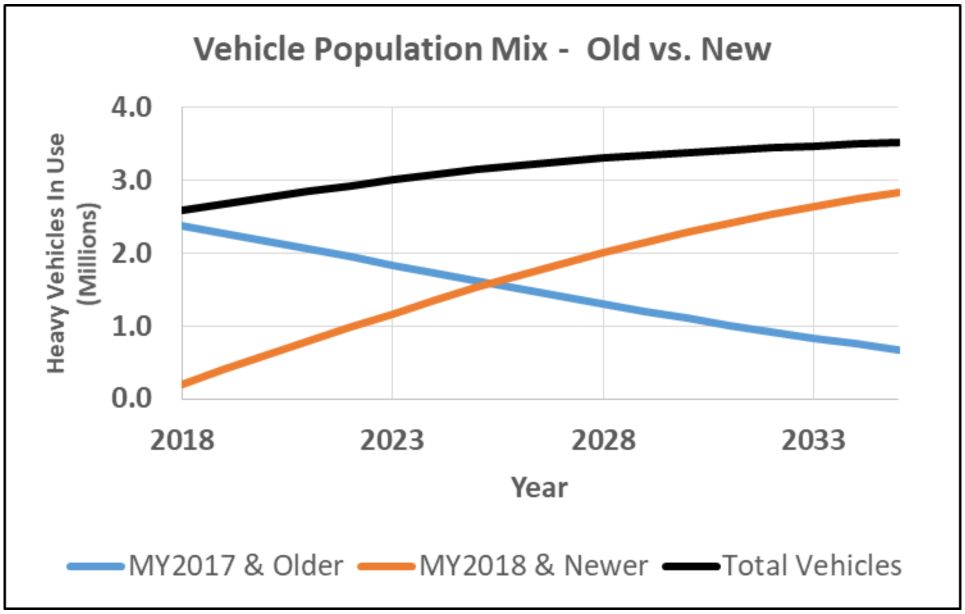


Figure 51. New Model Vehicle Market Penetration and Older Model Retirements (Mihelic) [112]

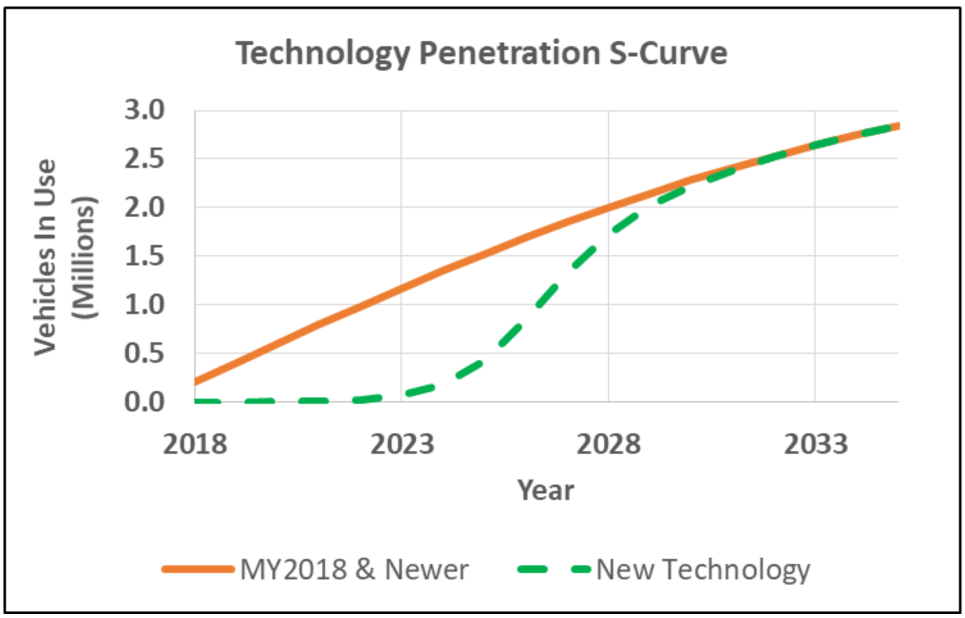


Figure 52. New Technology Market Penetration Representative S-Curve (Mihelic) [112]

Those regions with accelerated adoption of CBEVs may encounter a need for significant improvements in the regional electrical grid to accommodate the new demands placed by a high volume of CBEVs drawing power. Those types of infrastructure programs can be time and skilled-labor intensive, and may be the pacing items that moderate growth in use of electric vehicles.

17 ENERGY DELIVERY – GRID DETAILS

NACFE's interviews with fleets and industry groups have highlighted the need to understand what is meant by the electrical grid in discussions of electric vehicles. The phrase energy "grid" may be as nebulous as "the internet" or "the cloud" to visualize or describe in lay terms. The electrical system is composed of three main parts, generation, distribution, and transmission. The graphic in Figure 53 is a concise overview and includes key terms describing elements of the grid from a 2004 joint U.S.-Canadian Power System Outage Task Force investigating the causes of the 2003 blackouts in the Great Lakes region [119].

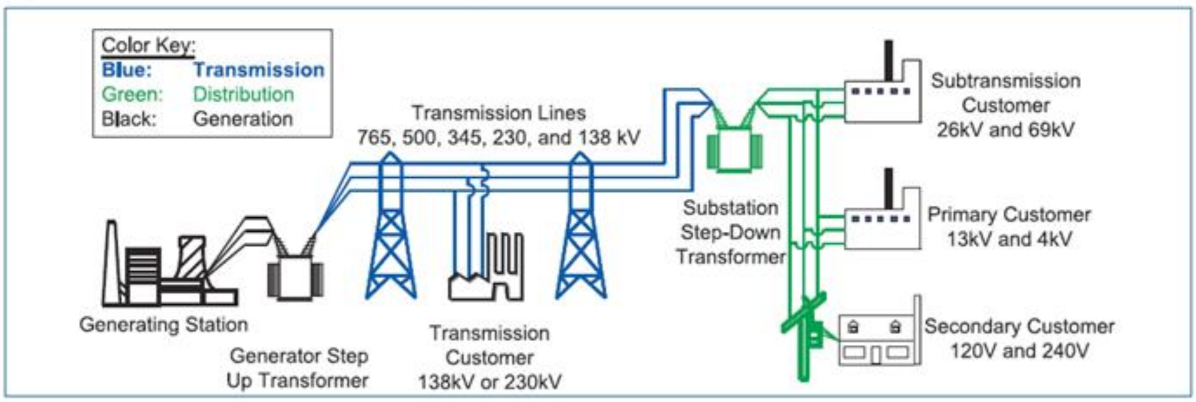


Figure 53. Basic Structures of the Electrical System (DOE/NRCan) [119]

Electric vehicle charging is a sub-element of the distribution part of the grid. Kellen Schefter of the Edison Electric Institute graphically describes this as shown in Figure 54, consisting of the electrical system from the transformer, through the meter, through the power panel, through conduits to the charging station and then into the vehicle [117]. These parts are described as Service Connection, Supply Infrastructure and Charger Equipment. As we will discuss, the dividing lines on responsibility for these elements may change in the future. The traditional breakdown would have the Utility responsibility end at the meter. The site owner would be responsible from the meter up to and including the charging station.

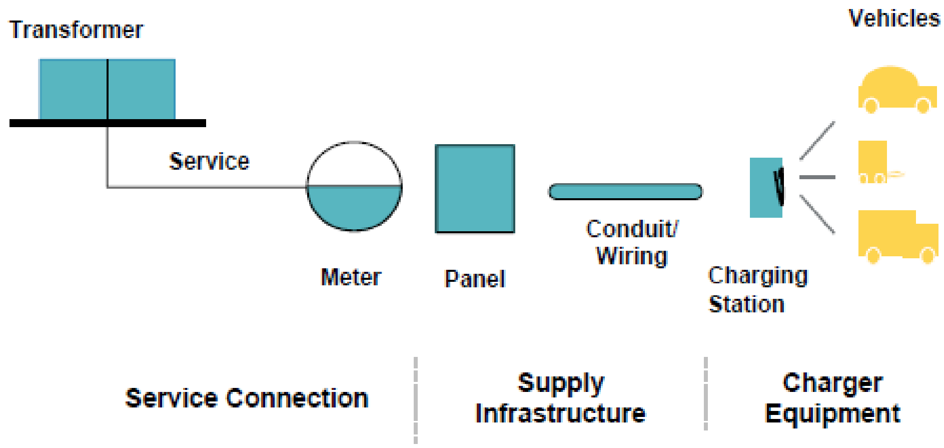


Figure 54. Vehicle Charging Infrastructure Defined (EEI) [116]

Schefter and others have presented that the evolving nature of the electric vehicle marketplace is creating opportunities to redefine the traditional business models for power distribution. Schefter presented three potential alternatives in a 2017 presentation shown in Figure 55, redefining where the utilities may step in to provide portions or the entire electric vehicle charging infrastructure [117]. This also suggests more innovative business arrangements may be possible, including third parties that step in with capital to create the post-meter system, with various usage rates that could remove the site owner from the complexity of managing part or all of the charging system.

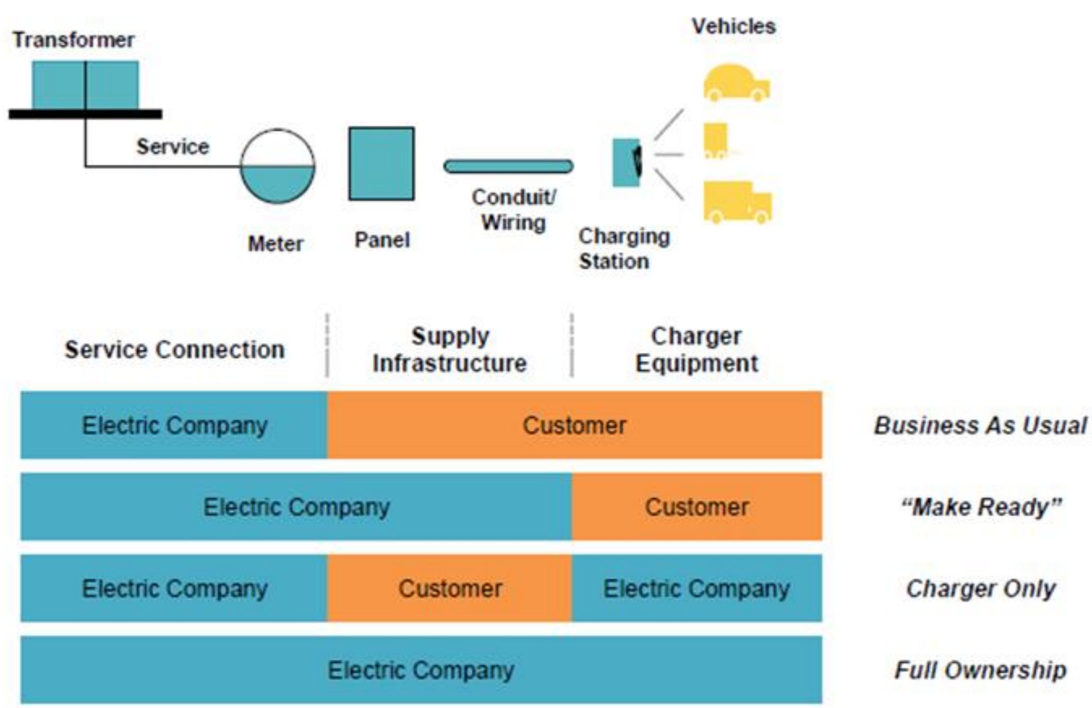


Figure 55. Some Charging Infrastructure Alternatives (EEI) [117]

Those third parties might include the vehicle manufacturers themselves. Vehicle purchase or lease arrangements for new electric vehicles may include agreement to install and manage charging systems for their customers.

17.1 Innovative Strategies for Delivering Power

The evolving electric vehicle marketplace is situated for significant business model innovation. Schefter presented two current examples of alternatives for charging infrastructure. The left image in Figure 56 shows the San Diego Gas & Electric Power Your Drive Program where the utility is providing the entire charging system infrastructure [118][121]. The right image in Figure 56 show Southern California Edison's Charge Ready program where the utility provides the infrastructure all the way to the charger, with the charger being the responsibility of the customer [118][120].

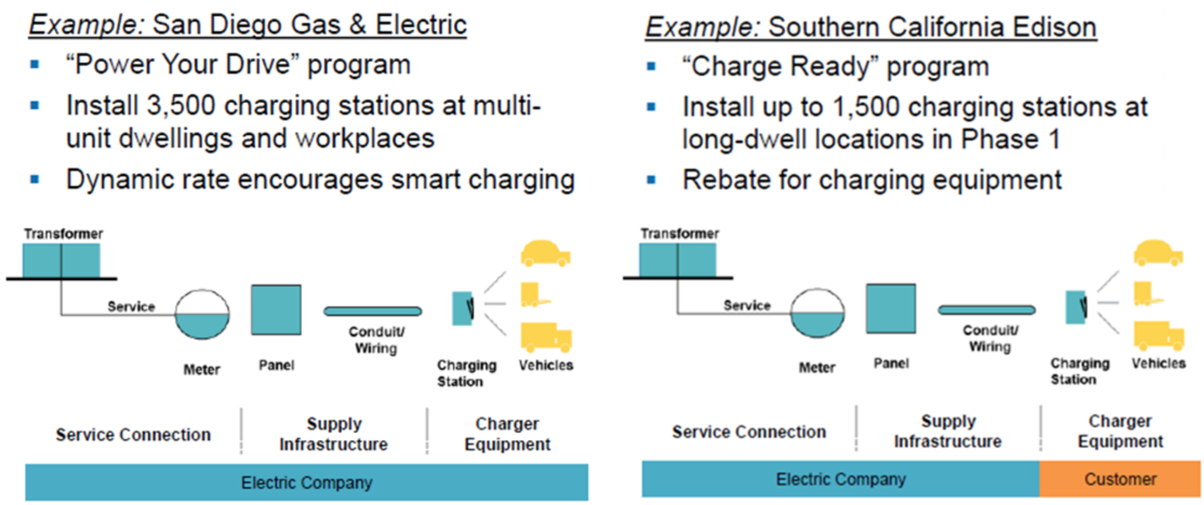


Figure 56. Two Examples of Alternative Charging Infrastructure Business Models (EEI) [118][120][121]

A key aspect of the utility providing the charging infrastructure is that the capital and operating overhead may be rolled into the kWh usage cost for the entire customer population. Having an entire community cover the costs for a specific site's charging infrastructure makes sense because the benefits from the CBEVs are common. The rationale suggested is that use of electric vehicles reduces air pollution, which promotes better health for everyone in the region (even when factoring in generation methods and vehicle manufacturing and salvage activities). More importantly perhaps is that the rationale suggests the use of electric vehicles reduces energy demand for a region (again, even factoring in generation methods and vehicle manufacturing and salvage activities). The improved energy use efficiency of electric vehicles versus other vehicle types then places downward pressure on energy costs by decreasing energy demand. A utility may rationalize that including the capital and overhead costs of a charging system installation at a specific site benefits the entire population served by the utility.

There are many possible future models for how to provide charging infrastructure beyond the traditional one that a site owner must install and manage their own system.

17.2 Charging Speeds

The charging rates currently possible and projected for automotive electric vehicles are described in a 2017 Department of Energy report titled Enabling Fast Charging and summarized in Figure 57 [116]. These may also apply to commercial vehicle systems. Level 1 is charging from 110V outlet. Level 2 is from a 220V outlet. These two are typical in residential and commercial sites. They are considered relatively slow, taking 35 hours for level 1 to charge for 200 miles of car range, and 7 hours for Level 2 car charging. This table assumes a car using 285 Wh per mile. Fast charging and Extreme Fast Charging (XFC) are needed for quicker charging times. XFC systems are not in production as of this report.

	Level 1 (110V, 1.4 kW)	**Level 2** (220V, 7.2 kW)	**DC Fast Charger** (480V, 50 kW)	**Tesla SuperCharger** (480V, 140 kW)	**XFC** (800+V, 400 kW)
Range Per Minute of Charge (miles)	0.082	0.42	2.92	8.17	23.3
Time to Charge for 200 Miles (minutes)	2,143	417	60	21,	7.5

Figure 57. Charging Infrastructure Capabilities (DOE) [116]

17.3 Solar, Wind and Green Energy

Commercial battery electric vehicle charging is no more tied to any one particular source of energy than the diesel pumped is tied to the country of the oil's origin or the process of extracting the oil from the ground. The grid delivers power to the charger, the origin of that power can be complex. An analogy is turning on your kitchen faucet for a glass of water – that water is likely the composite of a range of sources and processes, even though you are buying it from just one delivery service, your city water department.

A CBEV cannot distinguish the source of the energy coming from the charger. Well-to-wheel analyses are challenging because that energy could originate from many different sources that include coal, natural gas, solar, wind, geothermal, hydro, nuclear and others. Energy brokering has made this even more complex, such that a company can direct their utility to purchase green power from sources far away through use of Energy Attribute Certificates (EAC). Schneider Electric's Renewable Choice Energy describes that, "An EAC verifies that one megawatt hour (MWh) of renewable electricity was generated by a clean power facility and added to the electric grid. When the electricity is generated, an EAC is created simultaneously in a 1:1 ratio. Once renewable electricity joins the grid, there's no way to accurately track it. Organizations that own EACs in a corresponding volume to the amount of purchased electricity consumed are assured that the equivalent volume of green power was generated [201]." This is a very complex subject outside the scope of this report. For insights into this, see Schneider Electric's Renewable Choice Energy website to download their white paper, The Definitive Guide to Global Energy Attribute Certificates for Commercial, Industrial, and Institutional Buyers [202]. Rocky Mountain Institute's Renewables Center is one group helping connect energy users with green energy providers [204].

Solar panels installed on a vehicle can assist in CBEV battery range extension by helping charging during daytime activities. The development of flexible, durable solar panels capable of conformal mounting on tractor sleeper roofs and on trailer roofs is increasing market penetration for on-board solar systems for diesels as well as CBEVs. Details on available systems and potential are described in new NACFE Truck Solar on Tractors and Trailers Confidence Report [203].

17.4 Charging Connector Types

The diesel fuel pump pipe diameter and basic pump handle shape was normalized some time ago. Automotive diesel tank necks are sized for diesel pumps, and gasoline ones generally do not fit. For electric vehicles, there are a number of competing charging station connector types in the world. This is somewhat similar to what a traveler experiences trying to plug in portable devices like phone chargers or hair dryers to wall outlets across the world, needing an adapter kit and accepting different regional operating parameters. Complicating this is that charging electric vehicles can also be done by inductive methods located in pavements. One example of a charging station and connection is shown in Figure 58 [151].

Figure 58. Example Electric Charging Station and Connection (ChargeHub) [151]

The European Union is evolving standards under the International Electrotechnical Commission (IEC) under standards IEC 61851 Electric Vehicle Conductive Charging System and IEC 62196 Plugs, Socket-Outlets, Vehicle Couplers and Vehicle Inlets 104][105][108]. The U.S. is evolving under the Society of Automotive Engineers standard SAE J1772 SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler and various other commercial products from Tesla [107][108]. In the case of future heavy-duty commercial CBEV fast charging systems, connector designs may only be concepts at this point. The Chanje Class 5 Model V8070 and Mitsubishi Fuso Class 4 eCanter use the SAE J1772 [152][153]. The eCanter also uses the CHAdeMO connector [152]. The variety of automotive connectors are illustrated in Figure 59.

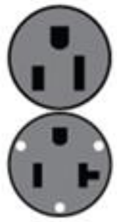
Connectors		Level	Asian Makes	US / EU Makes	Tesla
Wall outlets (Nema 515, Nema 520)		1	With adapter	With adapter	With adapter
Port J1772		2	Yes	Yes	With adapter
Nema 1450 (RV plug)		2	With adapter	With adapter	With adapter
CHAdeMO		3	Yes	No	With adapter
SAE Combo CCS		3	No	Yes	No
Tesla HPWC		2	No	No	Yes
Tesla supercharger		3	No	No	Yes

Figure 59. Charging Connector Types (ChargeHub) [151]

Asian: These vehicles use the CHAdeMO connector standard. Nissan Leaf, Mitsubishi i-Miev, Fuso eCanter etc.
American / European: These vehicles use the SAE Combo CCS standard: .Chevrolet Volt, Chevrolet Spark, BMW i3, Mercedes, Volkswagen, Chanje, Fuso eCanter, etc.
Tesla: Tesla uses its own Tesla connector standard. Model S and Model X.

Standardizing connectors may eventually occur for regional marketplaces as one configuration wins significant market share advantage over others. In the near term, commercial vehicles may be developed with several adapters to deal with various charging station constraints, or forced to use proprietary connections and be limited to proprietary charging stations. The connector choice may not be an issue for fleets with only one CBEV model and with dedicated A-B-A type routes where the vehicle only charges from its home base. Where that fleet may be using competing CBEV models from different manufacturers, but wanting to use the same charging system, there may be need for adapters. This situation is somewhat akin to needing to have diesel, gasoline and natural gas systems to support today's existing mixed fleets.

18 BATTERIES

Just as a diesel engine is the core technology for an internal combustion engine (ICE) vehicle, the battery is the core technology for the CBEV. Diesel engines have become more efficient over time through continuous development. Batteries similarly are undergoing continuous improvement.

18.1 BATTERY TYPES

The Department of Energy 2016 Advanced Batteries 2016 Annual Report provided this graphic in Figure 60 showing a 2012 baseline of $600/kWh, 100 Wh/kg, 200 Wh/l, and 400 W/kg. The DOE has had a target since before 2012 for commercial viability of CBEVs in 2022 of $125/kWh, 250 Wh/kg, 400 Wh/l, and 2,000 W/kg. NACFE's interviews with industry experts confirm confidence that these targets are feasible based on the history of significant battery development to date [115][123].

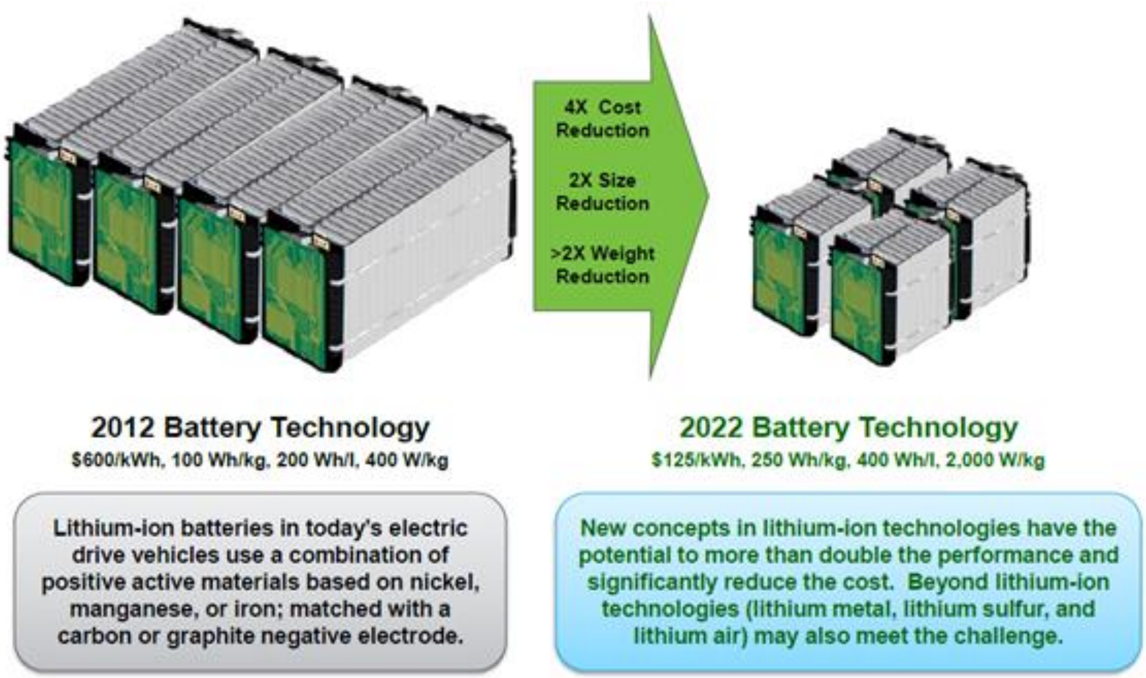


Figure 60. Baseline and 2022 Targets for Commercially Viable EV Batteries (DOE) [115][123]

The California Air Resources Board has summarized battery development in their 2015 Technology Assessment: Medium- and Heavy-Duty Battery Electric Trucks and Buses [122]. CARB highlights the factors considered in battery design include:

- Energy-to-weight ratio, or specific energy (gravimetric energy density), which reflects how much energy is available in watt-hours per kilogram of battery weight (Wh/kg);
- Energy-to-volume ratio, or volumetric energy density, which is similar to specific energy but addresses how much volume will be taken up to provide the needed energy in watt-hours per liter (Wh/L);
- Specific power, which reflects the amount of current that can be provided (W/kg)

• Expected lifetime of the battery, both calendar life and charge cycles;
• How long it takes to recharge the battery and whether fast charging can be employed;
• Specific temperature management requirements (heating or cooling); and
• Battery safety, both in-use (thermal runaway potential) and disposition at the end of its useful life in vehicle operations.

18.2 Battery Degradation Rate

CARB also discuss that battery capacity tends to decline with age and number of recharging cycles. Temperatures also affect battery lifetime capacity. The target stated in a number of BEV source documents is that for vehicle batteries, the target useful life is 80% of original capacity.

The 80% capacity threshold for replacing a CBEV's batteries can be a concern for fleet buyers. An analysis of battery history highlights that the 80% life needs to be put in context of other factors, making it somewhat less of a concern. For example, the design life target for the Smith Electric Newton, and the Navistar eStar trucks was 10 years. The expected mileage of 10 years of use with various daily range averages is tabulated in Figure 61.

Average Miles per Day	10 Year Vehicle Life Miles (5 Days/Week, 50 Week/Year)	10 Year Life Recharging Cycles (1 recharge per work day)
50	125,000	2500
100	250,000	
150	375,000	
200	500,000	
250	625,000	
300	750,000	
350	875,000	
400	1,000,000	
450	1,125,000	
500	1,250,000	
550	1,375,000	
600	1,500,000	

Figure 61. Lifetime Mileage and Recharging Cycles Estimates (NACFE)

A battery would need to decrease charging capacity at a rate of 0.008% per charge for it to be at 80% of its original capacity after 2500 cycles and 10 years. Actual degradation history for production electric commercial vehicles is slim at present, but there is a statistically significant volume of field data on production electric cars. Maarten Steinbuch has tracked field data on Tesla car battery degradation from Tesla user forums and posted his analysis [124]. The graph in Figure 62 shows the range loss as the vehicles accumulated mileage. The trend curve shows that at 200,000 km (124,000 mi) to 250,000 km (155,000 mi) of use, the battery packs are still above 90% of the original range capacity. The data also shows that there are vehicles with poor performance in under 50,000 km (31,000 mi). This might be considered in terms of the typical infant mortality that products have, modeled traditionally as a "bathtub" curve where products see significant failure rates at the start of life or near the end as shown in Figure 63 [125]. This will be discussed in more detail in the section titled CBEV Learning Curve.

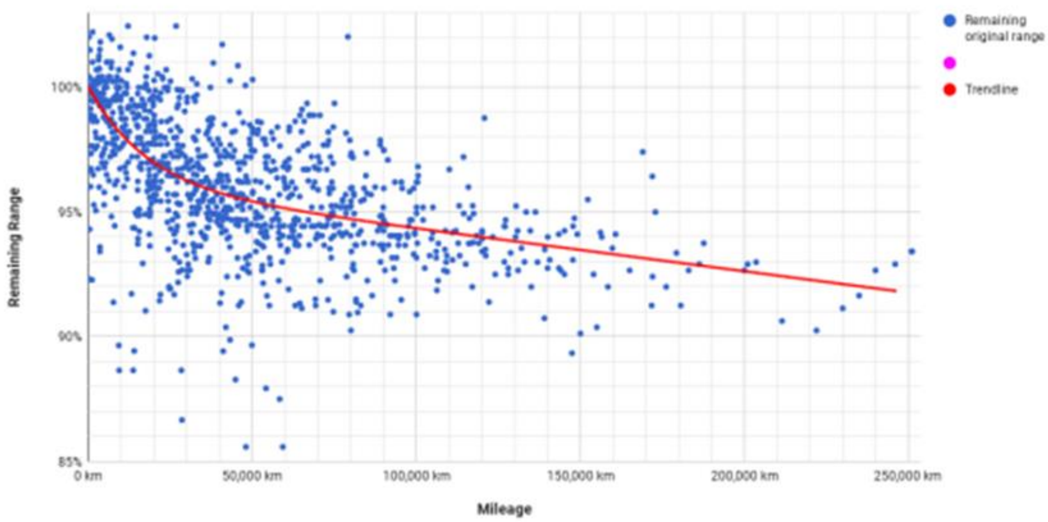


Figure 62. Automotive Battery Range Degradation over Lifetime Use (Steinbuch) [124]

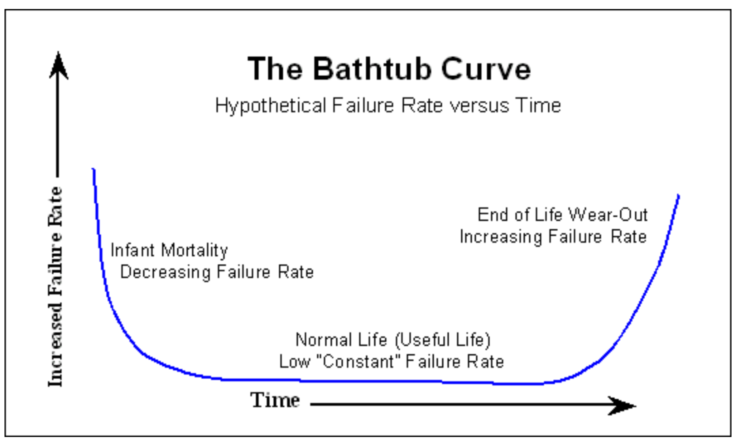


Figure 63. Typical Product Reliability "Bathtub" Curve over Time (Reliasoft) [125]

Edmunds in a 2013 evaluation of the total cost of owning hybrid cars states, "Toyota, for example, reports that its battery packs have lasted for more than 180,000 miles in testing. A large number of Ford Escape Hybrid and Toyota Prius taxicabs in New York and San Francisco have logged well over 200,000 miles on their original battery packs and are still running well [157]."

The experiences with the Smith Electron Newton by Frito-Lay since 2011 from NACFE interviews supports that for their duty cycles, with a fleet of approximately 400 vehicles, the majority of the battery systems will survive a 10 year vehicle life at multiple U.S. locations. They did see also infant failures with systems, as did fleets experimenting with the Navistar e-Star. Consider this as not unusual in light of any new vehicle model introduction where new technology is involved.

The 80% of original capacity threshold is also an opportunity for capturing residual value for these batteries. While the automotive industry will discard batteries at that point, the 80% life still represents a significant capability. Market innovators are reviewing second life opportunities for salvaging and repurposing batteries into other uses along with electric motors and other parts of CBEVs. NACFE interviews highlighted that these components may carry a premium in the salvage market for reuse in home energy storage systems, farm stationary equipment operations, and other applications.

All BEV battery designs are not the same, even from the same vehicle manufacturer. An example of this may be comparing the field history of two Nissan LEAF BEV automobile battery capacities. Battery life data has been collected from owners of the Nissan LEAF between manufactured between 2011 and 2017 by a group of New Zealand researchers [205]. This report is not yet peer reviewed.

These batteries came in 24kWh and later 30 kWh variants. While the exact design life is likely proprietary information, Nissan warrantied, for example, the Model Year 2015 lithium-ion battery first for manufacturing life defects (96 months or 160,000km, whichever comes first), and then for battery capacity (60 months or 100,000 km, whichever comes first). The capacity coverage "warranted against capacity loss below nine bars (of twelve) of capacity as shown on the vehicle's battery capacity level gauge…[206]."

The New Zealand researchers collected state of health (SoH) 1,382 data points from 283 LEAFs manufactured between 2011 and 2017 [205]. The report documents the rate of decline for the two battery pack versions. This is important to the New Zealand car market where many battery electric vehicles are purchased as previously used vehicles from other countries. The report concludes that the 24 kWh battery decreased capacity at a rate of 2.9% in the first year and 3.1% in the second year. Figure 64 shows the majority of the 24kWh pack reported data exceeded the 5 year life capacity warranty goal, although there were vehicles that were between 70-80% at five years. The newer 30kWh battery pack data only covers two years of production and the data shows anomalies for which the authors did not have definitive explanations. Root causes may be due to a variety of reasons, including anomalous tracking software, sensors, infant design issues not yet corrected, unexpected duty cycles, and/or analytical issues. Warranty life is estimated statistically, with an expectation that some parts will not meet their target life. This is why vehicles have warranties - an investment/bet by the manufacturer that the design will meet its goal, and insurance for the buyer that if it doesn't, it will be repaired at the manufacturer's expense.

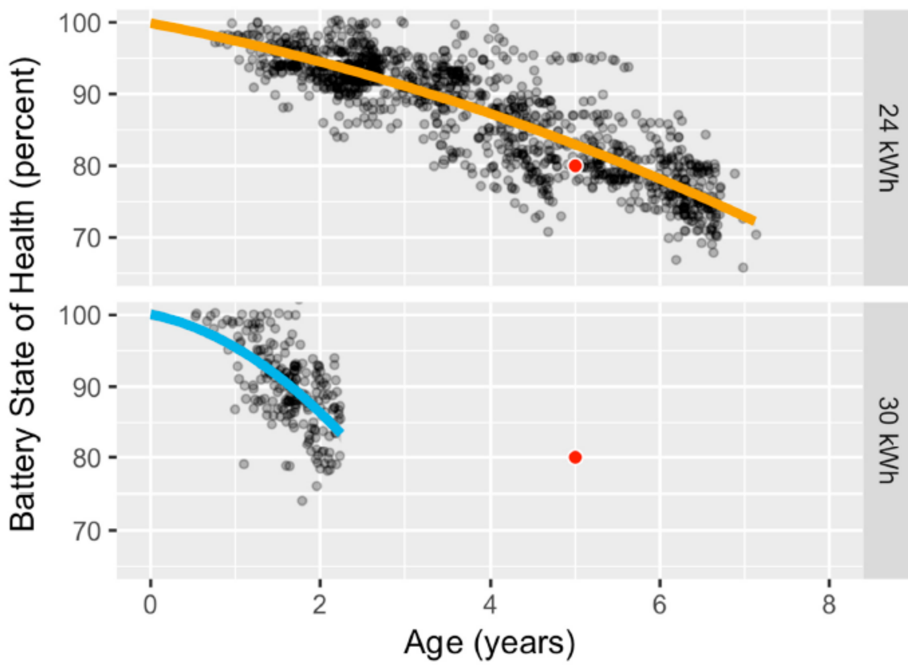


Figure 64. Sampling of Nissan LEAF Battery Life (Myall) [205]

This example perhaps highlights an industry truism that not all batteries are the same. The 24 kWh data shows that a manufacturer can design a product to a stated warranty goal, but there will be vehicles that do not perform, for a variety of reasons, to statistical expectations.

18.3 Battery Basics

The 2015 CARB Technology Assessment describes the basics of batteries in a succinct manner [122]. CARB investigated six battery chemistries, concluding that for the near term, lithium-ion batteries are "the most likely to be used in zero-emission medium- and heavy-duty truck and bus applications [122]." Their conclusion is consistent with a number of reports from investment research groups, university and private technology researchers and public agencies in Europe and North America [3][4][32][126][127][128][129][130][131]. There are several permutations of lithium-ion systems and researchers have demonstrated sustained improvements over time. Details of the various chemistries and construction of batteries can be researched through the references cited in this report. The ICT graph shown in Figure 65 from a 2011 ICT/DELFT study is indicative of the trends, although somewhat dated in an industry seeing significant research and improvement each year.

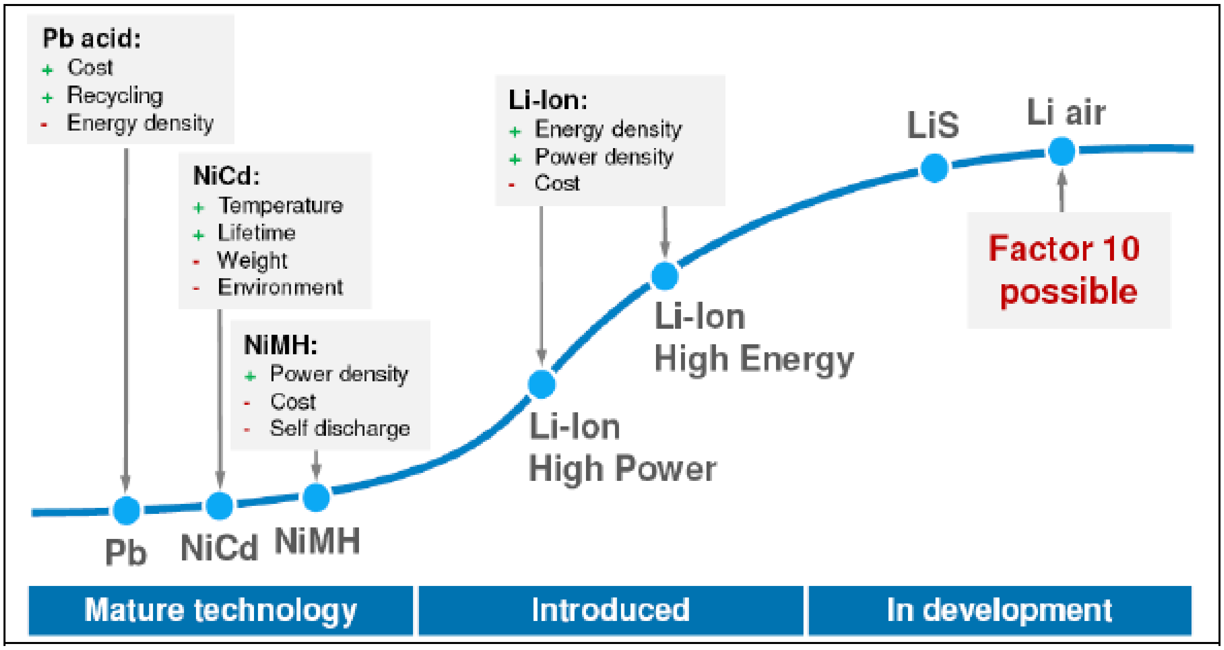


Figure 65. Battery Technology Roadmap presented in 2011 (ICT/DELFT) [130]

A more recent 2017 MOBI Research Group paper published in Energies highlights a variety of lithium based technologies currently in development and the near term lithium battery roadmap shown in Figure 66 [131]. They conclude that "other types, such as sodium-ion, zinc air, lithium-air are still in a very early phase" so were not included in the roadmap.

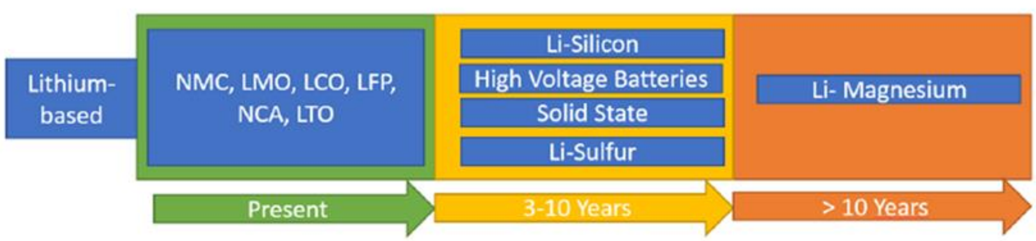


Figure 66. Battery Technology Roadmap presented in 2017 (MOBI) [131]

This report characterizes the "present" competing lithium-based technologies by their energy density, cost and lifetime as shown in Figure 67.

Cathode Material	Energy Density (Wh/kg)	Cost	Lifetime
$LiCoO_2$ (LCO)	546	Medium	Medium
$LiMn_2O_4$ (LMO)	410–492	Low	Low
$LiNiMnCoO_2$ (NMC)	610–650	High	High
$LiFePO_4$ (LFP)	518–587	Medium	High
$LiNiCoAlO_2$ (NCA)	680–760	High	Medium

Figure 67. Present Lithium Based Battery Technology Characterized (MOBI) [131]

As volumes of commercial vehicle grade battery systems enter production, researchers will have both manufacturing and in-use field data to guide research and development. Mass production generally brings with it cost reduction. Mineral mining and salvage will determine supply capacity that will also factor into the growth path for these technologies.

19 Battery Electric Vehicle Learning Curve

NACFE's interviews with fleets that have deployed electric commercial vehicles identified a key lesson learned by all is to moderate early expectations when deploying new technology. All fleets interviewed experienced learning curve issues when initially deploying vehicles. This was consistent with their comments on initial deployment of natural gas engines. Similarly, any new diesel engine technology that is significantly different from a prior year's such as 2007 and 2010 engines has typically had challenges to meet early expectations. The message these fleets told NACFE is that drivers, maintenance staff, and managers need to restrain their judgment of new vehicle technologies until past the initial learning curve. New designs experience the harsh real world conditions when introduced to the field. Technologies proven in lab environments and limited field tests encounter combinations of issues when in real world use. They see conditions and operations previously not expected by designers. Also, all designs are a tradeoff between cost, schedule and requirements. Zero failure rates are rare in any industry. This is why vehicles have warranties, and why fleets see failure rates. Failures are one way designs improve as they mature, the causes are investigated, lessons learned, designs and operating practices are improved.

20 CBEV Warranties and Parts

The battery electric vehicle has fewer moving parts than an equivalent diesel one. Thor, a CBEV manufacturer, states, "You go from a vehicle with 2,000 moving parts to fewer than 20, so maintenance is cheaper [173]." Friction is a leading cause of repair and maintenance work. The hope then is that electric vehicles are inherently more robust and should see less repair and maintenance downtime. There is, however, very little concrete evidence to evaluate this at present. A small volume of electric commercial vehicles have some field history spanning a few years of use. Some of these early vehicle model manufacturers have gone out of business, leaving the vehicle owners to arrange to maintain and service the units themselves. Others never progressed past prototype testing, where the vehicles were known to be pre-production quality and needing special handling. Current testing of drayage units and urban delivery units may fall in this category as well. Answering whether CBEVs have less downtime and maintenance and repair will be resolved in due course of production vehicles seeing significant mileage and time. Until then, the field history on electric buses and on electric cars provides some insight on the question.

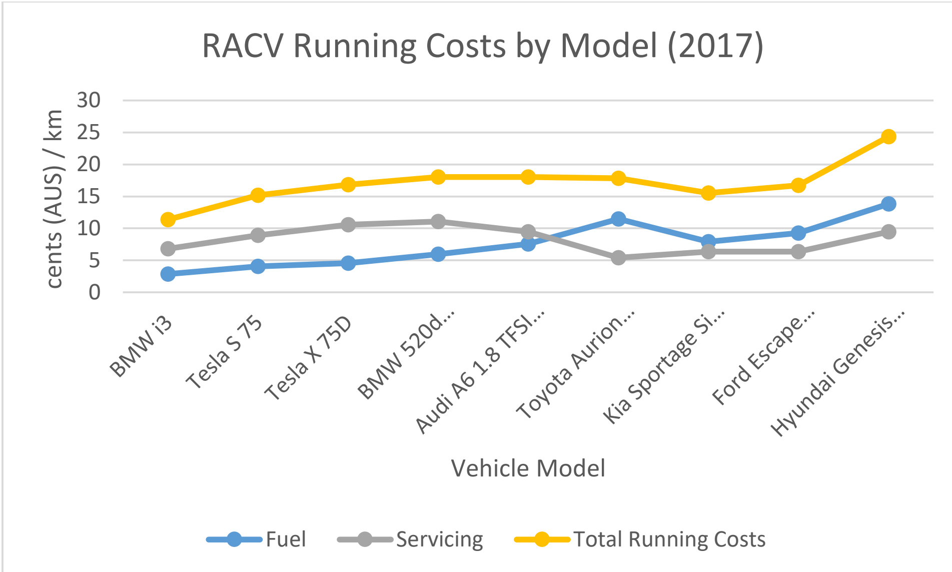
Consumer Reports reviewed battery electric car owner feedback and assigned "average" for the 2014 Model S, "below average" for the 2015 Model S, "average" for the 2016 Model S, and "its first above average" rating for the 2017 Model S [131][132][133]. These ratings were based on survey feedback from 1,400 to 1,500 owners each year. Some caution is needed since survey data is a measure of customer perception and recollection, not physical measurements of actual warranty claims and or repair records. For background, see Consumer Reports FAQ [134]. The same survey processes are reportedly used for all comparable vehicle models.

Consumer Reports' director of automotive testing stated in a CNBC interview about the 2016 rating said, "In terms of any new or redesigned vehicles, we often see a tumble on reliability." He continued, "As the years go by, we always see reliability continue to improve as companies work out bugs and design issues [133]." "The fact that the Tesla Model S is average at all, is impressive, considering the short life of this company, when you have automakers such as Fiat Chrysler unable to make very conventional cars reliable, the fact that the Tesla Model S is average is a very impressive feat."

The Royal Automotive Club of Victoria (Australia), an organization with 2.1 million members, maintains a Car Running Costs database evaluating the total cost of ownership of cars and SUVs, including electric and hybrid models. The data includes service and repair cost expectations based on the following methodology:

> *"This comprises two costs: the cost associated with regular servicing and the cost of unscheduled servicing and repairs.*
>
> *Standard service parts and labour times follow the owner's handbook schedule and services are performed using only original equipment parts. The manufacturer-specified service intervals for time or distance are used, whichever comes first. Where available, fixed or capped-price service programs are adopted.*
>
> *Unscheduled servicing and repairs incorporates a number of common replacement parts including parts that experience wear and tear due to normal use of a vehicle. For example, brake pads and rotors, windscreen wipers (assumed to be replaced yearly) and a battery are included. Windscreens are commonly damaged as a part of normal driving and so their replacement cost is also included.*
>
> *Standard labour times as specified by the vehicle manufacturers are used for each service and for the replacement of unscheduled replacement parts.*
>
> *Parts prices are sourced from the vehicle manufacturers as the most up-to-date information. Windscreen and battery prices are sourced from RACV Windscreens and RACV Batteries or the manufacturer when needed.*
>
> *Labour rates have been averaged from a survey of metropolitan service centres. The average labour rate is varied for each manufacturer [137]."*

The RACV data for 2017 states that service costs summarized in the table in Figure 68.



Units	Factor	BMW i3	Tesla S 75	Tesla X 75D	BMW 520d (2.0 l turbo diesel w/8sp automatic)	Audi A6 1.8 TFSI (1.8 l turbo w/7sp automatic)	Toyota Aurion (3.5 l w/6sp automatic)	Kia Sportage Si AWD (2.0 l turbo w/6sp automatic)	Ford Escape Ambiente (1.5l turbo w/6sp automatic)	Hyundai Genesis (3.8 l w/8sp automatic)	Average
cents (AUS) /km	Fuel	2.84	4.07	4.58	5.96	7.56	11.5	7.94	9.28	13.85	7.51
	Tyres	1.74	2.18	1.65	1.01	1.01	0.92	1.19	1.09	1.01	1.31
	Servicing	6.82	8.91	10.58	11.09	9.45	5.4	6.37	6.35	9.47	8.27
	Total Running Costs	11.4	15.16	16.81	18.06	18.03	17.83	15.51	16.72	24.34	17.10

Figure 68. Automobile Running Costs (RACV 2017) [137]

The RACV estimates of running costs show that the electric vehicles service costs, the gray line in Figure 68, at this time in the Australian market may not significantly differ from comparable diesel or gasoline models. The table also suggests that net operating costs including fuel (energy), tires and service in the Australian market are better than comparable diesel or gasoline cars. The comparisons not shown, but also included in the RACV data are other factors such as purchase price, insurance, residual value, etc. [137]

21 Service Skills & Infrastructure

Troubleshooting and repair of electric commercial vehicles will change the shop skill sets, with a greater emphasis on software and electronics than on mechanical skills, although both will still be required. Vehicles will have elements of traditional trucks on new electrical ones, such as braking systems, heating and air conditioning systems, sensors, lighting, tires and wheels, trim, dashboards, safety systems, wipers, glass, mirrors, etc. What will change is that emissions systems, fuel systems, DEF systems, engine, accessory drives, etc. will likely be completely removed from shop work on electric vehicles. However, most shops will continue to have significant volumes of diesel support work well past the next decade, as discussed under Mixed Fleets and also previously discussed regarding the transition involved with commercial vehicle population turn over.

Emissions systems were identified as the most significant reason for vehicle downtime in the 2017 Heavy Duty Trucking Fact Book as shown in Figure 69 [136]. NACFE interviewees observed that electrical/wiring ranked sixth, a factor present in both diesel and electric vehicles.

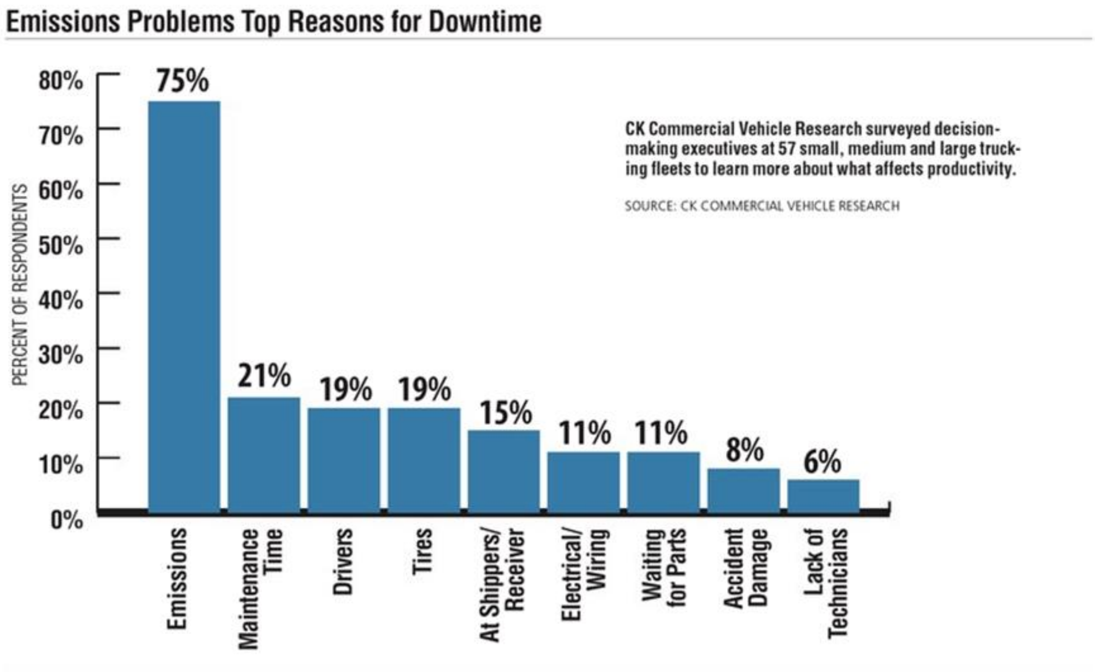


Figure 69. Top reasons for Down Time in 2017 (HDT) [136]

The transition to electric vehicles may highlight shortages of experienced service locations. While electric vehicles may be equipped to a degree for remote diagnostics and system updates as seen with electric cars, physical issues not solvable through software will still occur. Simply running out of charge may require a tow back to the base facility as adequate charging may not be possible mid-way on a route, or at a remote destination. Remote servicing will be a concern, somewhat similar to that seen when wide base tires were introduced and roadside service was not yet universally available. Natural gas powered commercial vehicles have also had this risk, as not all service centers are equipped for natural gas servicing. Servicing infrastructure availability may be a factor in operational deployment of electric commercial vehicles. Outsourcing electric vehicle service is an option. Bill Dawson, Vice President of Maintenance and Engineering at Ryder, stated in a 2017 HDT article, “Vehicle technology continues to become more complex as diagnostic tools and telematics integration is making it difficult for fleet operators to keep pace. The required investments in shop technology and technician-training resources are just some of the factors driving the marketplace to make the decision to outsource. Many fleet operators faced with the decision to invest in these areas are finding that it’s not their core competency [195].” Jim Johnston, PepsiCo Fleet Reliability Manager, reinforced this at the March 2018 TMC event, saying, “About 10% of PepsiCo’s fleet is either plug-in electric or electric hybrid.” He said the company’s experience overall with electric vehicles “has been positive for the technician.” However, “the challenges have been emerging technology and making sure that we remain current with our diagnostic software, training and configuration of the vehicle.” He also stressed that trucks run on software. “The modern vehicle is no better or worse than the software that is controlling it.

Consequently, if a technician has a truck with a problem and they pull it in the shop and the first thing they do is go grab their wrenches and open the toolbox, they went the wrong direction. They need to go get the laptop and plug in to the truck [197].”

22 Mixed Fleets

Feedback during fleet interviews is that the business focus on efficiency has led several companies to optimize vehicle selection based on each specific duty cycle used in the company. This has led some companies to endorse having mixed technology fleets rather than a one-size-fits-all approach to vehicles. These decisions are driven by careful evaluation of the total cost of ownership and return on investment. The trend may not be true for all fleets, but it does reflect a modern trend toward specialization for product mixes. Henry Ford’s original concept that you can have any color you want as long as its black has given way to the ability to extensively optimize product selection based on duty cycles. Countering this trend, to some degree for electric vehicles, is that these new technologies may initially have limited option choices to focus on securing reliable performance and minimize introduction costs.

Choices of battery pack and motor sizes may be limited in early production models of CBEVs. Range or operational limitations may dictate that a CBEV is chosen for urban delivery routes, while a diesel may be selected for cross country runs. Natural gas, fuel cells, diesels, hybrids, turbines, electrics, etc. may each be optimized for specific duty cycles, and may be less well suited in others. This is true today with diesel on-highway where the tractors are optimized for the length of the highest volume sleepers when mated to aerodynamically equipped 53 ft. long dry van trailers. As the operations diverge from those optimum points, performance can decrease [61][63].

23 Soft Costs/Soft Benefits

Fleets requested that NACFE help expand traditional capital budgeting to include more factors to help in making business cases for electric vehicles. Total Cost of Ownership, or TCO, is not rigidly defined and may not be the all-inclusive term “Total” would indicate. Conventional cost accounting for capital budgeting includes generally readily quantifiable factors as shown in Figure 70 from EPA’s “An Introduction to Environmental Accounting as a Business Management Tool: Key Concepts and Terms” [143][144].

Conventional Costs

- Capital equipment
- Materials
- Labor
- Supplies
- Utilities
- Structures
- Salvage value

Figure 70. Conventional Cost Accounting (EPA) [143]

Richard Macve summarized ROI decision-making in a 1997 National Academies paper as, "For economic decisions, what matters is how costs will change as a result of each decision. Therefore the concern is whether the extra costs are justified by the extra revenue or other benefits that result [146]." In essence, investment decisions compare the difference between a baseline system and a new system. While the factors in Figure 70 may be precisely quantified, they omit other less well-defined costs and benefits. Allen White of the Tellus Institute in a 1992 paper proposed that a more comprehensive methodology was needed, described as Total Cost Assessment (TCA). White delineates costs in four tiers, as shown in Figure 71.

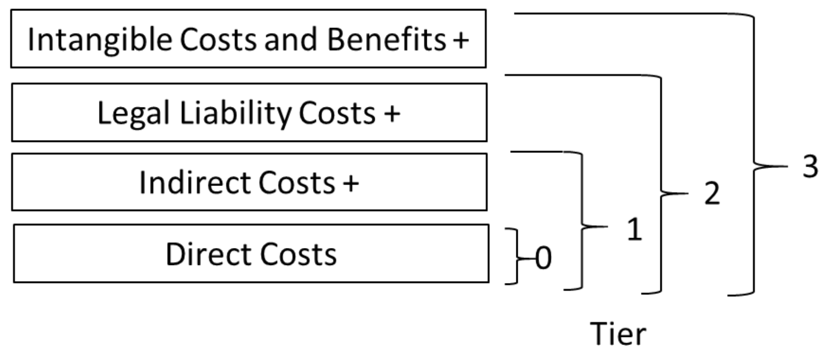


Figure 71. Total Cost Assessment Tiers (adapted from White/Macve) [145][146]

Macve states, "Conventional accounting systems and evaluation procedures measure the indirect costs at Tier 1 but suffer either from not tracing these costs to processes and products or from allocating them arbitrarily, distorting their relevance. Tiers 2 and 3 may not be recognized at all." Tier 3 costs and benefits are sometimes referred to as "soft," a term that reflects accounting insecurity as they may be estimations.

Tier 0 and 1 cost parity between diesel powered vehicles and CBEVs may exist for Class 3 to 4 vehicles at present or in the near future. Class 5 through 8 cost parity using just Tier 0 and 1 costs may take a decade. Including Tier 2 and 3 costs and benefits may shorten that estimate. Noise abatement is one example of Tier 2 and 3 costs and benefits that can influence cost parity calculations between diesel and battery electric vehicles.

Göran Nyberg, President of Volvo Trucks North America, said in a 2018 CCJ interview, "By using electrically powered and quieter trucks for goods transport in urban areas, we meet several challenges simultaneously. Without disturbing noise and exhaust gases, it will be possible to operate in more sensitive city centers. Transport may also take place throughout less busy periods, for example in late evening and at night. This will reduce the burden on the roads during daytime rush-hour traffic, allowing both the road network and vehicles to be utilized far more effectively than today [138]."

Trucks.com reported that KTH Royal Institute of Technology testing of specially equipped quiet Scania and Volvo vehicles in Sweden "… found use of quiet-running electric urban delivery and distribution trucks made nighttime deliveries feasible in crowded central Stockholm. Because the trucks didn't have to deal with daytime traffic, assignments typically were completed in a third of the normal time [141][142]."

The study authors saw that "transportation efficiency is improved from several perspectives compared with daytime deliveries. The speed of the consolidated truck was on the average driving 31% faster during off-peak hours than morning peak hours. The average network speed is almost 60% higher during off-peak hours than during afternoon peak hours. The measurements also showed a decrease in fuel consumption during off-peak operation compared to daytime operation, as well as longer service times during daytime." They conclude, "…that the benefits from off-peak deliveries exceed the costs [142]." While off-peak delivery is not limited to any one powertrain, the battery electric truck is uniquely well suited due to its quiet and emissions free operation.

Localities that have strict noise abatement or emission limitations may make diesel or gasoline based systems unviable. This may occur through ratcheting up emissions standards to a point that a compliant internal combustion engine is too costly to develop. The ROI on a new vehicle in these situations changes from cost comparison of A vs. B of two competing technologies, to only allowing B. The discussion here shifts to how to rationalize all costs and benefits so the net has a positive return. There is a cost to not making an investment, called "opportunity cost." It is the lost revenue of operating in the noise-abated market versus not operating. Other "soft" factors here may include lost opportunities to improve corporate image, losses from reduction in word-of-mouth sales, etc.

Grants, tax breaks, etc. may be required elements of the ROI evaluation. Placing dollar values for driver satisfaction, driver learning curve, etc. may also be needed. Reliability needs to be factored in, not just the warranty costs of parts and labor, but also the net impact of vehicle downtime to operations. Replacing a $1 part via a service bay visit may take a truck out of service for 8 hours or more, may cause late delivery fines, or cancellations. Those delays may impact driver's ability to complete a week's work load. That lost opportunity cost needs to be factored in the Total Cost of Ownership calculations.

Methods to value flexibility—the capacity to integrate the vehicle into future operations and environments—may be needed. For example, adjusting torques or braking on traditional diesel vehicles has involved mechanical servicing. An electric vehicle may be adjustable via cloud based software commands, over the air (OTA), with no interruption to the driver's schedule. As connectivity improves between infrastructure and vehicles, and between vehicles, electric vehicles may have an easier time adapting. Ways to value that ease in terms of dollars are needed. The ability to take advantage of a future technology by uploading new software versus not being able to take advantage has some quantifiable measure. There is value to predictive maintenance and monitoring on electric vehicle drivetrains to identify issues via software before they cause downtime. Fixing all of the fleet at one time through a software update, versus scheduling service bay visits for each, also has value. Offsetting these benefits may be that troubleshooting electric systems when in a service bay or in the field may be more time intensive, when needing to physically work with the vehicle.

Environmental benefits may include clear measures. Emission credit trading is an evolving market. A commercial battery electric vehicle manufacturer who does not make diesel products will collect emission credits. These credits have no value to its own production, but may have value on the open market for diesel based OEMs that may need emission credits to enable selling more diesel vehicles. The EPA GHG phase 1 and 2 rules include "averaging, banking and trading" (ABT) of credits to enable sales. If a diesel truck manufacturer is short emissions credits, it risks revocation of certification to sell product, extensive fines of up to $37,500 per vehicle, and a requirement to correct any fielded units to compliance [91]. The market value of a GHG emissions credit might be significant in this situation, perhaps up to or more than the OEM's margin for the vehicle, depending on his customer, brand image, and other "soft" factors.

Infrastructure overhead, as previously discussed, is also not limited to traditional business practices. Alternatives may reduce or eliminate CBEV charging infrastructure from capital budget considerations.

"Coolness" for lack of a better phrase, also has value in attracting and keeping new talent to companies [178]. Battery electric vehicles may have a desirable image to new hires and experiences in driving or servicing may be positive such that driver and service technician turnover and the inevitable training costs of replacements are reduced. Learning curves may also differ from diesel systems, potentially reducing the ramp up for new drivers and technicians, which has measureable efficiency effects to the bottom line. The "coolness" may also factor into attracting and retaining critical management positions at fleets.

Liability differences may also be a factor. CBEVs may have lower centers of gravity, so will be less likely to roll over in turns. Servicing may have fewer risks to personnel than mechanical powertrains. There may be an increased risk from fires in accidents. Shop part disposal costs and risks will see differences.

Fluids are another potential intangible. There are significant amounts of fluids on diesel vehicles that must be stored, handled and disposed of in service operations. Costs to maintain tanks, pumps, hoses, gauges, etc. may be buried and lost in facility overhead. Delivery to the site of these fluids may also be buried in overhead. Disposal/recycling of waste fluid similarly may not be assignable by vehicle as direct costs. These fluids are largely missing from CBEV operations.

Investment decisions must depend on sound and complete pictures of competing systems. Macve states, "The emphasis must be on the total life cycle costs and benefits to the company from current, future and potential perspectives [146]." CBEV cost justification may require better focus on the entire picture of both the diesel and electric operations (Figure 72). Both the traditional baseline and the CBEV alternative should have similar levels of total cost assessment (TCA) detail for an apples-to-apples comparison.

Figure 72. Example Hard and Soft Total Cost Assessment Factors (NACFE)

NACFE will detail the elements of the total cost of ownership in subsequent Guidance Reports by market segment and propose ranges of costs depending on certain duty cycles. End users and manufacturer decision makers can use this analysis to add their business specific numbers to help guide their purchase intent.

24 Effects of Regulations & Incentives

Return-on-investment truck purchase decisions typically compare an Option A versus an Option B choice. Regulations can intercede to completely eliminate one option, as seen with recent mandates in California, England, Norway, China, France and Germany. These and other regions are moving to require zero emission automotive and commercial vehicle use inside various cities, regions and even nationally [191]. Commercial vehicle fleet choice in these markets will require picking from competing zero and low emission technologies, but the diesel baseline may no longer be relevant to the ROI comparisons, replaced by the option to not operate at all in those locales. Tom Dollmeyer, Cummins Director of Technology Engineering, Cummins Electrified Power, characterized truck routes under future zero emission regulations in his 2018 TMC presentation as one of four missions, as shown in Figure 73 [198].

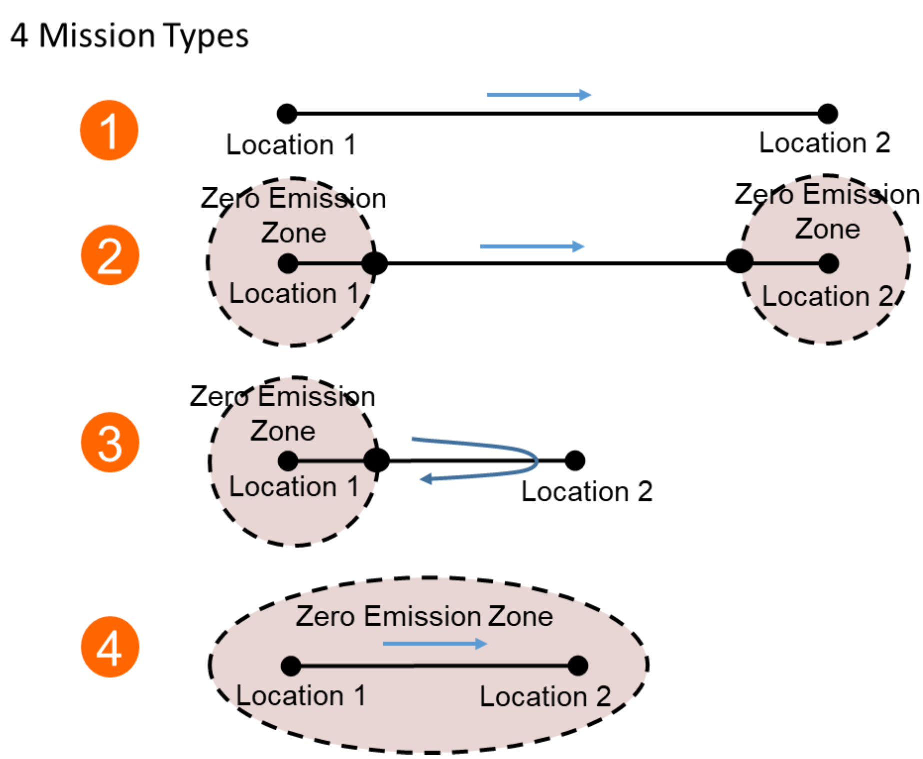


Figure 73. Routing Types under Future Zero Emission Rules (adapted from Cummins) [198]

There are a number of resources to research these regional visions, including reports from ICCT, RMI, McKinsey, ACT, IEA and others [127][190][184][187][188][185]. Implementation details from government agencies responsible for managing these visions are currently scant. For example, while announced rule planning generally focuses on new vehicles, little detail is provided on transitioning existing vehicles. Will these be grandfathered in? Will they be allowed to operate under additional permits or fees? Will programs be set up to incentivize trade-ins? Will there be other markets to sell older vehicles into? How will these regulations provide for continued freight movement while the regulations take effect? These details must be addressed as the regulations progress from proposals to actual rules.

Incentives, grants and other financial mechanisms for promoting adoption of new technologies are a factor today in business decisions on new truck purchases. These methods are used to normalize pricing of fledgling new technology versus the baseline diesel powertrains. These methods are not unique to new technologies. Arguments can be made that a range of government actions and inactions have contained pricing of U.S. diesel, have incentivized exploration for oil, and have assisted in building out pipeline and storage infrastructure. Grants are even used to encourage purchase of newer diesel trucks that have improved fuel economy over older models. The debate over the merits and failings of grants, incentives, and other financing methods is beyond the scope of this report. This report underscores only that these are existing mechanisms used by fleets in making investment decisions on new truck and infrastructure technologies. A concise November 2017 overview of several funding sources for vehicle electrification is available from the Center for Climate and Energy Solutions [191]. The DOE Alternative Fuels Data Center has a more comprehensive search engine for federal and state laws and incentives [196].

25 Decision Bias & Investment Timelines

Investments in new technology is not simply done on a logical, fact based technical analysis of competing technologies. Two good references to review are John Gourville's 2006 Harvard Business Review article "Eager Sellers and Stony Buyers: Understanding the Psychology of New-Product Adoption [150]" and the National Academy of Engineering's 1992 white paper "Time Horizons and Technology Investments [148]."

Gourville's article relates that consumers and producers both have psychological biases that affect investment decisions. He states, "The bias leads consumers to value the advantages of products they own more than the benefits of new ones. It also leads executives to value the benefits of innovations they've developed over the advantages of incumbent products. That leads to a clash in perspectives: Executives, who irrationally overvalue their innovations, must predict the buying behavior of consumers, who irrationally overvalue existing alternatives. Consumers reject new products that would make them better off, while executives are at a loss to anticipate failure. This double-edged bias is the curse of innovation [150]."

Gourville summarizes that the potential for new products to be adopted depends on the degree of product change versus the degree of consumer behavior change required for the product. He graphed this in a quadrant chart as seen in Figure 74.

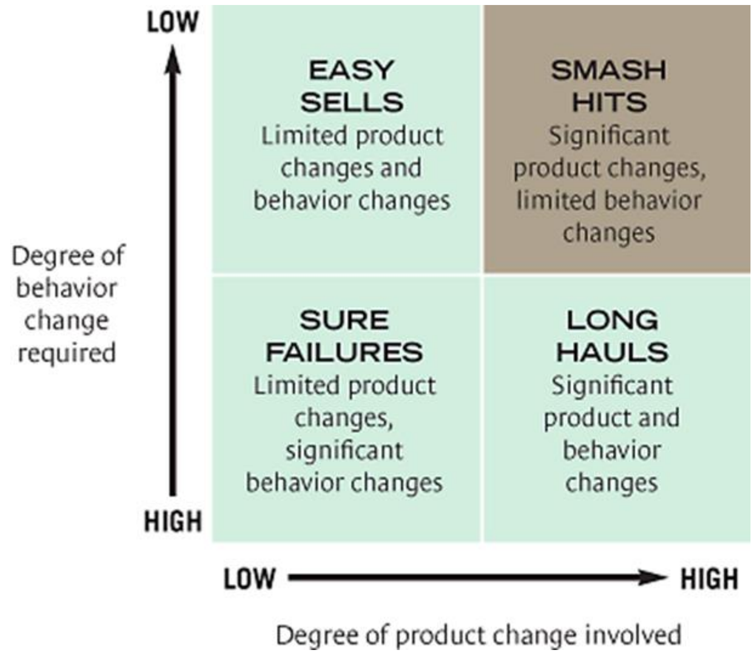


Figure 74. Potential for New Product Adoption (Gourville) [150]

Commercial battery electric vehicles arguably fall somewhere between the "Long Hauls" category, where the product requires significant user behavior changes and the product change is significant and the "Smash Hits" category where there is limited user behavioral changes but significant product changes. Driving an electric vehicle is largely the same as driving a modern automatic equipped truck, with some driver tuning required to deal with differences in acceleration and deceleration. "Fueling" a battery electric truck becomes a daily requirement versus less frequent fueling stops for diesels, but beyond that, the act of fueling is plugging a pipe into a vehicle (only the pipe is wires). NACFE's interviews with executives from PepsiCo's Frito-Lay Division and others have found that many drivers prefer driving electric trucks over their diesels after having had road time with them. Servicing is very different between battery electric and diesels, as is supplying the "fuel" to the "pump."

Guerneville summarized a range of studies that highlight that a new technology would need to be three times better than the existing one to have the best chance of market adoption. Compounding this is that producers of new technology often over value the benefits of their new technology by a factor of three. In total, he states, "The result is a mismatch of nine to one, or 9X, between what innovators think consumers desire and what consumers really want [150]."

The National Academy of Engineering report "Time Horizons and Technology Investments from 1992" outlines that there may be a schedule bias favoring short-term investment over long term. While somewhat dated, the themes exist today with pressures for quick returns. They concluded, "There are significant numbers of industries, or segments of industry, in which short-horizon behavior seems to be both the norm and a considerable source of competitive disadvantage [148]." They felt there was evidence "…that appears to indicate a broad-based tendency toward short-term planning and performance criteria on the part of U.S. industry [148]." They cautioned that this might be viewed simplistically and stated that time horizons for technology investments do vary considerably. Complicating this further is that the transportation market is cyclical, with significant peaks and valleys from national economic trends. Truck producers and buyers investments in longer term technologies can suffer in recessionary periods, or even when fuel prices drop.

The diverse committee authoring the report concluded, "Companies with deep and genuine competence in commercial application of technology will have a distinct advantage in adopting longer time horizons for technology investments because they are able to reduce the risk of those investments [148]." While the report focuses on the perception of cost of capital in the 1990's, the insight on short-term versus long-term investment horizons are applicable to the discussion of battery electric vehicles.

One strategy used by venture capitalists is to invest in 10 products that have great potential knowing that nine may fail. The one that succeeds, pays for the others. An opposing strategy is to wait for industry to flesh out the successful technology from the morass of competing ideas, and then make the investment. This argument is appealing in light of the rapid development of the battery electric vehicle market. Especially when considering that each generation of vehicle battery pack may be significantly better than the prior one.

NACFE and others have tracked technology trends on fuel economy improvers and found that one of the simplest solutions to improving fuel economy for a five-year-old vehicle is to simply buy a new model year vehicle. Fleets have demanded continuous fuel efficiency improvements of OEMs and their own operations. This market demand has produced notable advancements since 2010. Those advancements are in improved aerodynamics, advanced engine technologies, lower rolling resistance tire technology, better routing and tracking, packaging reduction, lightweighting, freight density improvement, reduced idle times, better driver training including driver fuel efficiency incentivizes, and more. Efficiency improvement is not a single point in time, but an on-going process that continually requires growth.

NACFE's 2017 Annual Fleet Fuel Study summarizing the purchase history of 19 technology early adopters shows that adopting any new product only ratchets up the comparison point for the next round of investment. Delaying investment until the risks are nearly eliminated is a very conservative approach resulting in a momentary spike in ROI for the year the investment is made because the comparison baseline is so far behind the current market. The following year then is challenged to reach the same bar.

Decision bias and investment horizons are factors that should be recognized in evaluating any new technology. They are particularly relevant to comparing battery electric vehicles to diesel ones.

26 Vehicle Purchase Cost

Estimating the net purchase price of commercial Class 3 through 8 battery electric vehicles is complicated. List prices are just the starting point of the calculations. CBEV OEMs have a wide range of additional factors to adjust their costs and pricing. Manufacturers providing a 10-year warranty, for example, have to factor in the expected costs of that with respect to their balance sheets. Vehicle purchasers have a range of possible grants, incentives, tax breaks, and more that can offset purchase prices. Fleets need to consider fleet downtime expectations in their cost of operations and that may factor into their purchase price negotiations with OEMs. Residual value, whether for resale or for salvage, are factors. Infrastructure required to run and maintain the vehicles, and technical support may also factor into the purchase price discussions. There are also questions yet to be universally answered, such as how do electric trucks pay fuel taxes to support roads and infrastructure? On the environmental side, does buying an electric truck improve a fleet's brand image such that it secures new customers? Can an OEM sell more diesel trucks at a profit by selling a parallel line of electric vehicles in complying with emissions regulations? Can an OEM sell an electric truck at a premium knowing its customer must have a zero-emission-vehicle in a particular location? What is the market value of an electric truck's emission credit exchanged between two OEMs? A not insignificant cost of a current diesel truck is the cost to manage the complexity of a very large options list demanded by current buyers, how much of this complexity and management cost will be needed for electric trucks? All these factors are similar to those encountered with the introduction of CNG fueled vehicles. The mix of variables will likely be different for each fleet and each location.

What is an acceptable Class 7/8 CBEV list price? Three entrants to this market have discussed in media price levels between $150k and $200k for their vehicles. Tesla initially projected their Semi pricing based on two range options at $150k for 300 miles of range and $180k for 500 miles [160]. Thor has stated their new model will launch at $150k with 300-mile range [161]. BYD produces a yard tractor estimated at $300,000 but with over $150,000 in available grants to offset that price to $150,000 [162][163]. Orange EV's new electric truck in late 2016 had prices from $244,950 to $284,950 [164], with grants again dropping the cost to about $150,000 [163][164][165]. These are four distinctly different Class 7/8 products all with a possible price tag of about $150k, suggesting that is a marketing price point these companies feel the market will accept for CBEVs. As to actual production costs, a reference point might be that the Tesla Model X SUV retails for between a basic $80k to fully loaded at over $140k per Edmunds for a vehicle in Texas [166].

A counterpoint to this is that Carlton Rose, President, UPS Global Fleet Maintenance and Engineering, announced in 2018 in collaboration with Workhorse Group Inc. that a clean sheet new design of a Class 5 electric delivery truck has "comparable in acquisition cost to conventional-fueled trucks without any subsidies [199][200].

Accurately predicting net pricing for CBEVs currently may be challenging, but predicting the trends is less so. The most significant cost in a CBEV truck is expected to be the batteries. These are an evolving technology that is improving in both performance and cost. A battery price point often highlighted is $150/kWh as a transition point when CBEVs have parity cost with diesels. An ICCT September 2017 paper Transitioning to Zero Emission Heavy Duty Freight Vehicles states [127]:

$1,000/kWh battery cost in 2007

$326/kWh battery cost in 2015

$228/kWh battery cost in 2020

$168/kWh battery cost in 2025

$120/kWh battery cost in 2030

The 2015 Nykvist and Nilsson paper Rapidly Falling Costs of Battery Packs for Electric Vehicles, is a frequently cited source on battery cost and includes the graph in Figure 75 [32].

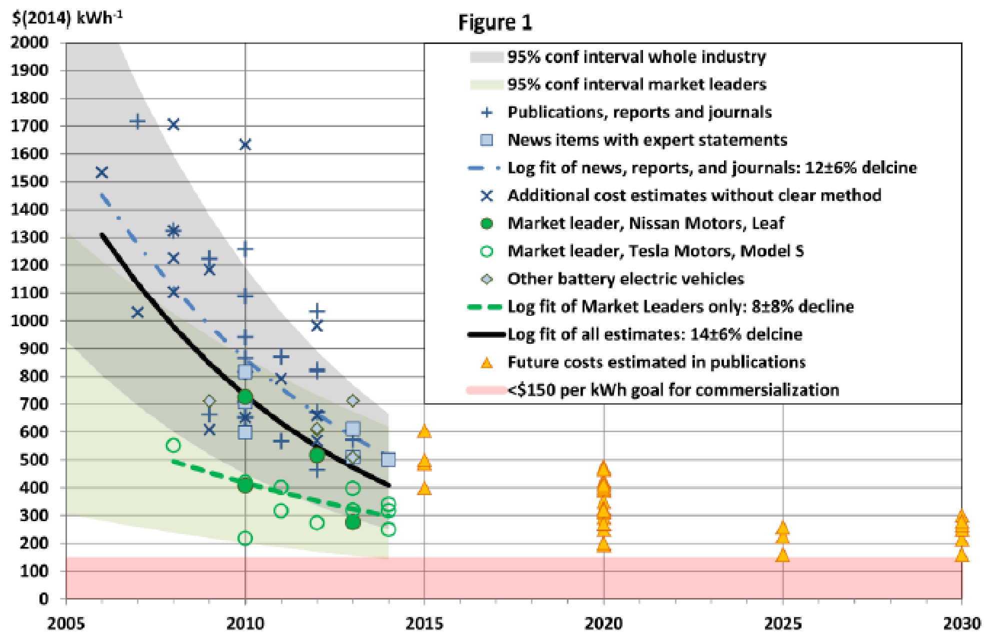


Figure 1. Cost of Li-ion battery packs in BEV. Data are from multiple types of sources and trace both reported cost for the industry and costs for market-leading manufactures. If costs reach US$150 per kWh this is commonly considered as the point of commercialization of BEV.

Figure 75. Battery Pack Cost Trends (Nykvist) [32]

Estimates for motors and related equipment are available in multiple references from CALSTART, DOE, NREL, ICCT, McKinsey, etc. Few actual production costs exist, most are projected models with many assumptions or many tax breaks, grants, and other offsets. The vehicle class dictates scale of each component.

The Clean Energy Manufacturing Analysis Center (CEMAC) and Bloomberg New Energy Finance (BNEF) have created manufacturing cost models via independent efforts aimed at benchmarking current costs of production [181][182][183]. The DOE Vehicle Technologies Office (VTO) modeled costs meant to estimate the projected commercial-scale production cost of technologies that are currently in R&D. The graphs in Figure 76 and Figure 77 illustrate the expectation of continued significant improvement in battery cost and performance. VTO estimates the cost reduction is expected from improvements in manufacturing (that come with volume increases) and improvements in energy density (from investment in battery research).

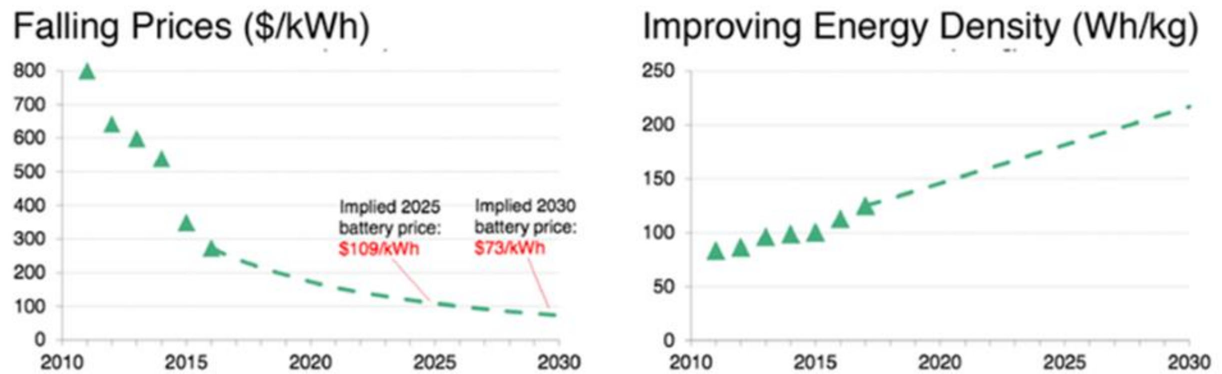


Figure 76. Battery Price and Energy Density Improvement Expectation (BNEF) [181]

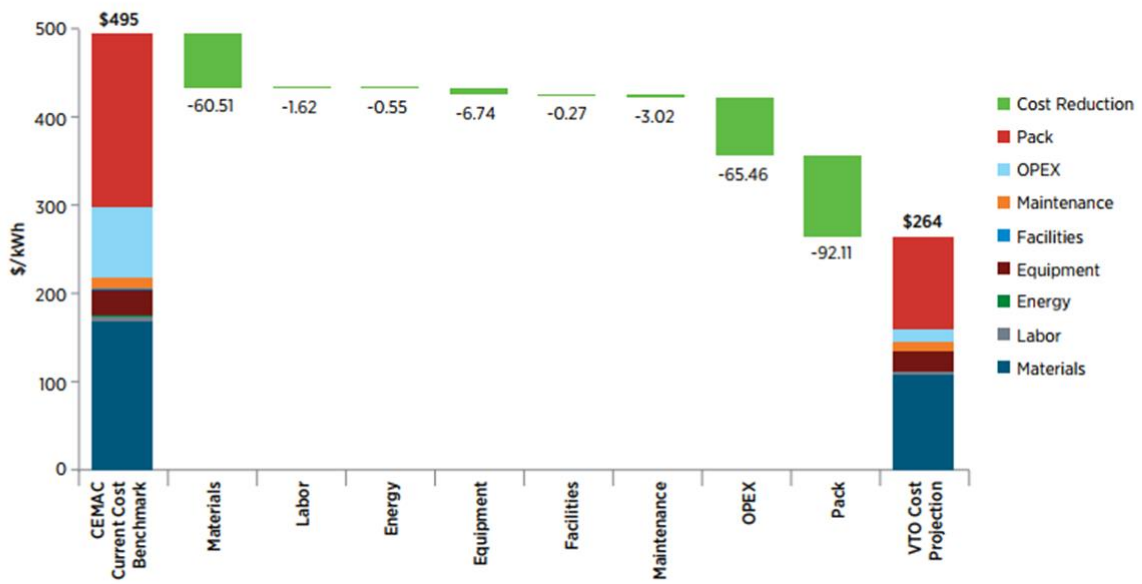


Figure 3. Comparison of 2015 modeled cost of commercially available technology (CEMAC) and current modeled cost projection for innovative technologies in development (VTO). Illustrative cost reductions are driven by potential improvements in energy density and manufacturing yield.

Figure 77. Projected Commercial Battery Cost Reduction Areas (VTO) [182][183]

The DOE reported in 2016 that, "The 2015 DOE PEV Battery Cost Reduction Milestone of $275/kWh was accomplished. DOE funded research has helped reduce the current cost projection (from three DOE-funded battery developers) for a PHEV 40 battery to an average $264 per kilowatt-hour (of useable energy). This cost projection is derived by using material costs and cell and pack designs, provided by those developers, which are then input into ANL's peer-reviewed (and in public domain) Battery Production and Cost model (BatPaC). The cost projection is based on a production volume of at least 100,000 batteries per year. The battery cost is derived for batteries that meet DOE/USABC system performance targets. The battery development projects focus on high voltage and high capacity cathodes, advanced alloy anodes, and processing improvements. Details of the material and cell inputs and cost models are available in spreadsheet form and in quarterly reports. DOE's goal is to continue to drive down battery cost to $125/kWh by 2022 [114]."

27 Charging Infrastructure Purchase Cost

Costs for electrical charging station infrastructure depend on the speed of the desired charging. CALSTART estimated in 2014 that charging station costs would vary from $25k for 20kW power to as much as $1M for 500 kW charging. Figure 78 shows estimated charging station costs up to 150 kW.

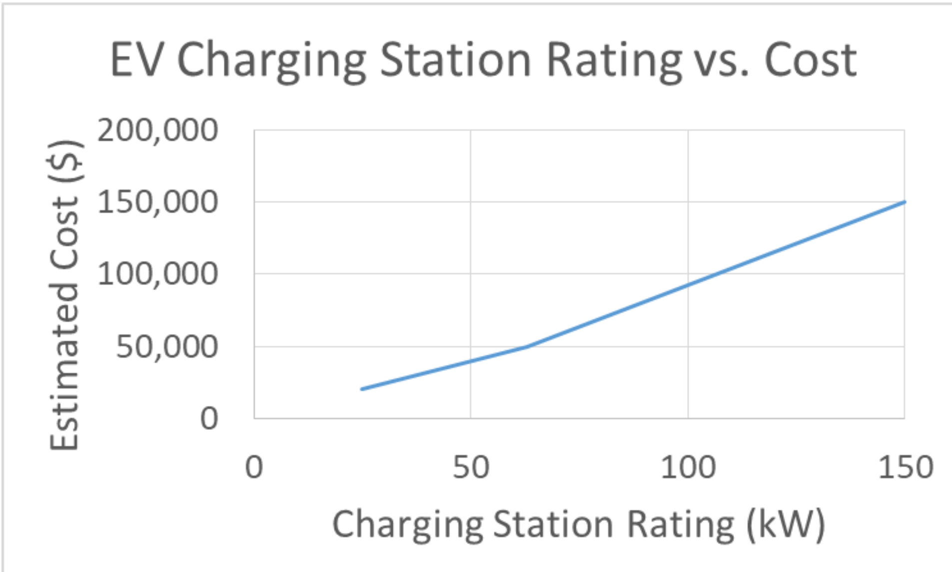


Figure 78. Estimated Costs per Charging Station (adapted from CALSTART) [4]

The NREL Frito-Lay example saw average cost of $22,000 using Clipper Creek CS-100 EVSE Chargers with continuous power rating up to 20 kW and specifications as shown in Figure 79.

Voltage & Wiring	220/240 VAC single-phase 208 VAC 3-Phase, Why-Connected 240 VAC 3-Phase, Delta Connected
Current	100 A
Frequency	50/60 Hz
Continuous current rating	16 to 80 A
Continuous output power rating	3.8 kW to 19.2 kW
Cable length	22 ft.
Dimensions (H x W x L)	12 in. x 18 in. x 8 in.
Operating temperature range	-40°F to 122°F
NEMA rating	NEMA 4 – Outdoor use, watertight
Agency approvals	UL Listed, FCC, CUL, ETL, cETL
Codes and Standards	UL 2594 UL 2231 UL 1998 UL 991 NEC 625 SAE-J1772

°F = degrees Fahrenheit
A = amps
cETL = Electrical Testing Laboratory of Canada
CUL = Underwriters' Laboratories of Canada
ETL = Electrical Testing Laboratory
FCC = Federal Communications Commission
Hz = hertz (cycles per second)
NEC = National Electric Code
NEMA = National Electrical Manufacturers Assoc
VAC = volts alternating current

Figure 79. Clipper Creek CS-100 EVSE Charger Specification (NREL) [89]

28 Range Extending

NACFE's focus in this report is the plug-in commercial battery electric vehicle. Feedback from fleets and OEMs is that hybrid powertrains may also represent an interim solution that bridges currently available production battery technology and significantly improves future versions. Hybrids allow for longer range operations with perhaps greater energy source flexibility. They also may permit electric operations in cities where zero emission noise and emission regulations prohibit ICE engine use, while allowing diesel, gas, CNG, etc. use outside city limits where the regulations no longer apply.

Hydrogen fuel cells, considered a series hybrid, are really a single powertrain as the fuel cells generally power batteries and it's the batteries that drive the electric motors, much as in a diesel-electric train the generators drive the wheels. Vehicles in development by Nikola, Kenworth, Toyota, U.S. Hybrid and others, are similar to CBEVs but have the addition of an on-board ability to convert hydrogen to electrical energy rather than relying on the electrical grid to recharge batteries [167][168][169][170][171][172]. They accomplish this by adding high pressure tanks, additional cooling and heating systems, and plumbing. For example, Kenworth's prototype Zero Emissions Cargo Transit fuel cell truck carries 2,000 lbs. of batteries that can provide 30 miles of range, while the addition of the hydrogen fuel cell, tanks and associated equipment gives the vehicle an estimated 150 mile range capability [167][168].

Fleets and suppliers expressed to NACFE a concern with hybrid technology that drivetrain complexity increases with redundant on-board power systems, so maintenance and breakdown potential may increase. These concerns are based in part on prior experiences with past new technology introductions such as with early diesel APUs as no idle solutions [159]. One fleet summarized their early APU experience after extensive use that having two engines on a truck increased downtime, maintenance and troubleshooting.

This concern for hybrid reliability for commercial trucking may be overly cautious or biased. Automotive hybrid reliability and maintenance experience reported by groups like Consumer Reports, Edmunds, Australian Royal Automobile Club of Victoria and JD Power all highlight that production hybrid automobiles are roughly on par or better than their non-hybrid counterparts in terms of reliability and maintenance costs [137][156][157][158].

Consumer Reports states, "In our tests, we've found that some hybrids, such as the Toyota Prius, receive top marks in reliability and require very little maintenance, but there is variability among other makes and models. We checked with Honda and Toyota about maintenance and reviewed the service schedules of two of the most popular hybrids and found that neither requires any special maintenance beyond what a regular car needs. Coolant changes on the Prius and other Toyota hybrids might be somewhat more complicated and expensive than in regular cars, but they don't have to be done any more often [156]."

Consumer Report also states, "Hybrid models that run nickel-metal hydride hybrid batteries typically have very good reliability in our Annual Auto Survey of our subscribers. Lithium-ion batteries are too new to have a proven long-term track record. Automakers are required to warranty the batteries on any hybrid as an emissions control part for eight years and 80,000 miles in most states. In about 10 states, they're required to warranty them for 10 years or 150,000 miles, so the automakers have a vested interest in making them durable. Outside the warranty period, new nickel-metal hydride battery replacements can run as much as $3,000, but replacements have been relatively rare. And used batteries are available for much less. Batteries in some older Ford and Honda Hybrids have been more problematic than those in more popular Toyotas [156]."

Edmunds reported in a 2013 evaluation of hybrids that, "Hybrid critics warn of potentially expensive repairs associated with the hybrid-specific parts, such as battery packs. And there doesn't seem much reason to worry. All the hybrid-specific components in every hybrid vehicle currently on the market are covered under warranty for eight years/100,000 miles or 10 years/150,000 miles, depending on the state, but these components have been shown to have a much longer lifespan in testing and in real-world conditions [157]."

Edmunds believes hybrid model maintenance costs are on par with non-hybrids, stating, "Most hybrid cars do not require any additional regular maintenance on the hybrid-specific components. An exception is the air filter on the battery system of the now-discontinued Ford Escape Hybrid, which needs to be replaced every 40,000 miles [157]."

There are few direct comparisons of servicing costs available where the same model comes in hybrid and non-hybrid configurations. The RACV studies total cost of ownership for automobiles in Australia which includes specifics comparing two identical Mitsubishi Outlander SUVs, one with a 2.4L engine and the other a plug in hybrid model [137]. The RACV 2017 data shows the service costs per kilometer for the non-hybrid is 6.92 cents (AUS)/km, while that for the hybrid one is 8.39 cents (AUS)/km. The RACV evaluation of the Camry non-hybrid service cost is 4.86 cents (AUS) /km while the hybrid version is 5.20 cents (AUS)/km [137]. These differences may be due to the different levels of maturity to the ICE platforms versus the newer designed hybrids, rather than a fundamental difference in technology. The hybrid Camry and Outlander servicing is still approximately on par or better than other ICE models in their classes.

29 China, Europe and Global Technology Development

The Chinese commercial vehicle market represents a significant volume of vehicles in a wide range of weight classes. An ACT Research 2014 report projected the 2018 Chinese annual market production (including exports) at 628,750 heavy straight trucks, 334,000 heavy tractors and 301,750 medium-duty trucks [187]. A PR Newswire report in 2018 states, " …the Chinese electric truck market will be the global electric medium heavy-duty truck leader and is expected to be dominated by fully electric trucks with 61.1% market share, followed by plug-in hybrid with 28.5% and hybrid with 10.4% by 2025 [185]." A 2017 Trucks.com article on an ACT Research panel reported BYD Vice President of Sales Andy Swanton's estimate that, "In China roughly 120,000 zero-emission battery electric buses are running, making up more than 20 percent of the domestic market share. That's compared to some 10,000 similar buses in the U.S. [189]."

Will the advances in product development in China and Europe translate to the North American market? Feedback from some U.S. component suppliers interviewed by NACFE for this report indicated that while there were possible parallels between the Chinese, European and U.S. products, the duty cycles and requirements differ significantly. This view was expressed also in the proceedings from Rocky Mountain Institute's 2016 Design Charrette on Chinese Logistics and Trucking Efficiency held in

Senzchen, PRC, concluding, "International experience with fuel economy improvements is not always relevant due to differing duty cycles (e.g. much lower average speeds) [190]." Details of the variation in worldwide duty cycles for tractors and straight trucks were assembled in the 2017 report by ICCT's Delgado including Brazil, China, Europe, India and the U.S. The report recognizes that within each region are significant variation in classes and duty cycles. The analysis was simplified for evaluation by consolidating national fleets, "…considering only one tractor-trailer vehicle profile per region to estimate technology potential for the entire market [193]." These regional specification variations are summarized in Figure 80, Figure 81 and representative duty cycles in Figure 82.

	Brazil	China	Europe	India	US
Gross vehicle weight (tonnes)	36	40	40	40	36
Vehicle curb weight (tonnes)	16.7	15	14.5	13	14.7
Maximum payload (tonnes)	19.3	25	25.5	27	21.3
Volume capacity (m^3)	108	86	96	93	114
Axle configuration	6x2	6x4	4x2	4x2	6x4
Typical trailer type	Dry bulk	Stake	Side curtain	Platform	Box van
Trailer axle number	3	3	3	3	2
Engine Displacement (liters)	13	10	12.8	5.9	15
Engine power (kW)	324	250	350	134	340
Engine emissions standard	Proconve P7[a] (NOx limit = 2 g/kWh)	China IV[b] (NOx limit = 3.5 g/kWh)	Euro VI (NOx limit = 0.4-0.46 g/kWh)	Bharat III[c] (NOx limit = 5 g/kWh)	EPA 2010[d] (NOx limit = 0.27 g/kWh)
Vehicle fuel efficiency standard	NA	China Stage 2	NA	NA	EPA/NHTSA 2014[e]
Transmission type[f]	AMT	MT	AMT	MT	MT
Transmission gears	12	10	12	6	10
Transmission gear ratios[g]	11.32 to 1	14.8 to 1	14.9 to 1	9.19 to 1	12.8 to 0.73
Rear axle ratio	4.38	4.11	2.64	6.83	3.70
Tire type	Radial	Radial	Radial	Bias	Radial
Tire size	295/80R22.5	12R22.5	315/80R22.5	10R20	295/75R22.5

Notes: Values presented come from a combination of sources including but not limited to Polk/IHS sales databases, KGPAuto market penetration databases, publicly available literature sources, ICCT consultants' analyses, and ICCT internal expertise. [a]Equivalent to Euro V. [b]Equivalent to Euro IV. [c]Equivalent to Euro III. [d]U.S. Environmental Protection Agency. [e]National Highway Transportation Safety Administration. [f]AMT: Automated Manual Transmission, MT: Manual Transmission. [g]First gear and last gear ratios are shown.

Figure 80. Amalgamated representative tractor-trailer characteristics by region (ICCT) [193]

	Brazil	China	Europe	India	US
Gross vehicle weight (tonnes)	9.7	12	12	12	11.6
Vehicle curb weight (tonnes)	3.2	5.8	6.5	4.0	6.3
Maximum payload (tonnes)	6.5	6.2	5.5	8.0	5.3
Axle configuration	4x2	4x2	4x2	4x2	4x2
Engine displacement (liters)	3.8	4	5.1	3.8	6.7
Engine power (kW)	119	101	185	92	201
Engine emissions standard	Proconve P7[a] (NOx limit = 2 g/kWh)	China IV[b] (NOx limit = 3.5 g/kWh)	Euro VI (NOx limit = 0.4-0.46 g/kWh)	Bharat III[c] (NOx limit = 5 g/kWh)	EPA 2010[d] (NOx limit = 0.27 g/kWh)
Vehicle fuel efficiency standard	NA	China Stage 2	NA	NA	EPA/NHTSA 2014[e]
Transmission type[f]	MT	MT	AMT	MT	AT
Transmission gears	5	6	6	5	5
Transmission gear ratios[g]	5.72-0.76	6.3-0.797	6.75-0.78	8.02-1	3.1-0.7
Rear axle ratio	4.30	5.00	4.00	5.29	4.88
Tire type	Radial	Radial	Radial	Bias	Radial
Tire size	235/75R17.5	8.25R20	305/70R22.5	8.25R20	255/70R22.5

Notes: Values presented come from a combination of sources including but not limited to Polk/IHS sales databases, KGPAuto market penetration databases, publicly available literature sources, ICCT consultants' analyses, and ICCT internal expertise.[a]Equivalent to Euro V. [b]Equivalent to Euro IV. [c]Equivalent to Euro III. [d]U.S. Environmental Protection Agency. [e]National Highway Transportation Safety Administration. [f]AMT: Automated Manual Transmission, MT: Manual Transmission, AT: Automatic Transmission. . [g]First gear and last gear ratios are shown.

Figure 81. Amalgamated representative rigid truck characteristics by region (ICCT) [193]

		Duty cycle	Average speed (km/h)	Maximum Payload (tonnes)	Representative Payload (tonnes)
Tractor-trailers	Brazil	WHVC. 10% Rural, 90% Motorway	76.3	19.5	19.5
	China	WHVC-China. 10% Rural, 90% Motorway	72.7	25.0	25.0
	Europe	VECTO Long Haul	77.3	25.5	19.3
	India	WHVC-India	32.9	27.2	27.2
	US	US Phase 2 cycles. 5% ARB Transient, 9% 55-mph, 86% 65-mph	99.1	21.3	17.2
Rigid trucks	Brazil	US Phase 2 cycles. 70% ARB Transient, 13% 55-mph, 2% 65-mph, 15% idle	36.0	6.5	3.2
	China	WHVC-China. 10% Urban, 60% Rural, 30% Motorway	51.3	6.2	3.1
	Europe	VECTO cycles. 50% Urban, 50% Regional	49.0	5.5	2.7
	India	ARB Transient	24.6	8.0	4.0
	US	US Phase 2 cycles. 70% ARB Transient, 13% 55-mph, 2% 65-mph, 15% idle	36.0	5.3	2.6

Figure 82. Representative Worldwide Duty Cycles per ICCT Study (ICCT) [193]

The technology behind key electric truck elements such as operating systems, sensors, battery and motor designs may be directly transferrable between regional markets, but the specific components may be less so because each may be optimized for their specific market requirements, raw material sources, capacities, price points, margin expectations, standards and environmental demands. Chinese and European manufacturing and engineering lessons learned from fielding large volumes of battery electric vehicles and charging systems likely can accelerate cost reduction for the North American producers and speed product improvement.

30 Small Fleet & Large Fleet Perspectives

Commercial battery electric vehicles are not limited to large fleet introductions. While large fleets may be able to experiment at the same time with a range of technologies, small fleets with six or fewer trucks have greater challenges. These fleets, according to ATA and the U.S. Department of Transportation, as of May 2015, make up over 90% of the U.S. haulers [194]. ATA estimates 97% of U.S. fleets operate less than 20 trucks [194]. The business motives to consider CBEVs applies irrespective of fleet size.

The 2017 ICCT report on Transitioning to Zero-Emission Heavy Duty Freight Vehicles highlights in the near term that CBEVs, "…are most suited for applications with short ranges and duty cycles that can take advantage of regenerative braking and where required electric battery packs sizes are lower. An analysis of duty cycles suggests urban delivery vans and delivery trucks, refuse trucks, and drayage trucks as targets for electrification [127]." Operations with well-defined, repetitive routes under 100 miles are opportunities. Fleets needing to operate where zero-emission requirements are pending are candidates for CBEV vehicles. These factors apply to both small and large fleets.

Smaller fleets may not have the depth of resources needed to run internal testing of alternative technologies. These fleets make investment decisions relying on shared experiences from the larger fleets, suppliers, agencies and other publicly available information, such as NACFE reports. This NACFE report discusses a variety of innovative methods evolving for funding infrastructure and vehicles, which may be equally applicable to large and small fleets. Small businesses may even have some advantage to exploit tax incentives, grants, and other financing methods where rules limit available amounts.

31 Findings

NACFE's research identified common themes in arguments against and for Class 3 through 8 electric commercial vehicles. These all-inclusive "red flag/green flag" comments can end a conversation on CBEVs before it begins. One of NACFE's goals of this report was to evaluate the pluses and minuses of these claims in an unbiased approach to see if there were technology opportunities being too quickly dismissed. NACFE/ACT's fleet survey for this report highlighted 10 fleet concerns consistent with NACFE's findings, expressed here as point-counter point opinions.

1. *Vehicle tare weight is too high to support my freight needs vs. CBEV weight is not an issue*
2. *Technology is not ready vs. CBEV technology is proven and here now*
3. *Charging infrastructure is not ready vs. trust the market to provide CBEV charging solutions*

4. *Charging Infrastructure is not fast enough vs. trust the market to provide CBEV charging solutions*
5. *The electric grid cannot support growth in electric vehicles vs. the grid and market will evolve with CBEVs*
6. *Maintenance will be more costly vs. maintenance may be less costly*
7. *Vehicle purchase price is too high for a positive ROI vs. CBEVs will be competitively priced*
8. *Vehicle operating costs are too great for positive ROI vs. CBEVs will be less expensive to operate*
9. *Vehicle residual value is questionable vs. CBEVs will command a premium at resale*
10. *Vehicle life is too short vs. CBEVs will last beyond 10 years*

NACFE's summarizes our findings on these 10 hot buttons of electric truck disagreement here:

1). *Vehicle tare weight is too high to support my freight needs* vs. *CBEV weight is not an issue*: Competitive vehicle tare weights are possible in all classes for many duty cycles. Diesel powertrains also include fluids, emissions systems, exhaust systems, cooling systems, mountings, etc. that in total represent a significant weight reduction when removed. Typical payloads in many applications are well below maximum GVWR. The combination of both of these factors allows for CBEV solutions with equivalent freight carrying capacity in many applications, but not all.

2). *Technology not ready vs. CBEV technology is proven and here now*: 2017 was a banner year for media coverage of battery electric truck development. Multiple new companies are entering the U.S. market with models ranging from Class 3 to Class 8. Established OEMs have been developing prototypes for field testing in specific markets. Automotive and bus battery electric vehicles have been in production for years and advancing on their learning curves in real world use. Battery capacities are expected to increase with time, cost and weight to decrease. The technology is on the steep part of the development S-Curve, where big improvements are regularly expected.

3). *Charging infrastructure is not ready for me to invest in electric vehicles vs. trust the market to provide CBEV charging solutions*: Off-shift charging of vehicles is possible today with existing systems. The challenge is high speed charging. CBEVs needing sub-30 minute charging speeds require high capacity production charging systems that today are only in the conceptual phase. Technically, these high speed systems are thought feasible by a range of experts, but practicality is still a question for them. Fleets with well-defined one-driver shift A-B-A, or A-B-C-A type routes, for example, are well positioned for have base depot charging. Even fleets with routes between hubs, if range is sufficient, could have charging at both ends of the trip. Fleets with variable routes and no guaranteed return trips, will need growth in remote charging capacity before considering replacing diesels with CBEVs. Where these vehicles must transit zero-emission urban zones, hybrids may be needed.

4). *Charging Infrastructure is not fast enough for my needs vs. trust the Market to provide CBEV charging solutions*: The speed needed for charging depends on each fleet's duty cycles and daily and weekly route scheduling. Many operations have defined cycles that permit off-cycle daily charging. Fleets that require sub-30 minute charging will need practical commercial vehicle capable charging technology to catch up their needs.

5). *The electric grid cannot support growth in electric vehicles vs. the grid and market will evolve with CBEV's with no issue*: The market penetration rate of commercial battery electric vehicles will be on decades time scale. The U.S. has energy production capacity for significant volumes of electric cars and trucks. Adding vehicle charging stations to a warehouse or factory is like adding a new line, a process utilities regularly perform for commercial sites. High rate charging expected for any sub-30 minute charging of commercial vehicles, does create a significant demand on the grid. Alternatives to mitigate this through leveling and storage systems are being considered.

6). *Maintenance will be more costly* vs. *maintenance may be less costly*: Automotive experience with CBEVs suggests maintenance of production designs should be on par or better than equivalent ICE powertrains. Experience with limited production of first generation medium-duty commercial CBEVs such as the Smith Newton, suggest that once the initial vehicles have gone through design maturing from field use, they likely will have equal or better maintenance than equivalent ICE vehicles. There are too few production Class 7/8 CBEVs in use to assess their real world maintenance at this time. Prototypes and pre-production models generally see high infant failure rates and are managed more intensely, so the experience there is not representative of production units in normal field use. Long warranty periods promised by CBEV manufacturers may reduce fleet financial risks on maintenance projections for commercial CBEVs, but warranties do not alter truck potential downtime impacts.

7). *Vehicle purchase price is too high for a positive ROI* vs. *CBEVs will be competitively priced*: Investment in CBEVs may require quantifying the true total cost of ownership of both diesels and battery electric vehicles by including so-called intangible "soft costs," liability costs, indirect costs and opportunity costs buried in overhead or ignored in traditional ROI calculations. These are real company costs and benefits, but require greater diligence to estimate with confidence. Industry pricing of CBEVs is still largely ill defined. Pricing experience is largely based on prototype and pre-production experience and estimation. There are many variables including grants, tax breaks and incentives and a largely unknown residual or salvage value. The industry is also developing alternatives to traditional purchasing or leasing which will factor into attaining positive ROI for CBEV investment. The battery system is the most expensive cost item. The trend over the last decade is expected to continue for the next, continuing to see large reductions in cost and significant gains in performance. Diesel performance, in contrast, is unlikely to yield large gains in performance with reduced costs. Diesel powertrains, after a century of commercial vehicle development, are at a different point in maturation where gains are small and expensive, and complicated further by increased demand for emissions reduction.

8). *Vehicle operating costs are too great for positive ROI vs. CBEVs will be less expensive to operate*: Operating costs can be less for CBEVs. The electric drives are more energy efficient than diesels. The reduction in diesel based friction sensitive mechanical systems such as pumps, valves, transmissions, and belts should reduce maintenance and servicing. The track record to date is mixed because much of the truck experience has been through first generation products in small numbers, and in prototypes. These early vehicles were expected to have higher failure rates. One fleet said that after segregating out the early failures, the operating costs have been much better than comparable diesels. Compounding this is that these early products are largely from smaller start-up manufacturers and the large, mature OEMs have not brought their significant experience to bear in production models. Automotive experience has also been mixed with reliability of early battery electric models about average compared to gasoline or diesel cars, but this trend may be improving with experience and volumes.

9). *Vehicle residual value is questionable* vs. *CBEVs will command a premium at resale*: Introduction of electric vehicles (cars and trucks) has most of them still within their first owner's use. The used electric vehicle is in its infancy. Residual value is a question. With Class 3 through 6 vehicles, they may not typically have a second life. The first owner may run them until they are scrapped. The value of electric motors and batteries in salvage may prove an advantage as they can be repurposed for non-vehicle uses and may have significant life left. Mechanical systems at the end of vehicle life require reconditioning which can reduce their net value in salvage.

10). *Vehicle life is too short* vs. *CBEVs will last beyond 10 years*: NACFE's discussions with fleets, OEMs and suppliers is that they expect a Class 3 through 8 vehicle life of seven to 10 years before major refurbishing or salvage. With CBEVs the battery packs are the most common concern expressed. The act of charging CBEV battery packs tends to reduce their capacity. The manufacturers expect the battery packs to be replaced when they reach 80% of their initial capacity. NACFE projected the frequency of recharging events based on automotive experience and determined that batteries will likely exceed the seven to 10 year vehicle life. The fleet's specific duty cycles and environments need to be evaluated when researching CBEV choices. Electric motors, computers, chassis and body, etc. have established reliability data. They are present in degrees on current diesel vehicles.

32 SUMMARY

NACFE asked fleets and suppliers during interviews and surveys exactly what they would want to see in this report, what they thought would compel them to read this overview of the potential of commercial battery electric vehicles. Their questions ranged from technical feasibility to practicality. Some stated frankly that CBEV's were not in their near-term future because they were not well suited to their duty cycles and needs. Others were actively pursuing or using them as viable solutions to improve efficiencies in portions of their operations. No one felt they were a solution for every situation, but they thought there were situations where they make sense.

The goal of this paper was to provide an unbiased overview of the key information needed to understand the pluses and minuses of the evolving commercial battery electric vehicle world so that fleets, manufacturers, and others could be armed for substantive discussions.

At this time, the industry is primarily trying to compare one-for-one replacement of diesel vehicles with alternative technologies. In time, the industry will be more open to customizing operations to capitalize on the strengths of CBEV technology. The term "parity" is often used in comparisons, meaning equivalence. NACFE believes that parity is not the goal for investment in new technologies. Significant market adoption of new technology requires there be substantial improvement over the equivalent baseline diesel systems.

The evaluation of CBEV suitability as a replacement for diesel systems is very dependent on vehicle class and duty cycle. NACFE will be preparing a series of follow-on reports detailing battery electric vehicle specifics related to these five segments.

- Light Duty Delivery Truck (Class 3)
- Medium Duty Box Truck (Class 4-6)
- Heavy Duty City Tractor (Class 7/8)
- Heavy Duty Regional Tractor (Class 7/8)
- Heavy Duty Long Haul Tractor (Class 7/8)

These five duty cycles, for discussion purposes, are those identified by fleets and manufacturers requesting NACFE's focus. The first four duty cycle details tabulated in the first four columns of Figure 83, were developed from actual fleet data compiled by NREL, CALSTART and the FHWA and consolidated by ORNL [186]. The fifth column, Class 7/8 Long Haul comes from the NACFE 2017 Run-On-Less database [179].

	Weight Class & Type				
Factor	Light Duty Delivery Truck (Class 3)[d]	Medium Duty Box Truck (Class 4-6)[d]	Heavy Duty City Tractor (Class 7/8)[d]	Heavy Duty Regional Tractor (Class 7/8)[d]	Heavy Duty Long Haul Tractor (Class 7/8)[e]
Average Drive Disitance (mile/day)	37	40	164	119	457
Annual Travel Mileage[a]	13,551	14,478	60,001	43,386	114,250[f]
Max Drive Distance (mile/day)	79	81	568	612	1,076
Average Drive Time (hr/day)[b]	1.12	1.18	4.36	4.29	9.06[g]
Max Drive Time (hr/day)[b]	2.14	2.05	11.52	13.8	11.00[g]
Average Vehicle On Time (hr/day)[c]	1.6	2.98	7.26	9.06	7.30
Max Vehicle On Time (Hr/day)[c]	3.29	18.16	15.69	23.96	14.30
Average Drive Speed (mph)[b]	33.19	33.52	37.71	27.7	54.5
Max Drive Speed (mph)[b]	70.34	70.66	71.87	76.5	80.0[h]
Average Vehicle On Speed (mph)[c]	22.84	18.23	18.93	14.11	50.45
Average Stops per Mile	0.81	0.78	0.49	1.02	0.13
Max Stops per Mile	3.03	3.04	8.45	13.37	8.05
Average Stops per Day[d]	8.89	8.58	10.68	7.1	6.5
Max Stops per Day[d]	17	16	23	28	16

a: 1 year = 365 days; b: Vehicle speed >0; c: Vehicle speed ≥0; d108 : stop or idling time >5 minutes.
d: Data from ORNL Gao, NREL Fleet DNA, CALSTART, FHWA [186]
e: Data from NACFE Run On Less 2017, f: 50 week year/5 days/week driving g:FMCSA HOS 11 Hour Max Rule;h:80 mph max posted speed in some states [179]

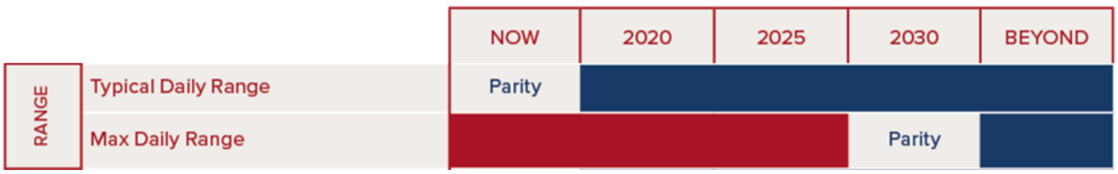
Figure 83. NACFE CBEV vs. Diesel Duty Cycle Baselines (NACFE, ORNL)

There are, of course, many more duty cycles in use in the real world. These five are only representative for the purposes of discussion of the market opportunities for CBEVs. Ultimately a fleet's specific duty cycle makes the greatest sense for comparison.

NACFE determined the light- and medium-duty segments have the greatest near-term potential for market penetration. Production level vehicles are available in these two segments and more offerings are entering the marketplace. Positive ROIs are attainable in specific operations. The three Class 7/8 segments currently exist as prototypes or limited pre-production units in field testing. The ROIs for these vehicles are less clear at this point in time due to the limited information on actual products and projections from automotive and bus CBEV field history.

This report discusses a number of significant attributes for viability of commercial battery electric vehicles to compete as alternatives to diesel powertrains. Parity, that point where CBEV and diesel are equally viable, is summarized for each of these key attributes in the following two charts. Figure 84 summarizes with respect to Class 3 through 6. Figure 85 summarizes with respect to Class 7/8.

An example in how to interpret these charts is to look at the Class 3 through 6 Weight. As stated in the report, battery capabilities and weight have evolved to the point that production CBEVs are available and capable of many medium-duty urban delivery services. These are where daily routes are in the 25 to 100 mile range, where load density cubes out, and where traffic stop-and-go conditions accentuate use of regenerative braking systems to recover energy. Parity exists today for Typical Daily Range achievement. However, consider that a diesel-fueled truck may have 30, 60 or more gallons in its fuel tank, meaning a potential daily range of hundreds of miles. While that truck only drives 25-100 miles per day, it could go much farther. Parity here requires advances in battery technology – that is, energy density improvement and weight reduction. The report outlines that this improvement is occurring and significant change is expected in the next decade. So parity when max daily range is equivalent between similar capacity medium-duty urban delivery trucks is predicted in 2030.



This example highlights that electric truck viability is a series of trade off discussions, not one single thumbs up or thumbs down.

The availability of production vehicles in volume is part of NACFE's assessment of parity timing. While there is at least one production Class 7/8 model line today, the major OEMs have been fielding prototypes or still have concepts in work. Production Class 7/8 CBEVs are projected in the 2019–2020 time frame by several manufacturers.

New model technology has a learning curve stressed by field deployments. New technology has a history of going through growing pains before stabilizing. This is related to production volumes in commercial use discovering design and reliability issues not found during limited volume testing. This period of learning typically sees higher service and maintenance costs and labor. Downtime is another factor for fleets. Parity with respect to new electric vehicle technologies requires accumulation of a significant number of miles and seasons of experience in real world operations. Diesels, by contrast, have decades of field history so are less likely to have these infancy issues. NACFE factored technology maturity into its parity assessments.

In some instances, CBEVs have not been around long enough to assess firm results. Case in point is residual value of Class 7/8 vehicles where little is truly known. Even CBEV cars have not been around long enough for a used market to be well defined.

CLASS 3 THROUGH 6 CBEV PARITY VS. DIESEL SYSTEM (NACFE)

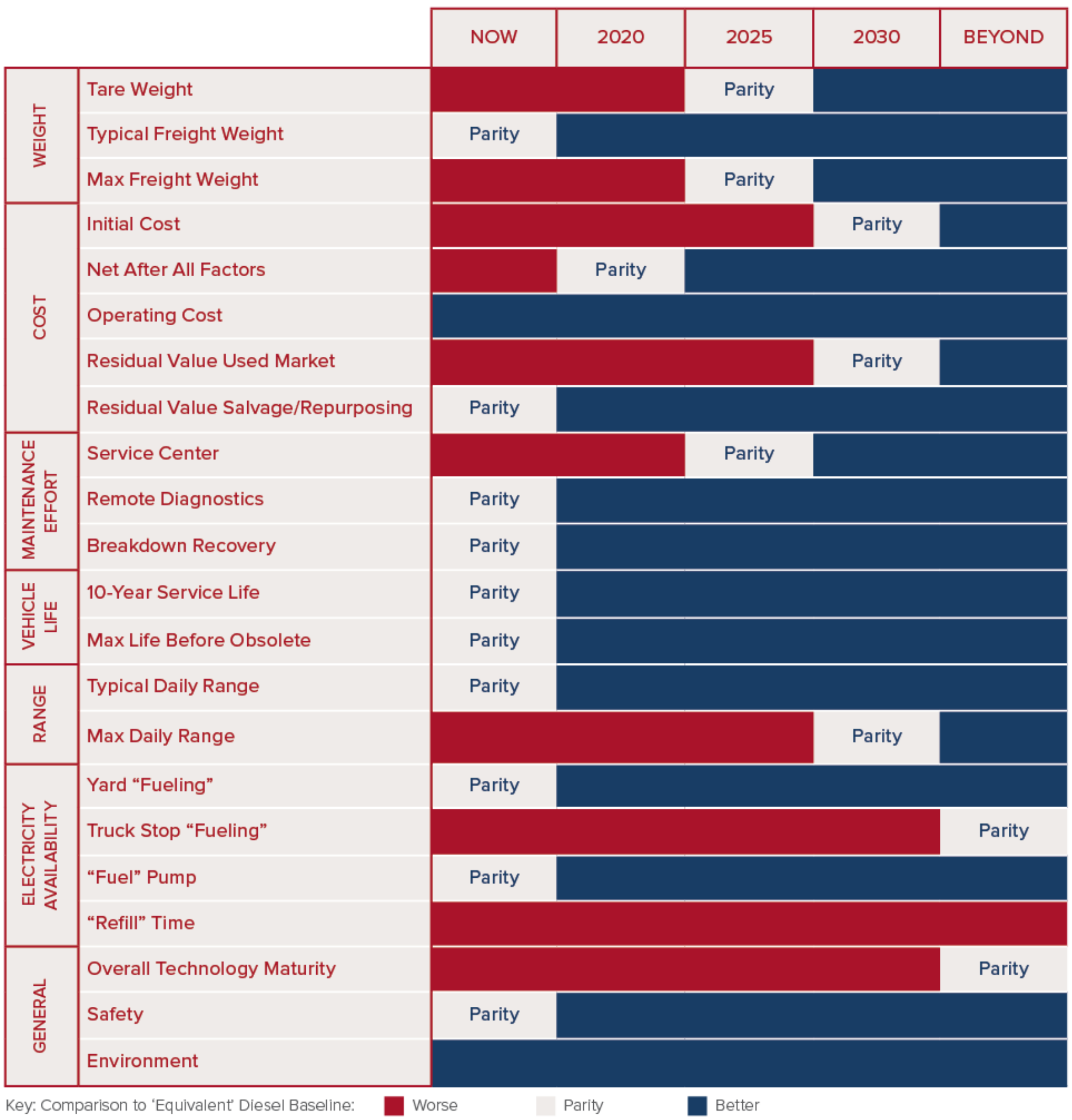


Figure 84. Class 3 through 6 CBEV Parity vs. Diesel System (NACFE)

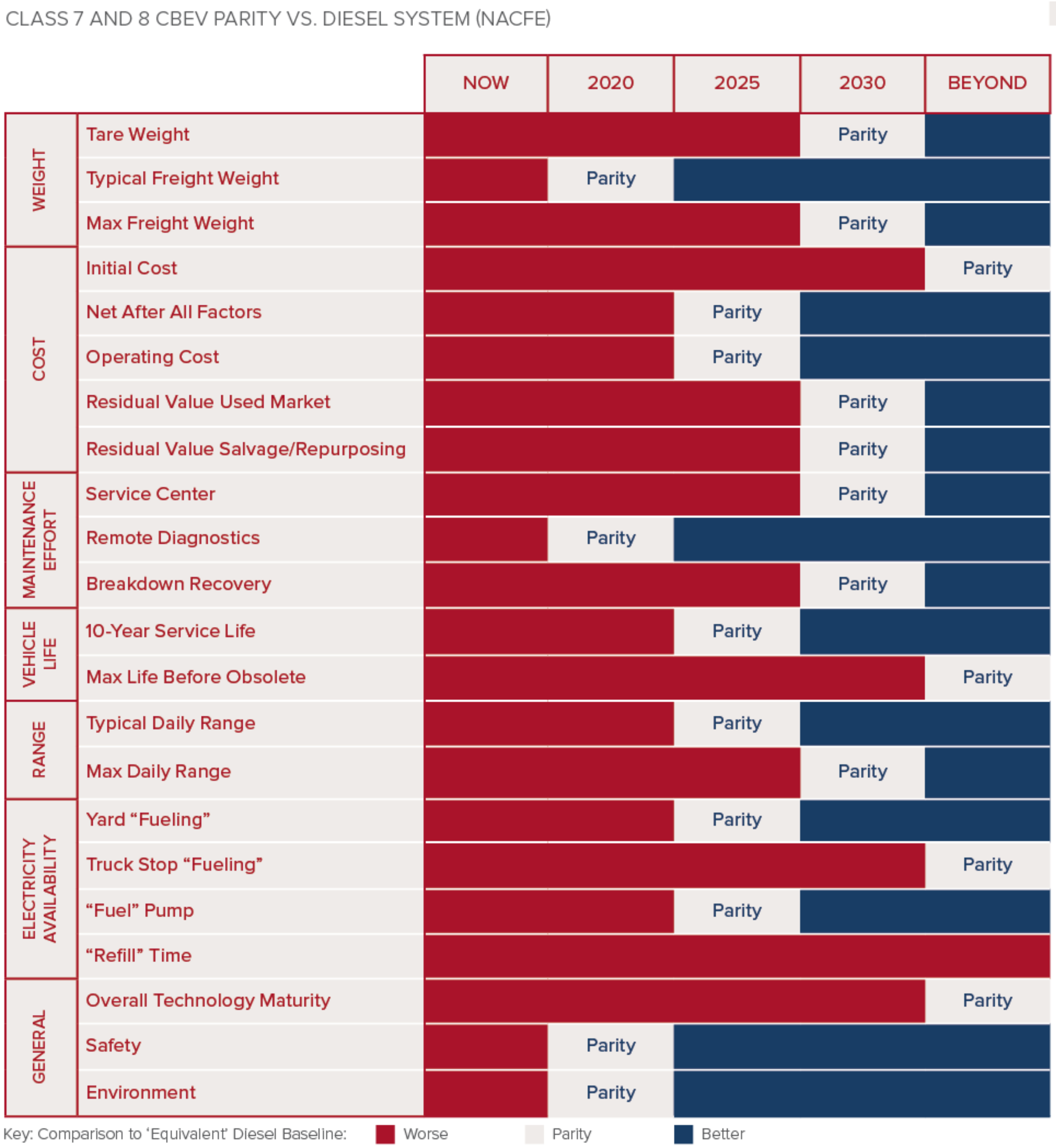


Figure 85. Class 7 and 8 CBEV Parity vs. Diesel System (NACFE)

33 CONCLUSIONS

NACFE's research finds that commercial battery electric vehicles will have an increasing role in freight transportation in Class 3 through Class 8. The transition in specific market segments will be drawn out over decades, sharing space with traditional diesel and gasoline powertrains and also competing with other new technologies like fuel cells and hybrids.

The rapid pace of battery energy density improvement will spur increases in CBEV efficiency that likely cannot be matched by evolutionary changes to the internal combustion engines. These competing technologies are at different points in maturing on their innovation S-curves, with the greater potential going to the newer CBEVs.

CBEVs require new electrical charging infrastructure, which will take time and capital to build. There are new business opportunities for the charging infrastructure that may accelerate this, such as utilities or third parties providing the charging stations to factories and warehouses. The lack of current infrastructure is not a detriment to CBEV adoption. Rather it is an opportunity for market growth. Infrastructure generally always follows product innovation. New technologies spawn development of improved infrastructure. That development encourages product market penetration, a recurring cycle seen in many new technologies.

Commercial battery electric vehicles must be reliable to gain market confidence. The experiences in this decade have largely been with small volumes of vehicles produced by smaller manufacturers. These early entrants have experienced typical learning curve issues with new product introductions. Reliability of the new CBEV technologies will improve through OEM experience with increasing numbers of vehicles on the road. The large OEMs will enter the market with production CBEVs providing long-term stability for fleets considering CBEVs. New OEM entrants such as Tesla, Thor, Chanje, and others will speed innovation through competition for market share.

Maintenance and service cost reduction is an open question at this time. The industry is still at the early stages of development where designs have not yet matured through significant field experience. Preliminary indicators from automotive experience show that these costs are average or slightly better than typical internal combustion alternatives. Feedback from medium-duty electric truck operators suggests that after separating out early failures, these vehicles have lower maintenance costs than diesel over the long run.

Cost is always a critical factor in fleet technology decisions. The net costs/benefits of CBEVs require more effort than traditionally limited ROI calculations. Multiple factors need to be included, from the straight forward such as grants, incentives and taxes, to hard-to-dollar-quantify items such as emissions credits, brand image, liability costs, disposal costs, indirect costs, driver/technician retention or attraction, potential customers and other opportunity costs/benefits buried in overhead or ignored in traditional ROI calculations. There are also new business model innovations related to costing delivering energy to the vehicle.

The CBEVs will not be a solution for every market or every lane. Mixed fleets (that may include diesel, natural gas, hybrid and CBEV) optimized for specific routes and duty cycles will likely be the norm through 2050. Early adopters will be in the urban delivery Class 3 through 6 segments where operations are characterized by fairly stable route definitions between 50 and 100 miles per day, loads tend to cube out, and vehicles run one shift per day and return to the same base location. Longer ranges and heavier weights in Classes 7 and 8 are possible in specific operations, but will not be viable in all roles. Roy Horton, Mack's Director of Product Strategy, summarized this well in a *Heavy Duty Trucking* interview in December 2017. He said, "Mack believes the earliest adopters of electrification will be operations with the chance to charge at a home base and not depend on general infrastructure for fuel. That includes refuse, local delivery, and public transportation fleets. Next would be applications with fixed routes where infrastructure is established but longer ranges are less of a concern. That opens opportunities for local distribution, regional haulers, and select vocational segments. Longhaulers would be the last to use the trucks, drawing on power from secured infrastructure [140]." These thoughts are echoed in NACFE's interviews with OEMs, suppliers and fleets for this report.

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