GUIDANCE REPORT:

Medium-Duty Electric Trucks Cost Of Ownership

ABSTRACT This report focuses on total cost of ownership (TCO) decision factors for North American medium-duty commercial battery electric vehicles (MD CBEV). NACFE's provides unbiased reporting detailing the multiple factors to consider in selecting medium-duty CBEVs, with attention to considering all of the cost/benefit factors in estimating return on investment. 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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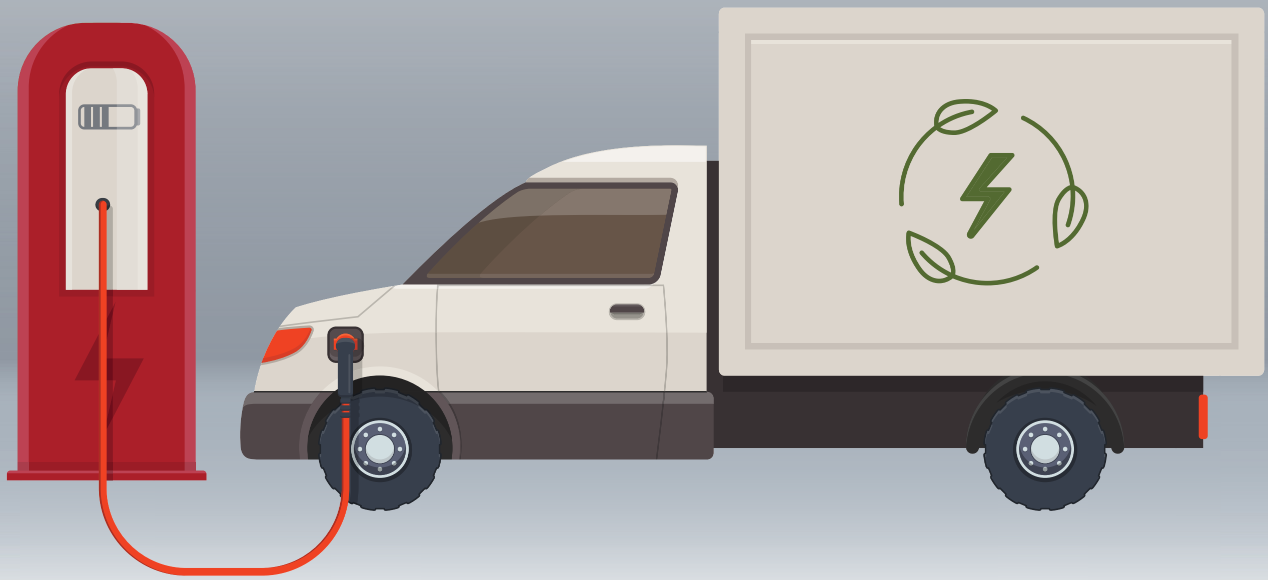

MEDIUM-DUTY ELECTRIC TRUCKS—COST OF OWNERSHIP

Innovation and technological advances in commercial electric trucks are producing technologies and practices that could affect decisive, revolutionary, and potentially disruptive opportunities across the transportation industry. As novel concepts, new applications, and creative 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. The North American Council for Freight Efficiency (NACFE) believes the first generation of production technologies will perform better and have higher return on investment when fleet managers, manufacturers, and others use insights from NACFE Guidance Reports.

NACFE created this Guidance Report to help fleet owners understand the total cost of ownership (TCO) decision factors for North American medium-duty commercial battery electric vehicles (MD CBEVs). Battery electric technology exists as an option in competition with other powertrains; modern fleet managers must evaluate when and how to add MD CBEVs to their fleet. Also, we expect the multitude of manufacturers, truck builders—both established and start-ups—and component manufacturers to utilize the findings in this report to improve their initial and ongoing product offerings.

Currently, these decisions must be made with little long-term field history; CBEVs lack significant historical operational, maintenance, or cost data that would typically support such investment decisions. Yet these unknowns are not stopping fleets from moving forward. Evolving emission regulations have created demand for zero- and near-zero-emission vehicles. At the same time, e-commerce is changing trucking. The rise of online purchases (and returns) has increased "last mile" delivery volume and demand for medium-duty trucks. These issues, combined with potential fuel price volatility, are forcing the industry to pursue emerging technologies.

To support the industry's adoption of the most promising fuel efficiency technologies, NACFE expanded its role with Guidance Reports—providing information on emerging 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 pioneering 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.

This Guidance Report on medium-duty electric trucks represents the second in a series that will be released in 2018 and 2019 by NACFE. The first, *Electric Trucks—Where They Make Sense*, was released in May 2018. Subsequent reports will focus on charging infrastructure and the cost of ownership of heavy-duty regional-haul tractors and heavy-duty long-haul electric-based tractors, resulting in five Guidance Reports in the series.

The goals of this Guidance Report are to (1) provide insights on the known and unknown factors affecting the cost of MD CBEVs, (2) provide a foundation for using the NACFE TCO calculator to evaluate MD CBEVs, and (3) provide quality information to make sound business decisions on this emerging technology.

METHODOLOGIES

This report's conclusions were generated through interviews of people with firsthand knowledge of MD CBEVs at fleets, original equipment manufacturers (OEMs), industry groups, and agencies. NACFE researched an extensive list of over 300 references with the same diligence and thoughtful processes it uses for all of its Confidence Reports on existing technology. The complete list of references is available in the full report.

NACFE developed a TCO calculator to compare diesel and gasoline truck investments against comparable battery electric trucks. The use of this calculator will support the monetizing of the many factors that exist when operating an electric truck versus a gasoline or diesel one. The calculator is available at www.nacfe.org.

Image courtesy of Motiv

Image courtesy of AmeriPride Services

SCOPE OF THIS REPORT

The report focuses on MD CBEVs currently in production or planned for early production in the near future. For the purpose of this study, NACFE uses the Federal Highway Administration definition of "medium-duty," which includes vehicles with a gross vehicle weight rating between 10,001 and 26,000 pounds.

FIGURE ES1

Gross Vehicle Weight Rating (lbs)	Federal Highway Administration	
	VEHICLE CLASS	GVWR CATAGORY
< 6,000	Class 1: < 6,000 lbs	Light Duty < 10,000 lbs
10,000	Class 2: 6,001–10,000 lbs	
14,000	Class 3: 10,001–14,000 lbs	Medium Duty 10,001–26,000 lbs
16,000	Class 4: 14,001–16,000 lbs	
19,500	Class 5: 16,001–19,500 lbs	
26,000	Class 6: 19,501–26,000 lbs	
33,000	Class 7: 26,001–33,000 lbs	Heavy Duty > 26,001
> 33,000	Class 8: > 33,001 lbs	

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Image courtesy of Ryder System Inc.

NACFE's primary mission is making freight movement more efficient. Therefore, the primary configurations discussed in this report are box trucks and step vans, although the information is also largely relevant to flatbeds, stake-sides, utility trucks, and other configurations. These findings exclude vehicles with fifth wheels and trailers. They also exclude buses and trucks in applications other than goods movement, such as medium-duty refuse trucks, service vehicles, and vehicles like snowplows.

This report compares the TCO of electric trucks to diesel- and gasoline-powered alternatives. NACFE concludes that these are the most pertinent comparisons facing medium-duty fleets. Other alternative fuel choices exist but are outside the scope of this report.

TCO is determined by the relevant direct and indirect costs; known and estimated cost information is divvied into buckets directly linked to manufacturing or diffused in overhead. NACFE employed the terms "hard costs" and "soft costs" in an earlier Guidance Report. Put simply, hard costs are consistently tracked and directly measurable; soft costs are less capable of granular tracking, obscured deep in overhead, or not included. Some soft costs are generally known, whereas others are less certain. Soft costs can also be positive (monetized benefits of electric trucks) or negative (costs). It is easy to avoid change and overestimate the risks to negative costs when considering something as strikingly new as an electric truck over a diesel or gas one.

EVALUATING ELECTRIC FOR YOUR MEDIUM-DUTY FLEET

The breadth of Class 3 through Class 6 duty cycles is significant. Based on vocation, medium-duty trucks have unique duty cycles influenced by their location, customers, truck type, and varying fleet business models. However, common factors make this class of vehicles more attractive for battery electric technology, at least in the short term. Medium-duty fleets typically operate from a fixed starting and return location, for example. These vehicles tend to be located in urban areas and have predictable daily mileage and stop-and-go driving patterns.

Medium-duty vehicles with one-shift-per-day operations offer the most straightforward application for battery electric vehicles; as trucks sit idle for long enough periods of time, they can be charged at cost-effective rates and with fewer infrastructure demands. The operational complexity increases as the number of duty shifts increases. Remote charging or additional vehicles may be required for three-shift-per-day operations because there is little or no downtime between shifts.

Weight is not typically a factor when evaluating the fuel source for medium-duty vehicles. Both fleet and OEM interviews indicated that most medium-duty vehicles cube out before overloading becomes a constraint. However, NACFE did identify some weight-sensitive medium-duty applications, such as linen, paper, and beverage delivery.

The duty cycles for medium-duty trucks have commonalities that make them attractive for battery electric technology, such as:

- Low daily average speeds (< 35 mph)
- Low average drive time (< 2.75 hours per day)
- Predictable daily distances
- Stop-and-go driving patterns
- Fixed start and return locations, often near urban areas

ELECTRIC VEHICLE INFRASTRUCTURE COSTS

Although trucks tend to get the brunt of media attention, the infrastructure for charging electric trucks is just as important to consider, especially when doing a TCO analysis. Because diesel- and gasoline-powered trucks have fueling infrastructure in place—or take advantage of public fueling stations—performing an equivalent cost analysis can be complicated. An inability or unwillingness to consider the infrastructure costs of diesel and gasoline trucks may bias the numbers in favor of internal combustion vehicles.

Buying an electric truck involves significant planning, particularly compared to diesel or gasoline trucks. A major factor in battery electric truck operation is the need to charge the vehicle. Whereas diesel- and gasoline-based trucks may travel for days between fueling, MD CBEVs will need to be partially or fully charged after or during a shift. Significant infrastructure will be required, because electric charging systems are not as prevalent—or as standardized—as oil-based fueling stations.

Electric vehicle infrastructure costs can vary widely depending on a range of factors. Typically, electric fleets require (1) dedicated time and real estate, (2) a charging system, (3) an adequate power supply, and (4) a battery management system. The needs and related costs generally multiply with the number of electric vehicles (a future report will address the charging infrastructure).

REAL ESTATE

The footprint of individual charging stations is fairly minimal. However, there are operational implications when a vehicle must be colocated with charging equipment for an extended period of time to allow for charging. The ramifications are that specific parking spots or warehouse docks need to be dedicated to a vehicle for the time it takes to charge.

CHARGING SYSTEMS

Getting electricity from the meter to a vehicle requires a connector. There are several automotive-based charging systems today, but the market has not yet evolved to any one standard. The reality is that trucks are being developed concurrently with charging systems. Both wired and wireless charging options are being explored, as are plugs, overhead, and in-ground conductive charging.

Although extreme fast charging (XFC) has been cited as necessary for the rapid adoption of personal-use electric cars, the importance of XFC in the medium-duty vehicle class is still unknown. Importantly, the rate of charge can affect the cost of charging equipment, infrastructure, and electricity.

ADEQUATE POWER SUPPLY

If a facility doesn't have adequate power supply from a utility provider, additional grid work may be needed. Other "behind the meter" solutions also exist, such as on-site battery storage and solar- or wind-power generation. One of the benefits of electricity is that it can be produced, stored, and delivered in many ways.

Unlike the well-established business models for diesel and gasoline fueling stations, the way charging systems are to be financed, owned, and operated is open to significant innovation. Charging system business models may include utilities, vehicle OEMs, third-party operators, site owners, municipalities, and others in addition to the fleet operator. Charging systems may be purchased outright, leased, rolled into the cost of electricity or the cost of the vehicle, or financed through other new approaches.

BATTERY MANAGEMENT

In addition to battery factors such as useful life, range, weight, cost, and safety, NACFE identified two key battery behaviors that fleets should understand: charging speed and battery cell balancing.

The speed at which lithium-ion batteries recharge depends on their level of depletion (i.e., the state of charge). Smart charging capabilities can simplify charging system operations and improve battery life, furthering opportunities to reduce costs.

Battery packs comprise hundreds of individual battery cells, each with their own "behavior." Performance typically is defined by the worst-performing individual cell. Degradation occurs over time but is not uniform.

Fleets can minimize downtime and extend battery life through established battery management practices and planning.

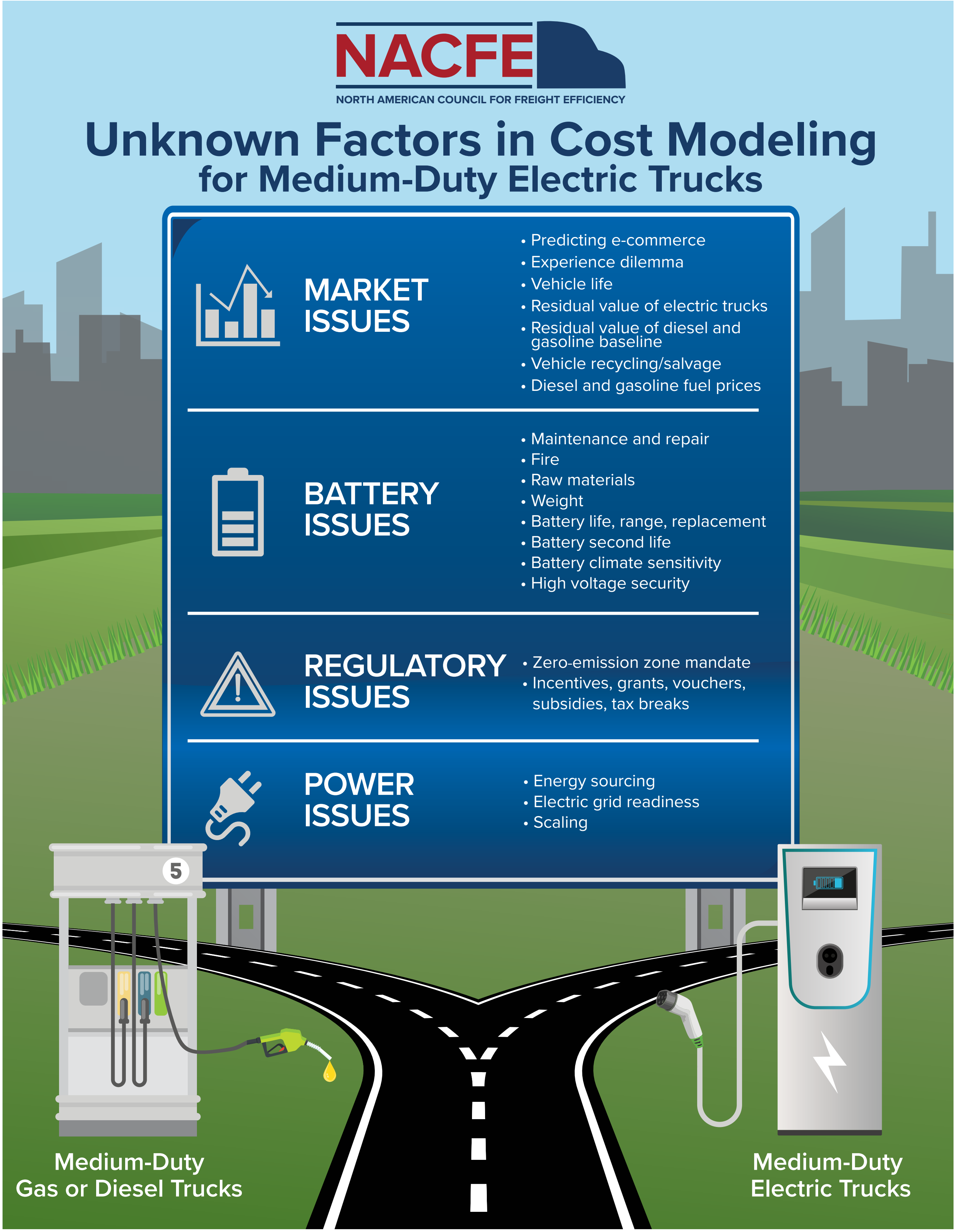
KNOWN AND UNKNOWN FACTORS IN COST MODELING

Because the field history is minimal, TCO cost modeling for battery electric vehicles involves a number of projections, estimates, and guesses. NACFE has identified 20 generally unknown factors concerning modern fleets.

Overwhelmingly, the uncertainties come from insufficient field data to establish a baseline for comparison against alternative truck types. In general, the lack of historical information makes TCO more difficult to calculate.

Image courtesy of iStock by Getty Images

FIGURE ES2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Unknown Factors in Cost Modeling
for Medium-Duty Electric Trucks
MARKET ISSUES
• Predicting e-commerce
• Experience dilemma
• Vehicle life
• Residual value of electric trucks
• Residual value of diesel and gasoline baseline
• Vehicle recycling/salvage
• Diesel and gasoline fuel prices
BATTERY ISSUES
• Maintenance and repair
• Fire
• Raw materials
• Weight
• Battery life, range, replacement
• Battery second life
• Battery climate sensitivity
• High voltage security
REGULATORY ISSUES
• Zero-emission zone mandate
• Incentives, grants, vouchers, subsidies, tax breaks
POWER ISSUES
• Energy sourcing
• Electric grid readiness
• Scaling
5
Medium-Duty
Gas or Diesel Trucks
Medium-Duty
Electric Trucks

Many of the uncertainties are accompanied by opportunities for innovation and growth:

- The future for medium-duty trucks to facilitate e-commerce is promising, but unknown. As demand for near-instant delivery increases, local delivery fleets may increase in size.
- Emission regulations will force manufacturers to produce viable alternative technology platforms and encourage purchases of lower-emission vehicles. However, zero-emission mandates may apply only to specific municipalities, regions, or states.
- It is difficult to predict future diesel and gasoline prices. However, politics, conflicts, innovation, natural disasters, and economics all play into oil pricing, whereas electricity-based vehicles are not tied to the economics of a single energy source.
- Insufficient information exists to establish a baseline period of ownership or an expected vehicle life span. But it is reasonable to assume that battery electric vehicles, if they are more reliable, may lead to longer ownership periods.

TOTAL COST OF OWNERSHIP

When deciding whether to replace old technology on a vehicle platform, there are four steps to calculate the cost of the life-cycle replacement:

1. First, identify costs that can directly carry over from prior designs. In the case of CBEVs, tires or headlamps may be the same for both electric and diesel vehicle designs.
2. Second, define where costs will vary only slightly; these can be estimated as a percentage change from the known prior costs. For example, brake replacement parts and labor costs might be expected to be less on electric vehicles because of regenerative braking. So, the costs would be the same but would occur less frequently.
3. Third, identify costs that must be projected using known sources rather than a historical baseline. For a battery electric truck, you might use the maintenance costs of an electric motor from another vehicle or machine type as a reference point.
4. After the first three numbers are calculated, educated guesses come into play. A key example might be estimating the residual value of battery electric vehicles in 10 or 20 years or estimating the market for used batteries.

Every value used in a TCO analysis includes risk. Where parts, warranty, maintenance, or disposal costs are well established, the risk is less. When dealing with new technologies, the risk is greatest due to the large number of unknowns. This is especially true with medium-duty battery electric trucks, where limited long-term field data exists. These risk values can be quantified in the cost groupings to provide an estimated range of possible total cost of ownership for a vehicle system.

COST CALCULATORS

In preparing this report, NACFE surveyed a number of publicly available calculators and tools to help manufacturers measure TCO. About a dozen calculators, ranging from simple to complex, are highlighted in an appendix in the full report.

NACFE considered the strengths and weaknesses of each calculator in developing its MD CBEV TCO calculator for comparing diesel and battery electric vehicles. The NACFE TCO calculator is intended to compare investment in one or several diesel- or gasoline-powered baseline trucks against an equivalent battery electric alternative. It accounts for the following criteria:

- System scope
- Duty cycle
- Battery factors
- Incentives (e.g., grants, rebates, and tax breaks)
- Charging infrastructure
- Residual value
- Cash, lease, and loan options
- Fuel and energy costs
- Maintenance costs
- Equivalent highway trust fund costs
- Other indirect cost factors

The downloadable calculator developed by NACFE is available at **www.nacfe.org**.

A LESSON TO BE LEARNED FROM DIESEL LOCOMOTIVES

There are a number of parallels between the dieselization of locomotive engines, which primarily took place in the 1940s and 1950s, and today's transition to CBEVs. For example, Jeffrey Schramm of Lehigh University documented one locomotive freight operator during this transition period. His case study highlights that simply substituting the new diesel-electric locomotive for the tried-and-true coal-steam locomotive was not a recipe for being a successful freight competitor. Fleets that adapted to optimize their operations for the attributes of the new diesel-electric technology were ultimately better positioned for success.

"The Lehigh Valley initiated dieselization to save money and effect higher operating efficiencies, but the change in motive power did not appreciably change the way that the railroad purchased locomotives or operated until well after complete dieselization was achieved. The railroad simply substituted diesels for steam locomotives and did not utilize the new motive power to reshape dramatically their operations. The railroad integrated diesels into the existing system instead of rebuilding the system around their different capabilities. The reasons for this failure to utilize fully the new diesel locomotive are many but include operational, labor, and business practices. The Lehigh Valley, while adopting a new technology, did not change its corporate culture or operating philosophy. In the broader historical context, this is a study of how large organizations built around a technological system, deal with the introduction of radically new technologies." [1]

Revolutionary technological change in freight has occurred many times in the past, such as wagon trains migrating to steam locomotives, the introduction of the internal combustion engine in urban and rural truck freight hauling, the dieselization of freight train services, the introduction of jet engine overnight freight transport, and the introduction of digital engine control modules.

Electrification of freight trucks is just starting. Whether it revolutionizes the industry will depend on a number of factors, many of which are uncertain at this point in time, but the historical example of dieselization of locomotives can highlight how quickly significant changes can occur in the freight hauling space.

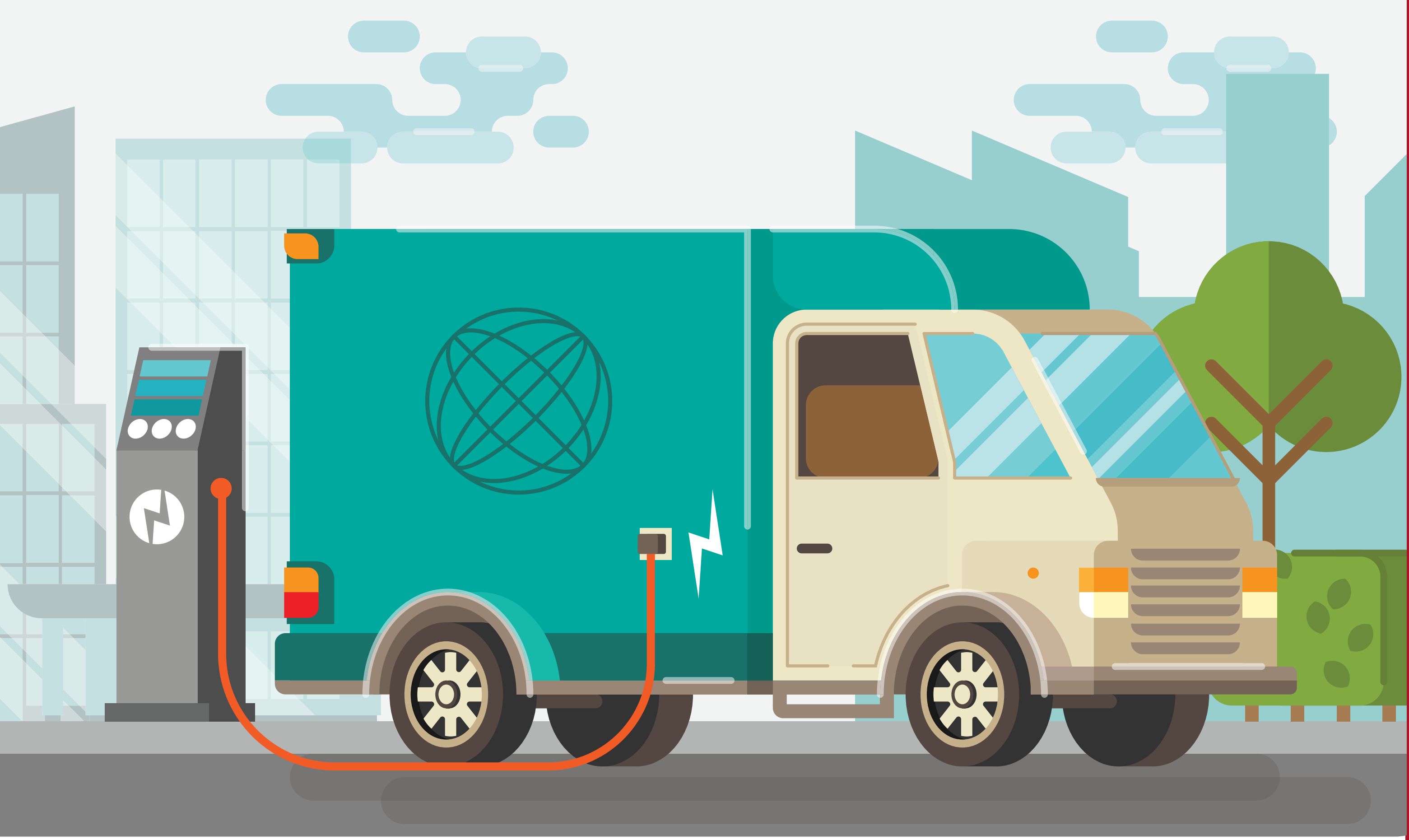
"First, we are nearing upfront cost parity for MD electric trucks, and the total cost of ownership will be lower. Second, these powertrains will operate more efficiently, and third, with zero on-road emissions, quiet operation, and the cool technology employed, these trucks engage and excite employees, knowing they're working for a company with a greater purpose."

—Scott Phillippi, Senior Director of Maintenance and Engineering, UPS

Image courtesy of Thor Trucks

Image courtesy of DHL

[1] Jeffrey Wilfred Schramm, *Black Diamonds No More: A Technological History of the Dieselization of the Lehigh Valley Railroad*, master's thesis, Lehigh University, 1995; http://preserve.lehigh.edu/cgi/viewcontent.cgi?article=1349&context=etd.



CONCLUSIONS AND RECOMMENDATIONS

There are a large number of knowns and unknowns that influence the total cost of ownership for medium-duty commercial battery electric vehicles. More miles of fleet use are needed to predict performance, maintenance costs, residual markets, and other key factors with confidence.

Emission rules, the growth of e-commerce, and other factors will continue to change trucking. OEMs and fleets will be challenged to meet increasing mandates on acceptable economic terms. Even so, CBEVs are a viable alternative for many operations and applications. The diversity of companies that could benefit from the electric truck marketplace may give the industry inertia that prior innovations didn't have. Because CBEVs are not constrained to a single source of fuel, their development should not be affected by political and economic storms that can hinder internal combustion vehicles.

CBEVs are no longer speculation. They are clearly entering the North American marketplace, with every major existing OEM and a number of new ones introducing products. Although they are not the solution for every market, they are a viable alternative for many urban operations with reasonably predictable daily ranges and return-to-base operations that permit economical overnight charging.

Fleets choosing electric trucks today will get on the learning curve ahead of those that wait. Early adopters will expose flaws and omissions that OEMs and charging system suppliers will correct. They will validate or dismiss CBEV claims. They will also learn how to optimize their operations to make the most of electric vehicles for improving their company's bottom-line financials. As CBEVs improve, these early adopters will be better positioned to rapidly take advantage of the improvements, and their experiences will drive innovation.

THE FULL REPORT

The full report is available at www.nacfe.org and includes 318 references; a robust, current, relevant bibliography of CBEV works; 173 figures; and 28 NACFE graphics, of which 23 are new. See the Table of Contents below for more information on the full report:

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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 Rocky Mountain Institute (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 INTRODUCTION

This report focuses on total cost of ownership (TCO) decision factors for North American medium-duty commercial battery electric vehicles (MD CBEV). NACFE previously identified in the Guidance Report: Electric Trucks – Where They Make Sense that the medium-duty market is the most likely one for significant near-term adoption of battery electric technology versus comparable diesel and gasoline powertrains [1]. This is the second in a series of NACFE guidance reports on electric trucks. It will be followed in 2019 by guidance reports on charging infrastructure and one covering heavy-duty Class 7-8 electric vehicles.

NACFE's intent is to provide an unbiased report detailing the multiple factors to consider in selecting medium-duty CBEVs, with attention to considering all of the cost/benefit factors in estimating return on investment. These include the traditional items like part cost, labor, insurance, etc., that are relatively straight forward to estimate in terms of dollars, referred to as hard costs. They also include a multitude of less easily quantifiable factors, classified as soft costs.

Technology is not an end in itself but rather a means to accomplish the commercial goal of moving freight for profit. Battery electric technology exists as an option in competition with other powertrains including diesel, gasoline, fuel cell, natural gas, hybrid and others. Pascal Amar, Principal Investigator at Volvo Group, stated in a panel on alternative fueled vehicles at the 2018 ACT EXPO, "We don't bring technology to the market, we bring solutions [2]."

Fleets, media, OEMs, regulators, NGOs and the public tend to frame electric trucks versus diesel and gasoline ones as a winner take all, knock-down drag out fight with a single winner. This one-size-fits-all mentality has no parallel in the real world of freight transport. The argument tends to needlessly cloud discussion. Shipping in the U.S. uses planes, ships, barges, trains, containers, diesel engines, gasoline engines, natural gas engines, with trucks varying from GVW Class 3 to 8 from a variety of manufacturers with differing views on how best to optimize performance. Fleets employ vans, semis, box trucks, flat beds, day cabs, sleepers and straight trucks. Mixed technology has always been part of freight movement. Even brand-centric fleets have differing vintages of emissions technology. Electric trucks are just one more alternative available to fleets. NACFE believes industry and media need to move on from discussing one versus the other in some epic title bout and look to reality where they coexist and are used where they make sense for each fleet. The market will decide what works and what doesn't. Freight has never had a one size fits all fleet even with Ford's Model T. Henry had to compete with technologies such as railroads, ships, horse-drawn carriages, steam powered vehicles and, yes, even electric trucks.

Significant capital and speculative investment in battery electric vehicle development is bringing a number of products out of the nebulous paper design and prototype phase into commercial production. The evolving regional and national emissions regulations have created sufficient demand for zero and near zero emission vehicles that major OEMs and start-ups are bringing viable battery electric vehicles to market. This report is intended to help explain where the risks lie for long-term capital investment in electric trucks. It provides a foundation for scenario comparisons using a NACFE Total Cost of Ownership calculator.

5 SCOPE

The report covers medium-duty CBEVs currently in production, or slated for early production by 2019 for freight delivery. There are many interpretations of "medium-duty." NACFE uses the Federal Highway Administration (FHWA) definition, which lists medium-duty as between 10,001 to 26,000 lbs. gross vehicle weight rating (GVWR) as shown in Figure 1 [3][4]. NACFE recognizes that terms like "light-duty" are sometimes interchangeably used for Class 3 vehicles, or for the entire medium-duty range [4][5][6]. Discussion of just the engines can further confuse the issue such as where EPA GHG regulations include terms like "light heavy duty engines" and "medium heavy duty engines" and even "heavy duty engines" in these classes [3][5][6].

Gross Vehicle Weight Rating (lbs)	Federal Highway Administration	
	Vehicle Class	GVWR Catagory
<6,000	Class 1: <6,000 lbs	Light Duty <10,000 lbs
10,000	Class 2: 6,001–10,000lbs	
14,000	Class 3: 10,001–14,000 lbs	Medium Duty 10,001–26,000 lbs
16,000	Class 4: 14,001–16,000 lbs	
19,500	Class 5: 16,001–19,500 lbs	
26,000	Class 6: 19,501–26,000 lbs	
33,000	Class 7: 26,001–33,000 lbs	Heavy Duty >26,001 lbs
>33,000	Class 8: >33,001 lbs	

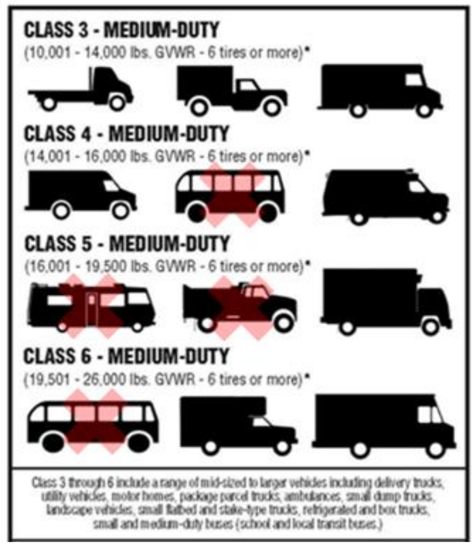


Figure 1. NACFE Report Vehicle Class Weight Definitions (EPA AFDC & FHWA OPS) [3][4]

NACFE's mission is to improve the efficiency of freight hauling by commercial vehicles. As such, this report excludes discussion of medium-duty buses, recreational vehicles, vocational vehicles, ambulances, and other special purpose vehicles.

This report includes relevant references to battery electric buses and cars, where parallels exist and field data on production trucks are not yet available.

The report focuses on comparison to diesel and gasoline powered vehicles. This report does not exhaustively contrast CBEVs directly against pure fuel cell, natural gas, propane or other alternative fuel approaches. The report does not discuss use of range extension alternatives such as with various hybrid approaches.

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.

7 Report Methodology

NACFE's research for this report included interviewing key people with first-hand knowledge of medium-duty battery electric vehicles at fleets, manufacturers, and industry groups. The report includes an extensive list of references to assist reader's interested in pursuing more detail. These references were researched with the same diligence and thoughtful processes NACFE uses with its technology Confidence Reports. A NACFE-developed Total Cost of Ownership Calculator for comparing a diesel or gasoline truck investment to a comparable battery electric truck accompanies this report. Interviewees were specifically asked what they would want to see in this report and NACFE has taken care to include these wants in the final report. This report builds off the NACFE Guidance Report: Electric Trucks – Where They Make Sense, published in May 2108. Subsequent reports, as with this report, will focus on various vehicle classes not covered in this report, infrastructure and associated technologies.

8 Medium-duty Market Defined

The medium-duty market covers many different vocations. A sampling are described on the Freightliner Commercial Custom Chassis (FCCC) website [207]:

- Construction
- Baking & Snack Delivery
- Parcel & Home Delivery
- Linen & Uniform
- Utility Companies
- Municipalities
- Small Tools Sales
- Dry Cleaners
- Gutter Repair & Replacement
- Vending/Food Service
- Florists
- Carpet Installation
- Laundry Services
- Ice Cream
- Airlines
- Locksmiths
- Soft Water & Water Conditioning
- Nurseries & Landscaping
- Small Appliance Repair
- Catering
- Sewer Cleaning
- Electrical Contractors
- Newspaper Delivery
- Audio/Video Production
- Pet Care
- Rug Services
- Blood Banks
- Salvage
- Swimming Pool Supply
- Libraries & Bookmobiles
- Carpenters
- Plumbing
- TV News
- Police & Fire Departments
- Parts Trucks
- HVAC
- Exterminators

Fleets in each of these vocations have their own unique duty cycles based on their locations, customers, truck types and business models. Their vehicles share a common characteristic in that they typically operate daily from a fixed starting location and return there at the end of their day. These businesses tend to be located in urban areas where their vehicles see predictable daily mileage and stop-and-go traffic. Predictable range and the ability to take advantage of regenerative braking are key factors for implementing battery electric trucks. A current compendium of medium-duty electric vehicles and relevant other vehicles of significance can be found in Appendix A. Charging system suppliers are outlined in Appendix B. Existing Diesel and gasoline product makers are listed in Appendix C.

8.1 Representative Duty Cycles

The breadth of Class 3 through Class 6 duty cycles is significant. Defining a few "typical" duty cycles for this market does a disservice to the complexity of the many end user businesses. The growth in e-commerce has muddied the water further by introducing "last mile delivery" as a common term. Last mile can be interpreted many ways. The common use is for parcel delivery, but last mile could equally apply to a range of other commodities from hospital uniforms, laundry delivery, cement, aggregate, hay bales, appliances, bricks, furniture, trusses, plants, sod, tornado shelters, and a range of other items now purchasable through the internet. Electric vehicles may be appropriate for any of these markets. NACFE's report focuses on medium-duty trucks. It excludes vehicles with fifth wheels and trailers. The primary configurations discussed in this report are box trucks and step vans, although the electric vehicle information presented is largely relevant also to flat beds, stake sides, utility, and other configurations.

The major factor in battery electric truck operation is the need to provide time to charge the vehicle. Where diesel and gasoline based trucks may travel for days between fueling, medium-duty battery electric trucks generally need to be charged after or during each shift.

8.1.1 One-Shift-Per-Day Vehicle Duty Cycles

One-shift-per-day operations offer the most straightforward application for battery electric vehicles as the trucks sit idle for long enough periods of time to permit more cost effective electric charging rates, with lower cost infrastructure demands and complexity. An example of a high-level duty cycles is illustrated in Figure 2. There are multiple variations possible with this flow, including charging mid-shift, remote charging, continuous charging, etc. Figure 2 illustrates the simplest approach where the driver starts and ends his shift at a depot facility, where the driver's only charging responsibility is unplugging the vehicle at the start of the shift and plugging the vehicle in at end of shift. The vehicles daily range is within the capability of the battery packs with a margin for weather conditions, traffic, emergencies, loads, etc. The vehicle charges while the driver is off shift. It likely sits at the loading dock overnight allowing the vehicle to be loaded or unloaded so the driver's time is focused on his delivery and pick-ups.

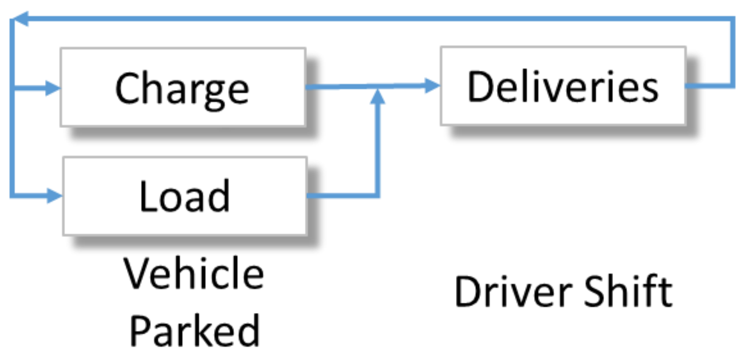


Figure 2. Example One-Shift-Per-Day CBEV Operation [NACFE]

There are a number of business types that might fit into this model. Parcel delivery, traditionally the realm of United Parcel Service (UPS), Federal Express (FedEx), DHL, the U.S. Postal Service (USPS), is now being joined by a number of competitors including branches of fleets like Schneider, Werner, USXpress, Swift, etc., and retailers such as Amazon and Walmart. Grocery delivery has been resurrected as another growing market that likely has one-shift operation. (More on this in the section 10.1.1 on predicting e-commerce). Furniture, appliances and large electronics are being delivered daily by Home Depot, Lowes, Nebraska Furniture Mart, Best Buy and other retailers. Vehicles may reload multiple times during their shift or only be loaded once per day. The drive cycles vary from urban to rural routes. They include various portions of city, freeway and rural highway driving. The cycles include significantly more stop-and-go deceleration and acceleration events than seen by long distance drive cycles. This allows for energy recovery through regenerative braking and other energy efficiency improvement mechanisms including route optimization, adaptive cruise control, and future traffic infrastructure interaction.

8.1.2 Two-Shift-Per-Day Vehicle Duty Cycles

The complexity with charging increases with two-shift-per-vehicle operations. Figure 3 illustrates one of many permutations, showing that the vehicle likely must recharge between or during each shift.

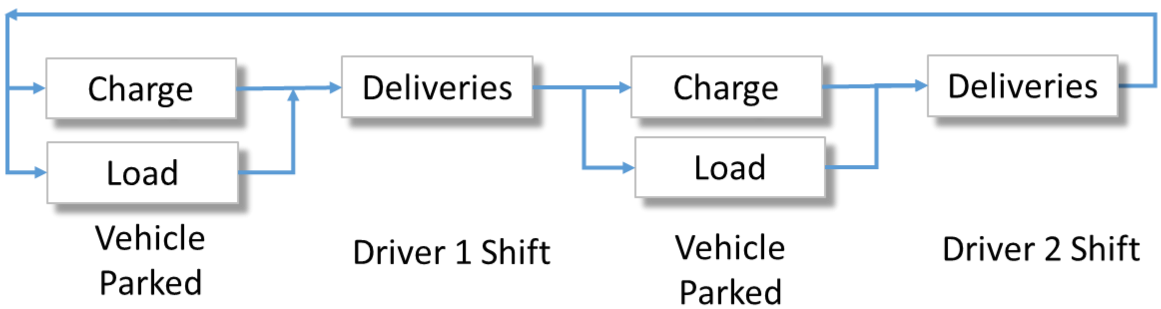


Figure 3. Example Two-Shift-Per-Day CBEV Operation [NACFE]

For diesel or gasoline based vehicles, fuel tank capacities generally exceed a daily need for fills by two or more days. A truck averaging 11 mpg with 30 gallons has a 330-mile range. Duty cycles with 50 mile per shift, could go three days before refueling. That diesel or gasoline refueling event is measured in minutes. A current medium-duty battery electric truck may have a 70 to 100 mile range capacity before it needs to be recharged. That charging event may be measured in hours. A two-shift operation with no significant break time between shifts would necessitate in-shift partial charging to ensure both shifts achieve their daily requirements for the truck. Full recharging could still occur in the off shift. This complexity may mean that operations may need to evolve to adapt to the electric vehicle charging needs. A two-shift operation may need a sufficient break time between first and second shifts to "top off" energy sufficiently to ensure the second shift completes its route unimpeded.

8.1.3 Three-Shift-Per-Day Duty Cycles

The ultimate challenge for battery electric vehicles to fit into existing business operations are those fleets that operate three-shift-per-day operations. An example of the ramifications of introducing daily recharging per shift is shown in Figure 4.

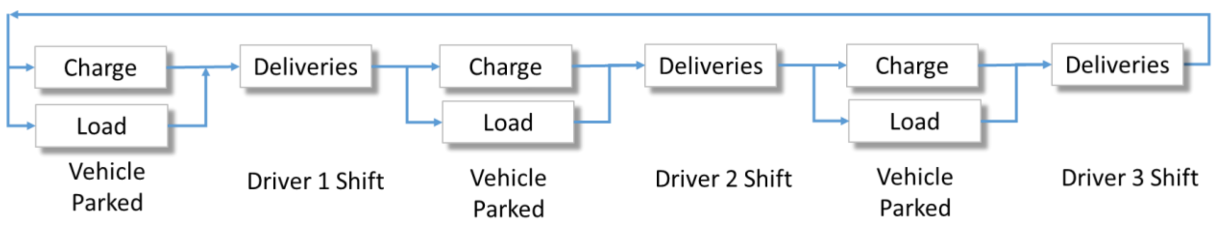


Figure 4. Example Three-Shift-Per-Day CBEV Operation [NACFE]

Three-shift operations require mid-shift charging. There is no downtime between shifts for this to occur, making charging part of the driver's time use. Operations with several returns to depot per day may allow charging to not impact driving time. Three-shift operations might require remote charging capability at delivery points. Slip seat 24-hour operations might require two vehicles for each set of three drivers to ensure route distances are covered each day.

8.1.4 Representative Duty Cycles

NACFE identified well-documented drive cycles in Figure 5 developed from the National Renewable Energy Laboratory (NREL) Fleet DNA database and based in part on the Department of Energy Oak Ridge National Laboratory (ORNL) analysis of that database by Gao et al [1][7][8]. The data set comprises eight duty cycles crossing Class 3 through Class 6 applications. The data originates from actual fleet vehicles in use in real world routes. While not inclusive of all vehicles and duty cycles, the data is indicative of trends and representative enough for discussing the range of requirements facing commercial battery electric vehicles.

	Weight Class & Type							
Factor	Food Delivery Truck (Class 3)	Parcel Delivery Step Van (Class 4)	Parcel Delivery Walk-In (Class 4)	Linen Delivery Van (Class 5)	Food Delivery Truck (Class 5)	Parcel Delivery Walk In (Class 6)	Linen Delivery Step Van (Class 6)	Linen Delivery Walk In (Class 6)
Average Drive Disitance (mile/day)	37	52	46	66	40	36	63	78
Annual Travel Mileage[a]	9,620	13,471	11,911	17,160	10,400	9,404	16,487	20,332
Max Drive Distance (mile/day)	79	132	232	141	81	88	201	262
Average Drive Time (hr/day)[b]	1.12	2.75	2.18	2.42	1.18	2.03	2.07	2.29
Max Drive Time (hr/day)[b]	2.14	4.56	6.17	4.21	2.05	4.16	4.92	5.10
Average Vehicle On Time (hr/day)[c]	1.60	6.73	5.50	6.18	2.98	3.48	4.82	4.54
Max Vehicle On Time (Hr/day)[c]	3.29	11.38	8.78	12.63	18.16	8.40	12.14	11.65
Average Drive Speed (mph)[b]	33	19	20	27	34	16	30	33
Max Drive Speed (mph)[b]	70	71	81	70	71	70	75	68
Average Vehicle On Speed (mph)[c]	22.84	8.30	10.92	11.87	18.23	8.91	14.39	17.78
Average Stops per Mile	0.97	4.04	3.11	1.56	0.92	6.33	1.22	1.07
Max Stops per Mile	3.03	6.87	6.45	3.02	3.04	16.75	3.37	2.65
Average Stops per Day[d]	30.26	181.83	147.53	97.72	30.46	147.00	71.38	68.40
Max Stops per Day[d]	49	284	242	183	65	277	216	145

*a: 1 year = 5*Ave Drive Distance/day * 52 weeks*
b: Vehicle speed >0
c: Vehicle speed ≥0
d: all duration stops

Compiled from data from ORNL Gao, NREL Fleet DNA, CALSTART, FHWA

Figure 5. Example Duty Cycles for Medium-Duty (NREL/ORNL/NACFE) [7][8]

The duty cycles for medium-duty vehicles have some common themes:

- Total daily average speeds are low – below 35 mph.

- Occasionally see high speeds — above 60 mph.
- Vehicles are actually moving a small portion of their daily shift – below 2.75 hours per day.
- Vehicles can occasionally be in use all day – exceeding 10 hours per day.
- Vehicles see considerable stopping events.

Not included in this data are freight weights. NACFE interviews with fleets and OEMs indicates that vehicles in the linen delivery services may be freight weight sensitive, while other types of operations tend to see freight volume constrained by cubing out.

8.1.5 Baseline Diesel and Gas Vehicles

Investment in battery electric vehicles likely is in comparison to choices for an existing internal combustion engine (ICE) vehicle powertrains. Those powertrains may be diesel or gasoline. Fleets that have operated these vehicles are assumed to have some level of actual performance detail, an understanding of their duty cycles, fuel use, maintenance costs, uptime/downtime, etc. NACFE's total cost of ownership evaluation assumes fleets have a foundational experience in their current costs.

There are differences between diesel and gasoline baselines. One perspective on this can be found in an October 2015 article highlighting differences found by one fleet manager reported in *Government Fleet* magazine [162]. A more recent 2018 view is from *Work Truck* magazine, which discusses findings from Vincentric for light-duty trucks and vans [187][188]. Both reports highlight that diesel trucks tend to be more expensive to purchase, maintain and operate than gasoline ones. NACFE interviews highlighted that aftertreatment emissions systems are a key aspect of these differences.

Other alternative fuel comparison choices exist, but are outside the scope of this report.

9 Charging Infrastructure ROI and Cost Modeling

NACFE interviews with fleets and industry groups consistently identify the charging infrastructure as the main electric vehicle subject needing clarification. People understand fuel pumps from years of first-hand experience filling their vehicles, both gasoline and diesel. They likely do not need to know and may not care about the details of how the fuel arrives at the pump. Even where depots have installed their own fuel pumps, likely only the facility managers have the details of the infrastructure at their fingertips, while everyone else just knows enough to manage pumping fuel into their vehicles, tracking gallons pumped and the odometer reading of the vehicle.

Commercial battery electric vehicles should be similar but with greater automation. The facility manager needs to know the details of installing and maintaining the infrastructure, but the vast majority of the staff only needs to know how to plug in or disconnect the vehicles. The charging system software should be capable of monitoring the charging process, recording details of the charging event, keeping the charging operation within specifications, tracking the usage by vehicle, and even monitoring the health of the vehicle battery systems.

The fundamental challenge with electric vehicles is that the capital investment in the vehicles must be accompanied by some arrangement to provide the infrastructure to charge them. Fleets purchasing diesel and gasoline based trucks already have the infrastructure factored into their costs. They either make use of publicly available fueling stations where the fueling infrastructure capital costs are built into the fuel price, or they already have their on-site fueling capability, where the capital investment to build the fuel pump infrastructure is not linked to the truck purchases, and its maintenance is buried in some net overhead factor for the facility.

An apples-to-apples equivalent cost comparison of electric vehicles and diesel/gas ones should include the same level of cost detail for both. The inability or unwillingness to consider the infrastructure cost of diesel/gasoline trucks biases the numbers in the ROI calculations to some degree in favor of the diesel/gas trucks. If you consider that a fleet buying a medium-duty truck may own it for 20 years, there is certainly some cost attributable to each diesel/gasoline truck tied to installation and maintenance of on-site fuel tanks and pumps, and on-going costs to fill tanks, and on-going costs to certify they are safe and not polluting.

If the fleet uses public diesel/gasoline fueling stations, then the challenge is determining how much of the fuel price is associated with the infrastructure capital and expense recovery. The U.S. Department of Energy estimates the cost of each gallon of diesel and gasoline fuel is broken into its constituent cost centers in Figure 6 [9]. Distribution, marketing and refining constitutes 28% of gasoline's gallon price and 33% of diesel's gallon price. An example gasoline medium-duty truck driving 20,000 miles per year with fuel economy of 10 mpg would use 2,000 gallons of fuel. At $2.80/gal (monthly national average for June 2018), that simplistically constitutes $5,600/year in distribution, marketing and refining cost recovery. Over a 20-year life, that equates to $112,000 in costs associated with infrastructure capital and expense cost recovery.

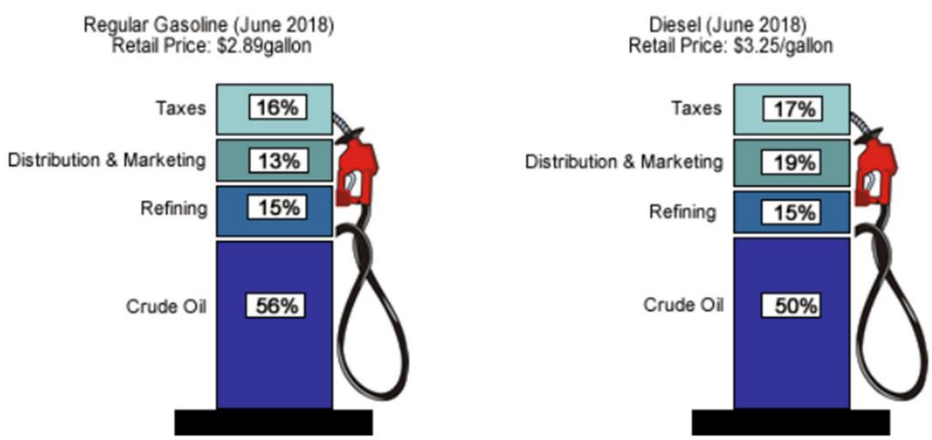


Figure 6. Cost Constituents of Diesel & Gasoline Fuel (DOE EIA) [9]

9.1 Charging System Overview

The way electricity gets to a fleet's electric truck can begin as far back as mining the coal for the power station, or drilling the well for natural gas that runs the power station, or even the fusion reaction in the sun generating the solar power and the moon's gravity effect on earth that combines with the sun to create the winds for the wind turbine farm. Equivalent true well-to-wheel analysis can be complicated. For simplicity, NACFE defines the "charging system" as starting at the point where the electricity enters the national electrical grid, labeled the "generating station" in Figure 7 [10]. The grid consists of all of the infrastructure from the generating station to the end user's facility, usually defined as the utility meter.

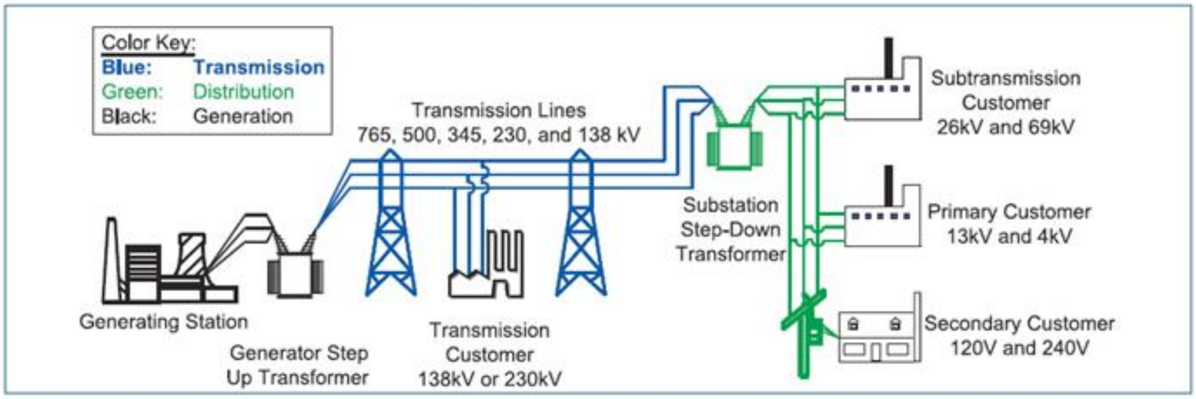


Figure 7. Basic Structures of the Electrical System (DOE/NRCan) [10]

The meter tracks the power consumed for billing purposes. Power is the combined factor of energy used, expressed typically in kilowatts, multiplied by time of use, typically hours – hence the unit of electrical power is kWh (kilowatt-hours).

The final leg of getting electricity to the vehicle involves the on-site infrastructure from the meter to the vehicle shown in Figure 8 [11]. If the facility does not have an adequate power supply from the utility, additional grid work may be needed to run additional lines to the site and install transformers. Other "behind the meter" solutions also exist such as installing on-site battery storage, on-site solar or wind generation, on-site generators run by natural gas, or others and even combinations of these. The nature of electricity is that it can be produced, stored and delivered in many ways; it's not limited to one solution.

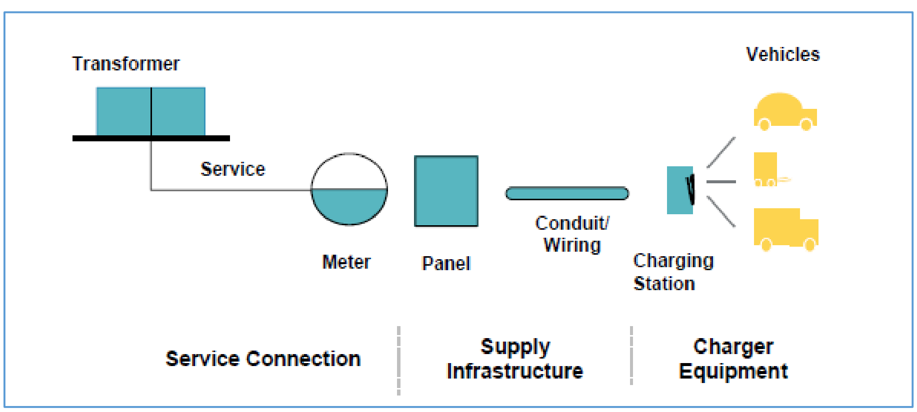


Figure 8. Vehicle Charging Infrastructure Defined (EEI) [11]

The ramifications of on-site charging for a fleet of vehicles are apparent using an example of early electric vehicle supply equipment (EVSE) installation shown in Figure 9 and documented in the 2014 NREL Field Evaluation of Medium-Duty Plug-in Electric Delivery Trucks [12]. Ten Clipper Creek CS-100 EVSE Chargers were installed at the PepsiCo Frito Lay North America depot at Federal Way, Washington [12].

Figure 9. Ten Charging Stations and Facility Power Supply (NREL) [12]

The footprint of the power supply and the individual charging stations is fairly minimal. However, the operational implications are that the vehicles must be co-located with the chargers for some extended period of time to allow charging. This implies that specific parking spots or warehouse docks need to be dedicated to a vehicle for the time it takes to charge.

Figure 10 illustrates how a dedicated parking area was reserved for vehicle charging at the Federal Way facility. Interviews conducted by NACFE with other fleets operating battery electric vehicles highlighted that in some cases the vehicle is charged at the loading dock, meaning that dock is dedicated to that specific truck for perhaps one or two shifts, depending on how fast the company chooses to charge their vehicles. Recall that the rate of charging affects the cost of the charging equipment infrastructure and the cost of electricity used to charge the vehicle.

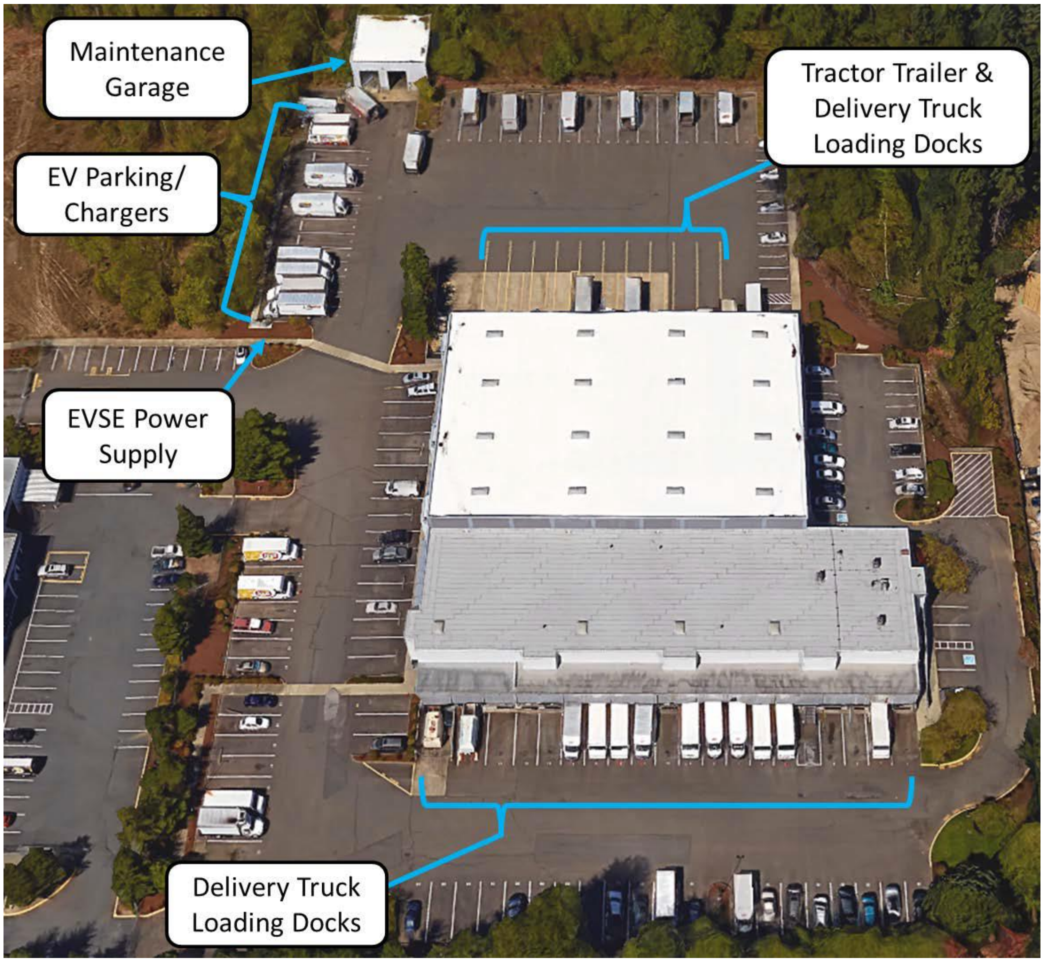


Figure 10. Aerial View of Federal Way FLNA Distribution Center (Base map: Google Earth) [12]

An example of how the infrastructure costs can increase with the speed of charging is provided by ChargePoint in the overview of their Express Plus EVSE system. Their modular approach to charging stations uses a Power Module inserted into a Power Block powering an Express Plus Station, as shown in Figure 11 [13][14]. Adding additional Power Modules into the Power Block increases the power level achievable in charging. Each Power Block can accommodate up to four Power Modules, as shown in Figure 12 [13]. The illustration shows that adding four Power Blocks (each with four Power Modules for a total of 16 modules) achieves 500 kW of energy.

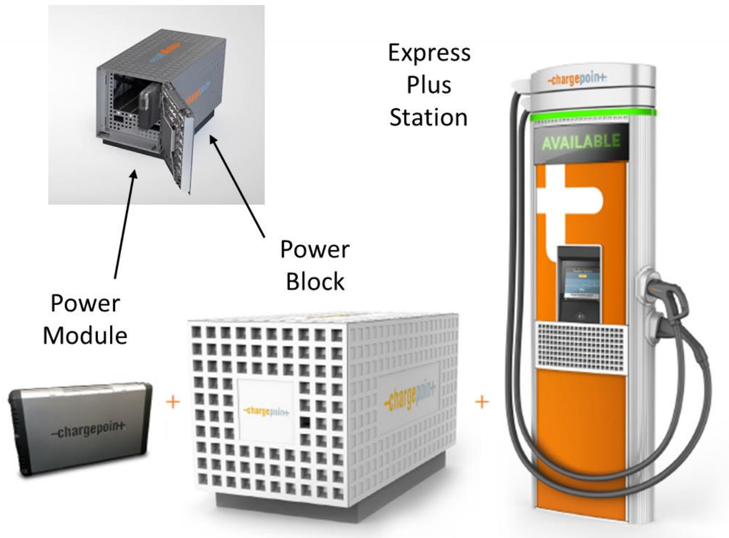
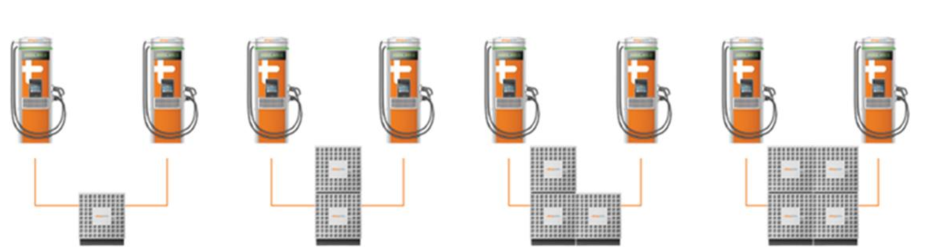


Figure 11. ChargePoint EVSE System Components (Adapted from ChargePoint) [13][14]



Example Configurations	A	B	C	D
Maximum Power/Port (kW)	125	250	375	500
Simultaneous Power/Port (kW)	62.5	125	187	250

Figure 12. Adding Charging Equipment increases capacity (adapted from ChargePoint) [13]

Charging requires definition of the interface, the connector. There are several automotive-based charging system connectors in use today. Various groups are working on standardizing these charging systems. Industry groups such as the Charging Interface Initiative e. V. (CharIN e. V.), SAE International (SAE), International Electrotechnical Commission (IEC), International Organization for Standardization (ISO), individual manufacturers like Tesla and others are defining requirements and recommendations for electric vehicle charging systems. Some vehicles carry multiple connections to allow flexibility in charging station types and capacities. An example is the Mitsubishi Fuso eCanter shown in Figure 13 with two charging methods, a standard 230 VAC single-phase J1772 connection and CHAdeMO 50 kW DC connection [21]. Others, such as the TransPower terminal tractor use only one as shown in Figure 14, a 208V 3-phase, 200A 70kWh fed on-board system [19][20].

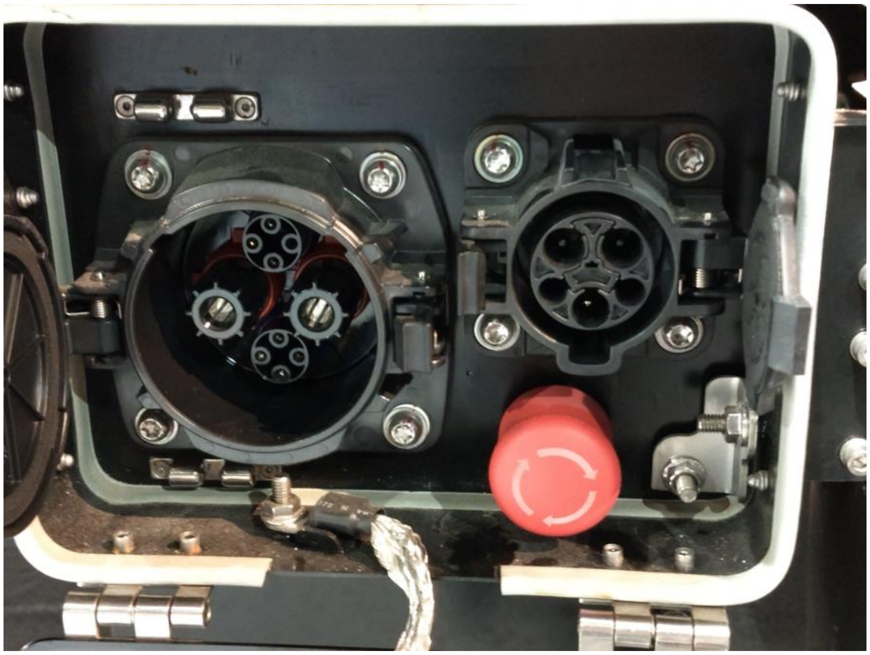


Figure 13. Mitsubishi Fuso eCanterJ1772 and CHAdeMO Charging Connections (Mihelic) [[18]

Figure 14. TransPower EV Yard Tractor 208V Connector (Mihelic, TransPower) [18][19]

The challenge is that electric trucks are being developed concurrently with charging systems and there are no clear indications of where rapid charging, battery technology, grid infrastructure, and electric trucks could go. There is also minimal field history at present with large volumes of electric trucks. Perspectives on this can be read in a 2018 article by Emma Hurt, “Industry Alliance Wants Charging Standard for Electric Trucks, Buses” [15]. Medium-duty trucks likely will build off of automotive experience, as described in the recent 2018 release of J3068 Electric Vehicle Power Transfer System

Using a Three-Phase Capable Coupler [16]. The standard is compatible, though somewhat different, for use also in Europe with the IEC 62196 Combined Charging System (CCS) [53]. The U.S. version is designated CCS 1 while the European one is CCS 2, shown side by side in Figure 15[22]. These examples use dielectric liquid cooled cables, connectors and contacts and are capable of 500A at 1,000V (500kW).

Figure 15. Combined Charging System Connector U.S. CCS 1 and European CCS 2 (ITT Cannon)[22]

The Department of Energy outlined challenges in a 2017 report "Enabling Fast Charging: A Technology Gap Assessment [11]." The report outlines that extreme fast charging (XFC) above 400kW power is needed for more rapid acceptance of electric cars. Megawatt level charging is being discussed as needed for rapid charging of Class 8 electric trucks with ranges of 400 or more miles [1]. Medium-duty vehicles seem to fall between the automotive and on-highway heavy truck charging needs.

The wires used to carry the energy from the power station to the vehicle increase in size and complexity with increasing power level demands. In the ITT Cannon example, cable diameter is reduced by incorporating a dielectric liquid cooling system. The reduced size permits higher level charging rates with cabling that can be maneuvered more easily by an individual [22]. Figure 16 outlines the charge levels.

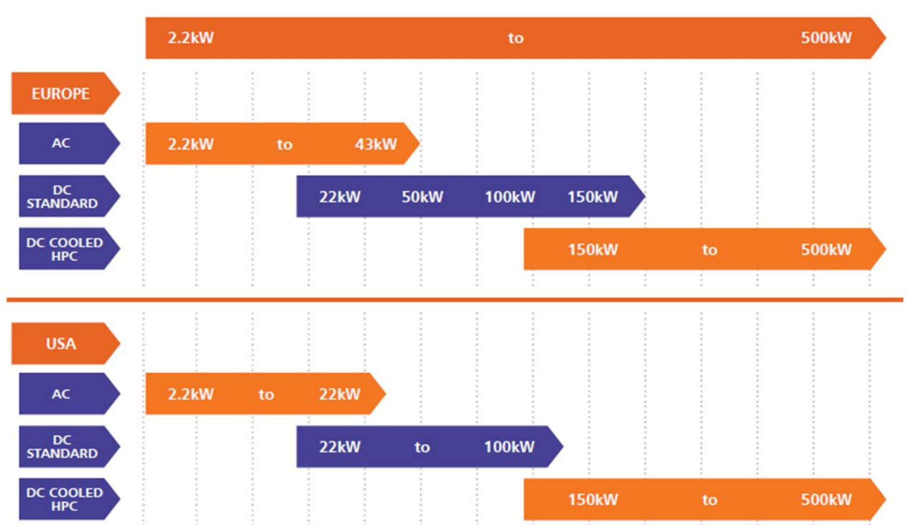


Figure 16. Liquid Cooled Cables Enable Higher Level Charging (ITT Cannon)[22]

Examples of wire diameter were found at Phoenix Contact where a 60A CCS1 cable was 27mm in diameter, a 125A rated CCS1 cable was 35.3mm in diameter, and a 200A rated CCS2 cable was 32mm in diameter. Phoenix Contact is developing cooled cable solutions so they are not yet listed in the catalog, but are described as having "the same geometries as the already established CCS and ergonomically flexible cables [23]". Cable ergonomics will be a consideration for high power/high speed charging systems, where cable weight and flexibility will be challenged at megawatt levels. Figure 17 illustrates the ergonomics of a TransPower charging system.

Figure 17. High Speed Charging Requires Large Diameter Cabling (TransPower)[19]

An alternative to charging through wires and plugs is termed wireless power transfer (WPT). Wireless charging can be via inductive or capacitive methods. A technical overview of these two methods can be found in a National Academies Press report by Khurram Afridi, Wireless Charging of Electric Vehicles [24]. Inductive charging employs magnetic field coupling between an on-ground or in-ground coil(s) and coil(s) mounted on vehicle. A variation of this is called magnetic resonance charging, a Wi Tricity example is shown in Figure 18 [27]. Capacitive methods use electric field coupling between in-ground or on-ground plates and those on the vehicle.

Wireless charging protocols are in use with automobiles and some buses. An example is the 2017 Recommended Practice SAE J2954 Wireless Power Transfer for Light-Duty Plug-In/Electric Vehicles and Alignment Methodology [25]. Applicability of wireless charging to medium-duty trucks is being investigated both in static situations where the vehicle is not moving, and in on-road methods were the vehicle is moving. Static charging presents the least technical challenge for wireless. The efficiency of transferring energy to the vehicle wirelessly is stated as 90%-93%, and energy levels from 3.6 to 22 kW (Level 2) are in use with automobiles [26].

Transit bus wireless charging at 200 kW level are in use. For example, Momentum Dynamics was reported in April 2018 as having deployed a 200 kW system in Wenatchee, Washington servicing a BYD K9S bus as shown in Figure 19 [28][29]. The system demonstrated rapid charging while the bus makes a brief transit stop. However, for the time being, wireless charging technology appears too expensive for the medium-duty truck market, with a few exceptions for niche markets.

Figure 18. Example Magnetic Resonance Wireless Charging System (Wi Tricity) [26]

Figure 19. Example 200kW Wireless Charging (Momentum Dynamics)[29]

Overhead or in-ground conductive charging systems are also being investigated [39]. According to Trafikverket, the Swedish Transport Administration, a "test stretch of the electric road will be inaugurated on the E16 in Sandviken (Figure 20). With that, Sweden will become one of the first countries in the world to conduct tests with electric power for heavy transports on public roads [37]."

In-ground conductive charging is also being tested as seen in Figure 21. "Approximately two kilometers of electric rail have been installed along public road 893, between the Arlanda Cargo Terminal and the

Rosersberg logistics area outside Stockholm. The electrified road works by transferring energy to the vehicle from a rail in the road through a movable arm. The arm detects the location of the rail in the road and as long as the vehicle is above the rail, the contact will be in a lowered position. The electrified road will be used by electric trucks developed as part of the project [38].”

Figure 20. Overhead Conductive Charging (Trafikverket) [37]

Figure 21. In-Ground Conductive Charging (eRoadArlanda) [38]

A stationary version of the pantograph system illustrates an alternative to a manual plug-in conductive charging. The vehicle drives under the charging point and the pantograph deploys to make a physical connection for charging as shown in Figure 22 with an overhead stationary charging system is in use in Louisville, Kentucky installed in 2015 [296][297]. A video of a Louisville bus engaging the overhead charging system is provided by the U.S. Department of Energy [298]. An alternative system from ABB is providing 450kW level fast charging for buses via the system shown in Gothenburg, Sweden [40].

View from Side
Engaging Charging

View at Roof –
Engaging Charging

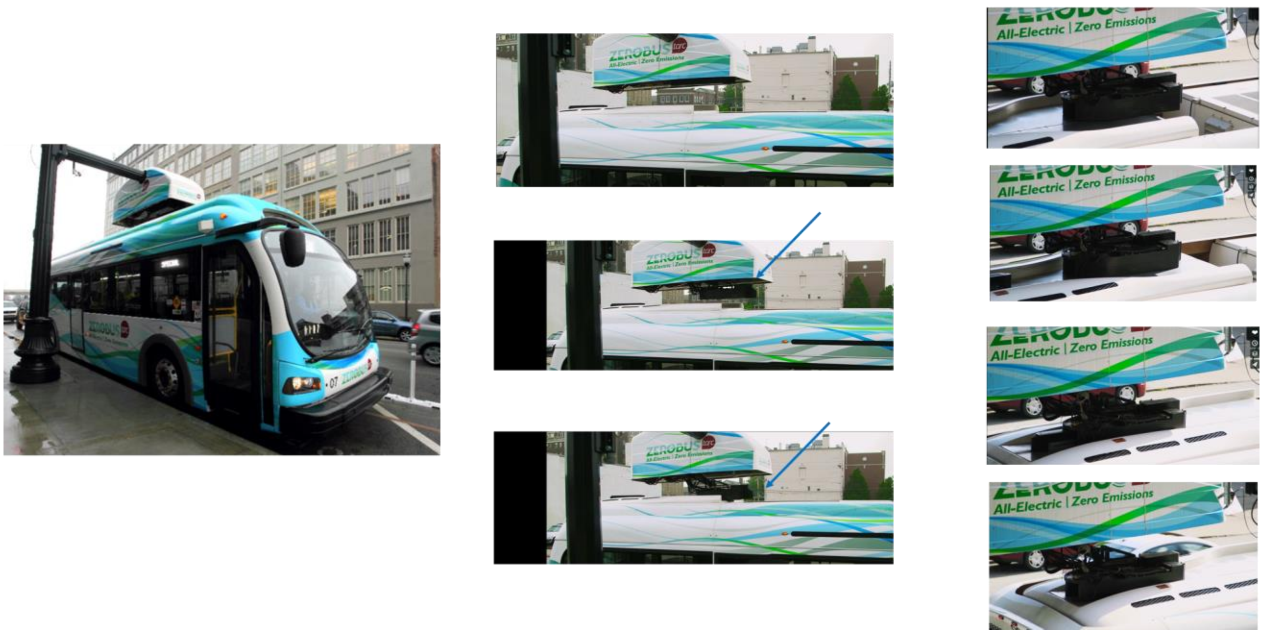


Figure 22. Stationary Pantograph Conductive Fast Charging (Ryan & DOE) [296][298].

The use of battery swapping as a charging scheme has somewhat disappeared from active discussion [214]. Battery swapping was advertised as a mechanism to rapidly charge vehicles by simply replacing the battery packs. The Smith-Newton CBEV had this as a possible option from NACFE interviews of customers with the battery packs located outside of the frame for easy access as shown in Figure 23. The swapping operation was never refined to be quick, and overnight charging evolved as the primary method for restoring battery charge. The Navistar/Modec eStar was designed in 2009-2010 with a "quick-change battery (that) can be swapped out in under 20 minutes [216]." An engineer tied to that program felt this battery swapping was best suited for fleets with two- or three-shift operations. One-shift operations relied on plug-in power for single shift users [215][216]. In automotive, the Better Place Company introduced battery swapping as a service in Israel with goals of marketing the scheme worldwide. The concept was to develop quick-and-drop battery switch stations with interchangeable batteries pre-charged and waiting for the next vehicle [44]. Ultimately this business proposal never materialized into long-term viability [43]. The complexity of rapid battery pack swapping highlights the need for uniform battery configurations across OEMs with consistent system requirements that include rapid swapping [214]. A variation on this was proposed by Mihelic in 2017 where the battery packs would be located in Class 8 semi-trailers, which inherently get swapped regularly at facilities and due to the 3-to-1 trailer to tractor average U.S. ratio, sit idly for long periods allowing slow, inexpensive charging rates [45]. The medium-duty market with fixed box vans and step vans does not have this option.

Figure 23. Smith Newton Battery Pack (Smith) [42]

This charging system overview highlights that innovative solutions to charging infrastructure are being pursued in hardware and in the operational field, not just on paper. There are a myriad of challenges that illustrate that buying an electric truck involves significant planning regarding the charging infrastructure. This is different than buying a diesel or gasoline truck where the infrastructure decisions have already been largely made for the customer. This should also highlight that because the infrastructure is essentially not established, fleets, OEMs, utilities, suppliers and other companies have many possible opportunities for inventing new business models to monetize services and vehicle designs as complete systems including the infrastructure.

9.2 Battery Charging

Battery charging/discharging is complex. Batteries for electric vehicles employ a battery management system (BMS) to deal with this complexity. Through interviews and research, NACFE identified two key behaviors that fleets should understand about batteries: battery charging speeds vary depending on the state of charge, and the individual cells of a battery pack are not the same and require battery cell balancing methods.

9.2.1 Battery Charging Speeds

The speed at which lithium-ion batteries recharge depends on their level of depletion – the state of charge. Batteries charge much quicker from a depleted state than when nearly fully charged. The dashed curve in the example in Figure 24 shows how charge capacity changes with charging time. The knee of this curve, the point where the charging process begins to slow is at about 80% of capacity. In the example graph, 80% of capacity can be charged in the first hour, while the remaining 20% requires two more hours. This is typical for lithium-ion vehicle batteries.

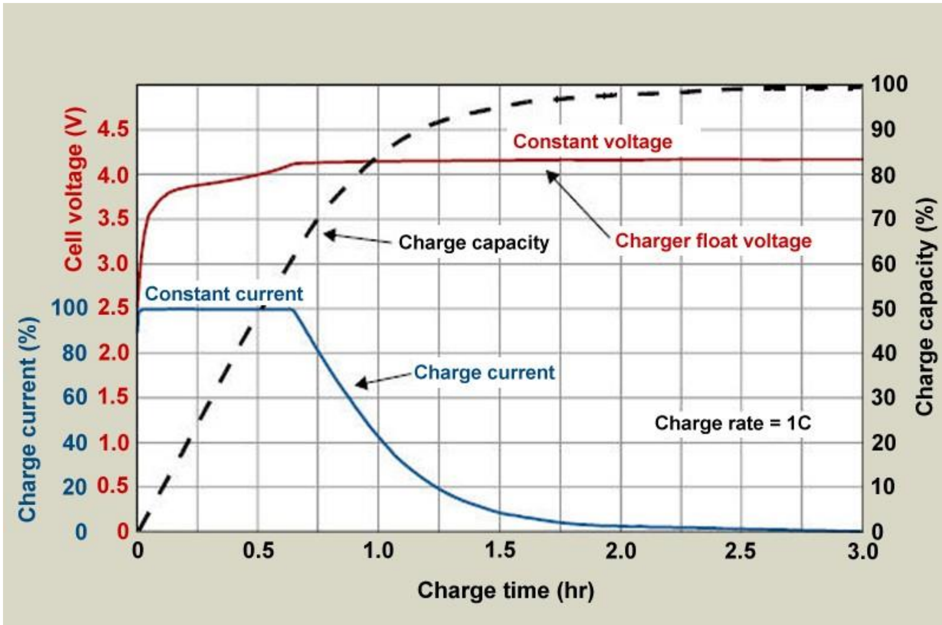


Figure 24. Battery Charging Basics (BatteryUniversity) [180]

This behavior of batteries creates opportunities for smart charging systems to prioritize the order of charging vehicles and to overlay time of day electricity rate variables to optimize charging from a fleet site perspective rather than by individual truck. NACFE interviews with fleets and OEMs highlighted that smart charging capabilities simplify operating charging systems and improve battery life. These can also create further opportunities to reduce costs.

9.2.2 Battery Cell Balancing

A battery pack is made up of hundreds of individual battery cells acting in series or in parallel. Each of those cells has its own behavior, exhibiting "some level of variation in capacity, open-circuit voltage, charge capacity, self-discharge rate, impedance, and thermal characteristics that affect its state of charge (SOC) [183]." The combinations of the cells tend to perform at the level of the worst performing individual cell. Over time, the performance of each cell also degrades. That degradation is not uniform and has some statistical distribution as shown in the example in Figure 25 [183]. Battery manufacturers moderate this behavior through a variety of passive and active cell balancing methods as part of the battery management system [184][185].

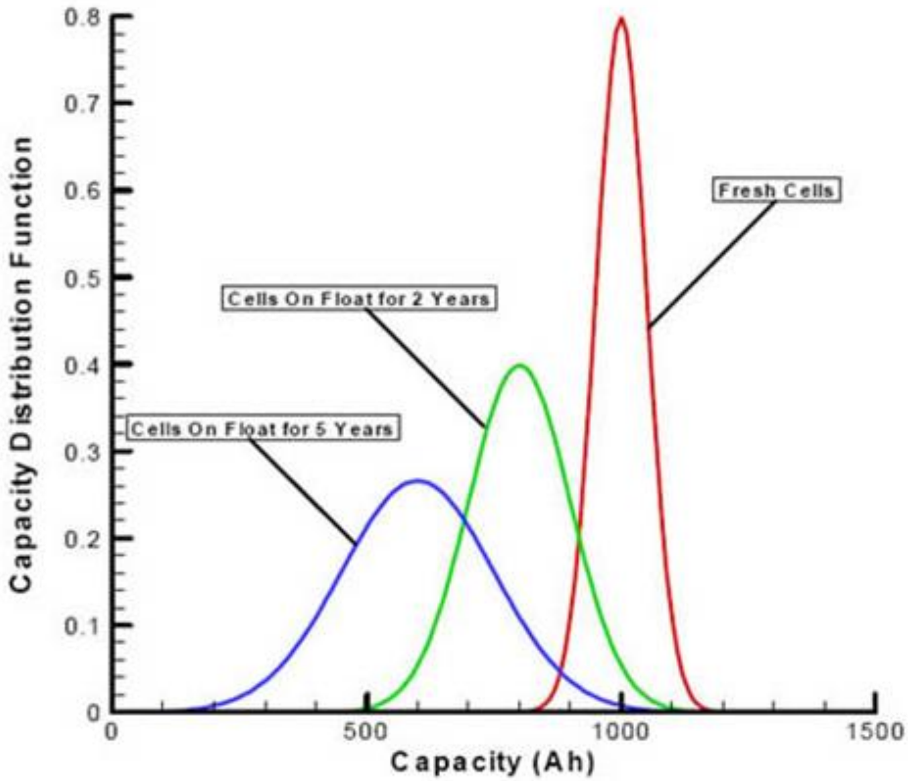


Figure 25. Battery Cell Capabilities Change With Time (Digikey/Infineon) [183]

The ramifications of the battery cell variability are that the battery pack is limited by the performance of its worst cells. An innovative approach to extending battery life was found in NACFE interviews with OEMs. The statistics of cell degradation suggest that replacing a percentage of a degraded battery pack may restore the entire pack to near new capacity. To illustrate how this might work, look at the example in Figure 26. This example has a battery pack with five cells. The state of charge is indicated by the 10 yellow dots with 10 being fully charged.

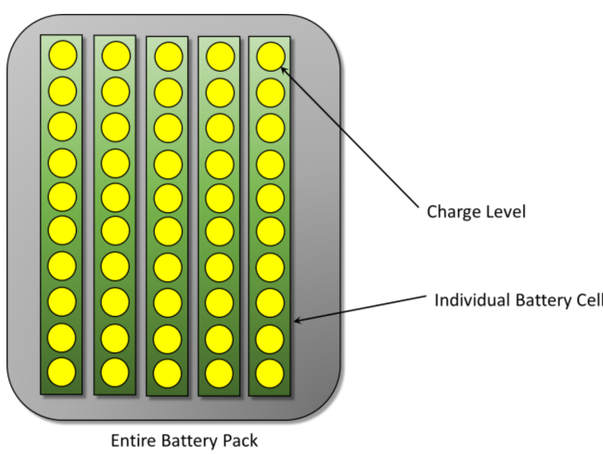


Figure 26. Example of Battery Pack With Five Cells (NACFE)

At some later point in time, the battery pack has degraded to a point that 80% of new capacity is the most it can be recharged. Figure 27 shows this example battery pack has one cell at 40%, one at 80%, two at 90% and one at 100% of original capacity for a net battery pack at 80%.

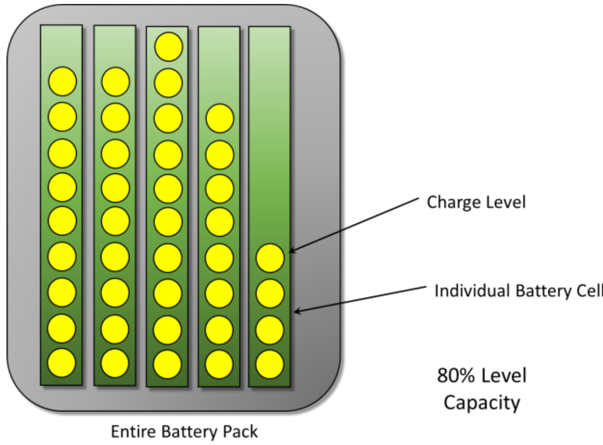


Figure 27. Example 80% capacity battery pack (NACFE)

As shown in Figure 28, if the 40% cell is replaced with one new cell at 100%, the net battery pack capacity is restored to 92% of original capacity.

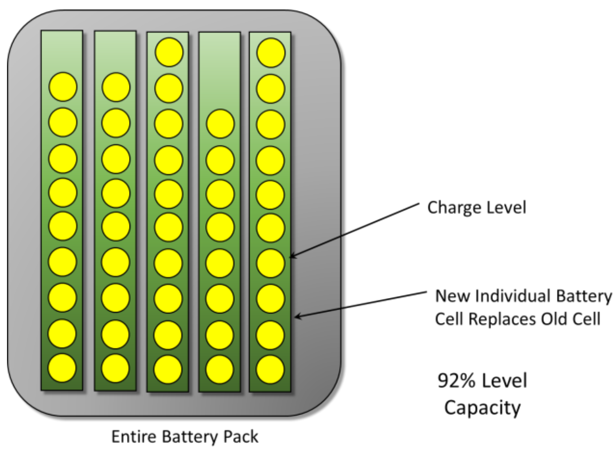


Figure 28. Refurbished Battery Pack With One New Cell (NACFE)

The example of replacing one poor performing cell in a battery pack highlights that there are possible cost saving alternatives to just replacing an entire battery pack when after recharging it reaches 80% of new capacity. This refurbishment will require sending the entire battery pack back to a manufacturer for the precision high voltage work. Downtime would be minimized at the fleet by having a replacement refurbished battery pack ready for installation. This swapping and returning of cores is an established practice with a number of current diesel and gasoline systems. An alternative is that innovators may develop battery management systems that can isolate poor performing cells from the battery pack, effectively raising the net performance without requiring battery swaps.

9.3 Charging Infrastructure Costs and Business Models

Though the electric trucks themselves tend to get the brunt of the media attention, the infrastructure for charging said trucks is just as important to consider, especially when doing a total cost of ownership analysis.

Charging infrastructure costs can vary widely depending on a range of factors such as: how many electric trucks are being procured, the time available to charge the truck(s), the site's existing electric infrastructure, and the current local grid capacity. For example, a fleet looking to pilot one or two electric trucks that will have two shifts worth of time to charge may be able to get by with a fairly standard Level 2 charger and minimal upfront investment, while a fleet looking to deploy 30 trucks at one location will likely need to invest in much more expensive DC Fast Charging (DCFC) chargers, as well as an upgraded facility transformer and potentially even upgrades to distribution lines and/or substations as well. Though again, this depends on the current electrical infrastructure on site. The analysis for this sort of large-scale deployment can be extremely time-consuming (with the process sometimes exceeding a year) and expensive (sometimes costing tens of thousands of dollars even before any infrastructure improvements are decided upon). Publicly available example case studies can help in scoping planning, two examples are found on the Chateau Energy website with Ameripride and Frito-Lay installations [267]. Other examples are discussed on the California Public Utility Commission website [269][270][271].

Part of what makes this process so expensive is the fact that it is still quite bespoke for each facility. Because of the relative newness of the technology, as well as the many variables, care must be taken to analyze the best options for each site.

However, even the charging stations themselves can have significant costs. Experts estimate that current Level 2 chargers on the market can range from $5000 to $7000 [50][51]. DCFC stations can cost upwards of $35,000 [268] [11]. The cost generally multiplies with the quantity of electric vehicles.

9.3.1 Charging Station Business Models

Based on research and interviews, NACFE has determined that there are two main business models for procuring charging stations. The most common is by buying the stations outright, often through an RFP process. In this scenario, the fleet owns the charging stations, which are then considered a capital expense.

However, leasing options are also available through some charging station suppliers. In this scenario, the supplier owns the stations and the fleet simply pays a fee for using them. This model allows the fleet to pay for the stations out of their operational expense budget.

In both the lease and own options, fleets often pay charging suppliers not just for the physical stations but also for access to their fleet management networks, which again, are a recurring operational expense.

Though even once a fleet has procured charging stations for their trucks, they must still procure the electricity needed to power them.

9.3.2 Electricity Business Models

Most fleets procure electricity the traditional way – through the local utility's electric grid. Depending on whether the region is a regulated or deregulated electricity market, fleets may have options with respect to which company they buy their energy from. In thinking through electricity pricing, fleets must be aware of their utility's rate card and should keep in mind that installing charging stations may change the rate card used for their account from a basic rate to a much more complicated EV rate. Fleets should also be aware of if and how demand charges are integrated into their rate card. Demand charges can be applied for either total facility use or time of use. In other words, the price for electricity may be determined not just by how much energy you use, but by how fast you use it, the peak rate, etc. Though emerging automated demand response (ADR) technologies may be able to help manage peak loads via smart charging.

However, the grid is not the only place to get electricity from. In fact, on-site "behind the meter" solutions such as microgrids and renewables like solar PV are slowly gaining popularity as a means of reducing grid demand, especially during peak times. However, integrating systems like these into electric fleet charging systems is a very new concept and no data is yet available as far as best practices.

9.3.3 Charging System Suppliers

A growing list of potential charging system suppliers updated in January 2018 titled Electric Vehicle Charger Selection Guide is available from the Energy Efficiency Coordinator (EEC) website [289][290]. NACFE is in the process of developing a detailed Guidance Report on Commercial Vehicle Charging Infrastructure to be published in the spring of 2019. NACFE identified in interviews and research a subset of past and present electric vehicle supply equipment (EVSE) charging system suppliers relevant to commercial truck use which are discussed in Appendix B. However, as the EEC reference shows, there are a considerable number of competing offerings that may be applicable to trucks due to commonality in connectors and charging levels [289][290].

10 Knowns & Unknowns for Medium-Duty CBEV Cost Modeling

Total cost of ownership cost modeling for battery electric vehicles and comparison to baseline diesel vehicles involves a number of projections, estimates and guesses. These unknowns represent considerations for financial investment in vehicles, and may be pertinent to estimating total cost of ownership. The number of fielded production level commercial battery electric vehicles is limited today. Long-term field history is minimal. Comparison to automotive and bus experiences may or may not be relevant. NACFE has identified a number of topic areas of concern to fleets. The following sections summarize NACFE's findings regarding considerations for the key topic areas:

- Predicting E-Commerce
- Experience Dilemma
- Vehicle Life
- Residual Value of Electric Trucks
- Residual Value of Diesel and Gasoline Baselines
- Zero Emission Mandates
- Incentives, Grants, Vouchers, Subsidies and Tax Breaks
- Maintenance and Repair

- Fire
- Raw Materials
- Weight
- Battery Life, Range & Replacement
- Battery Second Life
- Battery Climate Sensitivity
- Vehicle Recycling/Salvage
- Energy Sourcing
- Electrical Grid Readiness
- Scaling
- Diesel and Gasoline Fuel Prices
- High Voltage Safety

10.1.1 Predicting E-Commerce

Freight transport exists to support the commercial marketplace. That commercial space is rapidly changing, with traditional retail outlets being challenged by e-commerce companies and direct-to-consumer marketing. An Omnitracs senior director, Cyndi Brandt, referred to this as the Amazon Effect in a May 2018 webinar on changes to the wholesale industry [60]. The Federal Reserve trend data in Figure 29 shows the percentage of e-commerce sales growing continuously since 2000 with nearly 10% market share of retail sales in 2018 [61].

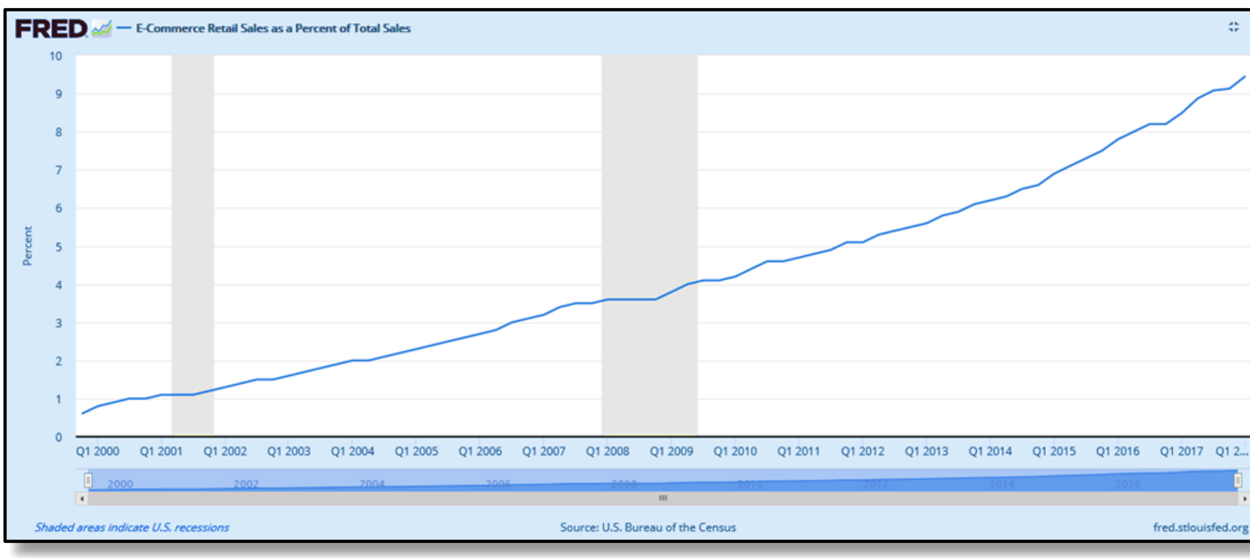


Figure 29. E-Commerce Growth as Percent of Retail Sales (Federal Reserve) [61]

This trend in terms of actual dollars is shown in a second Federal Reserve graph in Figure 30 showing 2018 equating to $120 billion in retail sales in the U.S. [62].

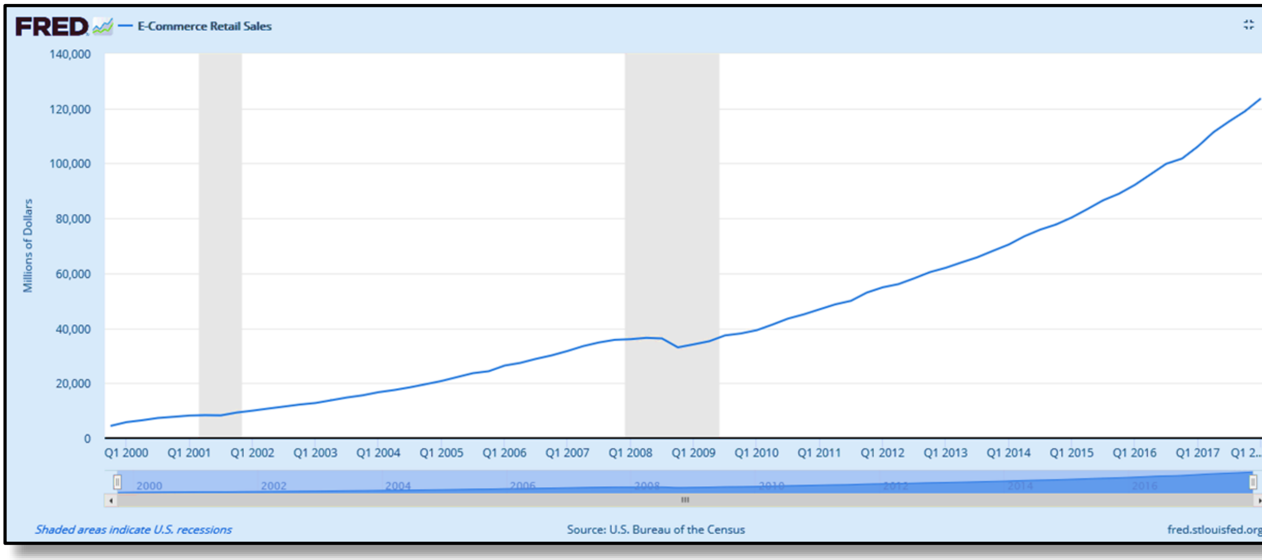


Figure 30. E-Commerce Growth in Dollars (Federal Reserve) [62]

This shift in retail has freight being delivered directly from warehouses to consumers, bypassing the traditional intermediate steps involved with getting the product to retail outlets. Brandt explained that the trend for these buyers is to smaller orders delivered more frequently. Brandt suggested that as demand for near instantaneous delivery increases, local delivery trucks may increase in size, acting somewhat as mobile local warehousing space.

This shift in orders and delivery is echoed by Deborah Abrams who wrote, “Many suppliers and manufacturers are moving from bulk sales orders — even to large wholesale accounts — to selling more at an item or case level. That changes their business model and supply chain, making them rethink relationships with what used to be their entire client base. In many cases, suppliers started directly competing against their clients [59].” Quoting Steve Scala, executive vice president of DiCentral, Abrams writes, “Smaller and start-up companies now have an easier route to market, not needing brick-and-mortar retailers for access and shelf space. “The dot-com infrastructure has provided a new path to market for the regular guys,” Scala said. But large brands are competing directly too — not only in their own company stores, but by selling through Amazon and their branded sites. Suppliers are learning how to strike that balance, increasing DTC (direct to consumer) sales while maintaining their wholesale relationships, which can still constitute the majority of their sales [59].”

The 10% value for e-commerce share is echoed in Canada according to McKinsey, where “online retail sales are growing quickly, from Cn $22.3 billion in 2014 to an expected Cn $39.9 billion in 2019, which would be nearly 10% of all retail sales,” from a Forrester.com report by Peter Sheldon [41].

While 10% of the retail sales market place in 2018 is e-commerce, it must be noted that 90% is not. Predicting IoT (internet of things) marketing trends is problematic, as the nature of the space is built on somewhat unpredictable rapid innovation. Factors like additive manufacturing, for example, where products are made on site on demand could cause significant perturbations to future freight planning. Rapid increases in transportation costs like fuel or energy could change the trajectory of some business models. Recession, inflation, policy changes, like tariffs and trade wars, can impact these trends.

An extreme thought experiment is what happens to freight if the Star Trek replicator existed in your home and you could print food or common objects on demand [55][56]? The e-commerce space has evolved significantly since 2000 expedited by the parallel technological development of SmartPhones and the rapid improvement in cellular network capacity and performance along with advances in IoT. What technological leaps might occur in the next decade? These unknowns in a period of revolutionary technological change are considerations for long-term capital investment.

Retail and change are synonymous. Local grocery delivery was experimented with in the heady dot-com period 1998-2000. Start-ups like Webvan, Peapod, HomeGrocer and Kozmo competed with large name grocery chains for web-based food delivery. Truck OEMs launched new medium-duty vehicle projects to optimize for the new demand in urban delivery vehicles. Major grocery retailers made investments in equipment and delivery services. These largely disappeared or scaled back by 2001 as rising fuel prices, labor costs and the dot-com crash made these business models less attractive [63][64][65]. An exception is Peapod, which survived and operates in 24 specific regional markets [147][148].

One could argue that current e-commerce is revisiting the Wells Fargo delivery of Sears & Roebuck catalog items which made the late 1880's U.S. retail a boon period for freight [57]. Once successful catalog retailing at Sears, Montgomery Wards, JC Penney and Service Merchandise declined significantly in 1990-2007. Sears described the current challenging environment in their 2016 SEC Form 10-K ,"The retail industry is changing rapidly. The progression of the Internet, mobile technology, social networking and social media is fundamentally reshaping the way we interact with our core customers and members [58]." Rapid change is a risk for long-term capital investments.

What are the demographics of this e-commerce market place? A Rockbridge Associates report characterizes their 2017 National Technology Readiness Survey (NTRS) survey results [66][67]. This is a survey of approximately 1,000 representative consumers over the age of 18. They found that "on-demand economy consumers tend to be younger, more educated and affluent, and more concentrated in urban areas. Specifically:

- 55% are between 25 and 44 years old
- 59% are male
- 45% have a four year college degree or higher
- 54% live in a suburb and 18% live in an inner city
- 68% report an annual household income of at least $50,000
- 47% report an annual household income of at least $75,000"

Rockbridge categorized on-demand consumer spending in Figure 31.

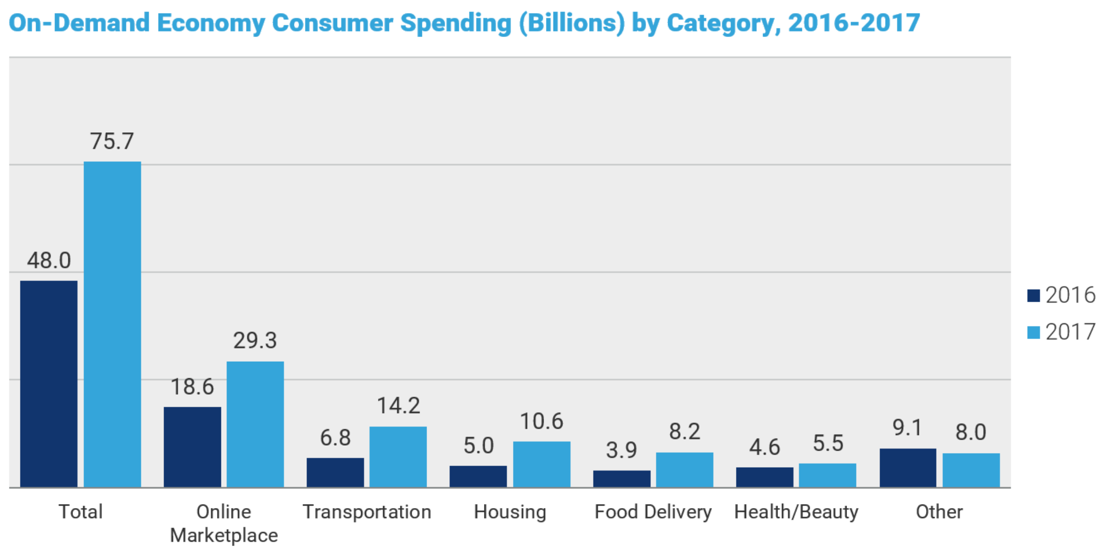


Figure 31. On-Demand Consumer Spending by Category (Rockbridge) [66]

Are there market places less sensitive to e-commerce online trends? A 2017 *Forbes* article looks to success at Home Depot and Best Buy retailers, concluding, "Companies which have physical stores are likely to deliver a better customer experience compared to pure online retailers. By integrating the online and store experiences, they can provide both the convenience of online shopping and the benefit of personal interaction, product demos and advice [68]." *Forbes* reported in 2017 that nine of the 10 top U.S. retailers have significant brick-and-mortar stores, and that Amazon's purchase of Whole Foods chain also gives them a 460 store foot print [69].

Accenture reported in 2017 from a survey of 10,000 consumers in 13 countries, that GenZ shoppers "crave speedy delivery more than millennials do and are willing to pay for it. In fact, more than half (58%) of Gen Z respondents said they would pay more than $5 for one-hour deliveries [76]. At the same time, however, the findings show that retailers cannot afford to neglect the physical store, since 60% of Gen Z shoppers still prefer to purchase in-store, and nearly half (46%) will still check in store to get more information before making an online purchase. In the U.S., over three-quarters (77%) of Gen Z respondents said that brick-and-mortar stores is their preferred shopping channel [76]".

McKinsey estimated in a 2016 report that, "Nearly 25% of consumers are willing to pay significant premiums for the privilege of same-day or instant delivery. This share is likely to increase, given that younger consumers are more inclined (just over 30%) to choose same-day and instant delivery over regular delivery [77]." McKinsey tempered that with, "But despite the large share of consumers willing to pay extra for same-day delivery, only 2% said they would pay sufficiently more to make instant delivery viable (assuming the consumer would have to bear the additional cost of this extremely fast service). In any event, same-day and instant delivery will likely reach a combined share of 20% to 25% of the market by 2025, and they are likely to grow significantly further, especially if the service is extended to cover rural areas to some extent [77]."

A 2016 Stanford joint report with the US Postal Service discussed the Technological Disruption and Innovation in Last-Mile Delivery [78]. They summarized, "Customers have an increasingly complex set of expectations regarding the speed, flexibility, security, and cost of delivery. A 2016 survey by shipping platform company Temando shows that most customers value same-day delivery options. Many customers would also like the flexibility to shop in store and have items shipped home or to have the ordered items shipped to a different location, such as an office, a self-service locker, or other pickup points [78][79]."

The rise in e-commerce may also be a reflection on the over-building of retail malls in the U.S. A 2018 *Wall Street Journal* article cites, "Retail landlords also have suffered from a glut of new shopping centers that were built in the years leading up to the 2008 financial crisis. For every person in the U.S., there is 24 square feet of retail space, far more than Canada's 16 square feet per capita, Australia's 11 square feet and five square feet in the U.K. [17]."

The e-commerce cycle has a hidden trucking efficiency challenge in that online orders delivered to homes or businesses have a 30% chance of needing to be returned, what McKinsey labels as "reverse logistics handling" versus perhaps 9% via traditional supply chain methods [41]. A RetailDive story from February 2018 states, "In 2017 the value of retail returns hit $400 billion; that's a 53% increase from 2015 [196]." A CBRE Report from December 2017 states, "Historically, returns of store-bought merchandise have amounted to 8% of total retail sales. However, for e-commerce, that share ranges from 15% to 30%, depending on the product category [197]." What is commonly referred to as "last mile delivery" tends to inflate "last mile pick-up." Whether these trends continue depends on the success or failure of reducing the need to make returns through improving ordering processes and data mining returns [196][198].

The increasing trend to greater online purchasing may continue, may accelerate or may plateau, as seen in Figure 32, as the result of the complex competitive, demographic and political forces combined with innovative technological advances.

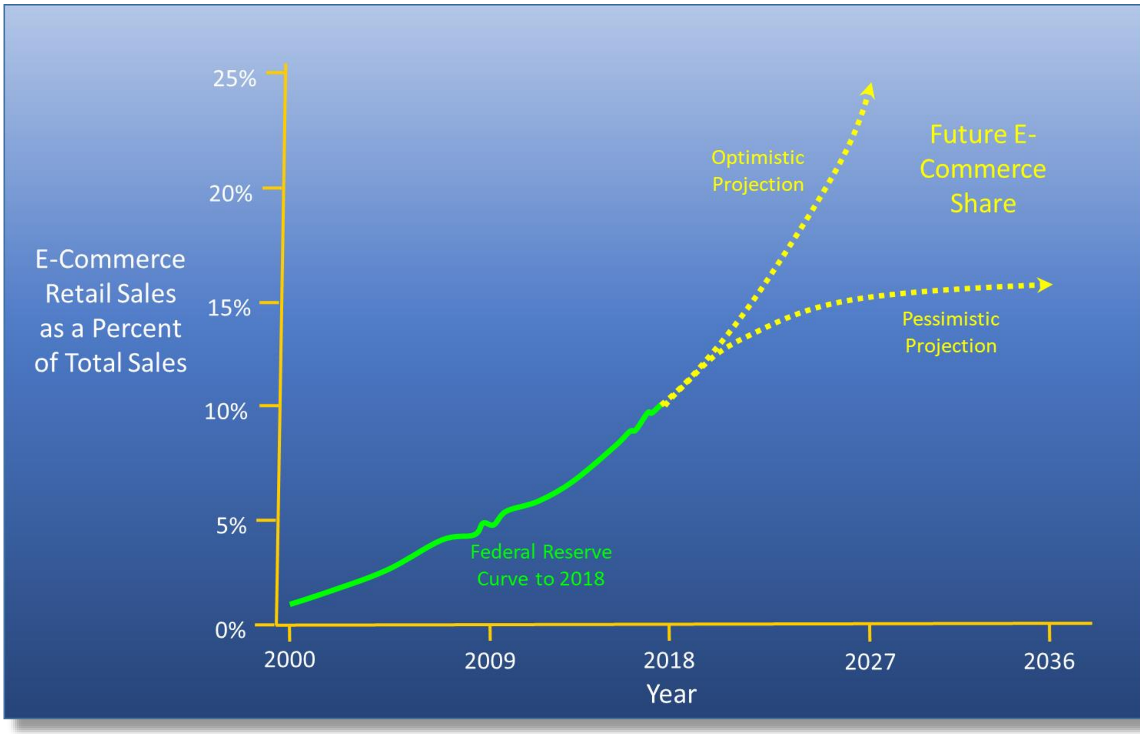


Figure 32. Future E-Commerce Challenging to Predict (NACFE)

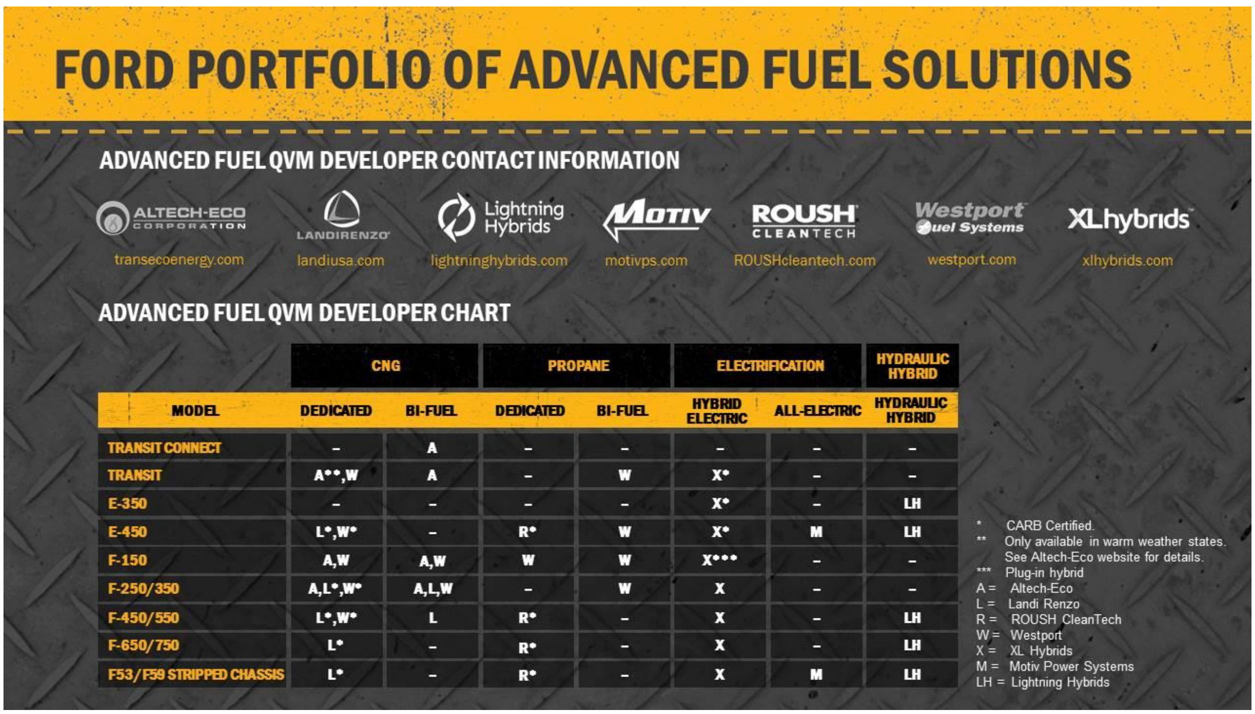
The future for medium-duty trucks to facilitate e-commerce growth in the next decade is promising. The use of battery electric vehicles as solutions is similarly promising. Capital investments in vehicles and infrastructure with 10 to 20 year timelines are inherently risky as revolutionary technology changes have been occurring in shorter time frames. As history shows, consumer and marketing shifts may occur to reinforce or diverge from today's visions on time frames of five to 10 years.

Mitigating this risk is the inherent flexibility of electric energy. Investments in charging infrastructure, just as investments in diesel or gasoline fueling stations in the past, have seen long-term economic life even through significant changes in vehicle designs, requirements and energy sourcing. Investments in vehicles have also shown over time that stable infrastructure reinforces long-term use of assets, even while significantly better new ones enter the marketplace.

10.1.2 Experience Dilemma

The experience dilemma is that new, small companies tend to innovative quickly by taking larger risks. They are generally not hamstrung by existing overhead associated with supporting existing product lines and past capital investments for them. Mature OEMs and suppliers provide experience and stability, but bring with them rigidity and the need to consider new investment opportunities in terms of supporting existing product lines and operations as well as starting new ones. These factors can hobble them from moving quickly on innovation, and taking risks. Fleet customers want to take advantage of the best new technology rapidly being developed by nimble new companies, but they also want the security that experienced companies offer.

NACFE fleet interviews identified a concern with risks with start-up companies and long-term stability needed for fleets to make investments. Several indicated that having established OEMs getting into the electric truck market was needed to reduce risk. Fleets had a parallel concern with speed-to-market, where established large companies may take longer to get innovative new product technology on the road versus more nimble smaller start-ups. One outcome of this is OEMs buying smaller technology innovators, for example Cummins' 2017 acquisition of Johnson Matthey Battery Systems (JMBS) as a high voltage battery maker and Brammo as a low voltage battery maker [80][81]. Eaton acquiring Cooper Industries in 2012 for position in electric power management [82], Daimler taking a major stake in StoreDot on fast charging batteries [83], Meritor taking a 50% equity stake in TransPower in 2017 to position itself for the EV market (and cementing EV relationships also with OEMs Peterbilt and Navistar) [84][85], CONMET partnering with Protean on electric in-wheel motors [86] or Dana purchasing the majority share of TM4, a motor and inverter company in 2018 [52]. Partnerships where OEMs provide a chassis to a builder for electric vehicle production are allowing other established OEMs to quickly enter the EV market with products. Ford is an example showing a range of alternative energy vehicle partnerships including Motiv and LightningElectric (formerly Lightning Hybrid) to offer product in many classes as shown in Figure 33 [87].



FORD PORTFOLIO OF ADVANCED FUEL SOLUTIONS

ADVANCED FUEL QVM DEVELOPER CONTACT INFORMATION

ALTECH-ECO CORPORATION – transecoenergy.com
LANDIRENZO – landiusa.com
Lightning Hybrids – lightninghybrids.com
Motiv – motivps.com
ROUSH CLEANTECH – ROUSHcleantech.com
Westport Fuel Systems – westport.com
XLhybrids – xlhybrids.com

ADVANCED FUEL QVM DEVELOPER CHART

	CNG		PROPANE		ELECTRIFICATION		HYDRAULIC HYBRID
MODEL	DEDICATED	BI-FUEL	DEDICATED	BI-FUEL	HYBRID ELECTRIC	ALL-ELECTRIC	HYDRAULIC HYBRID
TRANSIT CONNECT	–	A	–	–	–	–	–
TRANSIT	A**,W	A	–	W	X*	–	–
E-350	–	–	–	–	X*	–	LH
E-450	L*,W*	–	R*	W	X*	M	LH
F-150	A,W	A,W	W	W	X***	–	–
F-250/350	A,L*,W*	A,L,W	–	W	X	–	–
F-450/550	L*,W*	L	R*	–	X	–	LH
F-650/750	L*	–	R*	–	X	–	LH
F53/F59 STRIPPED CHASSIS	L*	–	R*	–	X	M	LH

* CARB Certified.
** Only available in warm weather states. See Altech-Eco website for details.
*** Plug-in hybrid
A = Altech-Eco
L = Landi Renzo
R = ROUSH CleanTech
W = Westport
X = XL Hybrids
M = Motiv Power Systems
LH = Lightning Hybrids

Figure 33. Ford EVQM Chassis Partnerships in Alternative Energy Vehicles (Ford) [87]

The ramification of mergers and acquisitions is that intellectual property developed in a start-up may be available to all OEMs but once an OEM acquires a start-up, that start-up's technology becomes proprietary to a specific OEM. This could affect service part pricing and availability for a fleet maintenance shops. *Heavy Duty Trucking's* Deborah Lockridge summarized Daimler perspective on this from June 2018 comments that Daimler's "…goal is to develop a single proprietary electric system that will be used on its products around the world. EMG (Daimler's new E-Mobility Group) will define the strategy for everything from electrical components to completely electric vehicles for all brands and all business divisions, while also working to create a single global electric architecture. [88]."

A fleet running trucks from multiple OEM, might have cost increases to handle specific proprietary service tools and software for each type of truck. A clear example would be battery packs, where there are no standards sizes, shapes, construction or performance. Where Michelin tires or Dana axles can be specified on your Freightliner, Peterbilt, Kenworth, Volvo, Mack, etc. tractor, you may have to lock into a proprietary battery pack for each. Motors, chargers, controllers, etc. are other examples. A consumer parallel to this is visible in the way printer companies make using proprietary ink cartridges a near requirement for their printers, locking in premium replacement cartridge pricing and securing recurring cash flow from customers.

Regarding innovation versus experience, one blogger evaluated an electric truck maker and disparaged their management team as, “Only one of Tesla execs have experience building heavy-duty trucks [88].” In truth, the argument can be made that nearly no one in early 2018 has significant production experience building commercial battery electric trucks. With innovative technology, it is not always the case that experience with older technology is applicable or beneficial. Companies like Royal Typewriter, Kodak Camera, Ford, GM and Chevrolet in the 1970’s, Blackberry and Nokia were not well suited to adapt to rapidly changing new technologies. When talking about experience and revolutionary innovation — lack of experience with older technologies is not necessarily a negative, and experience with older technologies is not necessarily a positive.

10.1.3 Vehicle Life

Capital investment in vehicles needs to factor a period of ownership and expected vehicle lifespan. The residual value at the point of trade-in is largely dependent on estimates of useful remaining life. Medium-duty vehicles tend to be long lived. A 2015 *Heavy Duty Trucking* article by Paul Clinton quotes IHS director of commercial vehicle solutions, Gary Meteer, “Class 6 GVW trucks now operating in commercial fleets now have an average 21.2-year lifespan due to their reliability, durability, and use in a variety of applications [144].” The article states, “Class 5 trucks are now the youngest truck class with an average age of 11.8 years as a result of this segment of trucks having historically low demand [144].” This implies that the average life of the other medium-duty classes falls somewhere between 21.2 and 11.8 years.

One NACFE interview with an OEM stated that their oldest battery electric truck in the field was four years old. The Smith-Newton fleets have been running approximately eight years. Battery electric buses are accumulating significant field mileage, but they also have not been around that long. Significant volumes of fielded production quality trucks are needed to establish a basis for estimating commercial lifespans in this developing marketplace.

10.1.4 Residual Value of Electric Trucks

NACFE’s interviews with OEMs and fleets have highlighted that residual value is an unknown for battery electric trucks. There are insufficient quantities of used CBEVs to establish any trends. It is possible to look at how residual values have fared in the automotive world. There are sufficient quantities of battery electric and hybrid automobiles for used values to be tracked. The National Automobile Dealers Association published a 2016 report by JD Power titled Alternative Powertrains: Analysis of Recent Market Trends & Value Retention. That report highlights that ”retained value of three-year-old plug-in hybrid compact cars ranged from approximately 31% to 38%” and all electric models ranged from 22%-27% versus ICE based vehicles with values of approximately 50% [160].

NACFE concludes that this steep depreciation reflects in part the higher list price of the vehicles before grants, incentives, tax breaks, or other subsidies. The purpose of these types of incentives is to level the price of new technology with that of existing choices. These incentives are pervasive. They are funded by a variety of somewhat transient mechanisms such as fines, fees, and grants, but are likely part of the electric vehicle equation for the foreseeable future. If the subsidies are factored in to the initial actual price paid by the customer, the depreciation improves. JD Power reached this same conclusion stating, "High new vehicle incentives mean prices of used EVs and plug-in hybrids fall at a much higher rate than they do for gasoline or traditional hybrid models [160]."

Argonne National Laboratory's Yan Zhou et al suggested a new metric be used, an "adjusted retention rate" that reflects the post subsidy vehicle price paid by a consumer. The report states, "Incentives decrease the purchase price or market value of an incentivized vehicle, but not the intrinsic value of the technology." The methodology subtracts the incentives from the manufacturer's suggested retail price (MSRP) to estimate acquisition cost for use in calculating depreciation. They concluded, "The adjusted retention rate is a more objective metric for comparing value retention or depreciation of PEVs (plug-in electric vehicle) and conventional vehicles. The report reviews three years of vehicle data from 2011 through 2014 and summarizes the results in Figure 34. The data concluded, "When adjusted for both state and federal tax credits, the sales-weighted average adjusted value retention rates of both BEVs and PHEVs are better than that of ICEVs at one year, and still comparable at two-year ownership. Adjusted retention rates for PHEVs at three years are somewhat lower, but data on three-year-old PEVs data are limited [161]."

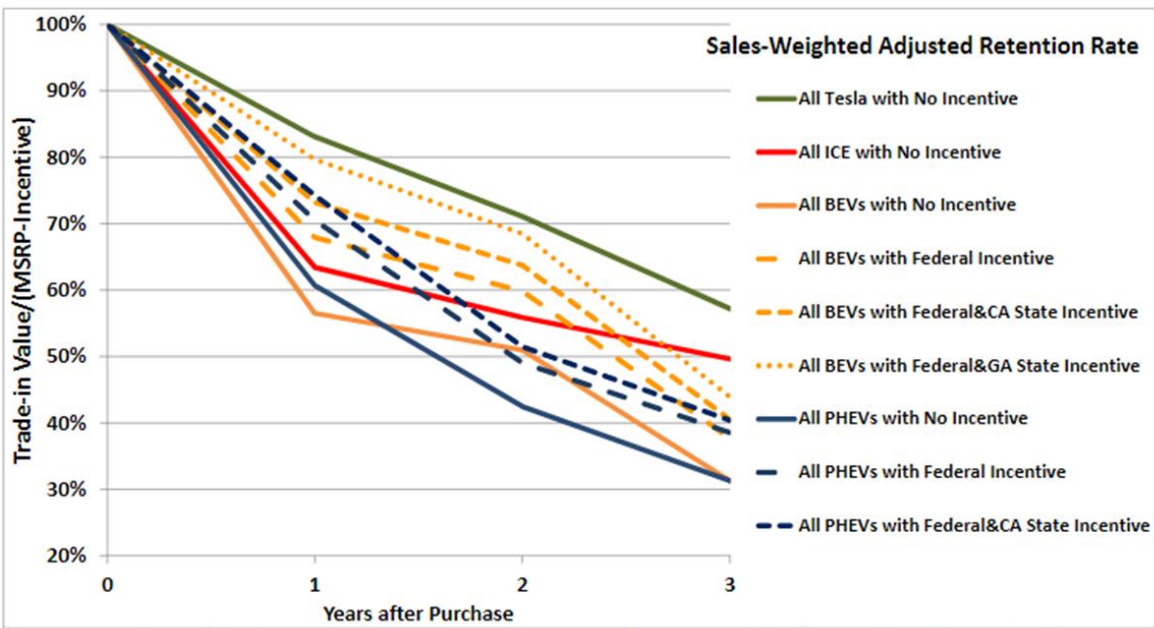


Figure 34. Sales Weighted Adjusted Retention Rates (ANL) [161]

The ANL analysis is interesting with respect to cars, but because the turn time for the vehicles is in terms of one, two or three year time frames, it is not particularly relevant to medium-duty trucks which may have 10 to 20 year investment lives. What is applicable to the medium-duty total cost of ownership estimates of residual value trends is the ANL conclusion that cost of acquisition should be reduced by the amount of incentives and subsidies. Some form of these incentives is likely to be in place until production volumes of electric vehicles reach significant numbers and industry has incorporated cost reduction innovations and economies of scale into their designs.

An alternative source on similar technology valuation might be to look at price trends for used CNG trucks. A *Successful Dealer* article by Jason Canon noted that a 2014 OEM panel at ACT EXPO recorded Andy Douglas, National Sales Manager for Kenworth Truck Company, stating, “The early 9-liters are just now seeing the secondary market, but the residual curve is similar to diesel [162].” The panel felt the 12-liter market did not yet have enough volume to trend used sales values. The article highlights that “fleets unsure of the truck’s resale value have been hesitant to commit sizable portions of their budget to trucks that can be difficult to sell for a yet-to-be-determined amount.”

The use of subsidies, grants and incentives that apply only to the new vehicle purchase means the used vehicle pricing forces competing technologies to be on an equal cost footing. The used vehicle market is where supply and demand govern pricing. NACFE believes vehicle decision making in these second markets is less about technology type, and more about fundamental functionality. Can the vehicle do the work the fleet needs it to do at acceptable operating cost levels with acceptable uptimes? If electric vehicles prove to have significantly less maintenance and better uptime than ICE alternatives, the used market may reward them with premium residual values.

NACFE believes that investment in alternative fueled vehicles in the early stages of technology typically will be for longer periods of ownership. NACFE believes it is reasonable to assume that battery electric vehicles, if they are more reliable, may lead to longer ownership periods. A similar trend has been seen with diesel trucks as designs with longer warranty periods entered the market. A change in planned ownership period adds a level of complexity to equivalent comparison to baseline ICE vehicles.

The replacement period is also an unknown, particularly in medium-duty markets. In a *Fleet Financials* article Sal Bilbona states, “Establishing replacement cycles for medium-duty trucks is both an art and science. It involves judgment, prediction, forecasts, and assumptions on one hand, and analysis of available data on the other [166].” Bilbona shows an example of how depreciation, maintenance/repair and the total life cycle cost (referred to as Equivalent Uniform Annualized Cost – EUAC or Equivalent Annual Cost – EAC) vary with time in Figure 35. EUAC, also stated as Equivalent Annual Cost (EAC) is the cost per year of owning and operating an asset over its entire lifespan. This total life cycle cost is typically presented as a bathtub shaped curve, according to Bilbona, over the full life of a vehicle although the shape may vary due to a number of factors [166].

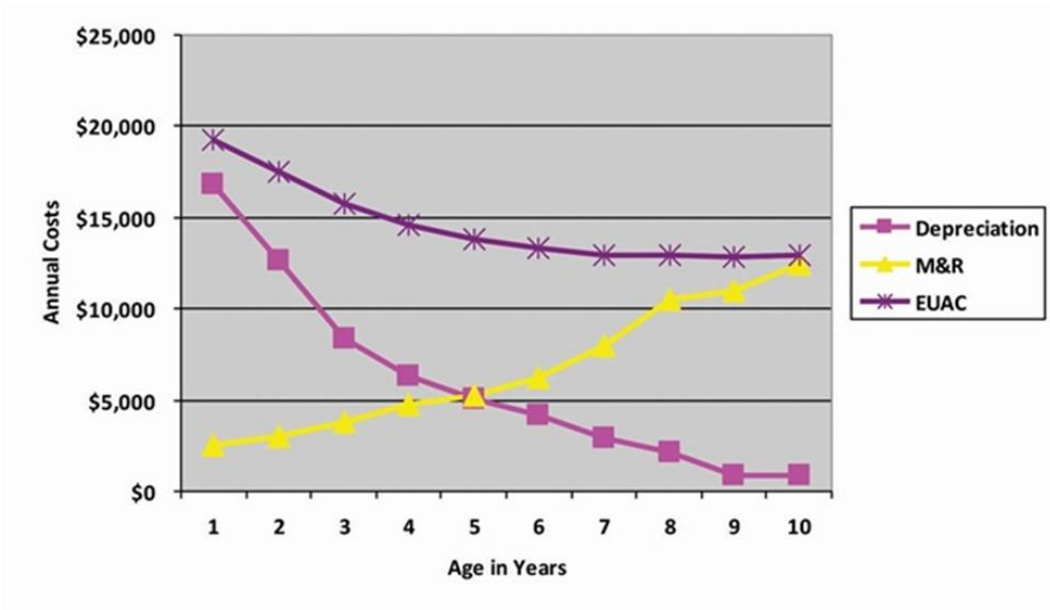


Figure 35. Simple Example of Vehicle Lifecycle Analysis (Fleet Financials) [166]

Trade cycles may also vary as innovation enters production availability. A *Work Trucks* staff article highlights that new technologies can accelerate sales of older vehicles as fleets chase the potential operational cost savings [165].

Estimating the lifespan of commercial battery electric vehicles is an unknown until there are sufficient suppliers of used vehicles to gauge market trends. The residual value of these vehicles is a guess at this point. Compounding that is the fact that incentives, subsidies and grants are mostly used up in the initial purchase and are not applicable in the second market. Another factor is the rapid pace of technology innovation for these vehicles may lead to product obsolescence at a faster rate than experienced with diesel vehicles.

10.1.5 Residual Value of Diesel and Gasoline Baselines

Estimating residual value of these long-lived diesel or gasoline trucks is largely an unknown in the face of zero emission mandates. Historical trends will not be applicable when a diesel truck is prohibited from use in specific markets. Alternative vehicle markets will need to be found with additional costs for shipping the vehicles to those markets, and possibly margin losses as the vehicles may become less desirable. Alternatively, programs may develop for retiring older vehicles as was done with the $3 billion 2009 Car Allowance Rebate System (CARS), colloquially known as the Cash-For-Clunkers automotive program by the U.S. Department of Transportation [145][146].

The unknowns on the residual value of the long-lived diesel or gasoline baseline truck and the expectation of the residual value for battery electric ones are considerations for capital investment in new vehicles. Expected vehicle lifespans are also considerations as the predictions depend on a great many market and regulatory unknowns.

10.1.6 Zero Emission Mandates

Regulatory mandates to adopt zero emission vehicles in specific regions force manufacturers to produce viable alternative technology platforms. The U.S. and Canadian rules generally apply directly to the manufacturers and their annual product mix. North American vehicle buyers are largely free to make their own free market decisions on which vehicles to purchase, but they are influenced by a significant number of grants, incentives, tax breaks, and other cost reduction assistances in purchasing zero emission technologies. In Europe and other regions, punitive measures are also taken to encourage end users to adopt low, ultra-low and zero emission technologies through fees and fines when operating in specific urban emission zones.

The primary concern for fleets making capital investment is reliably estimating the residual value of vehicles when the downstream market can significantly change. If a diesel product can no longer be sold or operated in a zero emission region, it has to be relocated to a market where it has a value. In one example, an operator purchased low emission vehicles in Los Angeles as replacements for older diesel vehicles subsequently sold into a Seattle market, where emission regulations are on a different timeline.

Where significant volumes of used vehicles flood the market due to new regulations limiting their use, supply and demand pricing tends to reduce residual value. Transporting products to other regions for resale also adds costs likely factoring into further reduction in residual value.

10.1.6.1 U.S. Emission Zone Mandates

The 10 U.S. States with California based Zero Emission Vehicle programs are California, Connecticut, Maine, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, and Vermont, as illustrated in Figure 36. The color coding reflects a three tier ranking assessment by the Electrification Coalition based on a) provision of state-level incentives to consumers, b) availability and support of public refueling infrastructure, and c) use of public outreach and education campaigns. This data includes ZEV automobiles along with buses and commercial vehicles [110][111].

ZEV State Policy Tier Rankings
Based on weighted categories of these metrics:
- Provision of state-level incentives to consumers
- Availability and support of public refueling infrastructure
- Use of public outreach and education campaigns

Figure 36. ZEV Program States (ACT News & Electrification Coalition) [110][111]

Zero emission mandates may apply to specific municipalities, regions or entire states. They generally have a target ZEV vehicle population by a target date, for example California's goal is "5 million ZEVs by 2030 [111]." Details can include a ramp up transition plan, as seen in Figure 37, as with California's 2018 car and light-duty truck rules which are based on a three year average of new vehicle volumes produced and delivered to California [112].

Model Year	Credit Percentage Requirement
2018	4.5%
2019	7.0%
2020	9.5%
2021	12.0%
2022	14.5%
2023	17.0%
2024	19.5%
2025 and subsequent	22.0%

Figure 37. California Transition Plan for Auto and Light Truck ZEV Vehicle Percentages (California)[112]

Note that under California rules, medium-duty vehicles "may be counted toward the ZEV requirement for PCs (passenger car) and LDTs (light-duty truck), and included in the calculation of ZEV credits" at the manufacturer's discretion [112].

The transition planning accommodates crediting factors for a variety of technologies including all electric, extended range battery electric, hybrid electric, hydrogen internal combustion engine, hydrogen fuel cell, and a category termed super-ultra-low-emission-vehicle (SULEV) which use combinations of alternative fuels.

These ZEV rules primarily apply to vehicle manufacturers, leaving purchasers to choose from the combination of vehicle technologies sold, which includes diesel and gas vehicles. Managing the annual supply of ZEV vehicles may be the responsibility of the manufacturers, but it also implies that purchasers actually buy them.

The consumer side of the ZEV mandates has created a variety of mechanisms for encouraging purchase and use of ZEV vehicles. According to a 2017 study by the Energy Information Administration analysis of "54 individual state-level direct incentives offered by 30 states as of December 2016. These include 19 incentives for vehicle purchase or lease, including rebates and tax credits, and 27 incentives for vehicle use, including HOV lane exemptions, state vehicle inspection exemptions, and free public parking. The analysis also includes eight incentives that offset the cost of installing home EVSE [113]." Here is a partial list of the types of assistance used to encourage the purchase of ZEV vehicles:

- Grants
- Rebates
- Tax Credits
- Sales Tax Exemption
- Inspection Exemption
- High Occupancy Vehicle (HOV) Lane Access

- Electric Vehicle Supply Equipment Incentives
- Free Services such as parking

There are also punitive measures being discussed that can apply to vehicle purchasers that operate older vehicles such as fees for entry into low, ultra-low and zero emission zones by non-ZEV vehicles. Examples from Europe include London where daily fines can range from £100 to £300 depending on zone and older vehicle emissions level [114][115]. There are daily fines in Paris were driving a non-compliant heavy goods vehicle (HGV) is 135€ [116]. These access fees/fines are not yet present in the U.S.

10.1.6.2 Canadian Emission Zone Mandates

The province of Quebec approved zero emission vehicle standards in 2016 affecting the volume of ZEV cars manufactured for sale and use in Quebec [117]. The standard applies to the vehicle manufacturers. The standard does not address medium-duty or heavy-duty trucks. Experience with this may pave the way for Canadian expansion into commercial vehicles.

10.1.6.3 European Emission Zone Mandates

Europe has a number of city specific and country specific regulations in process for adopting low, ultra-low and zero emission vehicles. London pioneered a low emission zone with daily fines for non-compliant vehicles. This evolved into Ultra Low Emissions Standards (ULEZ) for London. According to the Mayor of London website, "Most vehicles including cars and vans will need to meet new, tighter exhaust emission standards (ULEZ standards) or pay a daily charge to travel within the area of the ULEZ [114]." Driving a non-emission-compliant vehicle in London after 2019 will result in daily charges of either £100 for lorries over 3.5T not meeting a minimum of Euro VI standards and after 2020, £300 if Euro IV standards are not met. Failure to pay adds another £1000 penalty [115].

European regional urban access regulations are summarized by the European Commission highlighting specific limitations for a variety of cities [116]. This array of different emission zone requirements likely creates challenges for vehicle manufacturers and fleets that have to create and manage vehicles that encounter a range of these zones. With no one standard applicable in all trucking routes, vehicle OEMs and fleets may migrate to vehicles that universally can traverse all these zones. As the regulations tighten, there is concern that these older vehicles lose value becoming excluded from operating in specific markets.

10.1.6.4 Other Regions Emission Zone Mandates

Other countries and particularly larger cities with air quality issues are taking steps to reinforce adoption of zero emission vehicles and to constrict use of ICE ones. NACFE interviews with an organization working on transport projects in China highlighted that in some large cities, new ICE truck registrations are prohibited. Use of older vehicles has been restricted to evenings and only Monday-Wednesday-Friday-Sunday or Tuesday-Thursday-Saturday-Sunday operations based on license plate. Meanwhile, EV use has incentives but includes additional requirements for automatically tracking geographic operations. These types of concurrent reward and penalty approaches are being considered in a number of locations across the world. NACFE believes these are more moderate approaches than jumping directly to ZEV mandates, recognizing that the CBEV vehicles and infrastructure needed to support a ZEV mandate may not yet exist in adequate volumes and won't for some years.

10.1.7 Incentives, Grants, Vouchers, Subsidies and Tax Breaks

The primary purpose of incentives, grants, vouchers, subsidies, rebates and/or tax breaks is to encourage the behavior of buying and using zero and low emission vehicles, and in so doing, conversely discourage the behavior of buying and using diesel and gasoline vehicles.

The California Air Resources Board concludes, "The greatest barrier to purchasing cleaner trucks and buses is the higher price tag [170]." One solution is to artificially reduce the procurement price of the cleaner trucks to something comparable to current diesel and gasoline ones. There are a variety of methods to do this. All methods involve paying the manufacturer's suggested retail price (MSRP) but then subsidizing the buyer so the actual procured price is more equivalent to the diesel or gasoline baseline. Essentially these methods are like coupons, reducing the actual price paid by the consumer.

Justification for subsidizing an industry rests on the belief that a new technology cannot compete on price because it does not yet have the benefit of economies of scale. A consequence of these subsidies, however, may be general acceptance that electric vehicles should cost more than their equivalent diesel and gasoline competition, removing the incentive for manufacturers to develop vehicles that are competitive under free market pricing.

Subsidies are controversial. Whatever the case, there is no free ride. One obvious question is where does the money come from? In some cases, the consumers are indirectly paying for the subsidy through taxes. An example is government grants which originate in part from public taxes through the congressional budgeting processes [176].

In other cases, the consumers may be indirectly paying for the subsidy through the prices of products they buy where the manufacturers are paying fees related to emissions. California funds its Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) through the state emissions program cap-and-trade auction process [170][171].

In some cases, funding originates from fines related to company violations. Multiple states' programs are funded through actions like the Volkswagen emissions violation settlement [172][173]. The extent to which companies recover these costs through product pricing is an open question.

Fleets need to find information on the availability of subsidies. As they may be competing for funds in some cases, fleets may not be open to sharing this information. NACFE identified the U.S. Department of Energy site on Electric Vehicles: Tax Credits and Other Incentives [175]. A concise November 2017 overview of several funding sources for vehicle electrification is available from the Center for Climate and Energy Solutions [176]. The DOE Alternative Fuels Data Center has a search engine for federal and state laws and incentives [177]. AFDC also has an interactive state map for finding sources [178]. Plug In America, an industry group, has state and federal incentives listed [181]. The Goldman School of Public Policy at the University of California Berkeley issued a report in August 2018 summarizing Financing Low- and Zero-Emission Freight Transportation Technologies in California [291]. Suppliers such as ChargePoint and Motiv also may be useful resources for fleet information on grants [179][237].

Davis and Xue summarized the financing options as shown in Figure 38 into three primary categories, a Point-of-Sale voucher, an Application Process or a Proposal-Based Solicitation [291]. Additionally, Davis and Xue indicated that the VW Mitigation Trucks Program is not yet included in the graphic.

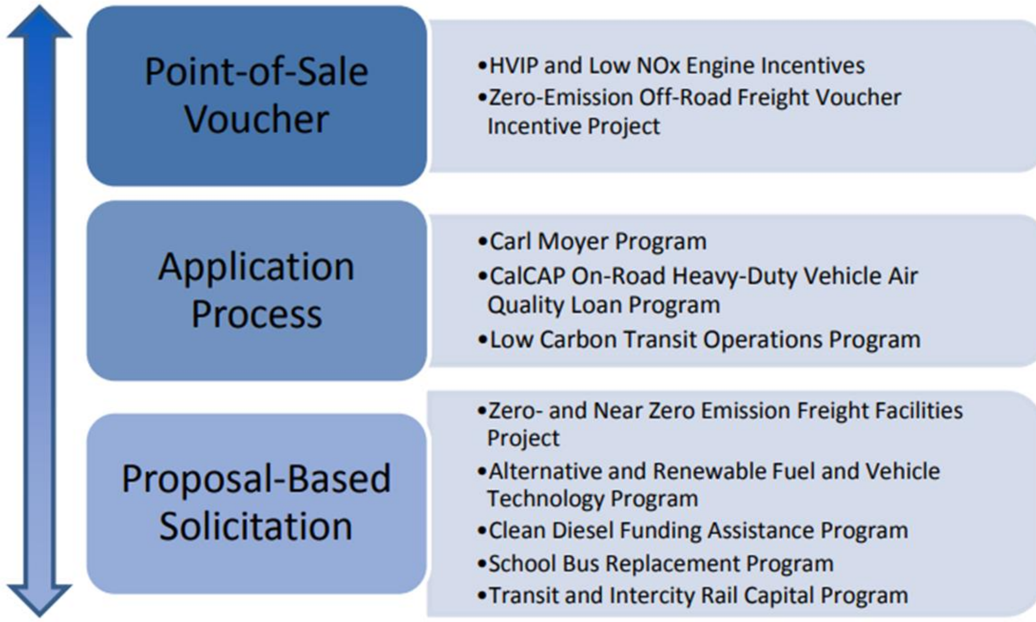


Figure 38. Different Procedures to Apply for Freight Incentives (Davis and Xue) [291]

An indication of the scope of that is from Electrify America, "created by the Volkswagen Group of America to invest $2 billion in financially sustainable business opportunities that advance the use of Zero Emission Vehicle (ZEV) technology, $800 million of which must be spent in California [292]."

The Electrify America report states "As laid out in the Cycle 1 California ZEV Investment Plan, Electrify America intends to develop a network of electric vehicle charging stations along highly traveled highways and in six carefully selected metropolitan areas during Cycle 1 (Figure 39). The planned network in California will consist of more than 600 DC fast charging dispensers at approximately 160 charging station sites. In addition, Electrify America will build approximately 1,500 charging stations at workplaces and multiunit dwellings in its six target markets. The network will deploy cutting-edge technology to deliver customer-centric charging to consumers safely and conveniently, and it will connect California to the Electrify America national network in 39 states [292]."

Figure 39. Electrify America Planned Fast Charging Sites in California (Electrify America)[292]

An example of a voucher process is outlined in CARB's HVIP manual as shown in Figure 40 [172].

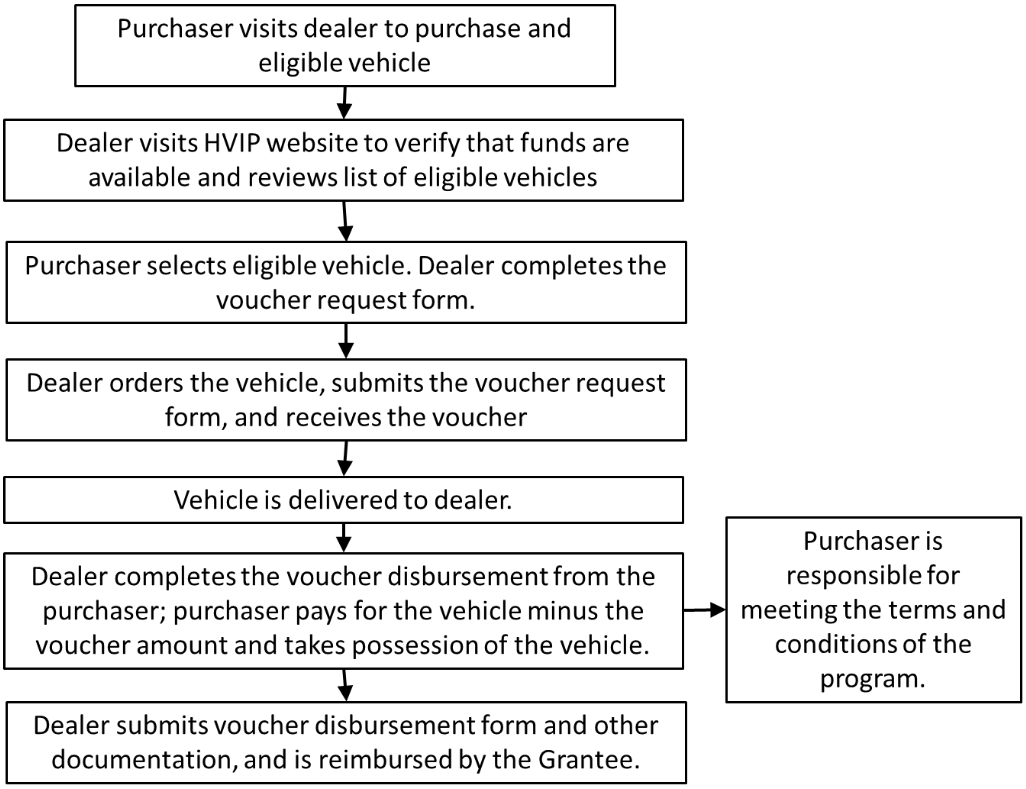


Figure 40. HPIV Voucher Program Process (adapted by NACFE from CARB) [172]

An example of the amount of MSRP price offset is outlined in the HVIP manual as seen in Figure 41.

GVWR (lbs)	**Base Vehicle Incentive**		
	1 to 100 vehicles[1]		>100 vehicles
	Outside Disadvantaged Community	In Disadvantaged Community	
5,001 - 8,500	$20,000	$25,000	$12,000
8,501 - 10,000	$25,000	$30,000	$18,000
10,001 - 14,000	$50,000	$55,000	$30,000
14,001 - 19,500	$80,000	$90,000	$35,000
19,501 - 26,000	$90,000	$100,000	$40,000
26,001 - 33,000	$95,000	$110,000	$45,000
>33,000	$150,000	$165,000	$70,000
Hydrogen Fuel Cell Electric Truck	$300,000	$315,000	$142,000

1 - The first three vouchers by a fleet, inclusive of previous funding years, are eligible for the following additional funding amount: $2,000/vehicle if below 8,501 lbs; $5,000/vehicle if 8,501 to 10,000 lbs; and $10,000/vehicle if over $10,000 lbs.

Figure 41. HVIP Zero Emission Truck Voucher Program Amounts (CARB) [172]

A hidden electric vehicle pricing incentive for fleets are OEM emissions credits for building battery electric vehicles. Under EPA Green House Gas Phase 2 rules and California ARB emissions rules, OEMs receive emission credits for each CBEV they build which can help offset diesel and gasoline vehicles sold [212][213][211]. These are incentives to OEMs to accelerate introduction of the electric vehicles. These are not directly relevant to the fleet consumer as the credits apply at the manufacturer's level. However, the credits are assets and can be sold among manufacturers [1]. A company that produces entirely electric vehicles has no internal use for emission credits, so can sell them to companies that make diesel and gasoline vehicles. The proceeds of those credit sales might then be used to help offset the pricing of the electric vehicles. The EPA GHG Phase 2 rules state that an all-electric vehicle has a credit multiplier of 4.5 [212]. The California ARB proposed in 2017 that the all-electric range credit multiplier would be 3.5 for vehicles with electric ranges over 35 miles [211]. The value of an emissions credit is very much based on supply and demand. A diesel truck manufacturer needing credits to offset diesels sold is at risk of being prohibited from shipping all products by being non-compliant. That manufacturer is also at risk of being fined $37,500 for each non-compliant truck, and must correct the non-compliance possibly requiring a costly vehicle recall [1][212][213]. The value of an emission credit in this circumstance could be significant.

Companies making capital investments in electric vehicle technology may wonder if subsidies could disappear before they have built out their fleet. The pervasiveness of subsidies combined with the slow adoption rate of commercial electric vehicles, suggests that subsidies may be a factor for the foreseeable future. Specific funding sources like VW's huge fines are likely not going to be counted on in future years, but mechanisms like California's cap-and-trade auction proceeds appear to be sustainable funding mechanism.

10.1.8 Maintenance and Repair

Maintenance cost reduction is a goal for fleets investing in CBEV trucks. Figure 42 illustrates some of the major maintenance systems and components that are on a diesel medium-duty chassis but that may be missing from a CBEV. These represent leaks, worn moving parts, failed sensors in caustic environments, pumps, filters, high temperature components, complex thermo-chemical systems, etc. An electric chassis, even one with a small ICE range extender-generator, in comparison has many fewer moving parts, less caustic and hazardous fluids, minimal high temperature exhaust or emission systems, as shown in the Workhorse example in Figure 43 [204].

Battery electric vehicles are expected to extend preventive maintenance (PM) schedules for items like brakes and tires. The use of regenerative braking systems means the wear parts of brakes do not see the duty cycle found in diesel and gasoline trucks. Interviews with OEMs suggests that tires may wear differently due to electric drive motors and the regenerative braking, possibly having longer lives. Insufficient field history exists to confirm this claim at this time.

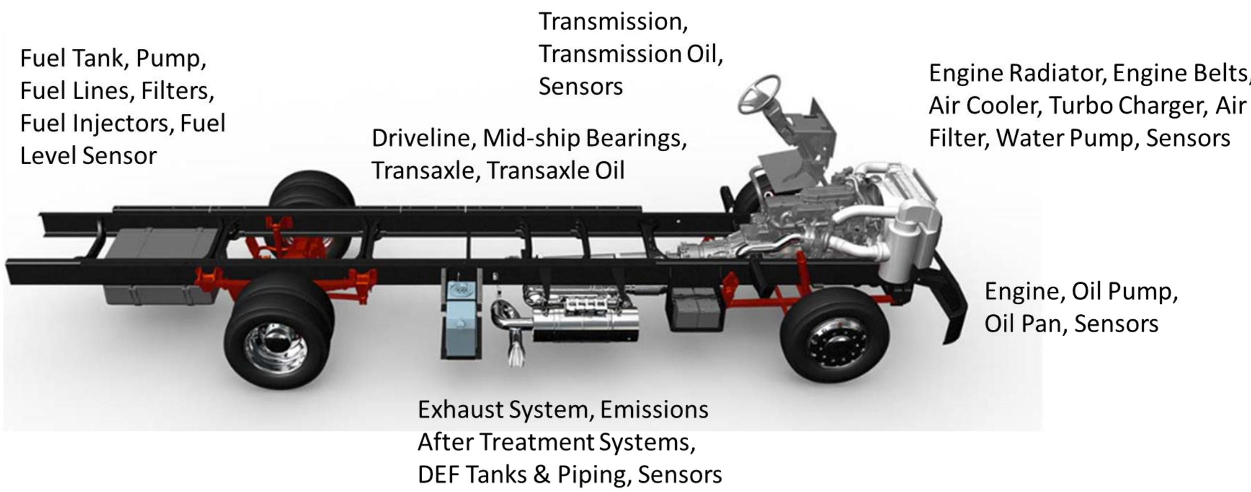


Figure 42. Maintenance Pain Points on Diesel Truck (NACFE modified from FCCC) [203]

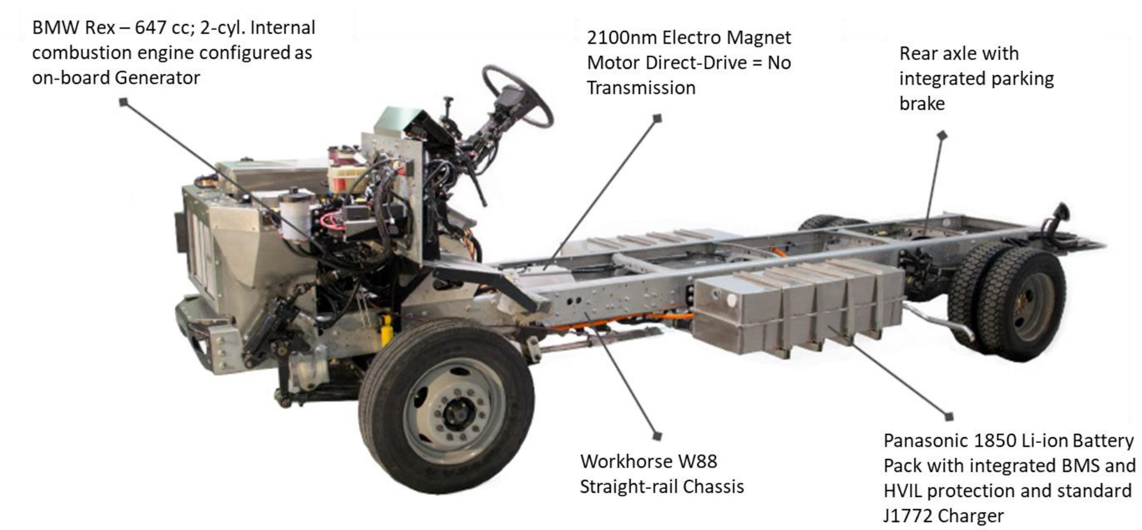


Figure 43. Example of Electric Chassis with ICE Range Extender (Workhorse) [204]

Diesel, gasoline and battery electric vehicles share some common maintenance pain points:

- Wiring and connectors
- Extensive electrical systems with public and proprietary software buses
- Integration of a number of electronic control modules and sensors
- Common brake systems, wheels and tires
- Steering systems
- Cabin HVAC systems
- Common 12V systems such as lights

NACFE reported in its 2018 Guidance Report: Electric Trucks – Where They Make Sense that data on automotive electric vehicle maintenance costs shows maintenance costs are about average with respect to their gasoline counterparts, still not mature enough to be seeing significant cost reductions from the technology [1]. NACFE interviews have found that fleets operating electric trucks and manufacturers producing them are not seeing maintenance savings yet because of the early production nature of these vehicles and limited field mileage. OEM engineers have not had significant feedback and iterations to improve designs. A CALSTART summary of 2012 testing with the early Navistar eStar and Freightliner Custom Chassis MT E-Cell, says, "At this early stage of vehicle development, true vehicle availability comparison between E-Trucks and conventional diesel vehicles would be difficult [215]." NACFE believes that conclusion is still applicable in 2018. OEMs recommended reviewing history of electric bus operators where there are some significant miles and numbers of vehicles in use. NACFE was unable to get access to hard data from bus makers to confirm or deny these claims.

Certainly the potential is there for significant maintenance cost reductions with battery electric vehicles, but NACFE concluded that maintenance reduction is not a near-term savings for medium-duty trucks and early generation vehicles may be equal to or worse than competing diesel or gasoline ones. NACFE projects this will change as sufficient production quality vehicles have had road time and engineers have incorporated improvements in subsequent model years. Interviews with fleets have confirmed that whether diesel, gasoline or electric, a down truck means lost productive miles, delayed deliveries, and unhappy drivers and customers.

Figure 44. A Down Truck (Mihelic) [200]

10.1.9 Fire

Catastrophic events occur with all vehicle types. Gasoline and diesel fueled vehicles can and do catch fire. *Money* magazine found that "about 174,000 vehicle fires were reported in the United States in 2015, the most recent year for which statistics are available from the National Fire Protection Association. Virtually all of those fires involved gasoline powered cars. That works out to about one every three minutes" [70][71]. BBC highlighted that 31 diesel bus fires have occurred in Rome in 2017-2018 [73]. Another source showed 14 more in 2016 [74]. Figure 45 shows NFPA fire causal factor data for 2003-2007, an era largely pre-electric vehicles, illustrating that fire does occur with ICE vehicle platforms [72].

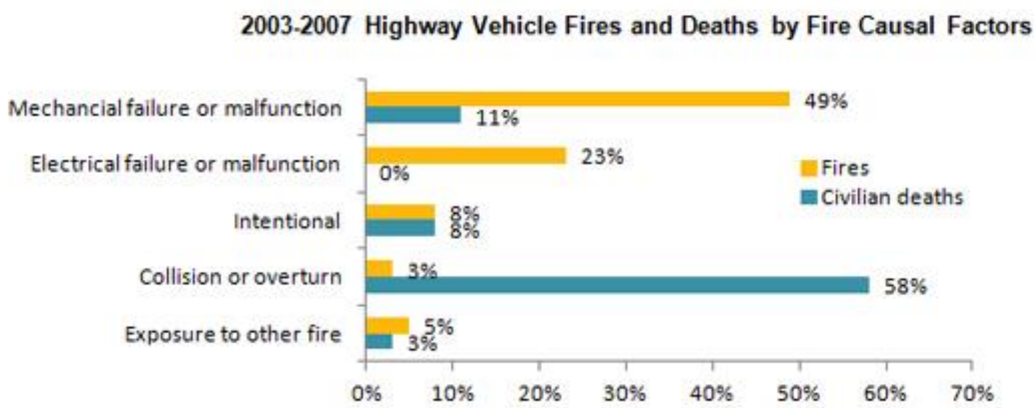


Figure 45. Pre EV Vehicle Fire Causes 2003-2007 (NFPA)[72]

A common argument made by detractors of BEVs is that they catch fire, and then in showing a vehicle burning, infer the frequency is somehow alarming. However, NHTSA/Battelle found there is no hard data suggesting this, while couching that there really is an insufficient volume of vehicles and history to accurately assess the issue [75]. There is even less data at present on commercial BEVs as there are fewer production vehicles in long-term use.

The 2017 NHTSA/Battelle report states, "Regarding the risk of electrochemical failure, the report concludes that the propensity and severity of fires and explosions from the accidental ignition of flammable electrolytic solvents used in Li-ion battery systems are anticipated to be somewhat comparable to or perhaps slightly less than those for gasoline or diesel vehicular fuels [75]."

The overall number of automotive BEV fire incidents should be small because the percentage of battery electric vehicles is relatively low (perhaps 1% of all vehicles sold). However, the incident rate within those vehicles appears to be at worst average versus similar ICE vehicles. Whether this experience can be extrapolated with any confidence to medium-duty BEVs is open to question. In some respects, the automotive EV experience represents something that might be scaled to truck, but in other respects, the systems are substantially different in capacity, performance and use.

The lengthy NHTSA/Battelle Report and their extensive references highlight that there are many unknowns about long-term battery statistics because of the rapid commercial evolution of the technologies. The report speculates on a variety of what-if failure modes and highlights that current manufacturing and testing standards will need to improve with experience. They conclude, "The investigation suggests that Li-ion battery safety can be managed effectively, although substantial research and development and codes and standards development is needed [75]." These recommendations seem also applicable to commercial vehicles.

The NHTSA/Battelle report graphically illustrates the variety of potential battery failure modes in Figure 46. The EV industry, while still relatively young, has developed standards. Industry standards organizations such as the International Electrotechnical Commission (IEC), SAE International, Institute of

Electrical and Electronics Engineers (IEEE), Guobaia (GB Standards), International Organization for Standardization (ISO) and others have published safety standards pertaining to design and testing of electric vehicle systems. A U.S. DOE website reminds buyers that "EVs must undergo the same rigorous safety testing and meet the same safety standards required for conventional vehicles sold in the United States as well as EV-specific standards for limiting chemical spillage from batteries, securing batteries during a crash, and isolating the chassis from the high-voltage system to prevent electric shock [182]." NACFE found that OEMS may provide training programs for first responders in addition to shop personnel.

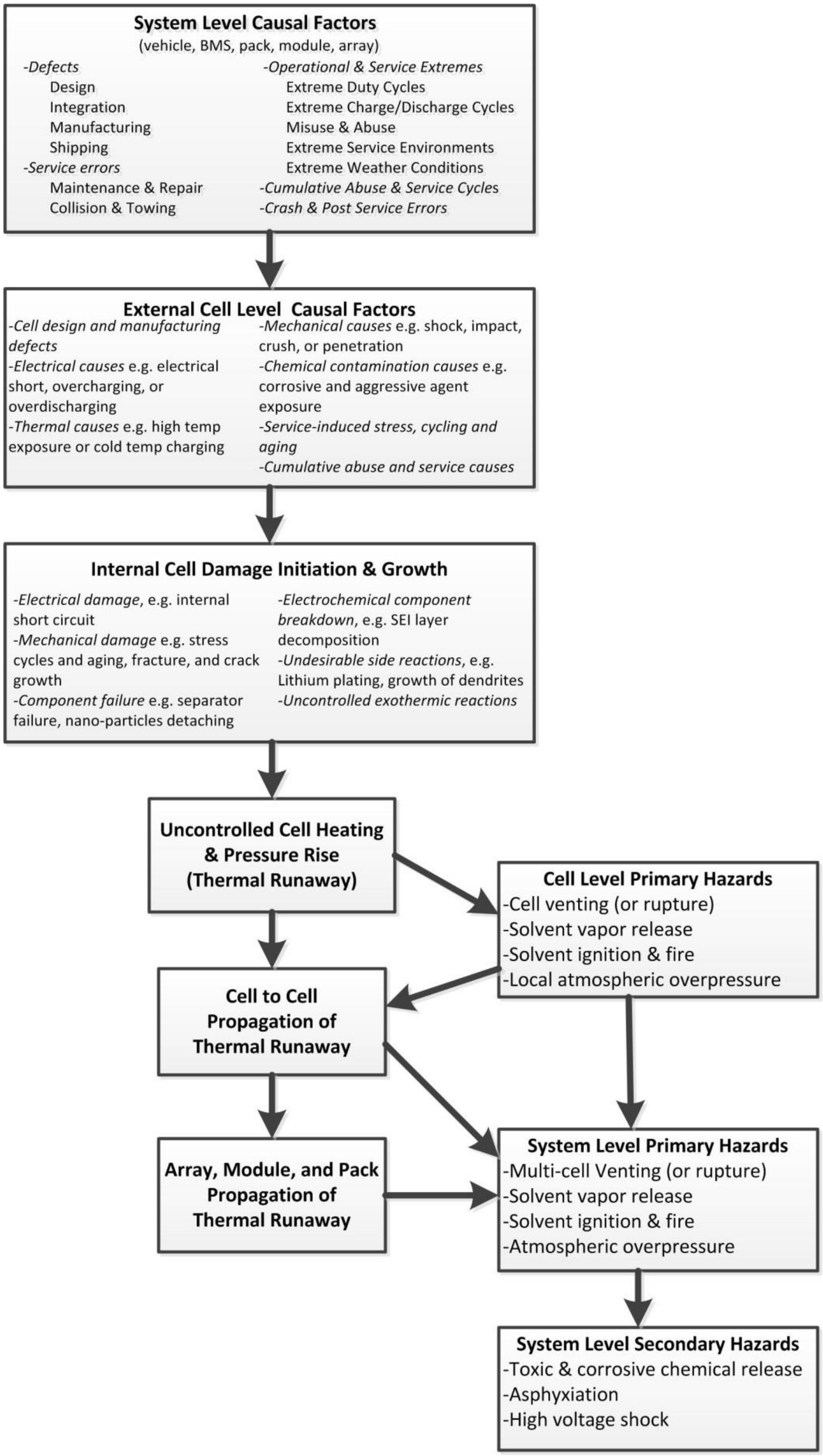


Figure 46. High-Level Flowchart of System Failure Causation and Hazard (Battelle/NHTSA)[75]

10.1.10 Raw Materials

The raw materials required to sustain production of battery electric vehicles represents concern to capital investment by fleets as OEM vehicle pricing is subject to flux from commodity volatility. The range of concerns includes labor practices, environmental practices and strategic issues in the supply chain that produces the battery packs for these vehicles. Three example materials discussed frequently in conjunction with battery electric vehicles are cobalt, rare earth metals and lithium. But less exotic materials like steel, aluminum and copper are also subject to significant pricing volatility from government policy decisions, supply and demand issues, and speculators. There are many sources of information on these commodities. This report provides in the following sections a range of possible sources for those wanting more detail on raw material supply.

Projections on world use of critical minerals involve complex predictions on innovation, policies, regional stability and financial speculation. Current mine production rates are used in projections of use of world reserves in the following sections to highlight only that the materials critical to electric vehicles are finite, and supply and demand rules commodity pricing. The specific growth rates used are only for example.

Innovation is ongoing with battery electric vehicle designs, with engineers and scientists producing higher energy density batteries regularly over the last decade and projections are for that to continue to evolve [1]. Innovation with respect to cost reduction is fundamental in modern vehicle engineering. Getting more with less is termed continuous improvement. It is embodied in cost reduction management practices standard in industry such as Six Sigma [151]. Finding alternative materials, making designs more efficient, or reducing critical material content while improving performance is a major aspect of on-going vehicle research and development. As commodities become more expensive, there is greater incentive for innovation to find substitutes and reduce content of the critical materials, while customers continually demand greater performance.

A good example of innovation affecting a key mineral is reflected in the projected cost of lithium batteries over time. Estimates of pricing in 2020 that were made in 2010 were on the order of $300 per kWh. By 2017, innovation in actual production batteries had progressed such that cost estimates in the $150 kWh range are realistic. A summary of projections over time was published by Berckmans et al in 2017 and shown in Figure 47 [148].

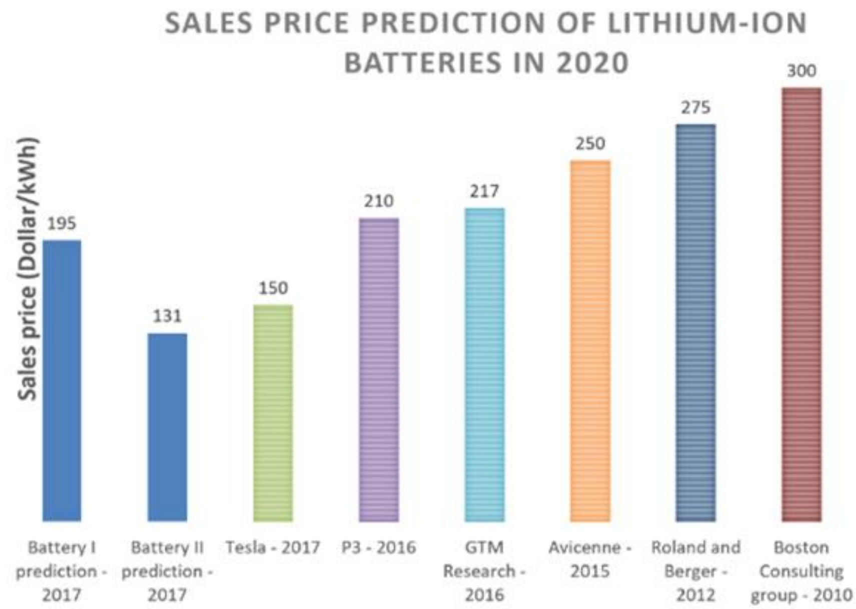


Figure 47. Sales Price Prediction of Lithium-ion Batteries in 2020 (Berckmans et al)[149]

The long-term supply and demand of raw materials such as cobalt, lithium and rare earth metals are identified as significant factors by Deutsche Bank, McKinsey and others for predicting future pricing of battery electric vehicles [150]. Others have predicted costs based on valuation of second life uses for batteries [152][153].

10.1.10.1 Cobalt

Cobalt is a significant component material used in batteries. Rechargeable batteries are the leading use for cobalt [90][107]. The leading source of more than half the cobalt demand in the world is the Democratic Republic of Congo (DRC) in central Africa [90][96][97][107]. It generally is a by-product of copper or nickel mining, meaning that, "Production (of cobalt) is driven primarily by the markets for the principal metals, not by the need for cobalt. This situation limits producers' flexibility in adjusting the amount of cobalt mined in response to changes in demand and can result in periods of oversupply or shortage. [107]." Figure 48 lists the U.S. Geological Survey 2018 estimates of production and reserves by region [90]. European Union estimates are similar [96][97].

The industry demand for rechargeable batteries has grown significantly. The total world mine production shown for 2017 is 110,000 metric tons, a 307% increase from the 1997 USGS estimate of 27,000 metric tons [90]. Reserves are estimated at 7.1 million metric tons. Estimating, for example, a 10% annual growth in annual cobalt mine output based on increased demand, this represents approximately a 20 year world supply.

Demand growth has highlighted supply concerns with an estimated 64% of world supply originating from the DRC, a region with a range of issues that can impact cobalt supply and pricing.

World Mine Production and Reserves: Reserves were revised based on Government or industry reports.

	Mine production		Reserves[7]
	2016	2017[e]	
United States	690	650	23,000
Australia	5,500	5,000	[8]1,200,000
Canada	4,250	4,300	250,000
Congo (Kinshasa)	64,000	64,000	3,500,000
Cuba	4,200	4,200	500,000
Madagascar	3,800	3,800	150,000
New Caledonia[9]	3,390	2,800	—
Papua New Guinea	[7]2,190	3,200	51,000
Philippines	4,100	4,000	280,000
Russia	5,500	5,600	250,000
South Africa	2,300	2,500	29,000
Zambia	3,000	2,900	270,000
Other countries	7,600	5,900	560,000
World total (rounded)	111,000	110,000	7,100,000

World Resources: Identified cobalt resources of the United States are estimated to be about 1 million tons. Most of these resources are in Minnesota, but other important occurrences are in Alaska, California, Idaho, Michigan, Missouri, Montana, Oregon, and Pennsylvania. With the exception of resources in Idaho and Missouri, any future cobalt production from these deposits would be as a byproduct of another metal. Identified world terrestrial cobalt resources are about 25 million tons. The vast majority of these resources are in sediment-hosted stratiform copper deposits in Congo (Kinshasa) and Zambia; nickel-bearing laterite deposits in Australia and nearby island countries and Cuba; and magmatic nickel-copper sulfide deposits hosted in mafic and ultramafic rocks in Australia, Canada, Russia, and the United States. More than 120 million tons of cobalt resources have been identified in manganese nodules and crusts on the floor of the Atlantic, Indian, and Pacific Oceans.

Substitutes: In some applications, substitution for cobalt would result in a loss in product performance. Potential substitutes include barium or strontium ferrites, neodymium-iron-boron, or nickel-iron alloys in magnets; cerium, iron, lead, manganese, or vanadium in paints; cobalt-iron-copper or iron-copper in diamond tools; copper-iron-manganese for curing unsaturated polyester resins; iron, iron-cobalt-nickel, nickel, cermets, or ceramics in cutting and wear-resistant materials; iron-phosphorous, manganese, nickel-cobalt-aluminum, or nickel-cobalt-manganese in lithium-ion batteries; nickel-based alloys or ceramics in jet engines; nickel in petroleum catalysts; and rhodium in hydroformylation catalysts.

[e]Estimated. — Zero.
[1]Cobalt metal. In 2014–17, the Defense Logistics Agency acquired cobalt-bearing battery precursor materials and cobalt alloys.
[2]Defined as net import reliance + secondary production, as estimated from consumption of purchased scrap.
[3]As reported by Platts Metals Week. Cobalt cathode is refined cobalt metal produced by an electrolytic process.
[4]Defined as imports – exports + adjustments for Government and industry stock changes for refined cobalt.
[5]See Appendix B for definitions.
[6]See Lithium for information about cobalt-containing materials for use in lithium-ion batteries.
[7]See Appendix C for resource and reserve definitions and information concerning data sources.
[8]For Australia, Joint Ore Reserves Committee-compliant reserves were about 390,000 tons.
[9]Overseas territory of France. Although nickel-cobalt mining and processing continued, the leading producer reported zero reserves owing to recent nickel prices.

U.S. Geological Survey, Mineral Commodity Summaries, January 2018

Figure 48. Cobalt World Mine Production & Reserves (USGS) [90]

Cobalt, as a commodity, has seen significant speculative price volatility over time, shown in Figure 49, with pricing ranging from $10/lb. to over $50/lb. [102].

Figure 49. Cobalt Pricing 2005-2018 (InfoMine.com) [102]

While research continues to find suitable substitutes for cobalt and to improve the efficiency of use of cobalt in the batteries, cobalt continues to be a fundamental part of most vehicle battery designs. To mitigate supply and cost sensitivities, designers are working to reduce the cobalt content of batteries. Tesla's 2017 SEC Conflict Minerals Report states in their newest battery designs, "The cobalt content of our Nickel-Cobalt-Aluminum cathode chemistry is already lower than next-generation cathodes that will be made by other cell producers with a Nickel-Manganese-Cobalt ratio of 8:1:1 [91]." Tesla's CEO was quoted in a May 2018 stating that they can get to nearly zero use of cobalt in next generation batteries [100][101]. Tesla's batteries are produced by Panasonic in a joint operation housed at Tesla's Gigafactory in Nevada. NACFE was unable to find Independent verification of the cobalt content, but clearly the Tesla SEC statements recognize the need to reduce cobalt use. General Motors, which produces the Chevrolet Volt and Bolt battery electric cars, does not list cobalt in its Conflict Minerals Report although the chemical composition listed as NMC-LMO Pouch includes cobalt [93][94][95]. This is possibly because GM procures the batteries from a supplier and falls under exclusions permitted in reporting [92][96].

A contributor to supply and pricing volatility are questionable labor practices in sourcing cobalt. The U.S. and EU, for example, have enacted policies to restrict import of cobalt and cobalt based products that originate through forced labor and child labor.

In response to concerns about sourcing, industry has developed policies for auditing and rating their supply chains through groups like the Responsible Business Alliance (RBA) formerly the Electronic

Industry Citizenship Coalition (EICC) [98]. Their mission is to support responsible supply chain management. "RBA members commit and are held accountable to a common Code of Conduct and utilize a range of RBA training and assessment tools to support continuous improvement in the social, environmental and ethical responsibility of their supply chains." A subgroup of EICC is the Responsible Minerals Initiative (RMI). This initiative has created "standards for responsible sourcing from conflict-affected and high risk areas [98]." This effort is in the process of establishing a Cobalt Reporting Tool (CRT). "The CRT was designed for downstream companies to gather and disclose information about their supply chains [99]".

Cobalt availability and pricing will continue to be a concern area for fleet investments in battery electric vehicles because of the limited sourcing options which can be affected by policies, weather, speculation and regional instabilities.

10.1.10.2 Rare Earths

High efficiency electric motors use rare earth magnets. Neodymium is an example used commonly in electric and hybrid vehicle drive motors and in other vehicle systems such as steering, door windows and locks, etc. [104]. The capital investment concern for commercial electric vehicles is that the primary worldwide source for rare earths is and has been China. Rare earth minerals exist in large quantities in the earth's crust but mining is largely localized in China, as seen in Figure 50, compiled from annual USGS estimates going back to 1994 [103]. Commodity pricing and supply are subject to political decision making such as international trade policies, growing trends in electric vehicle production for Chinese domestic demands and financial speculators.

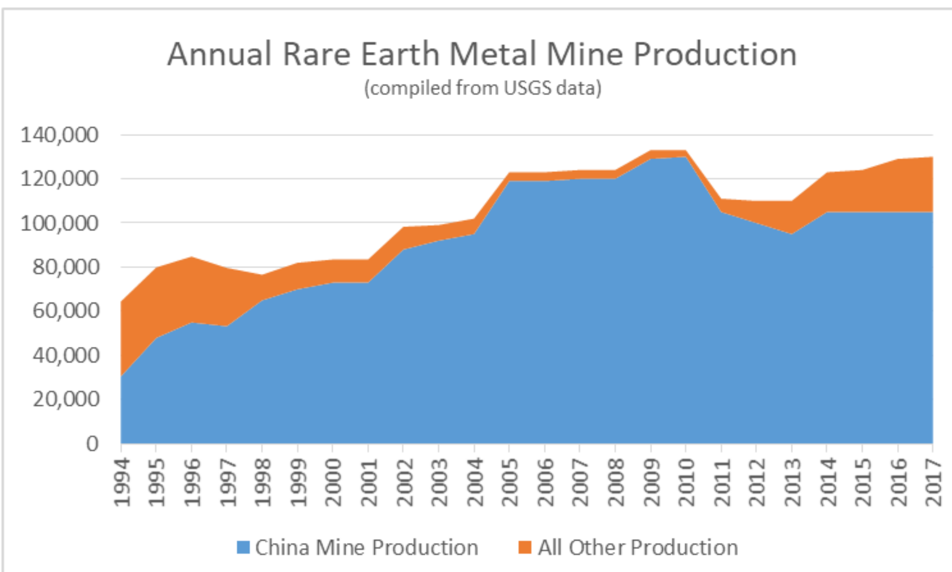


Figure 50. Rare Earth Mine Production (NACFE compiled from USGS data) [103]

As with cobalt, rare earth mineral price volatility has been significant. Prices have ranged from $83 to $429/lb. between 2011 and 2017 [103]. Production exists outside China in small volumes in Australia, Brazil, India, Russia and Thailand, with smaller amounts from other regions. The USGS shows no significant production in Canada or the U.S. in 2017 [103].

Capital investment concern for commercial battery electric vehicles is that rare earth commodity pricing is volatile and supply may be curtailed causing vehicle price increases and possible increases in replacement part costs.

10.1.10.3 Lithium

Lithium is abundant, it can be sourced nearly everywhere as shown in Figure 51. Lithium reserves are estimated at 16 million metric tons, while annual demand in 2017 was estimated by the USGS as 43 thousand metric tons [106]. Estimating, for example, an 8% growth in annual lithium mine output from increased demand translates to approximately 43 years of world supply if not factoring in recycling. Actual production is currently less broadly dispersed [106][107].

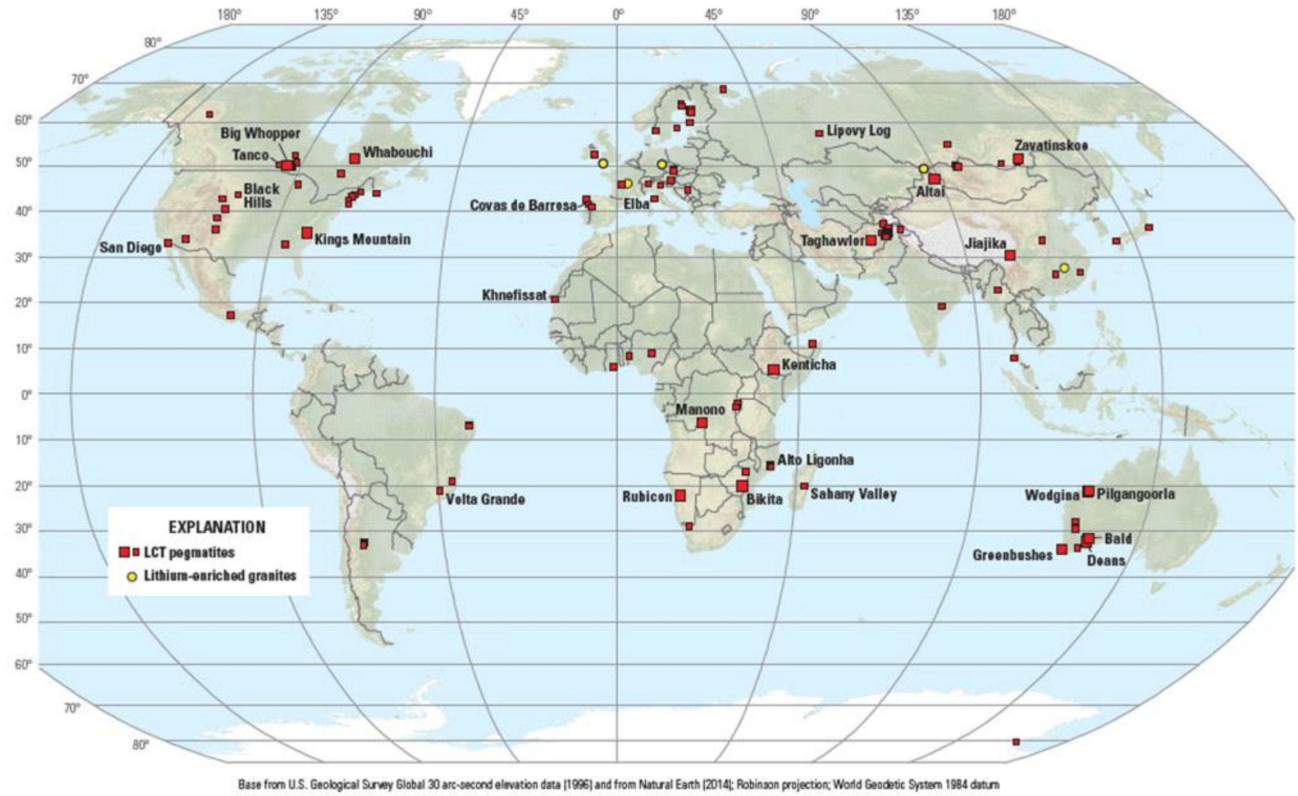


Figure 51. Selected Worldwide Lithium Deposits (USGS) [107]

That said, the USGS states, "Lithium supply security has become a top priority for technology companies in the United States and Asia. Strategic alliances and joint ventures among technology companies and exploration companies continued to be established to ensure a reliable, diversified supply of lithium for battery suppliers and vehicle manufacturers [106]."

Supply and demand drives the lithium commodity pricing, which has seen volatility since 2015 shown in Figure 52, along with cobalt and rare earth metals due to increasing demand, trade policies and speculators. Prior to 2015, lithium commodity pricing was fairly stable for the prior decade.

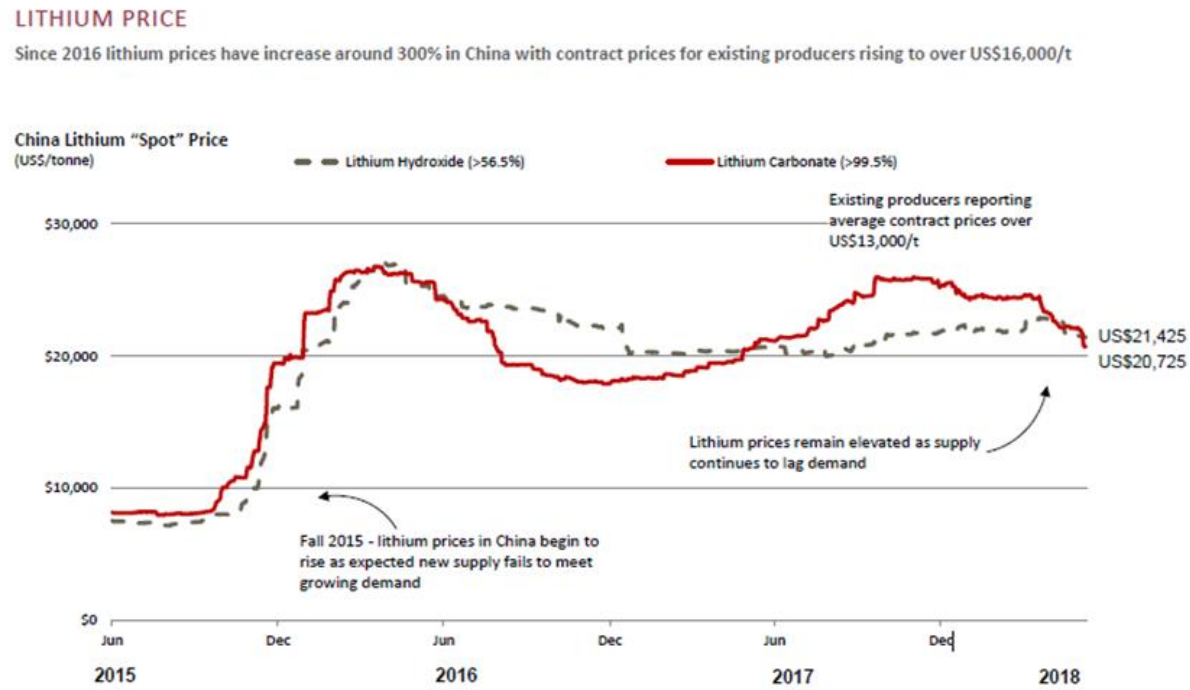


Figure 52. Lithium Commodity Pricing 2015-2018 (Lithium Americas)[108]

Recycling for lithium, cobalt and rare earth metals has not seen significant volumes. While recycling lithium-based batteries is technical feasible, the economics and yield are not an advantage over using raw ores [30][31][90][102][103][105]. Changes in supply and innovations in recycling processes may alter this equation in time

In summary, fleets making capital investments in battery electric vehicles may be subject to significant vehicle price volatility due to OEMs responding to flux in the commodity pricing that is largely out of their control.

10.1.11 Weight

NACFE interviews with fleets and OEMs confirmed that major segments of medium-duty delivery vehicles tend to cube out and are not sensitive to vehicle freight weight overloading. This is particularly true for parcel delivery operators as shown in Figure 53. However, the interviews also identified specific vocations that are very sensitive to vehicle weight. These include linen services, office supply services (for example boxes of paper), and beverages as illustrated in Figure 54.

Figure 53. Parcel Delivery Trucks Are Less Weight Sensitive (FCCC) [202]

Figure 54. Examples of Weight Sensitive Trucks (Mihelic & Crown Uniform) [200][198]

A parcel delivery expert stated that weight is not an issue, and that cargo space fills up long before weight capacity is reached. However, a linen delivery operator confirmed that vehicles typically operate near weight capacity. An electric vehicle OEM stated that in those weight sensitive cases, attention is paid to lightweighting the vehicle or an alternative is to select a higher GVW vehicle.

NACFE concludes that vehicle weight for Class 3-6 medium-duty electric vehicle applications, is not a significant risk for fleet operators as either they currently have sufficient weight margin with their freight loads or have alternate choices in GVW ratings and vehicle designs.

10.1.12 Battery Life, Range and Replacement

Battery life is dependent on a number of operational factors. The U.S. National Renewable Energy Laboratory (NREL) summarizes that major factors include environment temperatures, depth of discharge, recharging cycles and charging levels [136][138]. There are many contributing factors that can limit or degrade battery life. This is why vehicles require battery management systems to actively monitor the batteries, charging, discharging and thermal profiles. Battery thermal management systems have also been found to contribute to extending battery life by maintaining the batteries in a narrower set of environmental conditions than the vehicle might see. Battery performance has also been found to degrade over time [1][154]. Unlike a diesel vehicle where a gallon of fuel will likely last a similar number of miles over the life of the truck, an electric vehicle's kWh will not produce the same range as the vehicle ages. An industry guideline is that batteries should be replaced if their fully recharged capacity has decreased to below 80% of the new vehicle capacity [151][152][153][155].

Interviews with industry experts have found that some manufacturers are lowering this threshold for battery replacement to 60% or 70% of initial range. NACFE's opinion is that lowering the range at which batteries should be replaced only adds to the need to include excess capacity at the time of purchase to assure the intended vehicle duty cycles can be met for the life of the vehicle. At the 80% level, a vehicle rated at a nominal 100-mile range will be derated to 80 miles later in life. A battery with a 60% level would derate to 60 miles of nominal range at the end of vehicle battery life. For both vehicles to meet a duty cycle requiring a nominal range of 80 miles for the owned life of the vehicle, the 60% one would have to carry significantly more battery capacity when new and it would carry that extra weight over the life of the vehicle.

The nominal advertised range is also somewhat misleading. It may or may not reflect actual operational use, as it reflects a common duty cycle which does not represents every fleet's unique duty cycle. This duty cycle might even represent some fairly benign conditions, for example flat terrain in moderate temperate zones. Fleets likely will need to add some margin of capacity beyond these advertised ranges to assure their unique duty cycle needs are met.

On the other end of the battery use challenge is that batteries do not perform well when deep cycled below 10% to 20% of their capacity. NACFE has found that battery management systems are developing that cutoff power when the state of charge reaches 10% to 20% of capacity, derating vehicle power to a limp home mode with limited range and speed. This again has impacts for setting the new vehicle range capacity. Fleets may need to add 10% to 20% extra capacity in their new vehicles to ensure that vehicles can accomplish their duty cycles.

NACFE research has determined that battery warranties do not necessarily guarantee replacement of used batteries with new ones with full capacity. In some cases, derated batteries may be used as replacements with range capacities below 100% of new. These may be used or remanufactured units. Fleets need to clarify with OEMs as to what warranties guarantee with respect to battery replacement. Fleets should demand a clear definition of battery life expectations based on capacity with respect to their actual duty cycles. Fleets should require clear trigger capacity thresholds regarding when a degraded battery is to be replaced.

Specifying the initial capacity of a battery pack to meet a fleet's intended duty cycles will require knowing:

- The manufacturer's expected battery replacement life
- The depth of discharge cut-off
- How the nominal range estimate compares to the fleet's actual duty cycle requirements
- Charging rate used to predict life
- What battery capacity will be in replacement batteries

Fleets expressed a concern about battery life cycle during NACFE interviews. NACFE and others quantified the magnitude of cycles [1][152]. For example, a vehicle with a 10-year battery life that recharges once per work day, with five days per week, for 50 weeks use per year, will see approximately 2,500 charging cycles. The 80% capacity threshold for degradation before replacement equates to approximately 0.008% per charging cycle assuming a linear degradation rate. The actual degradation is not linear, but this value suffices for the purposes of this discussion. NACFE found that these levels of degradation are being met in some automotive uses where years of field history exist [1]. This reinforces the NACFE conclusion that battery life in the presence of effective battery management systems and battery thermal management systems, can likely meet design life targets.

Medium-duty vehicles tend to have long lives. If OEM battery design life is five, seven or 10 years, then the total cost of ownership over a 10 to 30 year lifespan will require inclusion of battery replacements. Those replacements may use the original capacity, or may take advantage of improvements made since the vehicle was manufactured. The battery electric vehicle industry is still fairly young, and these downstream questions have not seen significant use to establish trends. The choices of available replacement batteries will also depend on market supply and demand pricing, where added capacity may carry a premium, or where newer technology is more cost effectively produced and can be sold at a lower cost. The history of personal computers, tablets and cell phones suggests that better performance in the world of electronic components may be in parallel to lowering replacement costs. This trend would differ from diesel powertrain history where added performance has generally implied increased costs.

10.1.13 Battery Second Life

Batteries are the primary concern for electric vehicles. A common guideline is that electric vehicle batteries should be replaced when they have reached 80% of their original capacity. Battery capacity tends to degrade with a number of use factors such as charging cycles, charging rates, depth of charge depletion, and various environmental factors.

At 80%, the batteries still have significant utility for other applications, for example as energy storage for utilities, farms, warehouses or homes. The volume of batteries available for repurposing will grow as production of electric vehicles increase. Ethan Elkind, Associate Director of the Climate Change and Business Research Initiative at the UCLA School of Law’s Emmett Institute on Climate Change and the Environment and UC Berkeley School of Law’s Center for Law, Energy & the Environment, estimated growth in used battery capacity in a ACT EXPO 2018 presentation on battery reuse as shown in Figure 55. Two similar trend curve shapes but one estimating over 18 GWh of global used battery capacity available in 2025 and the other 180 GWh in 2025 have been reported by David Stringer and Jie Ma in Bloomberg where estimates are the majority of used batteries will come from electric buses, followed by electric cars [32].

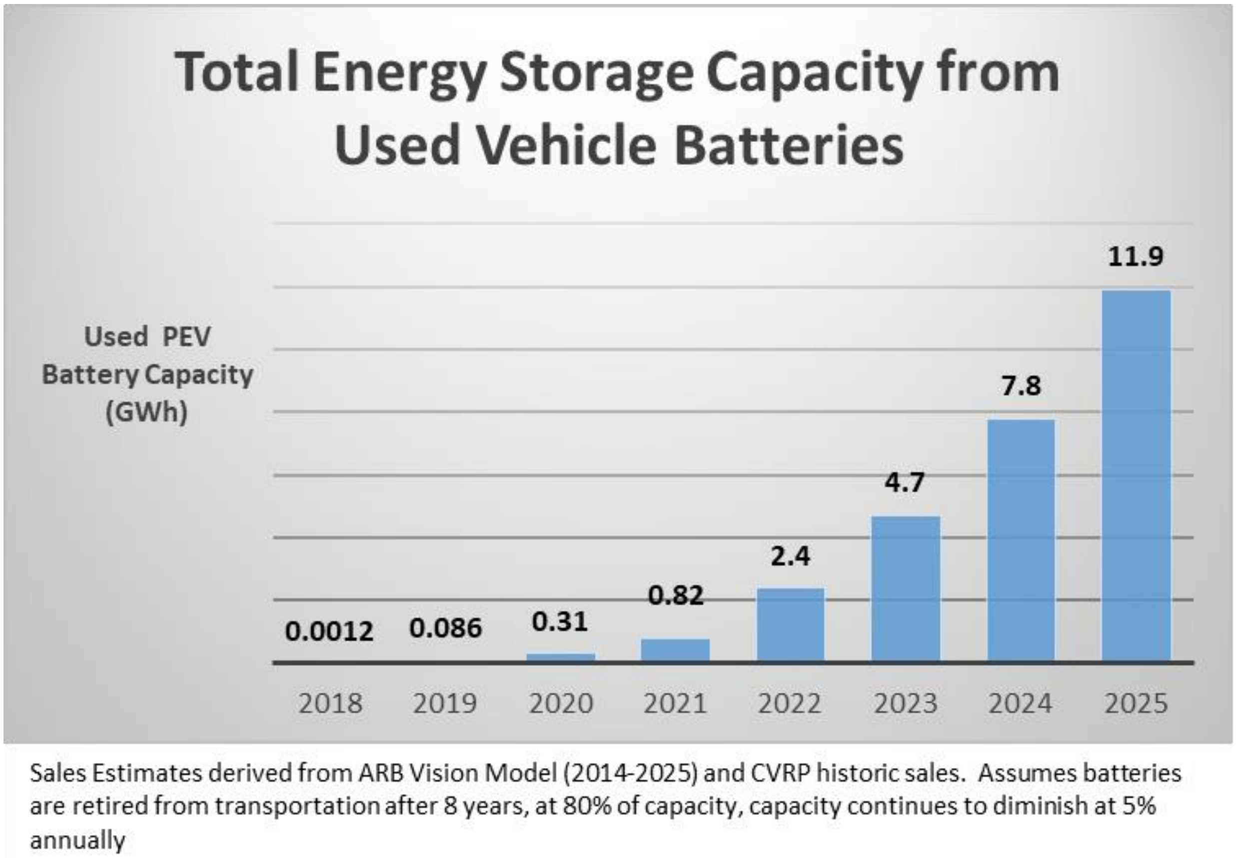


Figure 55. Growth in Volume of Used Batteries (Elkind) [31]

Ellkind stated in his 2014 report, Reuse & Repower, "The residual value of second-life batteries could help lower upfront electric vehicle costs, as automakers and consumers alike factor in the resale value as part of a reduced purchase price [30]." The Bloomberg article cites a number of companies creating business plans involving refurbishing or repurposing EV batteries, such as Powervault, Nissan, Eaton, EVgo, BMW, Renault, and Chevrolet [30]. The Edison Electric Institute (EEI) discusses a number of research reports on potential cost reductions to vehicles from second life re-use of batteries [153]. Delft University also discusses the potential of recycling or repurposing batteries [152].

Given the inevitable growing supply of used batteries as EV vehicle production increases, markets are expected to develop both out of necessity and due to regulations. In Europe, for example, The EU Directive on End of Life Vehicle, EU ELV Directive of 2000, specifies, "No later than 1 January 2015, for all end-of life vehicles, the reuse and recovery shall be increased to a minimum of 95% by an average weight per vehicle and year. Within the same time limit, the re-use and recycling shall be increased to a minimum of 85% by an average weight per vehicle and year [33]."

This reuse/recycle necessity is not without challenges. A policy brief from European Rare Earth (Magnet) Recycling Network, EREAN, identifies, "A new challenge is now the generation of a new type of ELVs, which will have to be handled by vehicle recyclers in the near future. Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV) represent different recycling challenges with respect to conventional Internal Combustion Engine vehicles (ICEV) [34]." Figure 56 highlights the issues.

Highlights

- Approximately 8-9 million tonnes of End-of-life (ELV) vehicles are generated in the EU every year. The End-Of-Life Vehicle Directive (Directive 2000/53/EC) has been a success with 23 member states meeting reuse/recycling targets by 2011 and a significant number exceeding targets.
- The new generation of End-of-Life Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV), poses new recycling challenges with respect to conventional Internal Combustion Engine vehicles (ICEV).
- The key areas of difference for vehicle recyclers are the larger quantity of high power/low weight motors on an (H)EV compared to the equivalent petrol/diesel technology. Typically, an EV (with a NiMH battery type) contains 4-5 kg of rare-earth elements (REEs) compared to less than a kilo in a new petrol/diesel car.
- Apart from REEs, (H)EVs contain other critical metals such as cobalt (Co), gallium (Ga), indium (In), niobium (Nb), platinum group metals (PGMs), antimony (Sb), tantalum (Ta), and tungsten (W).
- Cobalt in particular is now being singled out due to the rapidly rising demand for Co-containing Li-ion batteries for not only (H)EVs but also laptops and smartphones.
- The current ELV recycling practice, which includes shredding, causes random dispersion of the critical metals, especially for metals, which are concentrated within specific process streams but are used in small amounts in the whole vehicle (e.g. neodymium, samarium).
- Separation of neodymium- and dysprosium-containing rare-earth magnets has not yet been adopted by industry but is possible by dismantling relevant components before shredding of End-of-Life vehicles.
- The biggest technical challenge facing the motor disassembly process is the wide variation of rotor design and magnet size.
- The technical (disassembly) challenges should be met by legislators and vehicle manufacturers /recyclers either by depollution/removal of the high REE content motors prior to shredding and downstream processing or by further downstream processing of the shredded residues to separate the valuable REE-rich fractions physically.
- The disassembly of the magnet-bearing rotor is already profitable today, mainly because of the stators' high copper wire content, even if the REEs are not recycled.

Figure 56. Recycling Challenges for Electric Vehicles (EREAN) [35]

Recycling and repurposing medium-duty electric truck components will be a developing factor in the total cost of ownership estimation. At present, there is insufficient experience with second market aspects of these vehicles to place firm numbers on the value of used batteries, motors, controllers, etc. NACFE has found in interviews with fleets and suppliers a general consensus that second life use will represent significant value so that salvage value will not be zero. Estimating residual values five, 10 or 20 years out at this time is an unknown with significant risk of error.

10.1.14 Battery Climate Sensitivity

Regional environmental factors can contribute to battery discharge and charge rates. A 2016 report from Yuksel et al at Carnegie Mellon highlights that, "Temperature has an important effect on vehicle efficiency due to heating, ventilation, and air conditioning (HVAC) use and temperature related battery efficiency effects [191]." An earlier report from Yuksel and Michalek estimated that, "Battery electric vehicles (BEVs) can consume an average of 15% more energy in hot and cold regions of the US [189][191]." A 2018 SAE Automotive Engineering article discusses cold weather testing of EV cars in sub-zero centigrade tests in Norway [190]. The article highlights that where a diesel or gasoline vehicle creates heat as a by-product that can be used to heat vehicle occupant spaces, battery electric vehicles have to supply extra energy to provide in-cabin heating [190]. A 2018 Idaho National Laboratory (INL) report supports that cold weather impacts EV charging speeds [186][194].

At the other temperate extreme, vehicles operating in hot climates may have air conditioning systems which also drain battery power in EVs. NACFE interviews with OEMs and fleets found that medium-duty vehicles may not be equipped in all vocations with air conditioning systems since operators tend to drive open door to facilitate quick entry and egress.

The 2016 Yuksel and Michalek report summarized 7,000 trips of actual vehicle data compiled by FleetCarma from Nissan Leaf vehicles in the graph of energy consumption versus temperature shown in Figure 57. Note that the Nissan Leaf uses passive battery heating/cooling systems so is perhaps more sensitive to environmental conditions [192].

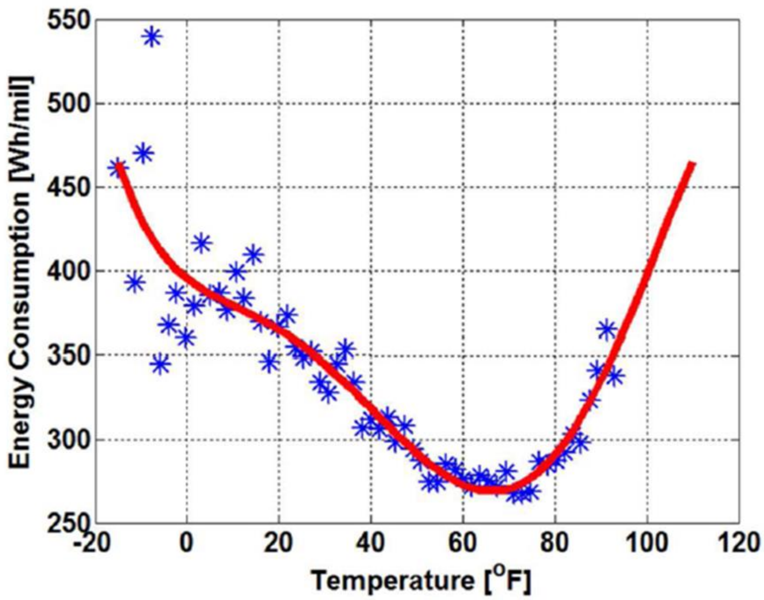


Figure 57. Example of Energy Consumption versus Temperature (Yuksel & Michalek)[189)

Wood et al of the U.S. Department of Energy modeled this Nissan Leaf data as shown in Figure 58 [192].

Trip Avg Speed, mph	Ambient Temperature, °C												
	-20	-15	-10	-5	0	5	10	15	20	25	30	35	40
2.5	203%	193%	186%	178%	167%	154%	141%	132%	129%	136%	153%	180%	213%
7.5	177%	168%	162%	155%	146%	135%	123%	115%	113%	119%	134%	157%	186%
12.5	163%	155%	149%	143%	134%	124%	114%	106%	104%	109%	123%	145%	171%
17.5	146%	139%	134%	128%	121%	111%	102%	95%	93%	98%	110%	130%	153%
22.5	135%	128%	123%	118%	111%	102%	94%	88%	86%	90%	102%	120%	141%
27.5	132%	125%	120%	115%	108%	100%	92%	85%	84%	88%	99%	117%	138%
32.5	135%	128%	123%	118%	111%	102%	94%	88%	86%	90%	102%	120%	141%
37.5	141%	134%	129%	124%	116%	107%	98%	92%	90%	94%	106%	125%	147%
42.5	147%	139%	134%	129%	121%	111%	102%	95%	93%	98%	111%	130%	154%
47.5	155%	147%	142%	136%	128%	118%	108%	101%	99%	104%	117%	138%	163%
52.5	164%	156%	150%	144%	135%	125%	114%	107%	104%	110%	124%	146%	172%
57.5	168%	159%	154%	147%	139%	128%	117%	109%	107%	113%	127%	149%	176%
62.5	182%	172%	166%	159%	150%	138%	126%	118%	115%	121%	137%	161%	190%

Figure 58. Relative Effects of Speed and Temperature on Battery Discharge Rate (Wood et al) [192]

The presentation colors in Figure 58 highlight in red shades where discharge rates increase from the effects of temperatures and speeds and in blue shades where the sweet spot is for longest battery performance, and thus range. While this analysis is based on estimations from the Nissan Leaf data, the trend is indicative of how environment and speed may impact battery range. Many EV autos are equipped with battery management systems that employ active heating and cooling systems to maintain batteries in a narrower set of temperature ranges [192]. However HVAC power draw is still a seasonal factor in shortening the range for vehicles.

Temperatures also can affect the rate of charging for vehicles [186][194]. OEMs are aware of these issues and some automotive solutions include resistive heating during charging [192]. This is also done to keep batteries from being damaged by charging in severe cold. These steps may be loosely equivalent to engine block heaters and fuel heaters used in ICE vehicle powertrains in colder climates.

The concern for fleets investing in CBEV vehicles is that deployment to harsher climate regions may necessitate more margin in battery sizing, or acceptance of shorter ranges than might be obtained in more moderate climes. The cost of charging may also be greater in colder climates.

10.1.15 Vehicle Recycling/Salvage

Total cost of ownership evaluation includes estimating the residual value of a vehicle when traded. Often with medium-duty vehicles, the first owner keeps the vehicle its entire life such that residual value at end of life is based on the vehicle's salvage value. In many cases, NACFE interviews highlighted that fleets may depreciate truck purchases over 10 years such that the book values are zero beyond that point. Some fleets may keep their medium-duty vehicles as long as 20 years.

NACFE interviews with fleets operating electric vehicles found that in some cases parting out an electric vehicle had value as the electric motors, batteries and parts of the control systems could be repurposed such as for agricultural stationary uses like water pumping. In other cases, fleets assigned some nominal scrap value to the vehicle and sold it off for scrap. Recycling of vehicle chassis components will be similar to the experience with diesel and gasoline trucks, but the electric vehicles may be less challenging to recycle if the batteries and motors can be sold into secondary markets because of the absence of environmentally challenging fluids.

10.1.16 Energy Sourcing

A key difference between diesel based vehicles and battery electric ones is that diesel is a fuel where electricity is more like an energy carrier, and the energy can be produced by a wide variety of methods. This inherent flexibility in electricity as a charging mechanism means that vehicles are not tied to the economics of one energy source. Electrical charging can be tied to any and all electricity sources. The Energy Information Administration of the U.S. DOE tracks U.S. energy usage [47]. The graph in Figure 59 illustrates the relative energy consumed by source over the history of the U.S.

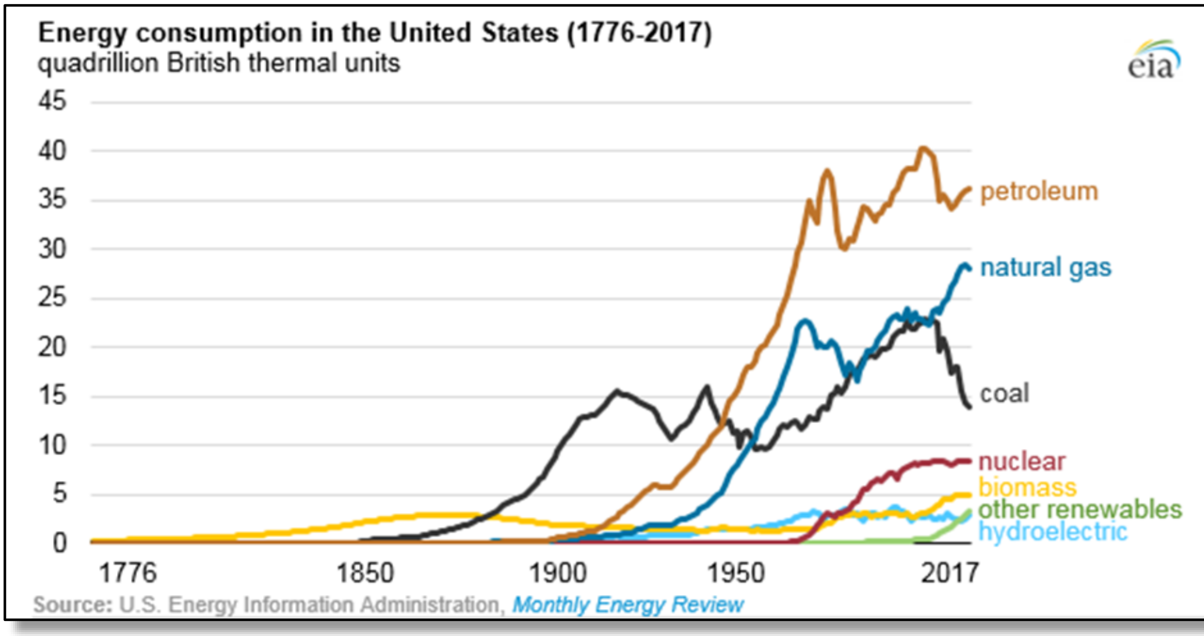


Figure 59. Energy Use By Source Over Time (EIA) [47]

The petroleum curve's peaks and valleys reflect significant changes in supply or demand, which directly impact fleet operators' fuel costs and profits. This unpredictability, or volatility, has resulted in such reactive pricing mechanisms as freight fuel surcharges and contracting long-term price hedges. Significant cost increases have resulted in upsurges in freight company bankruptcies, particularly smaller operators.

Electricity based vehicles however have the option of sourcing power from the entire range of energy providers, such that increases in costs in one source can be countered by switching to other sources. This is the case with coal and natural gas at the right of the curve shown in Figure 59.

The EIA illustrates the fluid nature of the U.S. energy grid as a flow with multiple inputs and multiple outputs (Figure 60) [46]. The grid can be envisioned as a river with multiple streams supplying water and multiple output end users such as farmers, cities, power generators, etc. Consumers really have no idea where their specific power originates, only who they pay for it.

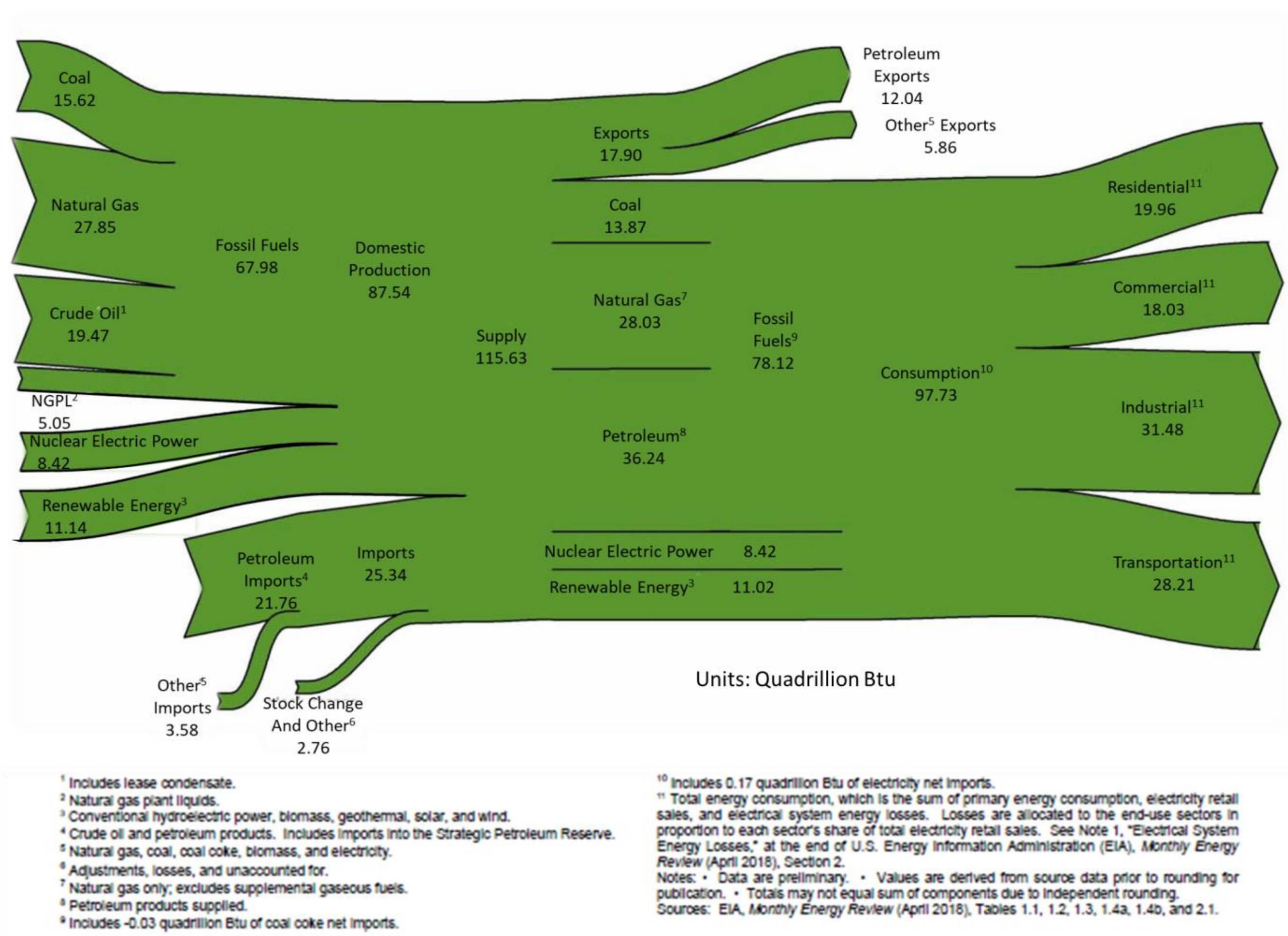


Figure 60. U.S. Energy Flow 2017 from Source to End Use (adapted from EIA) [46]

Electric energy sources for battery electric vehicles provide competitive pricing options not available to diesel and gasoline vehicles that must get their energy from refineries. Stated alternatively, electric vehicles have more robust energy supply options, which make them less at risk to energy market volatility.

The future for electrification is challenging to predict. One good overview is provided by NREL's Trieu Mai et al in a 2018 report Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States, where they state, "Technology adoption will ultimately depend on a set of complex considerations [35]." The report maps out a range of electrification growth in Figure 61, from an incremental reference case to significant high degree of change based on various models for growth in the constituent product uses of electricity.

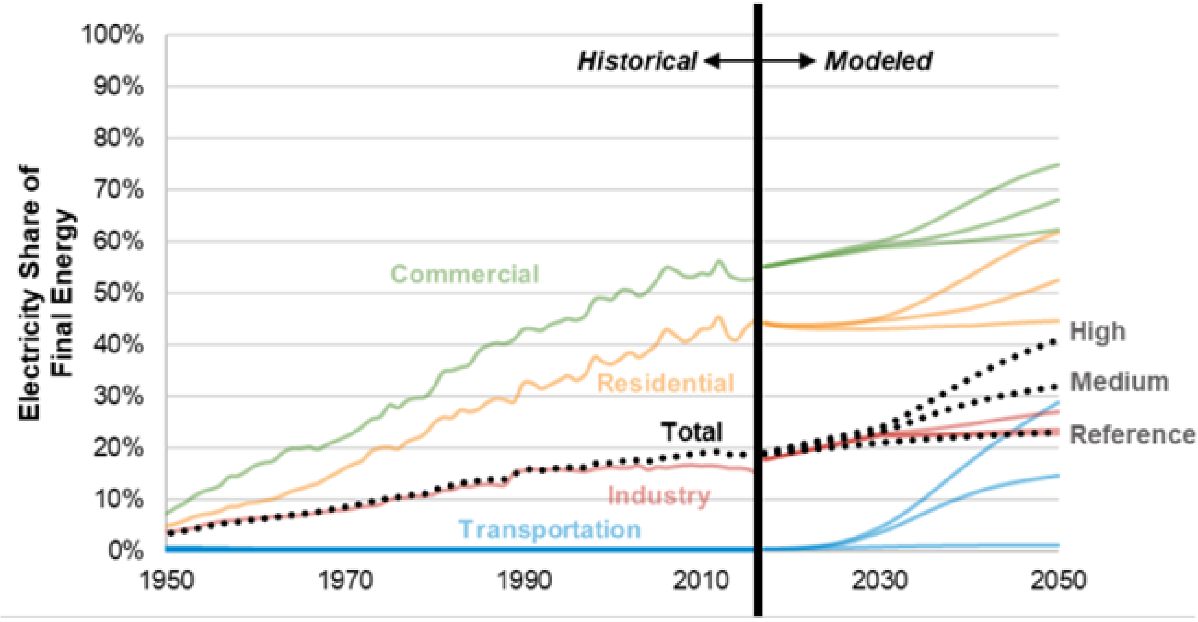


Figure 61. Electricity Share of Final Energy Consumption Predictions (NREL) [35]

The projections show that growth of electric vehicle use ranges from a few percentage points to perhaps 30% by the year 2050, illustrating the conclusion that mixed technologies in fleets will be expected for decades to come.

10.1.17 Electrical Grid Readiness

The electrical grid is a business. Capacity is the result of capital investments made in response to demand. NACFE believes grid capacity tends to lag demand because capital investment requires downstream cash flows to provide returns. Instantly building out the national grid to support proposed millions of future electric vehicles would mean a great deal of excess capacity waiting for OEMs to ramp up production. Instead, a more realistic investment path is that OEMs will ramp up production in response to increased consumers demand. The electrical grid will respond to the increased electric vehicle volumes by making investments where demand is exceeding supply. There likely will be some lag between the increased number of vehicles and the growth of the grid to support them. The free market behavior of investment following demand is complicated by the way utilities operate with tariff structures and controls on investment. Details on the complexity of modeling utility grid investment can be found in the course material available from the MIT OpenCourseWare class on Engineering, Economics and Regulation of the Electric Power Sector by Professor Ignacio Perez-Arriaga [168].

NACFE interviews with industry experts has found that truck makers are not likely to deliver electric trucks to fleets that do not yet have their charging systems in place. Rather, those vehicle build slots will be allocated to fleets that can confirm charging systems will be in place at delivery. NACFE found that lead times for installation of vehicle charging systems can be six months to in excess of a year. Several industry interviewees remarked similarly that, “The charging system is the most complicated part of the system, building the vehicle is easy.” One commented that the challenge “is not the vehicle anymore, it’s cost justifying the infrastructure.”

Diesel purchasers are not generally engaged in evaluating capital investment for fuel pumps and tanks. That infrastructure probably already exists or is using third party fuel stations that already exist. Fleets considering electric vehicles for return-to-base depot charging inherently have to consider the infrastructure to deliver electricity to the trucks. OEMs and charging system suppliers are recognizing that buying an electric truck is much more involved than buying a diesel one. A greater level of systems planning is needed, with project managers needing to work with utilities, municipalities, vehicle OEMs and charging system suppliers to plan out and execute a complete scheme.

NACFE has found that expansion of the grid does not represent technical roadblocks. Studies by utilities and others have found there is sufficient energy generation capacity to support significant near-term growth in electric vehicle volumes [1]. Delivery to the end user is where there are challenges. Older existing sites may require significantly greater site work and investment to address electrification than greenfield new build sites. Existing local grids may not have capacity and may need expansion. These are investment decisions that will be market based considering demand trends.

One utility industry expert interviewed by NACFE did mention concerns with labor supply of skilled electrical linemen and the long lead times needed to hire and train qualified field personnel. Project lead times may also increase as the number of vehicles per site increases.

10.1.18 Scaling

Interviews with fleets highlighted that scaling CBEVs was an area of concern. One NACFE OEM interviewee felt that lead time fell into three categories based on site fleet size, (a) with 1 to 5 vehicles being low concern about on par with vehicle purchase lead times, (b) 6 to 20 vehicles being moderate concern based on the age of the facility being prepared for electric trucks, and (c) high concern for fleets greater than 20 trucks because of lengthy utility and municipal planning and approval processes.

While deep pocket large fleets might experiment with a handful of CBEVs at different facilities with the assistance of grants and incentives, building out a significant number of vehicles at a site is somewhat unknown territory. Smaller fleets may actually have an advantage in rolling out CBEVs because the numbers of units at a site may be small, requiring relatively short lead times to install infrastructure. One fleet executive at a larger national fleet felt that infrastructure implementations might need to be staged. An initial demonstration might be with a small number of vehicles. Later, or in parallel, work may start on infrastructure for a large number of trucks at a site. This two-step approach, or concurrent approach can get CBEVs in operation quickly so critical first-hand experience is obtained, while the longer lead work on a larger deployment can be ongoing.

NACFE concludes that the greatest concern to scaling the number of CBEVs at a site is the lead times for the charging infrastructure. Lead times are inseparably linked to the way utilities make and recover investments in infrastructure. Large installations may require utilities to plan and obtain approval for infrastructure investments and rate tariffs, in addition to actually executing building out the infrastructure. It is common that the approval process can take one or two years due to the way utilities must operate. One example is the Port of Long Beach installation of 24 charging stations to support 68 electric terminal tractors documented in a request from Southern California Edison (SCE) to the California Public Utilities Commission (PUC) [269][270].

Infrastructure cost recovery by utilities is done through rate tariffs, essentially additions to the cost of energy. Rate tariffs vary by utility and by level of use. They can vary by season. They can vary by time of day. Typically they must be approved by commissions. The Public Utilities Commission of the State of Nevada defines tariffs as "a collection of rules that defines the relationship between a utility and its customers. Each utility has its own tariff. The tariff may consist of up to 20 or more rules. Rules address service area, rates, allocation of costs for line extensions, allocation of costs for new customer connections, requirements for new customers, and other issues, which define the responsibilities and authorities of the utility. Tariffs are intended to ensure that utilities apply non-discriminatory practices to all customers. Tariffs are formally accepted or approved by the Commission and can only be changed by Commission order. Complete and approved tariffs for each regulated utility are maintained by the Commission [195]."

Where the number of CBEV chargers at a site requires significant infrastructure changes to get power to a site, fleets will need to work with utilities and municipalities to coordinate the work. Some bureaucracies may move quickly, others may not. Gauging lead times is very site dependent with no "typical" rules of thumb. One consistent point made in interviews with NACFE staff is that older facilities can be more time consuming than planning for greenfield new ones.

10.1.19 Diesel and Gasoline Fuel Prices

Oil and refined diesel and gasoline fuel prices have seen significant volatility since 2007 as shown in Figure 62 from the U.S. DOE Energy Information Administration [143]. The EIA graph shows the significant spread of price predictions out through 2020. Long- term predictions may not have any credibility. The EIA shows that NYMEX oil spot pricing with a 95% confidence level may be between $110/barrel and $35/barrel. Few if any predicted the significant drop in pricing ahead of the Great Recession in 2008, or the surge in use of fracking in the U.S. propelling the U.S. back into position as a world leader in oil production. Politics, conflicts, innovation and economics all play into pricing oil. One new aspect of predicting the future pricing of oil is that growth in electric vehicles may decrease demands on oil production.

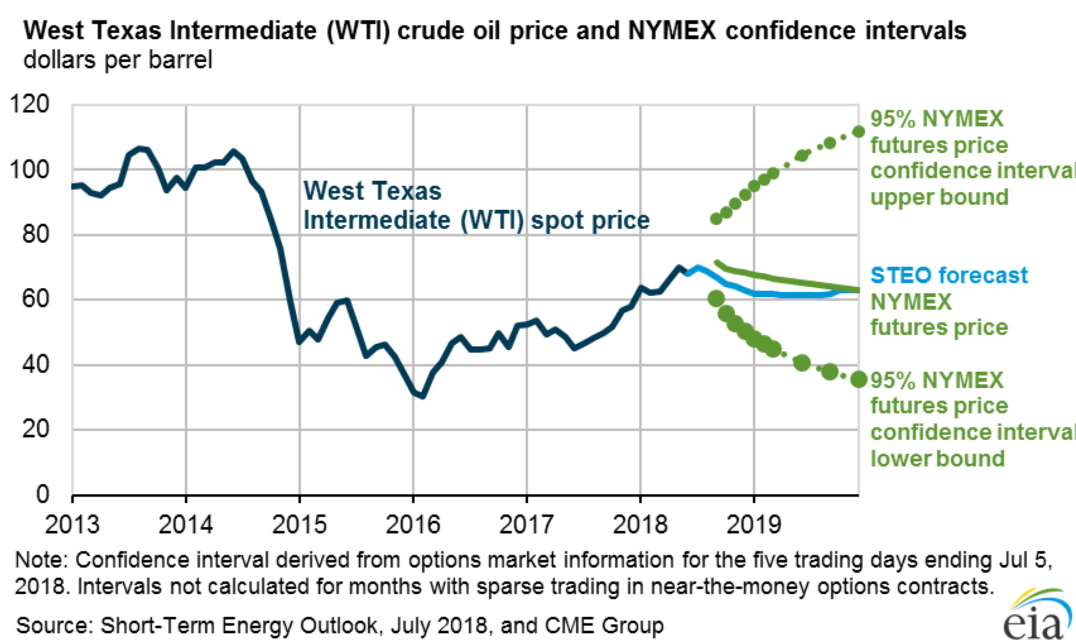


Figure 62. Short-term Oil Price Outlook and History (EIA) [143]

A consideration for capital investment in commercial battery electric vehicles is that cost justification done against baseline diesel vehicle platforms must assume some profile for future diesel or gasoline fuel trends. Those trend predictions can be significantly wrong, leading either to under or over estimating operating costs of the baseline diesel fleet.

10.1.20 High Voltage Safety

Fleets have concerns with driver and technician safety around high voltage battery electric vehicles. NACFE has found from fleets that are already operating electric vehicles and from OEMs producing vehicles that proper training is the key to ensuring a safe work environment. The vehicles are being designed with lock-outs and automatic cutoff systems to prevent exposure to high voltages. Jeff Coleman, Vice President of Sales, Original Equipment at of East Penn Manufacturing, presented in an ATA TMC Spring 2018 session that there are no live exposed terminals with high voltage and no parts of the high voltage circuit are connected to the frame. He stated there were pyrotechnic safety switches to disable batteries in the event of a crash, and the battery packs were equipped with fuses. He further stated that a full battery management system protects against over discharging or over charging, and will shut off completely if required. He stated that smart battery management systems are monitoring everything and diagnostic systems will tell service technicians what to replace. He stated there should be no “hot work,” that technicians will replace, not repair components [156]. NACFE found that some OEMs are providing safety training along with their vehicles for both service technicians and first responders. NACFE found that certifications are in discussion through various groups like American Trucking Associations, the National Institute for Automotive Service Excellence (ASE), and the Clean Tech Institute (CTI) [157][158][159].

NACFE concludes that the level of service technician risk from battery electric vehicles is comparable to or better than that seen with diesel vehicles. This level of risk should decrease in time as more production representative electric vehicles enter the market, fleets accumulate experience and provide operational feedback to manufacturers.

11 TCO AND EMISSIONS CALCULATORS

Total Cost of Ownership (TCO) goes by a number of names such as Life Cycle Analysis (LCA) or Life Cycle Cost Analysis (LCCA) [49][120][121]. While the phrase “total” would seem all inclusive, there are always qualifiers needed as to where to draw the system boundaries, what is in the analysis and what is not. A simplistic definition is that TCO includes the direct costs and indirect costs relevant to a system, an attempt to divvy up the cost information into buckets directly linked to manufacturing of a specific system, and those too diffused in overhead or unable to be tracked with consistency at a granular level tied to a system. Overhead, direct and indirect costs are severely lacking in clarity as what is actually included in each will differ by organization and there are still other company and end user costs that may not be included in these. NACFE proffered the terms “hard” and “soft” costs in its 2018 Guidance Report: Electric Trucks – Where They Make Sense [1]. Put simply, “hard” costs are consistently tracked and directly auditable (measureable). “Soft” costs would be all others much less capable of granular tracking, obscured deep in overhead or not even included. Figure 63 provides examples of each.

Figure 63. Example Hard and Soft Total Cost Assessment Factors (NACFE) [1]

Figure 64 illustrates dividing up current known costs on a baseline vehicle system into knowns, projections and estimates to arrive at an expected new cost of the new vehicle system. This categorization is explained in an SAE report, A Systems Approach for the Evolving Nature of Part Costs by Mihelic and Ray [118]. While this report focuses on a truck manufacturer's approach to costing a new vehicle development, it can be applied similarly to an entire vehicle life by grouping costs into values that are (1) exactly known from current baseline data, (2) slight modifications of existing known costs, (3) analogous to other similar baselines, and (4) completely new costs for which there are no existing comparable baselines.

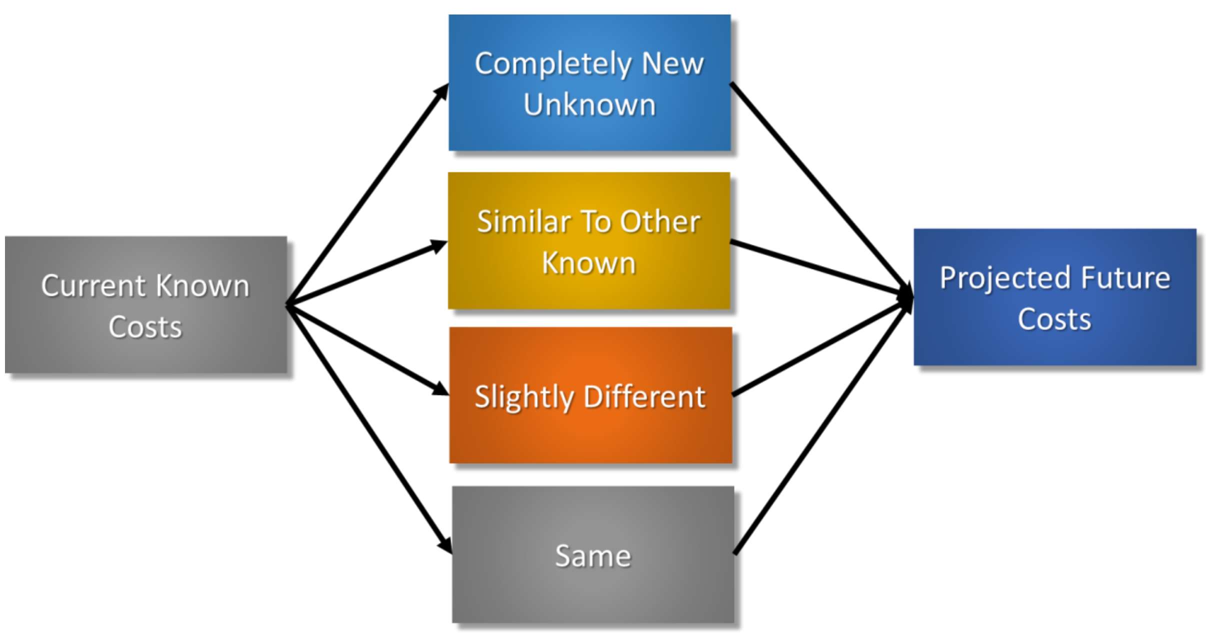


Figure 64. System Costs Grouped Into Knowns, Projections and Estimates (Mihelic)[118]

When looking at new technology replacing old technology on a vehicle platform, the first step is identifying costs that can directly carry-over from the prior designs. When comparing a battery electric truck versus a diesel one, costs in this category might be tires, wheels, chassis frames, headlamps, etc. Another case would be where a known cost is completely removed from the new vehicle, such as the case with servicing emissions systems on a diesel versus a battery electric vehicle.

The second step is defining where costs are just slight variations that can be estimated as a percent change from some known prior costs. An example of this might be where a vehicle hood is slightly larger so it's reasonable to estimate its new costs as some growth from the existing smaller part based on size. For a battery electric truck versus a diesel truck, one example would be brake replacement parts and labor costs where the brakes are expected to be used much less often because of regenerative braking, so the maintenance period is extended by some amount. Costs would be the same, but less frequently required.

The third step is identifying costs that must be projected from some other known system rather than from the baseline. For a battery electric truck, an example of this might be the cost of maintaining an electric motor where the knowledge base may be available from transport bus experience or factory machine experience.

The fourth step is what is left when the other three are totaled. These are the costs associated with an entirely new revolutionary system where there is no parallel in experience to draw from and there are too many uncontrolled factors in play. This is where educated guesses come into play. A key example here is estimating the residual value of a battery electric vehicle in 10 or 20 years, or estimating the market for used batteries that have reached 80% of their new range capacity and are no longer suitable for vehicle uses, or estimating a battery cost reduction expected from unknown future innovations.

These last costs are difficult to estimate prior to manufacturing and fielding, so represent a greater potential for cost change between prediction and final known costs. They may become goals or targets for system cost in a process called design-to-cost (DTC) [132][133]. For example, a vehicle manufacturer may impose a system design target that the market price be no greater than an existing diesel or gasoline version as UPS and Workhorse have done with their 2018 UPS prototype. 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 to be "comparable in acquisition cost to conventional-fueled trucks without any subsidies [130][131]." Similar system level requirements can be established that maintenance cost of an electric vehicle will be, for example, XX% less than an equivalent diesel. Accounting processes take the knowns and estimations and subtract those from the total system targets to define the available cost design space for the unknowns. Those unknowns are then portioned out to parts of the design as their cost goal. Some of these allocations are increases and others are decreases. An example would be estimating the cost of servicing a battery electric vehicle. In the past, a service shop might repair in situ a transmission or engine rather than replace it. The battery electric vehicles are likely more plug-and-play like servicing electronic control modules (ECMs) where a failed unit is just replaced rather than repaired. Higher content parts likely have greater purchase costs, but troubleshooting and replacement labor may be significantly reduced.

Every value used in a TCO analysis includes uncertainty. Where parts, warranty costs, maintenance costs, or disposal costs are well established from existing parts being carried over, the uncertainty is likely less. Where projections are made off of existing parts, the uncertainty increases due to a variety of uncontrolled factors like inflation, repricing by suppliers, scope growth, unplanned retooling needs, etc. When dealing with new technologies, the uncertainty is greatest due to the large number of unknowns. This is especially true with medium-duty battery electric trucks where only limited long-term field data exists on vehicles still in production and supported by going business concerns, or where vehicles do not exist in sufficient quantities and ages to establish any reliable trends on secondary market values, or where the cost of infrastructure, like charging, needs to be included in the vehicle TCO assessment (fueling infrastructure is something not usually considered with diesels even though it is buried in fuel pricing). These unknown values can be estimated as well in the cost groupings and added together to provide an estimate of the range of possible net TCO for a vehicle system.

NACFE interviews have highlighted that the greatest challenge in battery electric vehicles is that, "there are currently a lot of unknowns." NACFE recommends following Franklin Roosevelt's sage advice "that the only thing we have to fear is fear itself." Clarifying the knowns and unknowns on costs and defining what a fleet or OEM is including and not including in hard and soft costs of a TCO analysis are critical steps to scoping the true unknowns and quantifying the level of risk in investing in new technology. A more pro-active term than risk is confidence level.

Cummins' Tom Dollmeyer presented a comparison of TCO between battery electric vehicles and internal combustion ones in the graphic at the American Trucking Associations Technology & Maintenance Council March 2018 meeting shown in Figure 65 [119].

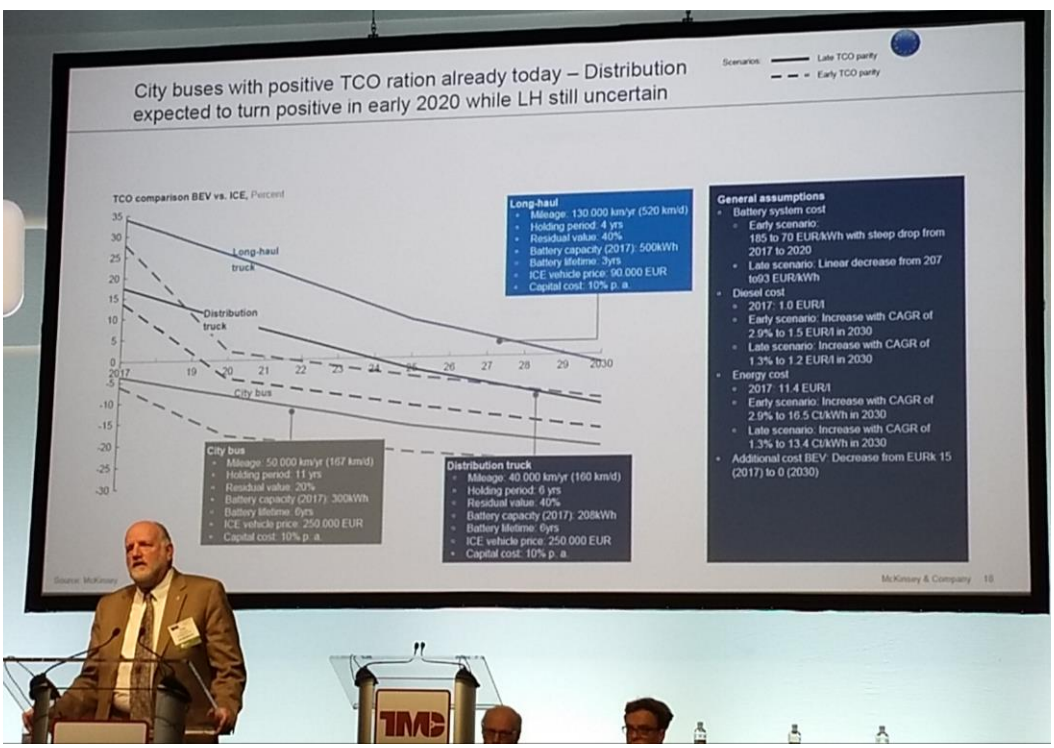


Figure 65. TCO Comparison BEV vs. ICE % (Dollmeyer, photo Mihelic) [119]

Cost calculators exist from a number of sources. NACFE surveyed a number of publicly available ones in preparing this report. The sampling highlighted that these range in transparency of assumptions and calculations. They vary in level of user input and types of default values used. Some include evaluations of just the isolated single vehicle cost, while others include fleet estimation, and others include infrastructure, incentive opportunities and purchase methods. Complexity also varies across the board from simple to very complex. Some focus on emissions level reduction, while others include fuel (or energy) efficiencies. Cost models can compare just a battery electric truck to a baseline diesel, while others include comparable evaluations of competing alternative energy concepts like hybrids, CNG, etc.

NACFE is providing in Appendix D of this report background on a select sampling of calculators that illustrate a range of uses and approaches to assisting fleets in decision making on battery electric technology investment. NACFE is providing its own downloadable calculator based on the research NACFE has done in preparing this report and the prior Guidance Report: Electric Trucks – Where They Make Sense [1]. The calculator is available at www.NACFE.org. NACFE Medium-Duty Battery Electric Vehicle TCO Calculator

The sampling of calculators provided in this report should illustrate these types of tools range from simple to complex. Each reflects a variety of needs and demands by users. NACFE has taken into consideration the strengths and weaknesses of these calculators in developing a NACFE Medium-Duty CBEV TCO Calculator for comparing diesel to battery electric vehicles for this report.

11.1 Capital Investment Comparison Methods

This NACFE report discusses a number of metrics for comparing alternative capital investments. These invariably involve the time-value-of-money, which says that a dollar today is worth less than a dollar next year. Investment comparisons take the projected series of cash flows over a period of ownership and try to relate them to a current equivalent apples-to-apples value. Common choices are ROI (return on investment), payback period, NPV (net present value), IRR (internal rate of return), EAC (equivalent annual cost), and others [164][165][167]. NACFE found a number of sources of information on these economic factors. An excellent resource for readers is the MIT OpenCourseWare class on Project Evaluation by Prof. Joseph Sussman and Carl Marland [167].

In NACFE's experience and in interviews with fleets and OEMs, both management and accounting groups at companies have differing perspectives on which factors are most important to use in making capital investment choices. They often also may disagree within individual companies as reported by Fleet Advantage president Brian Holland in *Heavy Duty Trucking*, "It is evident that both the operations and finance departments are focused on different priorities in terms of fleet management and costs, and this poses a challenge to collectively achieve a singular organizational goal [140]."

NACFE's TCO calculator attempts to provide comparison via a variety of metrics to facilitate discussion among stakeholders with differing perspectives.

11.2 NACFE TCO Calculator Background

The NACFE TCO calculator is intended to compare investment in one or several diesel or gasoline powered baseline trucks against an equivalent battery electric alternative. The spreadsheet includes factors NACFE found relevant to this comparison. Some background on development of the choices on structuring the TCO calculator is provided here.

11.3 System Scope

The starting point is defining the scope of the system comparison. Figure 66 outlines a CBEV system perspective starting from the generating station and ending at the battery electric vehicle.

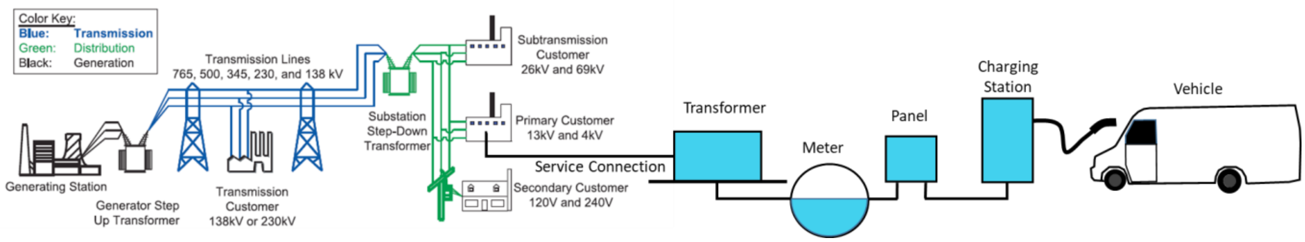


Figure 66. The Battery Electric System (adapted by NACFE- DOE/NRCan, EEI) [169][170]

A comparable complete system comparison for diesel would need to include the oil well source, the rail cars, trucks, supertanker, pipeline and intermediate storage used in transporting the oil to the refinery, the refinery, the pipeline, trucks, ships, rail cars and storage facilities used in getting the refined fuel to the pump, and then finally to the vehicle as shown in Figure 67.

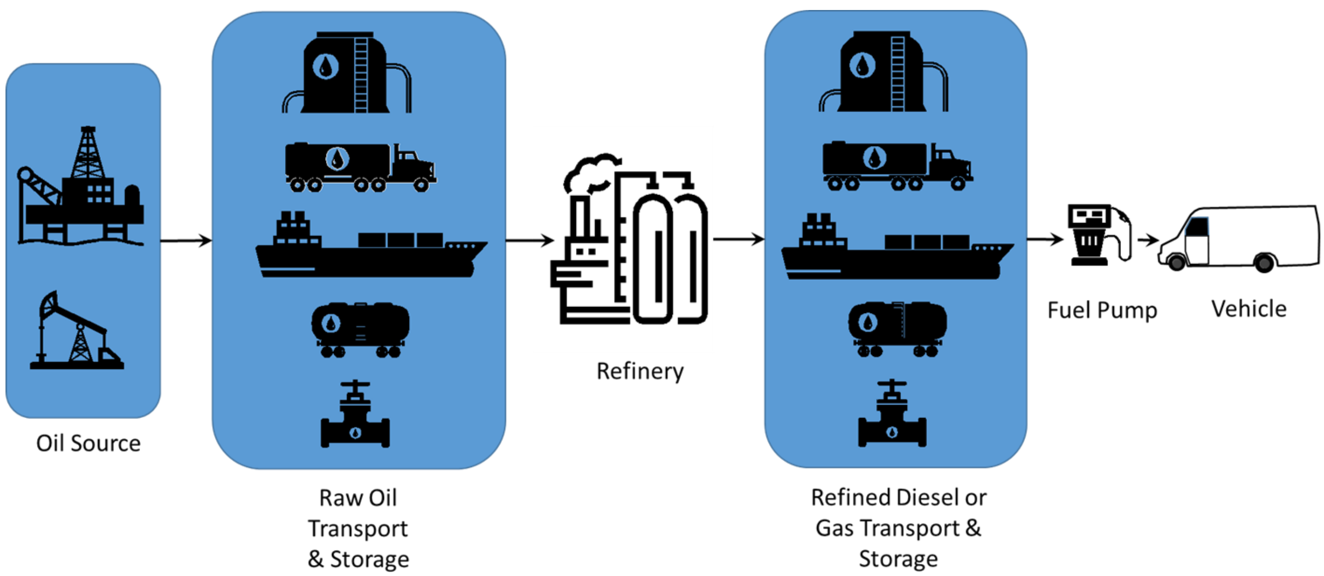


Figure 67. Gas & Diesel System Perspective (icons courtesy of iStock) [NACFE]

Most diesel and gasoline vehicle operators do not consider the costs buried in the fuel that cover the infrastructure bringing the fuel to the pump. A typical economic comparison for diesel or gasoline starts with the cost of fuel and focuses then on the truck.

The battery electric comparison could start at the end of the charger connector as well using just the price of electricity at the charging station and then focusing on the truck. However, that comparison would assume the service connection from the grid to the charging station exists. That is likely not the case at this time for most fleets considering battery electric vehicles.

A key challenge facing cost estimation for battery electric vehicles is also including the charging infrastructure. How far upstream in the energy delivery process must a fleet go to capture the cost of the infrastructure? How does a fleet calculate comparable diesel or gasoline infrastructure costs for the comparisons to be valid?

The U.S. DOE Energy Information Administration (EIA) estimated in June 2018 with diesel at $3.25/gallon that 50% of the cost paid at the pump is due to refining, distribution, marketing and taxes. The remaining 50% is attributed to the actual cost for the refiner to acquire the crude oil (refer to Figure 6 in Section 9.1) [9]. A simple way to include the cost from the refinery to the pump then is to estimate 50% of the current diesel fuel price. To make the evaluation comparable, the cost of the fuel used by the diesel truck in the TCO comparison would then need to be reduced by 50% with the other 50% then tied to infrastructure costs. Gasoline overhead is reported to be 56% of each gallon's price per the EIA as shown in Figure 6 (from Section 9.1 of this report) such that the cost of the actual raw oil to the refiner is 44% of June 2018's reported $2.89 per gallon [9]. Figure 68 illustrates how to include capital costs of diesel and gasoline infrastructure in a TCO model.

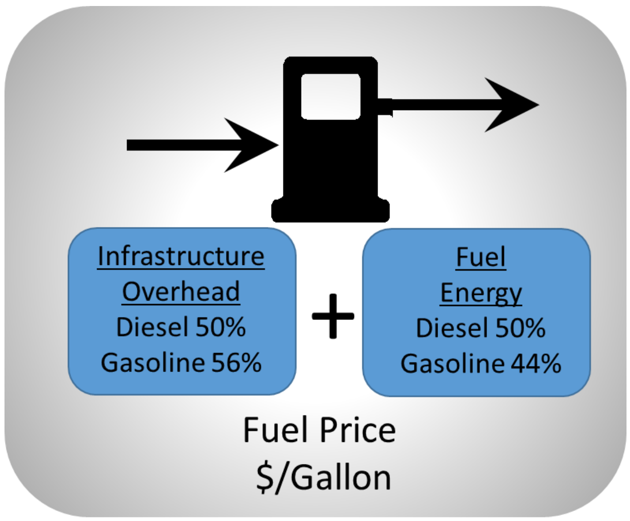


Figure 68. Apportioning Diesel and Gasoline Fuel Cost (icon courtesy iStock) [NACFE]

The cost of the electrical infrastructure from the generating source to the charger is very user specific by region, by source, etc. Power companies may differentiate the "energy charge" from the "delivery charge" when billing customers. A summary of electricity rates by state for commercial use can be found at the DOE Energy Information Administration site [54]. The EIA estimates of the net cost of electricity on a national average include 28% for distribution and 13% for transmission as shown in Figure 69 [205][206].

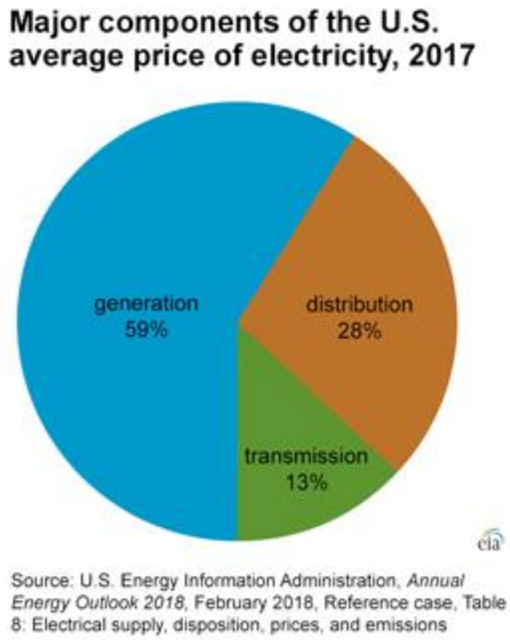


Figure 69. Electricity Price Breakdown (EIA) [205]

Unfortunately neither the EIA breakdown of the fuel costs nor the breakdown of the electricity costs is sufficient to isolate specific costs for a fleet.

NACFE is including in the TCO calculator the ability for users to enter the cost of the infrastructure for the electric truck charging. Users may decide this is an upfront expense or they may amortize it over the ownership period of the truck. They may also define the quantity of trucks assigned per charger. These are real costs and factors for a fleet considering electric trucks. Since the equivalent diesel or gasoline infrastructure has generally already been installed, there are not additional costs for a fleet for that diesel or gasoline infrastructure. The TCO calculator compares two streams of investment moving forward.

11.4 Duty Cycle

NACFE is using the duty cycles previously defined in Figure 5 (Section 8.1.4) for eight duty cycles crossing Class 3 through Class 6. Every vehicle has the potential of having a unique duty cycle, so these eight are provided as trend indicators. The tool permits users to enter up to five of their own unique duty cycles as well.

11.5 Battery Factors

Choosing the duty cycle determines the range needed for the battery electric vehicle. This range needs to include a margin to cover required range beyond the typical daily average. It also needs a margin for battery degradation over the period of ownership, and a lower bound for permissible depth of charge to maintain the health of the battery. NACFE interviews and research highlight that 20% degradation in range capacity over the warranty period is a typical guideline [152][153][155]. The research also indicated that depth of discharge targets are to not allow discharge below 10% to 20% of battery capacity. Figure 70 illustrates determining battery range based on duty cycle as the summation of average daily miles plus margins for worst case, for degradation and for low power cut off. As an example, the duty cycle for a parcel delivery Class 4 step van has an average daily mileage of 52 miles and saw a maximum daily mileage of 132 miles per day from the table in Figure 5 (Section 8.1.4). 132 miles represents a margin of approximately 2.5 times the average daily range to cover the worst-case range. If the vehicle is held to its maximum battery life degradation level of 80% of original capacity, the vehicle will need an additional 20% range so that it can cover the required worst case 132 miles over its entire life, so a 1.2 times factor. If the vehicle is equipped with a low power battery cutoff set at 20% of capacity, then 20% of the worst case mileage is not available for use, so another 1.2 times factor. This example shows that sizing a battery pack for an average daily mileage needs to be increased by 2.5 for worst case route, increased by another 1.2 to compensate for battery degradation over its life, and another 1.2 to compensate for the low power cutoff setting. The 52 miles average then becomes a battery system initial range requirement of 188 miles capacity.

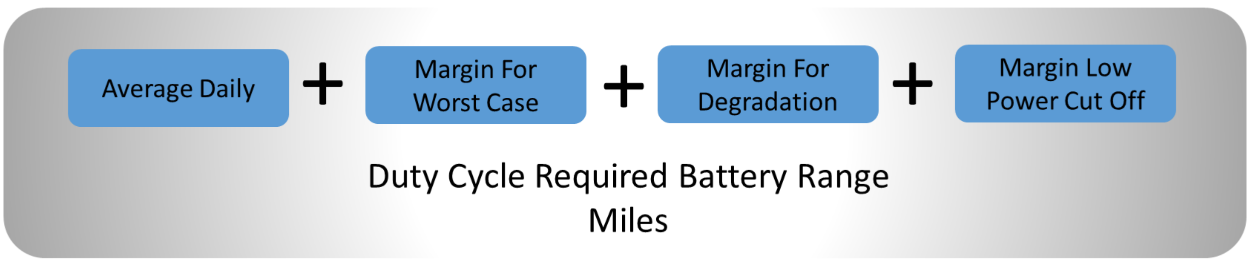


Figure 70. Initial Battery Range Estimation for TCO Calculator (NACFE)

Battery capacity is also dependent on extremes of environmental conditions. Driver and payload heating and air conditioning requirements rob batteries of range. Additionally, aggressive driving acceleration will limit battery range by using up batteries faster than average driving practices. Decelerating using regenerative braking in contrast has a significant positive effect on extending battery range as the motors recover energy acting in reverse as generators [210]. One manufacturer estimated for a Class 8 chassis that range could double for an urban duty cycle versus an on-highway one due to the contribution of regenerative braking [228][229]. The TCO calculator allows for driver habits to either improve or degrade range. These additional margin factors are added as shown in Figure 71.

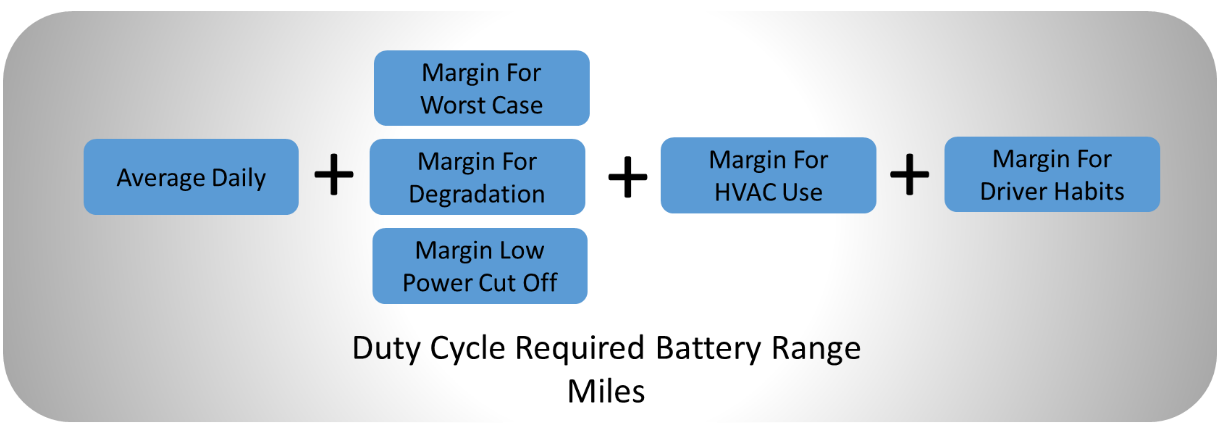


Figure 71. Final Battery Range Estimation for TCO Calculator (NACFE)

Some level of rationality should govern selection of battery capacity safety margins. Ranges for deliveries should be known before the vehicles are loaded, and extreme distances likely would be assigned to diesel or gasoline trucks in a typical mixed fleet operation. Layering too much margin on batteries can unnecessarily oversize them, while ignoring margins can lead to disappointed drivers and late deliveries. NACFE concludes that batteries should be sized for some percentage of load cases rather than the worst-case. Where a diesel fuel tank may carry extra fuel for worst-case conditions with minimal fuel cost, the penalty in vehicle cost for carrying excess battery capacity is severe when factoring in that batteries may exceed one-third of a vehicle's purchase price [209].

Range also depends on the battery technology. NACFE published background on the performance improvements over time as innovations and refinements have been occurring in battery technology in its Guidance Report – Battery Electric Trucks - Where They Make Sense [1]. The term energy density is often used to describe the battery performance with units of Watt-hours per kilogram. Ultimately, what a fleet cares about is a range efficiency of the batteries defined as kWh per mile (kWh/mi) or its inverse miles per kWh (mi/kWh). NACFE has found that a range of values exist for current production battery packs, the current best range between 1.0 kWh/mi and 2.5 kWh/mi when new. Consensus and the past track record is that these values will improve with time. Vehicles held longer than one battery lifetime will require battery replacement. A vehicle with a 22-year life might see three to four battery packs over its life that might incorporate improvements in battery efficiency. These improvements would necessarily improve the ability of the vehicle to meet its duty cycle or allow redefining the duty cycle. To simplify the potential "what ifs?" this creates, the NACFE TCO calculator assumes the initial battery efficiency is used throughout the vehicle's lifetime as shown in Figure 72.

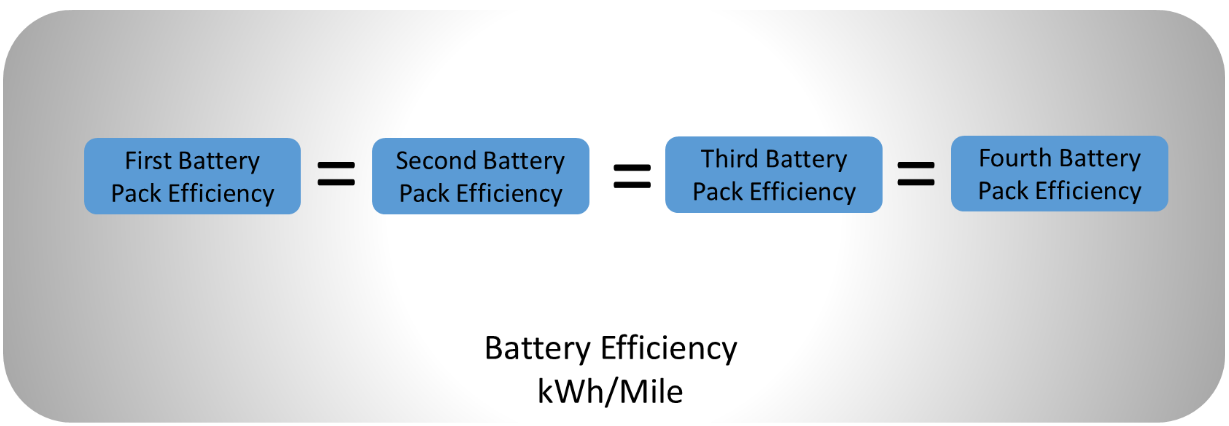


Figure 72. Battery Pack Efficiency over Replacements Assumed Constant (NACFE)

The cost per kWh for batteries has decreased from well over $1000/kWh to numbers closer to $200kWh. Projections appear to reach the $150/kWh level in the future. The crystal ball on innovation is always murky. NACFE provides a range of possible $/kWh for users to experiment with the impacts of potential battery improvements over the course of vehicle life as shown in Figure 73.

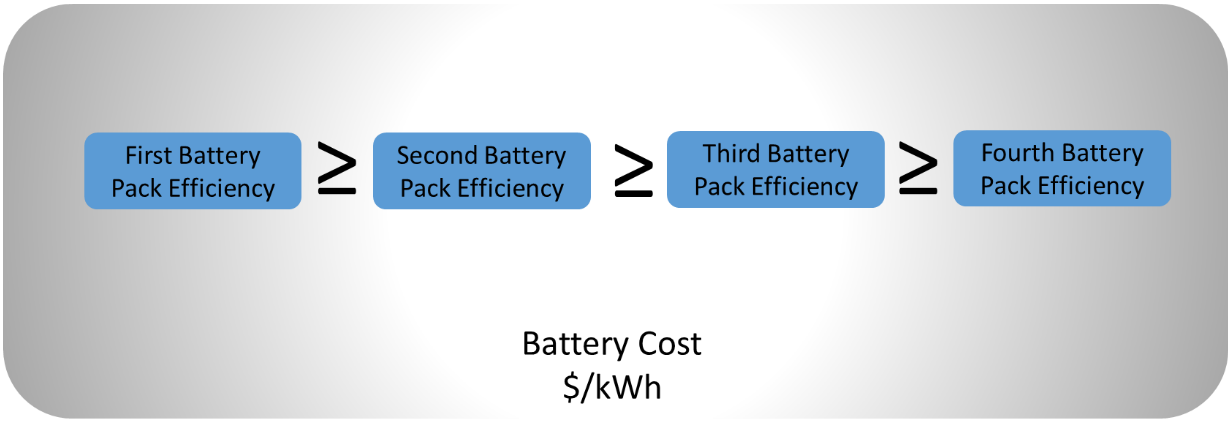


Figure 73. Battery Pack Replacement Cost for TCO Calculator (NACFE)

11.6 Grants, Incentives, Rebates, Tax Breaks, etc.

The battery electric vehicle TCO inherently involves discussion of grants, incentives and tax breaks. Various groups are assisting in leveling the price comparison between CBEV and diesel vehicles by providing funding through various mechanisms. The TCO calculator provides an ability to include these as adjustments to the vehicle acquisition cost as shown in Figure 74.

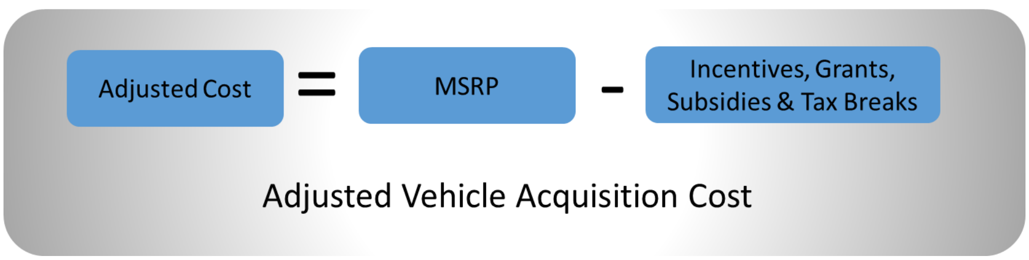


Figure 74. Adjusted Vehicle Cost for TCO Calculator (NACFE)

11.7 TCO Calculator Charging Infrastructure

NACFE found that there are multipliers to consider with respect to the charging infrastructure. These need to address both the speed of charging per vehicle, and the number of vehicles being concurrently charged. NACFE previously documented that the speed of charging can significantly increase costs of the infrastructure. However the costs of these systems are changing as the number of installations increase in the marketplace. A diesel pump at a fueling station can reasonably be assumed to fill a number of vehicles per hour. Not so for a charging system, where charging may take hours. This means that each vehicle may need its own charging system. Some charging systems can handle one, two or more vehicles per charger.

11.8 Residual Value

Residual value of CBEV's is an unknown as there are insufficient numbers of vehicles in the field to provide any reliable estimate of the secondary market value. However, many companies depreciate medium-duty trucks over a 10-year time frame, meaning that the expected residual value after 10 years is zero. Residual value below 10 years must be estimated. One approach NACFE encountered in interviews is to value the CBEV at the same market pricing as an equivalent diesel or gasoline truck. This assumes secondary market buyers will not assign a premium to the zero emission aspects of the product. Other NACFE interviews suggested that technology obsolescence for CBEVs will penalize secondary market pricing since new trucks are expected to have significantly better battery technologies. Still other interviews suggested that limited availability of CBEVs will force premium secondary market pricing.

The baseline diesel or gasoline truck also has unknowns on residual value depending on whether the market is in a region with zero emission plans and whether alternate markets can be found. Trade-in values may need to include migrating assets to other marketplaces where diesels retain higher used values. The cost of transporting those vehicles to these other markets needs to be considered. As with CBEVs, owners may depreciate the truck over 10 years. Estimates prior to fully depreciating would depend on market conditions and age.

The NACFE TCO calculator lets the user enter a percent of adjusted purchase price of each vehicle type as the residual value as shown Figure 75.

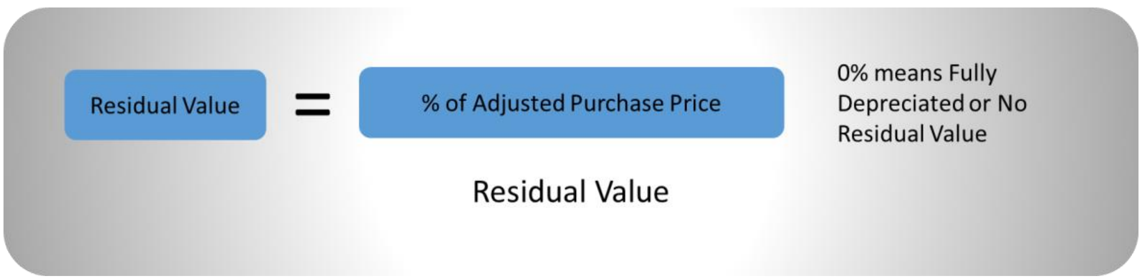


Figure 75. Residual Value (NACFE)

11.9 Cash, Lease or Loan

TCO for vehicles needs to include the method of purchase – financing, leasing, or outright cash purchase. The TCO calculator allows all three choices, but must be the same method for both the baseline and the electric vehicle.

11.10 Fuel and Energy Costs

The cost of diesel fuel varies in time. Projections in 2010 largely failed to forecast the significant drop in fuel prices in 2014-2015. NACFE is providing options for estimating the fuel price trends.

The cost of electricity is similarly challenging to predict. Complicating this is that innovative new methods for marketing energy may have the electricity pricing included in a vehicle lease agreement. Some costs may also be tied to time of use during the day. Diesel fueling stations do not typically change the price of fuel based on the hour of day the vehicles are filled. This demand-pricing model is another future possibility to consider in a TCO calculator.

11.11 Maintenance Costs

Operating costs are more than the price of fuel or electricity. They include the maintenance (planned and unplanned) and the cost of downtime for a fleet. These factors are likely documented for current diesel vehicles in a fleet. They are largely unknown factors with no track record for battery electric vehicles. There are assumptions that electric vehicles should be less maintenance intensive than diesels because the significant reduction in vehicle mechanical complexity. The technology is also early on its innovation S-curve and may see no significant improvements until sufficient volumes of vehicles have been fielded. A common theme is that maintenance costs increase with age of the vehicle. For this reason the TCO calculator includes the ability to model maintenance cost trends as straight-line cost increases based on percent per year change from today's cost for the diesel or gasoline baseline. The electric truck maintenance trend is modeled as a percent of the baseline diesel or electric costs. A 100% factor will make the costs equivalent, and they both will follow the growth trend specified for the baseline. Users can increase or decrease the electric maintenance cost versus the baseline diesel or gasoline, for example 200% will double the electric truck maintenance cost, while 50% will halve the cost.

11.12 Equivalent Highway Trust Fund Costs

Electric trucks do not pay for the Highway Trust Fund since that is based on a tax on fuels. This discontinuity in tax rules will likely be addressed as electric trucks hit the road in volumes. The Highway Trust Fund is a transportation fund in the United States which receives money from a federal fuel tax of 18.4 cents per gallon on gasoline and 24.4 cents per gallon of diesel fuel and related excise taxes. NACFE has addressed this in the TCO calculator by allowing the user to include or exclude the equivalent cost of a diesel or gasoline vehicles taxes which go to the Highway Trust Fund.

11.13 Other Indirect Cost Factors

NACFE identified other costs/benefits that are real and do hit a fleet's bottom line, but may be excluded from analyses because they are considered "soft" or indirect values, hard to predict or buried in overhead. Factors such as driver and technician retention is one of these soft factors. NACFE interviews found in fleets with battery electric vehicles, that the drivers and technicians value the vehicles above diesels because they are quieter, cleaner and perceived as more modern. The cost to hire and train a replacement technician or driver should be a known factor to fleets. Some percentage of that cost might be avoided by improving retention rates through adoption of battery electric vehicles.

The market value of emissions reductions from a CBEV versus a diesel or gasoline vehicle is hard to quantify. They are a factor in brand imaging and advertising, in corporate goals, in pursuing certain markets and inherently in some market places where the cost of operating a diesel may include increased fees or be entirely prohibited.

Other indirect factors that may be altered with using battery electric vehicles are the costs associated with complying with emissions and other regulations. Tracking, auditing, and filing reports have costs. Fines for non-compliance also have costs.

Other factors might include changes to valuing uptime. Manufacturers do not track this – their cost tracking is focused primarily on the labor and part cost to do a repair. Fleets, however, care about downtime effects on their bottom line as it affects late shipment fees, lost customers, etc.

11.14 Thoughts On Mixed Technology Fleets

NACFE has determined from interviews that most fleets pursuing battery electric vehicles at this time are adding them to an existing stable of diesel and other alternative fueled vehicles. This means that the benefits to service shop configurations are minimal, with no significant opportunity of eliminating infrastructure. On the positive side, NACFE interviews have found that adding battery electric vehicles to service centers generally does not include significant infrastructure additions. In many cases, NACFE found that high voltage component servicing may be outsourced to experts. The primary service tool is a laptop computer. The weight of batteries may require some custom lifting and handling fixtures. Servicing is expected to be primarily plug-and-play replacement rather than in situ repair. There may be need for some level of charging infrastructure to test charging systems.

The DOE Compressed Natural Gas Maintenance Facility Modification Handbook differentiates Major repair garage from Minor as follows [208]:

- **Major repair garage:** A maintenance facility in which major repairs are performed, such as engine overhauls, vehicle chassis and body repairs, and similar maintenance work that requires emptying the vehicle's fuel tank. Any work that involves service to a vehicle fuel system may only be performed in a major repair garage.
- **Minor repair garage:** A maintenance facility in which minor repairs are performed, such as lubrication, engine tune-ups, replacement of parts and tires, fluid changes, and similar maintenance work, that does not require emptying the vehicle's fuel tank. Any work that involves service to a vehicle's fuel system is not permitted in a minor repair garage.

The guide describes extensive modifications needed for a major maintenance facility servicing natural gas vehicles, or isolation of the service bays used for natural gas work, or working outside the building. In contrast, a battery electric vehicle likely is classified as a minor repair garage and requires minimal modification.

11.15 Net Present Value

Evaluating capital investment alternatives that include projected residual value can involve use of a number of accounting methods. Net Present Value (NPV) calculations establish capital investment equivalence of competing cash flow schemes that may have different investment horizons [164]. Another accounting tool that provides equivalent evaluation is Internal Rate of Return (IRR) [164]. The NPV value is used in another possible comparison factor, the Equivalent Annual Cost (EAC) calculation [166]. The Return on Investment (ROI) is less applicable where competing investment spans are different [164].

Figure 76 illustrates a simple view of cash flow for an investment in a truck. Arrows pointing down represent cash outflows for purchasing the truck, for all the annual operating expenses and a special cost like replacing a battery pack in year seven. Arrows up are for cash inflows such as from grants, incentives, vouchers, and/or trade-in of a prior vehicle, and then the residual value expected at the end of the ownership period of 10 years. A key factor in NPV calculations is called the discount rate. Discount rate is the minimum desired rate of return, sometimes termed the cost of capital or hurdle rate. Cost of capital would be the rate a company would pay to secure capital from a bond issue or a bank loan for example.

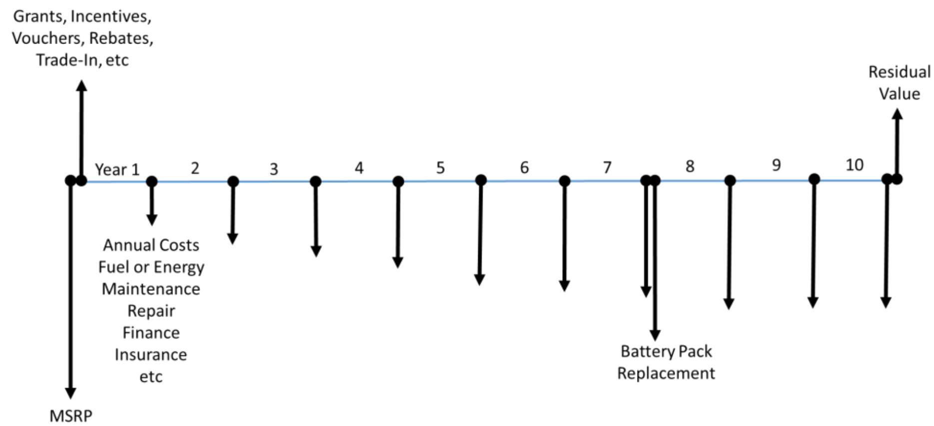


Figure 76. Example Cash Flow Diagram for an Electric Truck (NACFE)

NPV is a function provided in Microsoft Excel spreadsheet software where the inputs are the discount rate (entered as 0.08 for 8%, for example), and each of the net cash flows at the end of each period.

Total cost of ownership is then the initial costs and benefits at time zero plus the NPV of the series of cash flows over time.

12 Historical Perspective on Diffusion of Innovations

The rate of technology adoption can be modeled. A theory described by Everett Rogers in a 1962 book titled Diffusion of Innovations, defines diffusion “as the process by which (1) an innovation (2) is communicated through certain channels (3) over time (4) among the members of a social system [309].” With respect to the new technology, Everett states, “Newness in an innovation need not just involve new knowledge. Someone may have known about an innovation for some time but not yet developed a favorable or unfavorable attitude toward it, nor have adopted or rejected it. The "newness" aspect of an innovation may be expressed in terms of knowledge, persuasion, or a decision to adopt [309].” Everett illustrates adoption rates as S-shaped curves as shown in Figure 77, where acceptance of a product eventually reaches 100%. Note clearly that not all innovations ever reach 100% acceptance, but examples such as computer word processing replacing typewriters, the automobile replacing horse draw carriages, digital photography replacing film, and diesel-electric locomotives replacing coal powered steam ones are examples where nearly 100% adoption has occurred.

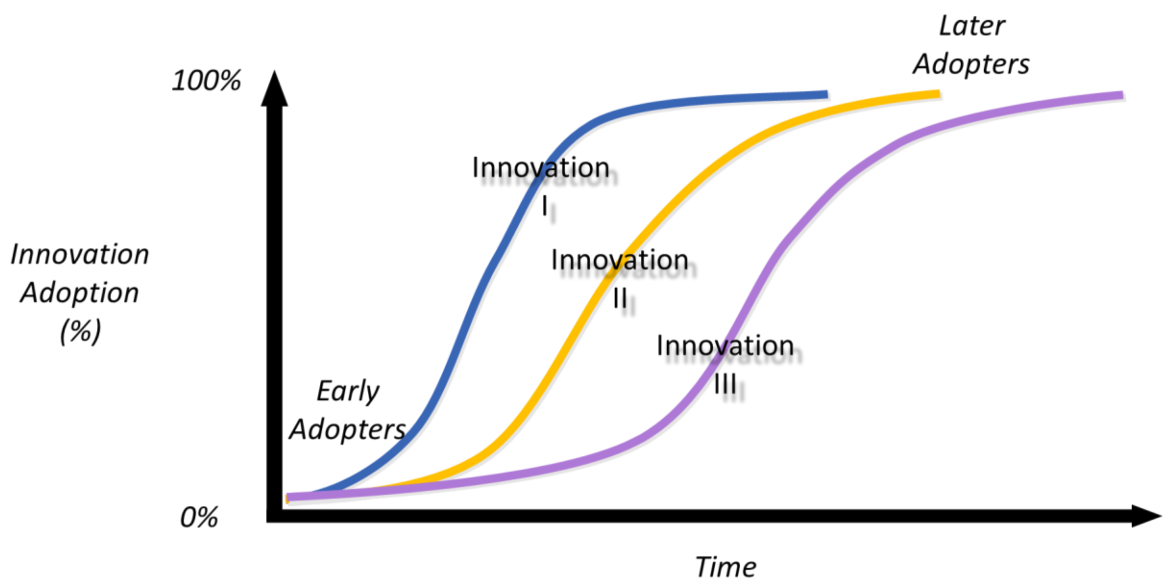


Figure 77. Diffusion of Innovation over Time (adapted from Rogers) [309]

The S-Curve can be viewed in terms of percent of market share captured over time, and imagined as a typical statistical bell curve as shown in Figure 78 [312]. This interpretation of Roger's data divides adopters into five segments as innovators, early adopters, early majority, late majority and laggards, ultimately taking 100% of available market share.

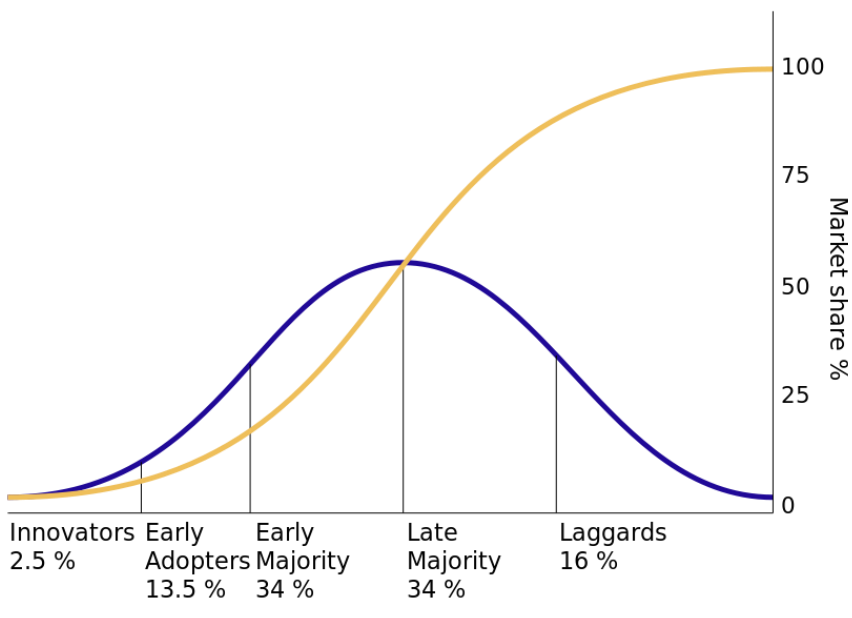


Figure 78. Diffusion of Innovation (Wikipedia) [312]

NACFE has documented this type of market behavior in its Annual Fleet Fuel Study with respect to the adoption rate of 85 freight efficiency technologies by 20 leading edge fleets since 2003, as shown in Figure 79 [310].

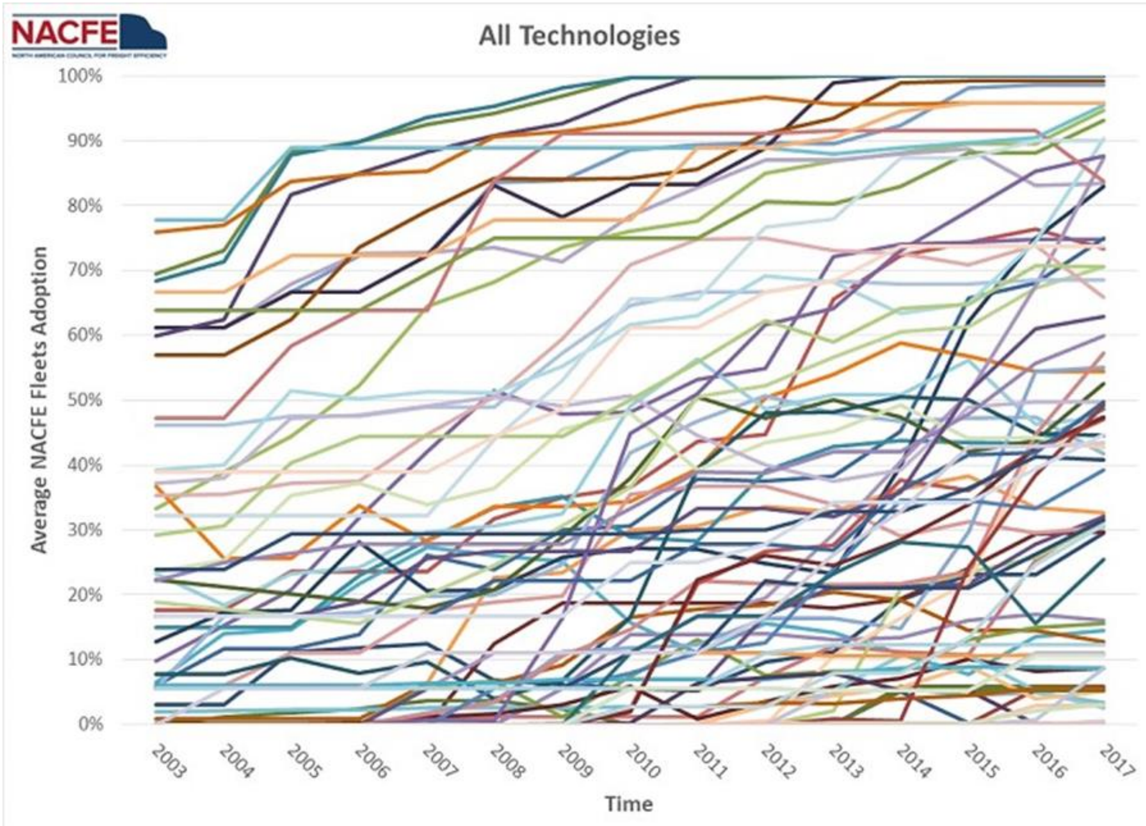


Figure 79. NACFE Technology Adoption Curves for 20 Fleets data (NACFE) [310]

Electrification of freight transport is occurring now, perhaps somewhere between the Innovator and the Early Adopters phases shown in Figure 78. The exact profile of the adoption curve and the time spans are speculation at this point, but a historical example of a similar significant freight system change can illustrate how adoption may progress.

It was called dieselization. The period was primarily the 1940's and 1950's. The following passage from a 1991 book by Louis Girifalco from University of Pennsylvania seems to offer parallels to today's arguments on electrification of freight trucks over diesel and gasoline ones.

> *"The advantages of diesel over steam are many. The diesel is quieter and cleaner, it does not require any feed water, and its energy efficiency is much higher. The diesel has a smoother ride and smoother acceleration, which results in greater comfort for passengers and less wear on the track system. Acceleration is more rapid, it can run at higher speeds, and standby costs are less since the engine can be turned off even for short idle periods as there is no need to maintain a head of steam. A great economic advantage is that the diesel locomotive has very low maintenance requirements and can make trips of thousands of miles without servicing. With these advantages, the widespread diffusion of diesel-electric locomotives was assured [304]."*

Mihelic described this historical example in a Stifel Investments presentation in August 2017 using the graphic shown in Figure 80 [311]. The 1940's saw the deployment of sophisticated, evolved, mature, steam technology as exemplified in the ALCO articulated 4-8-8-4 Big Boy steam locomotive. In parallel, train upstarts GM-EMD and GE where introducing early diesel electric units like the EMD FT. Diesel-electrics represented revolutionary changes to many aspects of freight operations.

Figure 80. Freight Transport Technology Change can Impact Many Factors (Mihelic) [311]

Girifalco modeled the adoption rate of diesel-electric locomotives from company data as shown in Figure 81 [304].

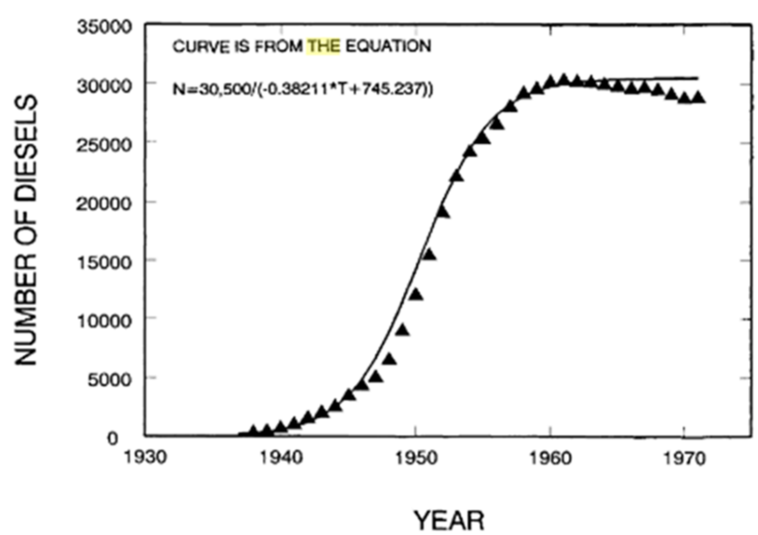


Figure 81. Diesel Locomotive population growth (Girifalco) [304]

The Union Pacific's Michael Iden presented similar trends in a 2017 presentation at the 19th Railroad Environmental Conference, documenting the transition from coal to diesel use, stating coal in terms of diesel gallon equivalents (DGe) as seen in Figure 82 [306]. The graph shows that coal use for freight hauling fell from a peak of 25,000,000,000 DGe's in 1945 to less than 4,000,000,000 DGe by 1960, while diesel as locomotive fuel rose from near zero in 1945 to handling a majority of freight by the same 1960 time frame. Fifteen years saw a near 100% transition from coal to diesel.

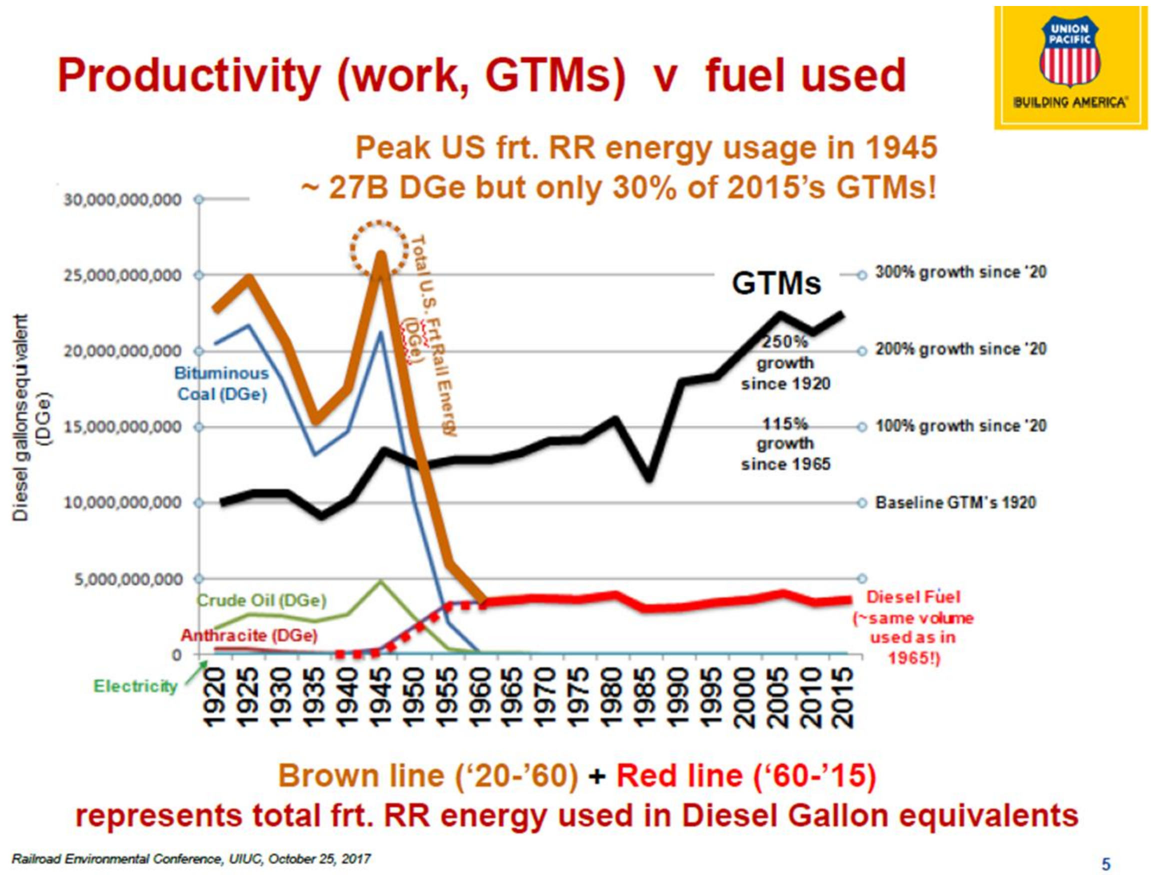


Figure 82. Locomotive Transition from Coal to Diesel Fuel (UPS) [306]

Albert Churella in a 1995 The Business History Review Journal (Harvard) described this rapid transition from the perspectives of the competing locomotive manufacturers [305]:

> *"By the 1930s, the American Locomotive Company (ALCo) and the Electromotive Company (EMC) controlled the diesel locomotive industry. Although ALCo enjoyed sound financial status, decades of experience in steam locomotive production, and close ties with its customers, it quickly lost ground to the newly established EMC. Electromotive's founder, Harold Hamilton, emphasized the importance of marketing, including post-sales support services, and his strategy helped Electromotive to surpass ALCo's diesel locomotive production by 1935. ALCo continued to neglect its marketing capabilities, and remained a poor second to Electromotive until it ceased production altogether in 1969. ALCo failed in large part because it could not modify its corporate culture, which was superbly equipped for steam locomotive production but ill-suited to the diesel locomotive industry [305]."*

Jeffrey Schamm of Lehigh University documented in 1995 a case study of one locomotive freight operator during this transition period in a thesis titled Black Diamonds No More: A technological history of dieselization of the Lehigh Valley Railroad [307].” The study highlights that simply substituting the new diesel-electric locomotive for the tried and true coal-steam one was not a recipe for being a successful freight competitor. Those fleets that adapted to optimize their fleet operations for the attributes of the new diesel-electric technology ultimately were better positioned for success.

> *“The Lehigh Valley initiated dieselization to save money and effect higher operating efficiencies, but the change in motive power did not appreciably change the way that the railroad purchased locomotives or operated until well after complete dieselization was achieved. The railroad simply substituted diesels for steam locomotives and did not utilize the new motive power to reshape dramatically their operations. The railroad integrated diesels into the existing system instead of rebuilding the system around their different capabilities. The reasons for this failure to utilize fully the new diesel locomotive are many but include operational, labor, and business practices. The Lehigh Valley, while adopting a new technology, did not change its corporate culture or operating philosophy. In the broader historical context, this is a study of how large organizations built around a technological system, deal with the introduction of radically new technologies [307]”.*

Revolutionary technological change in freight has occurred many times in the past, such as wagon trains migrating to steam locomotives, the introduction of the internal combustion engine in urban and rural truck freight hauling, the dieselization of freight train services, the introduction of jet engine overnight freight transport, and the introduction of digital engine control modules.

Electrification of freight trucks is just starting. Whether it revolutionizes the industry will depend on a number of factors, many of which are uncertain at this point in time, but the historical example of dieselization of locomotives can highlight how quickly significant changes can occur in the freight hauling space.

13 Electric Technology Timing

NACFE published in May 2018 a parity chart in the first Guidance Report on Electric Trucks – Where They Make Sense, documenting our estimate of when the technology will reach parity with respect to diesel and gasoline engine medium duty freight vehicles [1]. We feel the chart, shown in Figure 83, remains our estimated for predicting timing for the twenty-two comparison decision factors. The chart is included again here for reference.

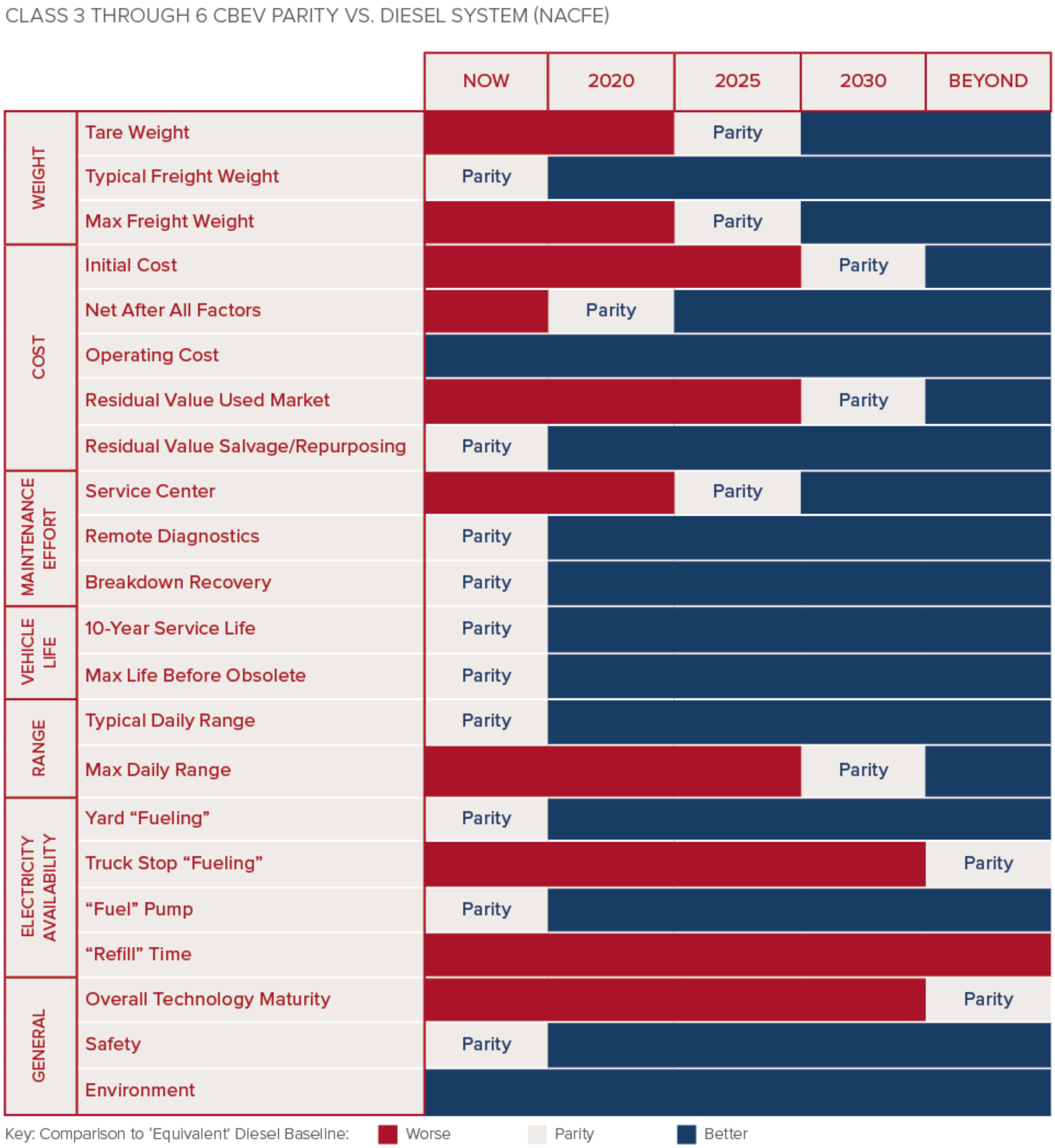


Figure 83. Class 3 through 6 CBEV Parity vs. Diesel/Gasoline Systems (NACFE) [1]

14 Summary Findings

NACFE has discussed 20 areas of knowns and unknowns for fleets considering investing in commercial battery electric vehicles. These are summarized in Figure 84.

Market Issues	Predicting e-commernce
	Experience dilemma
	Vehicle life
	Residual value of electric trucks
	Residual value of diesel and gasoline baseline
	Vehicle recycling/salvage
	Diesel and gasoline fuel prices
Battery Issues	Maintenance and repair
	Fire
	Raw materials
	Weight
	Battery life, range, replacement
	Battery second life
	Battery climate sensitivity
	High voltage security
Regulatory Issues	Zero emission zone mandate
	Incentives, grants, vouchers, subsidies, tax breaks
Power Issues	Energy sourcing
	Electrical grid readiness
	Scaling

Figure 84. CBEV Investment Knowns and Unknowns (NACFE)

These are uncertainties in large part because of a lack of a significant volume of production level vehicles on the road accumulating significant miles of fleet use. Long life performance of equipment, maintenance costs, residual markets, second life markets, and long-term viability of resources are speculation at this point. The CBEV technology is changing rapidly bringing into question also the ability to accurately forecast innovation. The potential for significant savings from CBEVs is there, but the industry is still very early in deploying quality vehicles into real world conditions. OEMs are very early in getting field history from fleets to help improve designs. In comparison, diesel and gasoline trucks exist in large numbers, with years of production and fleet feedback. This situation is visualized as two points on the truck innovation S-Curve shown in Figure 85. The maturity of ICE based vehicles means that significant improvements may now take considerable time and investment, and generally add complexity. The immaturity of electric vehicles conversely opens the path forward for rapid gains with less incremental investment.

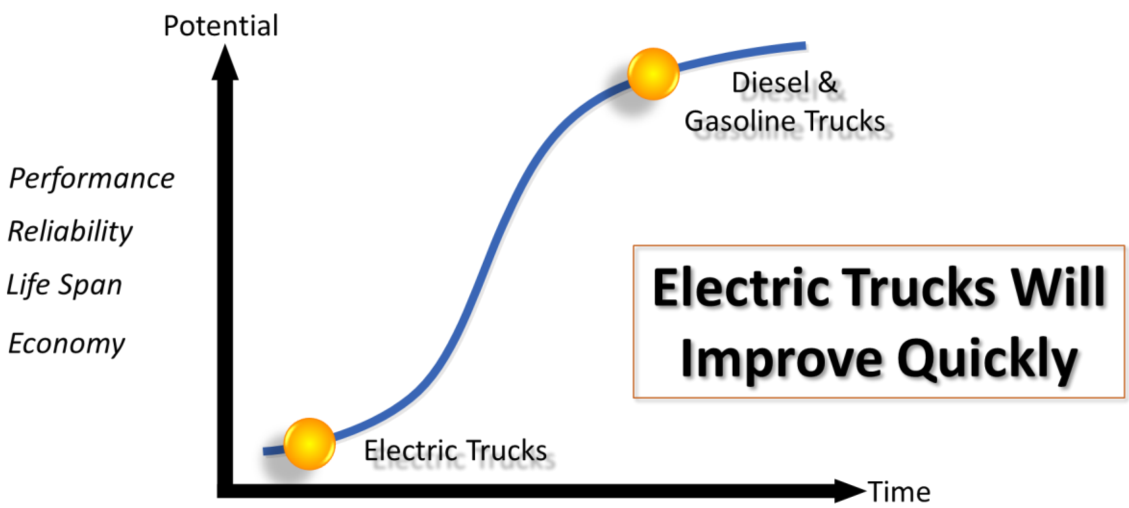


Figure 85. Innovations and Improvements Will Come Quickly for Electric Trucks (NACFE)

Fleets that purchase CBEVs now will help guide the rapid maturation of the vehicles and the infrastructure. OEMs that put CBEV vehicles on the road will gain experience in optimizing the vehicle designs and manufacture. Both will have valuable first-hand insights developing cost effective CBEV operations.

NACFE's research into CBEV experience to date has revealed a number of findings, summarized here from this report:

- Daily, return-to-base urban duty cycles below 100 miles are well suited for battery electric drivetrains.
- The primary justification of CBEV vehicles is to accomplish zero emission objectives.
- CBEVs have many unknowns because there is little long-term field history. The unknowns are not stopping fleets from buying CBEVs and getting first-hand operational data.
- Batteries are complex. The complexity is not preventing fleets from operating CBEVs.
- High voltage systems can seem scary. Fleets and OEMs are minimizing risks by prudent designs using lockout/tagout systems, and delegating high voltage work to certified experts.
- Repair of CBEVs is largely plug-and-play part replacement with little or no in situ repair work.
- Uptime on early generation CBEVs is no better or worse than early generations of diesels with emissions technology. Long-term expectations are 95%-98% uptime.
- Maintenance costs on early generation CBEVs are on par with diesel and gasoline trucks. Long-term expectations are that maintenance costs will be 40%-70% lower than for diesel or gasoline powertrains due to less complexity and elimination of problematic aftertreatment emission systems.
- Roadblocks to some are business opportunities to others – particularly true with respect to innovations in business models for electric trucks and charging infrastructure.
- E-commerce is increasing the need for medium-duty last mile deliveries.
- E-commerce is increasing the volume of returned merchandise, which also is increasing demands for medium-duty trucks.

- Batteries will degrade with use, but effective battery management systems combined with single shift operations that allow slower charging will extend battery life.
- Batteries do not degrade uniformly. It may be possible to refurbish battery packs while only changing out 20% of the pack. Vehicles would still likely have their whole pack replaced in a service bay, but the cost of the refurbished one would be much less than an entirely new pack.

15 Recommendations

Electric trucks are real. They are not the solution for every market, but they are a viable alternative for many where operations are urban in nature, with reasonably predictable daily ranges and return-to-base operations that permit economical over-night charging.

While CBEV technology is immature compared to diesel and gasoline powertrains, the significant level of investment and the broad diversity of companies entering the electric truck marketplace gives CBEVs inertia that prior technology introductions like natural gas did not have.

The energy source is not constrained to one source of fuel, meaning that CBEVs can weather geo-political and macro-economic storms much better than ICE vehicles that must depend largely on the oil supply chain. There are uncertainties, some of them disturbingly challenging such as the long-term supply and cost of cobalt needed for batteries. The electric grid is less of a concern as energy production exists sufficiently to support growth in electric vehicle adoption. Energy delivery, however, will require investment, just as with the successful roll out of the cell phone networks and the development of the internet. Where the business case supports the investment, the infrastructure will build out. Where the business case does not make economic sense, the investment will lag.

Electric trucks present a new world of potential business opportunities. An OEM may provide not just the truck, but also the charger, the electricity and the high voltage maintenance and repair services. Utilities may see business opportunities in providing long-term charging infrastructure and make use of charging trucks as utility system assets. Third party companies may create new businesses as system integrators for fleets. Remanufacturing high voltage batteries and motors are viable business opportunities as the population of electric trucks grows and ages. Repurposing batteries, motors and control systems will open new markets where vehicle systems no longer viable for transportation move to energy storage systems for factories, warehouses, homes and farms. A business roadblock to some may be a business opportunity to others.

E-commerce is changing trucking, with greater focus on last mile delivery. On-line consumers are ordering more frequently but in smaller quantities. There is also a significant growth in on-line returns which require transportation from the consumer back to the seller. These trends may accelerate the adoption of electric trucks.

Emission rules are also changing trucking. Some regions and cities are constraining the use of diesel and gasoline trucks while encouraging adoption of zero and low emission ones. These legislative moves affect estimating residual value of ICE vehicles; they challenge OEMs to introduce ZEV products in volume and with acceptable fleet economics. Grants, incentives, rebates, and tax breaks are making this possible today, but long term, OEMs need to produce cost equivalent electric vehicle alternatives. Some OEMs with all-new electric vehicle platforms are showing that this is feasible.

Funds to support road infrastructure will require changes in regulations and taxing methods. Fuel based state and federal taxes were an obvious choice in the old mono-culture of oil based ICE trucking, but electric trucks (and many alternative fuel concepts) will require energy-independent funding mechanisms such a vehicle miles traveled (VMT) systems.

Mixed technology trucks are the norm in fleet operations. The addition of electric vehicles to an existing fleet with various model years and types of diesel and gasoline trucks, and other alternative fueled vehicles, is likely not a significant change to shop complexity. In many ways, electric trucks may simplify maintenance as many systems will be plug-and-play replacement operations along with the elimination of complex systems to monitor combustion and emission processes. Handling, storing and disposing of hazardous fluids like diesel, gasoline and DEF are not an issue for electric trucks, but a mixed technology fleet will still have these in their shop environments.

Fleets, media, OEMs, regulators, NGOs and the public may prefer the simplicity of arguing electric versus diesel or gasoline as a winner take all championship bout. The reality is that fleets have always had a range of existing technologies in their stable of vehicles. Electric trucks represent just one more option available to fleets to wrest the best economics for their specific freight operations. Fleets will continue to have a variety of solutions and will continue to push OEMs to make all of them more efficient in a process called continuous improvement.

CBEVs are no longer speculation. They are clearly entering the North American market place with every major existing OEM and a number of new ones introducing products. Electric trucks will succeed or fail under the intense spotlight of the market place. Fleets choosing electric trucks today will get on the learning curve ahead of those that wait. Early adopters will expose flaws and omissions that OEMs will correct. They will validate or dismiss CBEV claims. They will also learn how to optimize their operations to make the most of electric vehicles for improving their company’s bottom line financials. As CBEVs improve, these early adopters will be better positioned to rapidly take advantage of the improvements. Their experiences will drive innovation.

16 BIBLIOGRAPHY

All website links were last accessed between May 2018 and July 2018.

1. Mihelic, R., Roeth, M., “Electric Trucks – Where They Make Sense,” Guidance Report, North American Council for Freight Efficiency (NACFE), May 1, 2018, https://nacfe.org/future-technology/electric-trucks

2. Pascal, A., “Technology Development, Demonstration and Commercialization,” Volvo, presentation at 2018 ACT EXPO, spoken quote, May 3, 2018

3. “Vehicle Weight Classes & Categories,” U.S. Department of Energy (DOE) Alternative Fuels Data Center (AFDC), last updated 2012, https://www.afdc.energy.gov/data/10380

4. FHWA, “Law Enforcement Vehicle Identification Guide,” U.S. Federal Highway Administration (FHWA) Office of Operations, https://ops.fhwa.dot.gov/publications/fhwahop10014/s5.htm#f21 and https://ops.fhwa.dot.gov/publications/fhwahop10014/long_f21.htm

5. EPA, “Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles— Phase 2,” Federal Register / Vol. 81, No. 206 / Tuesday, October 25, 2016 / Rules and Regulations, page 73478, https://www.gpo.gov/fdsys/pkg/FR-2016-10-25/pdf/2016-21203.pdf

6. EPA, “Regulatory Impact Analysis, Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2,” EPA-420-R-16-900, U.S. Environmental Protection Agency, Aug. 2016, https://nepis.epa.gov/Exe/ZyPDF.cgi/P100P7NS.PDF?Dockey=P100P7NS.PDF

7. Gao, Z., Lin, Z., Davis, S. and Birky, A., “Quantitative Evaluation of MD/HD Vehicle Electrification Using Statistical Data,” Oak Ridge National Laboratory and Energetics Inc., National Academy of Sciences (NAS) Transportation Research Board (TRB) Paper 18-04193, TRB 2018 Annual Meeting, Jan 2018, http://amonline.trb.org/18-04193-1.3990839?qr=1

8. NREL, “Fleet DNA: Commercial Fleet Vehicle Operating Data,” U.S. National Renewable Energy Laboratory, https://www.nrel.gov/transportation/fleettest-fleet-dna.html

9. DOE, “What we pay for in a gallon of Diesel,”, Energy Information Administration, U.S. Department of Energy, https://www.eia.gov/petroleum/gasdiesel/

10. U.S.-Canada Power System Outage Task Force, “Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations,” U.S. Department of Energy, 2004, https://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/BlackoutFinal-Web.pdf and also http://www.nerc.com/docs/docs/blackout/ch1-3.pdf

11. Howell, D, et al, “Enabling Fast Charging: A Technology Gap Assessment,” U.S. Department of Energy Office of Energy Efficiency & Renewable Energy, Oct 2017, https://energy.gov/sites/prod/files/2017/10/f38/XFC%20Technology%20Gap%20Assessment%20Report_FINAL_10202017.pdf

12. Prohaska, R., et al, “Field Evaluation of Medium-Duty Plug-in Electric Delivery Trucks,” U.S. National Renewable Energy Laboratory (NREL), 2016, doi:10.2172/1337010, https://doi.org/10.2172/1337010

13. "Express Plus," Specifications for Power Block, Power Modules and Station, ChargePoint brochure, https://www.chargepoint.com/files/datasheets/ds-expressplus.pdf

14. "ChargePoint Express Plus" ChargePoint website, https://www.chargepoint.com/products/commercial/express-plus/

15. Hurt, E., "Industry Alliance Wants Charging Standard for Electric Trucks, Buses, " Trucks.com, May 29, 2018, https://www.trucks.com/2018/05/29/industry-alliance-charging-standard-electric-trucks-buses/

16. "Electric Vehicle Power Transfer System Using a Three-Phase Capable Coupler," SAE International, Apr 25, 2018, https://www.sae.org/standards/content/j3068_201804/

17. Fung, E., "Malls Vacancies Hit Six-Year High as Online Shopping Takes a Toll," Wall Street Journal, Jul 2, 2018, https://www.wsj.com/articles/mall-vacancy-rate-hits-six-year-high-1530588600

18. Mihelic, R. Mihelic Vehicle Consulting LLC, photos from ACT EXPO 2018, May 1-3, 2018.

19. Transpower Connecting/Disconnecting Instructional Video, hosted on Vimeo, https://vimeo.com/254955118

20. "TransPower Electric Yard Tractor Standard Specifications Based on the Ottawa 4x2 Off Road Yard Tractor," Transpower spec sheet, http://www.transpowerusa.com/downloads/Spec-sheet-TransPower-Ottawa-4x2-Off-Road-Yard-Tractor.pdf

21. "eCanter," Mitsubishi Fuso product specifications brochure, http://www.mitfuso.com/en-us/models/ecanter

22. "Liquid Cooled CCS1 & CCS2 High Power Charging Solutions," ITT Cannon product brochure, https://www.ittcannon.com/Core/medialibrary/ITTCannon/website/Literature/Catalogs-Brochures/ITT-Cannon-EVC-DC-Liquid-Cooled-Brochure.pdf?ext=.pdf

23. "Charging technology for E-Mobility," Phoenix Contact catalog, provided by Steven Engineering https://stevenengineering.com/tech_support/PDFs/67SACC_E-MOBILITY-CHARGING.pdf

24. Afridi, K., "Wireless Charging of Electric Vehicles," University of Colorado Boulder, published in "Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2017 Symposium," National Academy of Engineering, 2018, Washington, DC: The National Academies Press. https://doi.org/10.17226/24906.

25. "Wireless Power Transfer for Light-Duty Plug-In/Electric Vehicles and Alignment Methodology J2954_201711," SAE International, Nov. 27, 2017, https://doi.org/10.4271/J2954_201711

26. "The Next Wireless Revolution: Electric Vehicle Wireless Charging - Power and Efficiency," Wi Tricity Corporation white paper, 2018, http://witricity.com/wp-content/uploads/2018/03/WIT_White_Paper_PE_20180321.pdf

27. "Highly Resonant Wireless Power Transfer: Safe, Efficient, and over Distance," Wi Tricity Corporation white paper, 2017, http://witricity.com/wp-content/uploads/2016/12/White_Paper_20161218.pdf

28. Lambert, F., "The first 200-kW wireless charging system for electric buses is deployed," electrek, Apr 19, 2018, https://electrek.co/2018/04/19/200-kw-wireless-charging-system-electric-buses/

29. Momentum Dynamics website, https://www.momentumdynamics.com/

30. Elkind, E., et al, "Reuse and Repower, How to Save Money and Clean the Grid with Second-Life Electric Vehicle Batteries" UCLA School of Law's Emmett Institute and Environment and UC Berkeley School of Law's Center for Law, Energy & the Environment (CLEE), Sep 2014, https://www.law.berkeley.edu/files/ccelp/Reuse_and_Repower_--_Web_Copy.pdf

31. Elkind, E., "Reuse & Repower: Harvesting Second-Life Energy Storage," presentation ACT EXPO 2018, May 1, 2018.

32. Stringer, D., Ma, J., "Where 3 Million Electric Vehicle Batteries Will Go When They Retire," Bloomberg, Jun 27, 2018, https://www.bloomberg.com/news/features/2018-06-27/where-3-million-electric-vehicle-batteries-will-go-when-they-retire

33. "DIRECTIVE 2000/53/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 September 2000 on end-of life vehicles" European Commission, amended 2013, http://ec.europa.eu/environment/waste/elv/legislation_en.htm

34. "Policy Brief EU H2020 MSCA-ETN DEMETER & MC-ITN EREAN," European Rare Earth (Magnet) Recycling Network, EREAN, May 2017, https://etn-demeter.eu/new-policy-brief-recycling-electric-cars/

35. Mai, T. et al, "Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States," National Renewable Energy Laboratory, NREL/TP-6A20-71500, 2018, DOI: 10.2172/1459351 https://www.osti.gov/biblio/1459351 or https://doi.org/10.2172/1459351

36. Verrender, I., "How government inaction fueled Australia's renewable energy boom," Australian Broadcasting Corporation (ABC) News, Jul 16, 2018, http://mobile.abc.net.au/news/2018-07-16/how-government-inaction-fuelled-the-renewables-boom/9996458

37. "First electric road in Sweden inaugurated," Trafikverket, Swedish Transport Administration, https://www.trafikverket.se/en/startpage/about-us/news/2016/2016-06/first-electric-road-in-sweden-inaugurated/

38. "Electrified roads – a sustainable transport solution of the future," eRoadArlanda website, https://eroadarlanda.com/ specifically https://eroadarlanda.com/globally-unique-electrified-road-enables-fossil-free-road-transport/

39. "How eHighway works," Siemens, https://www.siemens.com/global/en/home/products/mobility/road-solutions/electromobility/ehighway.html

40. "ABB powers 450kW fast charging for electric buses in Gothenburg," ABB website, Nov. 22, 2017, http://www.abb.com/cawp/seitp202/be24f0a9ca998b59c12581e00031630b.aspx

41. Arora, S., Mcconnell, S., "Four forces to watch in trucking and rail freight," McKinsey, May 2017, quoting Sheldon, P., "Canadian online retail forecast, 2014-2019," Forrester.com, Oct. 2014,

https://www.mckinsey.com/industries/travel-transport-and-logistics/our-insights/four-forces-to-watch-in-trucking-and-rail-freight

42. Mackie, R., "2012 DOE VEHICLE TECHNOLOGIES PROGRAM REVIEW PRESENTATION," Smith Electric Vehicles Corp., May 17, 2012, https://www.energy.gov/sites/prod/files/2014/03/f10/arravt072_vss_mackie_2012_o.pdf

43. "A Broken Place: The Spectacular Failure Of The Startup That Was Going To Change The World," Innovation Agents, April 7, 2014, https://www.fastcompany.com/3028159/a-broken-place-better-place

44. Bakke, N., Linhoj, J., Rask, M., "Better Place - Transforming the global auto industry?," Department of Business Administration, Business and Social Sciences, Aarhus University, Denmark, Nov. 20, 2015, https://www.researchgate.net/publication/260046588_Better_Place_Transforming_the_Global_Auto_Industry

45. Mihelic, R., "Envisioning Future Commercial Vehicles," presentation for Stifel Transportation Equipment Equity Research, Mihelic Vehicle Consulting, Aug. 30, 2017. (available from author, or through Stifel at https://stifel2.bluematrix.com/sellside/EmailDocViewer?encrypt=8fe7415e-801a-48c0-ade6-3a8e7418dddc&mime=pdf&co=Stifel&id=null&source=mail) http://www.stifel.com/

46."Energy Flow 2017," U.S. DOE Energy Information Administration (EIA) graph, https://www.eia.gov/totalenergy/data/monthly/pdf/flow/total_energy.pdf from https://www.eia.gov/totalenergy/data/annual/#summary

47. "Petroleum, natural gas, and coal still dominate U.S. energy consumption," U.S. DOE Energy Information Administration (EIA), July 3, 2018, https://www.eia.gov/todayinenergy/detail.php?id=36612

48. Valenta, M., "BUSINESS CASE OF ELECTRIC VEHICLES FOR TRUCK FLEETS," doctoral thesis submitted to Argosy University, Denver College of Business, Mar 2013, http://onthegreenllc.net/uploads/3/4/6/7/34678066/valenta_dissertation_published.pdf

49. Fuller, S., Petersen, S., "Life Cycle Costing Manual for the Federal Energy Management Program," NIST Handbook 135, 1995 Edition, National Institute of Standards and Technology (NIST), Feb 1996, https://ws680.nist.gov/publication/get_pdf.cfm?pub_id=907459

50. Fitzgerald, G., Nelder, C., "From Gas To Grid," Rocky Mountain Institute (RMI), https://www.rmi.org/insight/from_gas_to_grid/ or https://www.rmi.org/wp-content/uploads/2017/10/RMI-From-Gas-To-Grid.pdf

51. Long, M., "Charging All-Electric Trucks," Transport Topics (TT), May 11, 2018, **https://www.ttnews.com/articles/charging-all-electric-trucks**

52. "TM4 is now a Part of Dana Inc. with Hydro-Quebec Remaining as a Key Partner," TM4 Media Center, Jun 22, 2018, https://www.tm4.com/news-events/tm4-is-now-a-part-of-dana-inc-with-hydro-quebec-remaining-as-a-key-partner/ and Dana Media Center, http://dana.mediaroom.com/2018-06-22-Dana-Incorporated-and-Hydro-Quebec-Announce-Strategic-Joint-Venture

53. "Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles - Part 1: General requirements," International Electrotechnical Commission (IEC), IEC 62196-1:2014, https://webstore.iec.ch/publication/6582, "…-- Part 2: Dimensional compatibility and interchangeability

requirements for a.c. pin and contact-tube accessories, IEC 62196-2:2016 https://webstore.iec.ch/publication/24204 and "…- Part 3: Dimensional compatibility and interchangeability requirements for d.c. and a.c./d.c. pin and contact-tube vehicle couplers," IEC 62196-3:2014, https://webstore.iec.ch/publication/6584

54. "Electric Power Monthly," U.S. Energy Information Administration (EIA), https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

55. Germitz, D., "I've seen the future of 3D printing (think Star Trek replicator)," ZDNET and DIY-IT, July 7, 2017, https://www.zdnet.com/article/ive-seen-the-future-of-3d-printing-think-star-trek-replicator/

56. GE Reports Staff, "Printing The Future: What Additive Manufacturing Means For Innovation," GE Reports, Mar. 11, 2018, https://www.ge.com/reports/printingthefuture/

57. Williams, B.,"History of Package Delivery," Package Guard, Nov. 6, 2017, https://www.thepackageguard.com/amazon/history-package-delivery/

58. Sears, "Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934 For the Fiscal Year Ended January 28, 2017," Sears Holdings, https://searsholdings.com/docs/investor/SHC_2016_Form_10-K.pdf

59. Abrams, D., "Did suppliers, not Amazon, create the retail apocalypse?" SupplyChainDive, June 6, 2018, https://www.supplychaindive.com/news/suppliers-retail-apocalypse-amazon-direct-consumer/525043/

60. Brandt, C., "How the 'Amazon Effect' is Shaping the Future of Wholesale Delivery," Omnitracs webinar, May 16, 2018, https://event.webcasts.com/viewer/event.jsp?ei=1189348

61. U.S. Bureau of the Census, "E-Commerce Retail Sales [ECOMSA]," retrieved from FRED, Federal Reserve Bank of St. Louis; May 25, 2018, https://fred.stlouisfed.org/series/ECOMSA

62. U.S. Bureau of the Census, "E-Commerce Retail Sales as a Percent of Total Sales [ECOMPCTSA]," retrieved from FRED, Federal Reserve Bank of St. Louis; May 25, 2018, https://fred.stlouisfed.org/series/ECOMPCTSA

63. Aspray, W., Royer, G., & Ocepek, M. G. (2013). Anatomy of a Dot-Com Failure: The Case of Online Grocer Webvan. In W. Aspray, G. Royer, & M. G. Ocepek, Food in the Internet Age (pp. 25-35). Springer https://link.springer.com/chapter/10.1007%2F978-3-319-01598-9_2

64. Miller, C., "Delivery Start-Ups Are Back Like It's 1999," New York Times Magazine, Aug. 19, 2014 https://www.nytimes.com/2014/08/24/magazine/delivery-start-ups-are-back-like-its-1999.html

65. Fisher, G., Kotha, S., "HomeGrocer.com: Anatomy of a Failure," Business Horizons, Mar. 2014, DOI: 10.1016/j.bushor.2013.12.003 also through ResearchGate https://www.researchgate.net/publication/260015020_HomeGrocercom_Anatomy_of_a_failure

66. "The On-Demand Economy Continues to Grow," Rockbridge Associates, Apr. 5, 2018, https://rockresearch.com/on-demand-economy-continues-to-grow/

67. Maravillas, J., "The On-Demand Economy Is Growing, and Not Just for the Young and Wealthy," Harvard Business Review, Apr. 14, 2016, https://hbr.org/2016/04/the-on-demand-economy-is-growing-and-not-just-for-the-young-and-wealthy

68. Trevis Team, "Here's How Home Depot's E-Commerce Strategy Is Driving Growth," Forbes, Feb. 15, 2017, https://www.forbes.com/sites/greatspeculations/2017/02/15/heres-how-home-depots-e-commerce-strategy-is-driving-growth/

69. Thau, B., "Five Signs that Stores (Not E-Commerce) are the Future of Retail," Forbes, June 27, 2017, https://www.forbes.com/sites/barbarathau/2017/06/27/five-signs-that-stores-not-online-shopping-are-the-future-of-retail/

70. Isidore, C., "Are electric cars more likely to catch fire?" CNN Money, May 17, 2018, http://money.cnn.com/2018/05/17/news/companies/electric-car-fire-risk/index.html

71. "Highway vehicle fires," National Fire Protection Association (NFPA), updated 9/16, https://www.nfpa.org/News-and-Research/Fire-statistics-and-reports/Fire-statistics/Vehicle-fires/Highway-vehicle-fires

72. Ahrens, M., "Vehicle fire trends and patterns," National Fire Protection Association, June 2010, https://www.nfpa.org/News-and-Research/Fire-statistics-and-reports/Fire-statistics/Vehicle-fires/Vehicle-fire-trends-and-patterns

73. BBC, "Why do Rome's buses keep catching fire?" BBC News, May 8, 2018, http://www.bbc.com/news/world-europe-44041597

74. McCarthy, N., "Rome Has A Big Problem With Burning Buses," Statistica, May 9, 2018 https://www.statista.com/chart/13799/rome-has-a-big-problem-with-burning-buses/

75. Stephens, D., et al, "Lithium-ion battery safety issues for electric and plug-in hybrid vehicles," NHTSA/Battelle Report No. DOT HS 812 418, Washington, DC: National Highway Traffic Safety Administration, 2017, October, https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/12848-lithiumionsafetyhybrids_101217-v3-tag.pdf

76. Vujanic, A., "Generation Z to Switch the Majority of Purchases to Retailers That Provide the Newest Digital Tools and Channels, Accenture Research Reveals," Accenture, Mar. 1, 017, https://newsroom.accenture.com/news/generation-z-to-switch-the-majority-of-purchases-to-retailers-that-provide-the-newest-digital-tools-and-channels-accenture-research-reveals.htm

77. Joerss, M., Neuhaus, F. , Schröder, J., "How customer demands are reshaping last-mile delivery," McKinnsey & Company, Oct. 2016, https://www.mckinsey.com/industries/travel-transport-and-logistics/our-insights/how-customer-demands-are-reshaping-last-mile-delivery

78. Technological Disruption and Innovation in Last Mile Delivery," Stanford Graduate School of Business, June 2016, https://www.gsb.stanford.edu/sites/gsb/files/publication-pdf/vcii-publication-technological-disruption-innovation-last-mile-delivery.pdf

79. "State of Shipping in Commerce 2016," Temando, temando.com (accessed March 29, 2016). http://temando.com/en/research-2016 FIX CITATION

80. Cummins, "Cummins and Johnson Matthey Expand Efforts in Electrification," Cummins Newsroom press release, Jan. 31, 2018, https://www.cummins.com/news/releases/2018/01/31/cummins-and-johnson-matthey-expand-efforts-electrification

81. Cummins, "Get to Know Brammo, the Company Recently Acquired by Cummins," Cummins Newsroom press release, Oct. 17, 2017 https://www.cummins.com/news/2017/10/17/get-know-brammo-company-recently-acquired-cummins-0

82. Eaton, "Cooper Industries Acquistion," Nov. 30, 2012, http://www.eaton.com/us/en-us/company/investor-relations/investor-toolkit/dividend-information-and-forms/Cooper-Industries-Acquisition.html

83. Daimler, "Investment and Strategic Partnership: Daimler Trucks teams up with innovation leader for electric charging StoreDot Ltd. ," Daimler press release, Sep. 14, 2017, http://media.daimler.com/marsMediaSite/en/instance/ko/Investment-and-Strategic-Partnership-Daimler-Trucks-teams-up-with-innovation-leader-for-electric-charging-StoreDot-Ltd.xhtml

84. Meritor, "Meritor Announces Investment in TransPower to Accelerate Electrical Vehicle Platforms," Meritor press release, Dec. 7, 2017, https://www.meritor.com/ourcompany/news/pressreleases/Lists/allnewsitems/DispForm.aspx?id=1933&Source=/

85. Meritor, "It's a Bull Market," Meritor Investor Day presentation, Dec. 7, 2017, https://www.meritor.com/analystday/pdfs/2017-Meritor-Analyst-Day-Presentation.pdf

86. CONMET, "ConMet and Protean Electric join forces to develop Electric In-Wheel Drive System for the Commercial Vehicle Market," CONMET Press Release, Mar. 9, 2017, https://www.conmet.com/conmet-protean-electric-join-forces-develop-electric-wheel-drive-system-commercial-vehicle-market/

87. Ford, "Ford Portfolio of Advanced Fuel Solutions," Ford media center, https://media.ford.com/content/dam/fordmedia/North America/US/2017/03/14/Porfolio-of-Advanced-Solutions.jpg

88. Lockridge, D., "Daimler Trucks North America to Build Electric Cascadia, M2 Trucks," Heavy Duty Trucking, Jun. 6, 2018, https://www.truckinginfo.com/303913/daimler-trucks-north-america-to-build-electric-cascadia-m2-trucks

89. Anonymous, "Tesla Semi Launch: Delayed, Crew Missing," Seeking Alpha, May 16, 2018, https://seekingalpha.com/article/4174377-tesla-semi-launch-delayed-crew-missing

90. USGS, "Cobalt Statistics and Information," US Geological Survey (USGS) Minerals Information for year 1998 and year 2018, https://minerals.usgs.gov/minerals/pubs/commodity/cobalt/

91. Tesla, Inc., "Tesla, Inc. Conflict Minerals Report for the reporting period January 1 to December 31, 2017," Form SD Specialized Disclosure Report Tesla, Inc., US Securities and Exchange Commission (SEC), EDGAR database, May 29, 2018, https://www.sec.gov/Archives/edgar/data/1318605/000156459018014530/tsla-sd.htm and https://www.sec.gov/Archives/edgar/data/1318605/000156459018014530/tsla-ex101_7.htm

92. US SEC, "Conflict Minerals Disclosure A Small Entity compliance guide," US Securities and Exchange Commission (SEC), https://www.sec.gov/info/smallbus/secg/conflict-minerals-disclosure-small-entity-compliance-guide.htm

93. GM, "2016 Chevrolet Bolt Battery System," General Motors media release, Sep 16, 2015, https://media.gm.com/content/dam/Media/microsites/product/Volt_2016/doc/VOLT_BATTERY.pdf

94. US SEC, "Conflict Minerals Report," Form SD Specialized Disclosure Report General Motors Company, May 31, 2018, https://www.sec.gov/Archives/edgar/data/1467858/000146785818000073/gmformsd2017.htm and https://www.sec.gov/Archives/edgar/data/1467858/000146785818000073/ex10112312017cmr.htm

95. Levine, S., "Two industrial titans are duking it out over a technology that could make electric cars mainstream," Quartz, March 30, 2015, https://qz.com/369657/two-industry-titans-are-duking-it-out-over-a-technology-that-could-make-electric-cars-mainstream/

96. EC, "Critical Raw Materials," European Commission website, https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

97. EC, "Study on the review of the list of critical raw materials," European Commision, ISBN 978-92-79-72119-9, DOI 10.2873/398823, Jun 2017, https://publications.europa.eu/en/publication-detail/-/publication/7345e3e8-98fc-11e7-b92d-01aa75ed71a1/language-en

98. The Responsible Business Alliance website http://www.responsiblebusiness.org/

99. RMI, "Cobalt Reporting Template," Responsible Minerals Initiative (RMI) website, http://www.responsiblemineralsinitiative.org/emerging-risks/cobalt-reporting-template/

100. "Fueling Tesla's Model 3 Cobalt Plans," Culturebanx website, June 12, 2018, https://www.culturebanx.com/cbx-weekly-24/2018/6/10/fueling-teslas-model-3-cobalt-plans

101. Attwood, J., Ritchie, M., "Elon Musk Warns That Tesla's Cobalt Use Is Heading Toward Zero," Bloomberg, May 2, 2018, https://www.bloomberg.com/news/articles/2018-05-02/tesla-supercharging-its-model-3-means-less-cobalt-more-nickel

102. "Cobalt Price", InfoMine website graph, 2005-2018, http://www.infomine.com/investment/metal-prices/cobalt/all/

103. USGS, "Rare Earths," U.S. Geological Survey, index to annual reports: https://minerals.usgs.gov/minerals/pubs/commodity/rare_earths, example 2018 report: /https://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2018-raree.pdf

104. Guerra, M., "4 Things You Should Know About Magnets for Electric Vehicles," Electronic Design, Dec. 11, 2017, http://www.electronicdesign.com/analog/4-things-you-should-know-about-magnets-electric-vehicles

105. Szymkowski, S., "Rare-earth metals in magnets for electric-car motors: what you need to know," Green Car Reports, Sep. 21, 2017, https://www.greencarreports.com/news/1112807_rare-earth-metals-in-magnets-for-electric-car-motors-what-you-need-to-know

106. USGS, “Lithium,” U.S. Geological Survey, index to annual reports, https://minerals.usgs.gov/minerals/pubs/commodity/lithium/, example 2018 report: https://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2018-lithi.pdf

107. Schulz, K. et al, ”Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply,” U.S. Geological Survey, Professional Paper 1802, https://pubs.usgs.gov/pp/1802/pp1802_entirebook.pdf

108. “Lithium Americas Investor Presentation,” LithiumAmericas (LIC), Jun 2018, http://lithiumamericas.com/wp-content/uploads/2018/06/LAC-Investor-Presentation-June-2018.pdf

109. “Production Statistics,” International Organization of Motor Vehicle Manufacturers (OICA), website by year and country, http://www.oica.net/category/production-statistics/2012-statistics/

110. Electrification Coalition, “ZEV State Policy Rankings,” Electrification Coalition, June 2018, https://www.zevscorecard.com/wp-content/themes/ec/assets/doc/zev_state_policy_rankings_embargo_6_14_2018.pdf

111. Swalnick, N., “ZEV Scorecard Assesses States’ Progress on EVs,” Advanced Clean Transport News (ACTNews), Jun 19, 2018, https://www.act-news.com/news/zev-scorecard-shows-states-ev-progress/

112. California , “13 CCR § 1962.2 Zero-Emission Vehicle Standards for 2018 and Subsequent Model Year Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles,” California Code of Regulations (CCR), https://www.arb.ca.gov/msprog/zevprog/zevregs/1962.2_Clean.pdf and https://www.arb.ca.gov/msprog/zevprog/zevregs/zevregs.htm and https://govt.westlaw.com/calregs/Document/I505CA51BB0AD454499B57FC8B03D7856?viewType=FullText&originationContext=documenttoc&transitionType=CategoryPageItem&contextData=(sc.Default)

113. Bratvold, D., Cleaver, M., “Analysis of the Effect of Zero-Emission Vehicle Policies: State-Level Incentives and the California Zero-Emission Vehicle Regulations,” Leidos report prepared for the U.S. Department of Energy (DOE) Energy Information Administration (EIA), Sep 2017, https://www.eia.gov/analysis/studies/transportation/zeroemissions/pdf/zero_emissions.pdf

114. “Ultra Low Emission Zone,” Mayor of London, https://tfl.gov.uk/modes/driving/ultra-low-emission-zone

115. “Complying with ULEZ,” Mayor of London, https://tfl.gov.uk/modes/driving/ultra-low-emission-zone/complying-with-ulez and http://content.tfl.gov.uk/lez-ulez-comparison-table.pdf

116. Urban Access Regulations in Europe,” European Commission (EC), overview of European regions http://urbanaccessregulations.eu/overview-of-lezs#why and for France http://urbanaccessregulations.eu/countries-mainmenu-147/france

117. “The zero-emission vehicle (ZEV) standard,” Quebec Cabinet de la ministre du Développement durable, de l'Environnement et de la Lutte contre les changements, climatiques, http://www.mddelcc.gouv.qc.ca/changementsclimatiques/vze/index-en.htm

118. Mihelic, R. and Ray, B., "A Systems Approach for the Evolving Nature of Part Costs," SAE Technical Paper 2003-01-3402, 2003, https://doi.org/10.4271/2003-01-3402

119. Dollmeyer, T., “Electrified Powertrains – Why, what and what to consider,” presentation at American Trucking Associations (ATA) Technology and Maintenance Council (TMC) Spring 2018 Meeting, Cummins, Mar 2018, photo by Rick Mihelic.

120. “An Introduction to Environmental Accounting As A Business Management Tool: An Introduction to Environmental Accounting As A Business Management Tool: Key Concepts And Terms,” U.S. Environmental Protection Agency, EPA 742-R-95-001, Jun 1995, https://archive.epa.gov/p2/archive/web/pdf/busmgt.pdf

121. “Federal Facility Pollution Prevention Project Analysis: A Primer for Applying Life Cycle and Total Cost Assessment Concepts,” U.S. Environmental Protection Agency, EPA 300-B-95-008, Jul 1995, https://archive.epa.gov/compliance/resources/publications/assistance/sectors/web/pdf/ffppprojectanalysis.pdf

122. “Truck and Bus Regulation Fleet Compliance Assistance Tool,” Fleet Calculator, California Air Resources Board (CARB), https://www.arb.ca.gov/msprog/onrdiesel/compliancetool.htm and Truck and Bus Fleet Calculator https://www.arb.ca.gov/msprog/onrdiesel/documents/FleetCalc2018A.xls

123. “Greenhouse Gas Equivalencies Calculator,” U.S. Environmental Protection Agency (EPA), https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

124. “Fuel Sustainability Tool,” BSR website, https://www.bsr.org/en/collaboration/groups/future-of-fuels

125. “GREET Fleet - Carbon and Petroleum Footprint Calculator,” U.S. Argonne National Laboratory (ANL) website, https://greet.es.anl.gov/fleet_footprint_calculator

126. “GREET® Model - The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model,” Argonne National Laboratory (ANL) website, https://greet.es.anl.gov/ . Video on how to use: https://youtu.be/X3LzlWbKRCM?list=PLLT1SPoEVQqxWRoFTABWU_ibyLSpS18pO

127. “Environmental management -- Life cycle assessment -- Principles and framework,” International Organization for Standardization (ISO), 2006, https://www.iso.org/standard/37456.html

128. “Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) Tool,” Argonne National Laboratory (ANL), https://greet.es.anl.gov/index.php?content=afleet

129. “Truck Fuel Calculator,” ACT Research website, http://act2017.wpengine.com/actcalc/AltFuelCalculator.php

130. “UPS To Deploy First Electric Truck to Rival Cost of Conventional Fuel Vehicles,” UPS Press Release, Feb 22, 2018, https://www.pressroom.ups.com/pressroom/ContentDetailsViewer.page?ConceptType=PressReleases&id=1519225541368-230

131. Hurt, E., “UPS to Launch Electric Delivery Trucks That Match Gasoline Truck Costs,” Trucks.com, Feb 22, 2018, https://www.trucks.com/2018/02/22/ups-electric-delivery-trucks/

132. Hari, A., Shoval, S., Kasser, J., “Conceptual Design to Cost: A new systems engineering tool,” INCOSE, 2008, https://www.iltam.org/files/INCOSE%202008%20CDTC%20paper%20final%20Version.pdf

133. Gille, W., Kolkmeier, R., “Design to Cost Handbook,” U.S. Army Troop Support Command, Jan 1990, http://www.dtic.mil/dtic/tr/fulltext/u2/a232651.pdf

134. “Battery Second-Use Repurposing Cost Calculator (B2U),” National Renewable Energy Laboratory (NREL), https://www.nrel.gov/transportation/b2u-calculator.html

135. “Battery Second Use for Plug-In Electric Vehicles,” National Renewable Energy Laboratory (NREL), https://www.nrel.gov/transportation/battery-second-use.html

136. “Battery Lifetime Analysis and Simulation Tool Suite (BLAST),” National Renewable Energy Laboratory (NREL), https://www.nrel.gov/transportation/blast.html

137. “Battery Ownership Model (BOM),” National Renewable Energy Laboratory (NREL), https://www.nrel.gov/transportation/battery-ownership.html

138. Neubauer, J., “Battery Lifetime Analysis and Simulation Tool (BLAST) Documentation,” National Renewable Energy Laboratory (NREL), NREL/TP-5400-63246, Dec. 2014, downloadable from https://www.nrel.gov/transportation/blast-btm-lite.html

139. “Increasing Profitability by Lowering Your Real Cost of Ownership,” Daimler Trucks Financial, Freightliner Trucks, 2014, https://freightliner.azureedge.net/media/2260/freightliner-rco-guide.pdf

140. “Fleet Operations, Finance Departments Not Seeing Eye to Eye,” Heavy Duty Trucking (HDT), Jul 10, 2018, https://www.truckinginfo.com/306430/fleet-operations-finance-departments-not-seeing-eye-to-eye

141. “Latest Fleet Advantage Survey Shows Vast Communications Challenges Between A Company’s Fleet Operations and Finance Departments,” Fleet Advantage, Jul 10, 2018, https://www.fleetadvantage.com/press_releases.cfm

142. “ADVANCED TRUCK LIFECYCLE ANALYTICS & ADMINISTRATIVE SOFTWARE (ATLAAS),” Fleet Advantage, http://cdn2.hubspot.net/hubfs/424365/ATLAAS_Sell_Sheet_2-17-2016_Final.pdf?t=1532729479800

143. “Short-Term Energy Outlook,“ U.S. Energy Information Administration (EIA), Jul 10, 2018, https://www.eia.gov/outlooks/steo/report/prices.php

144. Clinton, P., “Class 6 Trucks Oldest on Road,” Heavy Duty Trucking (HDT), Nov. 11, 2015, https://www.truckinginfo.com/132350/class-6-trucks-oldest-on-road

145. “Consumer Assistance to Recycle and Save Act of 2009 (CARS Program),“ U.S. National Highway Traffic Safety Administration (NHTSA), https://www.nhtsa.gov/fmvss/consumer-assistance-recycle-and-save-act-2009-cars-program

146. Valdes-Dapena, P., “Cash for Clunkers ending, CNN Money,” Aug 21, 2009, https://money.cnn.com/2009/08/20/autos/cash_for_clunkers_end/index.htm?postversion=2009082016

147. Doering, C.,”Peeking inside the pod: A deep look inside Peapod's grocery delivery business,” FoodDive, Jul 30, 2018, https://www.fooddive.com/news/grocery--peeking-inside-the-pod-a-deep-look-inside-peapods-grocery-delivery-business/526056/

148. Peapod website, https://about.peapod.com/peapod-facts

149. Berckmans, G., et al, "Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030 ," Energies, 2017, 10(9), 1314; doi:10.3390/en10091314 www.mdpi.com/1996-1073/10/9/1314/pdf

150. Rajamanickam, V., "The future of electric vehicles lie in the sourcing of lithium and cobalt for batteries," FreightWaves, Aug 1, 2018, https://www.freightwaves.com/news/technology/the-future-of-electric-vehicles-lie-in-the-sourcing-of-lithium-and-cobalt-for-batteries

151. "Six Sigma Case Study: General Electric," SixSigma, May 22, 2017, https://www.6sigma.us/ge/six-sigma-case-study-general-electric/

152. Duleep, G., et al, "Impacts of Electric Vehicles - Deliverable 2, Assessment of electric vehicle and battery technology," Publication number: 11.4058.04, DELFT, ICF International and Ecologic Institute, Apr. 2011, www.cedelft.eu/publicatie/impact_of_electric_vehicles/1153

153. EEI's Fleet Electrification Steering Committee, "Transportation Electrification,", Edison Electric Institute, June 2014, http://www.eei.org/issuesandpolicy/electrictransportation/FleetVehicles/Documents/EEI_UtilityFleetsLeadingTheCharge.pdf

154. Nelson, P. et al, "Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles," U.S. DOE Argonne National Laboratory (ANL), Sep 2011, http://www.ipd.anl.gov/anlpubs/2011/10/71302.pdf

155. Roberts, J., "TMC Panel Educates Fleets on Real-World Electric Truck Operation," Heavy Duty Trucking, (HDT), Sep 2017, https://www.truckinginfo.com/157695/tmc-panel-educates-fleets-on-real-world-electric-truck-operation

156. Coleman, J., "How Vehicle Battery and Systems Change with Electrification – What Technicians Need to Know," East Penn, presentation at ATA TMC Spring 2018, from Rick Mihelic's Mar. 7, 2018 notes and photographs from the session.

157. Clean Tech Institute website, http://www.cleantechinstitute.org/Training/index.html

158. "Light Duty Hybrid/Electric Vehicle Specialist Test," Automotive Service Excellence (ASE), http://www.ase.com/Tests/ASE-Certification-Tests/Test-Series.aspx

159. American Trucking Associations Technology and Maintenance Council Fall 2018 agenda, https://events.atabusinesssolutions.com/tmcfall18/

160. "Alternative Powertrains: Analysis of Recent Market Trends & Value Retention," NADA Used Car Guide Perspective, Apr 2016, http://img03.en25.com/Web/NADAUCG/%7B49f71c70-31ef-4af9-870b-aeac4c6245bd%7D_201604_Alternative_Powertrains.pdf

161. Zhou, Y., et al, "Comparison of Value Retention of Plug-in Vehicles and Conventional Vehicles and Potential Contributing Factors," U.S. DOE Argonne National Laboratory (ANL), TRB16-6732, or EVS29-5920356, Jun 2016, http://docs.trb.org/prp/16-6732.pdf or http://www.anl.gov/energy-systems/publication/comparison-value-retention-plug-vehicles-and-conventional-vehicles-and

162. Canon, J., "OEM panel looks at natural gas truck market," Successful Dealer, May 6, 2014, https://www.successfuldealer.com/oem-panel-looks-at-natural-gas-truck-market/

163. Stanton, B., "Gas vs. Diesel: The Bad Investment Only Fleet Managers Know About, Government Fleet," Oct 19, 2015, https://www.government-fleet.com/156355/gas-vs-diesel-the-bad-investment-only-fleet-managers-know-about

164. Horngren, C., et al., "Introduction to Management Accounting," 16th ed., Pearson, 2013, ISBN- ISBN-13: 978-0133058789

ISBN-10: 0133058786

165. "Determining the Optimal Lifecycle for Truck Fleets," Work Truck, Nov 2014, https://www.worktruckonline.com/155754/determining-the-optimal-lifecycle-for-truck-fleets

166. Bibona, S., "How to Calculate Optimal Replacement Cycles," Fleet Financials, Jan 13, 2015, https://www.fleetfinancials.com/155875/how-to-calculate-optimal-replacement-cycles

167. Sussman, J., Martland, C., "1.011 Project Evaluation,"Massachusetts Institute of Technology: MIT OpenCourseWare, Spring 2011, https://ocw.mit.edu ,License: Creative Commons BY-NC-SA (https://creativecommons.org/licenses/by-nc-sa/4.0/) , https://ocw.mit.edu/courses/civil-and-environmental-engineering/1-011-project-evaluation-spring-2011/ .

168. Perez-Arriaga.I., "*IDS.505J Engineering, Economics and Regulation of the Electric Power Sector,"*.. Massachusetts Institute of Technology: MIT OpenCourseWare, Spring 2010, https://ocw.mit.edu, License: Creative Commons BY-NC-SA (https://creativecommons.org/licenses/by-nc-sa/4.0/), https://ocw.mit.edu/courses/institute-for-data-systems-and-society/ids-505j-engineering-economics-and-regulation-of-the-electric-power-sector-spring-2010/

169. 117. Schefter, K., "Electric Vehicle Infrastructure," Energy Lawyers and Contracting Officers Forum presentation, Edison Electric Institute, Nov. 16, 2017, https://energy.gov/sites/prod/files/2017/11/f46/33-fupwgfall2017_schefter.pdf

170. U.S.-Canada Power System Outage Task Force, "Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations," U.S. Department of Energy, 2004, https://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/BlackoutFinal-Web.pdf and also http://www.nerc.com/docs/docs/blackout/ch1-3.pdf

171. "Hybrid and Electric Voucher Incentive Program," California HVIP website, https://www.californiahvip.org/

172. IMPLEMENTATION MANUAL FOR THE HYBRID AND ZERO-EMISSION TRUCK AND BUS VOUCHER INCENTIVE PROJECT (HVIP) AND LOW NOx ENGINE INCENTIVES IMPLEMENTED THROUGH ," California Air Resources Board (ARB), Jan. 10, 2018, https://www.californiahvip.org/wp-content/uploads/2018/01/Final-IM-01172018.pdf

173. "Volkswagen Clean Air Act Civil Settlement," U.S. Environmental Protection Agency (EPS), Jan 11, 2017, https://www.epa.gov/enforcement/reference-news-release-volkswagen-agrees-plead-guilty-pay-43-billion-criminal-and-civil and https://www.epa.gov/enforcement/volkswagen-clean-air-act-civil-settlement

174. "State Planning for VW Settlement Funds Quick Reference Guide on Stakeholder Engagement," U.S. Department of Energy, Sep 2017, https://www.energy.gov/sites/prod/files/2017/09/f36/stakeholder-engagement-guide-VW-final.pdf

175. "Electric Vehicles: Tax Credits and Other Incentives," U.S. Department of Energy website, https://www.energy.gov/eere/electricvehicles/electric-vehicles-tax-credits-and-other-incentives

176. "Transitioning to Electrification: Funding Resources," Center for Climate and Energy Solutions (C2ES), Nov 2017, https://www.c2es.org/site/assets/uploads/2017/11/transitioning-electrification-funding-resources-1.pdf

177. "Search Federal and State Laws and Incentives," U.S. Department of Energy (DOE) Alternative Fuels Data Center (AFDC), https://www.afdc.energy.gov/laws

178. "State Information," U.S. Alternative Fuels Data Center (AFDC) website, https://www.afdc.energy.gov/states/

179. "Take Credit for Going Green," ChargePoint website, https://www.chargepoint.com/products/station-incentives/

180. "BU-409: Charging Lithium-ion," Battery University website, https://batteryuniversity.com/index.php/learn/article/charging_lithium_ion_batteries

181. "State and Federal Incentives," Plug In America website, https://pluginamerica.org/why-go-plug-in/state-federal-incentives/

182. "Electric Car Safety, Maintenance, and Battery Life," U.S. Office of Energy Efficiency & Renewable Energy website, https://www.energy.gov/eere/electricvehicles/electric-car-safety-maintenance-and-battery-life

183. Goldberg, L., "Battery Cell Balancing for Improved Performance in EVs - Part I: Passive Balancing Technologies," Digikey Electronics, Oct 19, 2011, https://www.digikey.com/en/articles/techzone/2011/dec/battery-cell-balancing-for-improved-performance-in-evs---part-ii-active-balancing-technologies

184. Ozkan, M., "A closer look at Li-ion cell balancing," ChargedEVs, Feb 19, 2013, https://chargedevs.com/features/closer-look-cell-balancing/

185. Daowd, M., et al, "A Review of Passive and Active Battery Balancing based on MATLAB/Simulink," International Review of Electrical Engineering (I.R.E.E.), 6(7):2974-2989 · November 2011 https://pdfs.semanticscholar.org/0c70/9b4b316d682e6503de5d342d84ef69738c15.pdf and https://www.researchgate.net/publication/231169729_A_Review_of_Passive_and_Active_Battery_Balancing_based_on_MATLABSimulink

186. Lillian, B., "National Lab: How Does Cold Weather Really Affect EV Charging?," Next-Gen Transportation (NGT) News, Aug. 6, 2018, https://ngtnews.com/national-lab-how-does-cold-weather-really-affect-ev-charging

187. "Diesel Vans Beat Gasoline Models in Total Ownership Cost," Work Truck magazine, Aug 8, 2018, https://www.worktruckonline.com/310494/diesel-vans-beat-gasoline-models-in-ownership-cost

188. "2018 U.S. Diesel Analysis Press Release," Vincentric press release, Aug 8, 2018, https://vincentric.com/Home/Industry-Reports/2018-US-Diesel-Analysis/2018-US-Analysis-Press-Release and https://vincentric.com/Home/Industry-Reports

189.Yuksel, T., Michalek, J., "Effects of Regional Temperature on Electric Vehicle Efficiency, Range, and Emissions in the United States," Environmental Science & Technology, Environ. Sci. Technol. 2015, 49, 3974−3980, DOI: 10.1021/es505621s, https://www.cmu.edu/me/ddl/publications/2015-EST-Yuksel-Michalek-EV-Weather.pdf

190. Blanco, S., "Testing for Cold Climate Comfort," SAE Automotive Engineering, May 2018, https://www.sae.org/news/2018/04/testing-for-cold-climate-comfort

191. Yuksel, T., et al, "Effect of regional grid mix, driving patterns and climate on the comparative carbon footprint of gasoline and plug-in electric vehicles in the United States," IOP Science, Apr 7, 2016, doi:10.1088/1748-9326/11/4/044007, http://iopscience.iop.org/article/10.1088/1748-9326/11/4/044007/pdf

192. Chatelain, A., et al, "What a teardown of the latest electric vehicles reveals about the future of mass-market EVs," McKinnsey, Mar 2018, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/what-a-teardown-of-the-latest-electric-vehicles-reveals-about-the-future-of-mass-market-evs

193. Wood, E., et al, "National Plug-In Electric Vehicle Infrastructure Analysis," U.S. Department of Energy (DOE), Sep 2017, https://www.energy.gov/sites/prod/files/2017/09/f36/NationalPlugInElectricVehicleInfrastructureAnalysis_Sept2017.pdf

194. Motoaki, Y., et al, "Empirical analysis of electric vehicle fast charging under cold temperatures," Energy Policy, Nov 2018 (published Jul 25, 2018), https://doi.org/10.1016/j.enpol.2018.07.036, https://www.sciencedirect.com/science/article/pii/S0301421518304828

195. "Tariffs," State of Nevada Public Utilities Commission(PUCN), http://puc.nv.gov/About/Docs/Tariffs/

196. "Returns got you down? Invest in strategic liquidation," RetailDive content by BStock, Feb 20, 2018, https://www.retaildive.com/news/returns-got-you-down-invest-in-strategic-liquidation/517099/

197. "CBRE Report: Holiday E-Commerce Returns Could Reach $32 Billion As Online Sales Surge," CBRE Report, Dec 13, 2017, http://cbreemail.com/rv/ff00c0ff0d83e5161f066ce64947850a52aa3547

198. McKefitt, J., "Online sellers could face $32B in returned goods this year," RetailDive, Dec 15, 2015, https://www.retaildive.com/news/online-sellers-could-face-32b-in-returned-goods-this-year/513182/

199. Crown Uniform website, http://www.crownuniform.com/about-crown-uniform.html

200. Rick Mihelic, Mihelic Vehicle Consulting

201. Ford Commercial Trucks website, https://www.ford.com/new-commercial-trucks/

202. “Walk-In Van Challenge,” Freightliner Custom Chassis Corporation (FCCC), https://www.fccccommercial.com/#button-bar and https://www.youtube.com/watch?v=TT-XfWDN3dg&feature=youtu.be

203. “MT Chassis,” Freightliner Custom Chassis Corporation (FCCC), https://www.fccccommercial.com/chassis/mt/

204. “Investor Presentation,” Workhorse Group Inc., Aug 2016, https://workhorse.com/storage/app/media/investors/presentations/2016-Q2-presentation.pdf

205. “Electricity Explained – Factors Affecting Electricity Prices,” U.S. Energy Information Administration, (EIA), https://www.eia.gov/energyexplained/index.php?page=electricity_factors_affecting_prices

206. “Annual Energy Outlook 2018,” U.S. Energy Information Administration (EIA), Feb. 26, 2018, https://www.eia.gov/outlooks/aeo/

207. Freightliner Custom Chassis Corporation (FCCC) website, https://www.fccccommercial.com/build-my-van/

208. Kelly, K. et al, “Compressed Natural Gas Vehicle Maintenance Faciliity Modifcation Handbook,” U.S. Department of Energy Office of Energy Efficiency & Renewable Energy, Sep 2017, https://www.afdc.energy.gov/uploads/publication/cng_maintenance_facility_mod.pdf

209. Moultak, M., et al, “TRANSITIONING TO ZERO-EMISSION HEAVY-DUTY FREIGHT VEHICLES,” ICCT, Sep 2017, https://www.theicct.org/sites/default/files/publications/Zero-emission-freight-trucks_ICCT-white-paper_26092017_vF.pdf

210. Kelly, K., et al “Medium- and Heavy-Duty Vehicle Duty Cycles for Electric Powertrains,” U.S. National Renewable Energy Laboratory (NREL), NREL/PR-5400-66228, Mar 20-24, 2016, https://www.nrel.gov/docs/fy16osti/66228.pdf

211. “Proposed California Phase 2 Greenhouse Gas Standards (CA Phase 2 GHG) and Potential Amendments to the Tractor - Trailer GHG Regulation Second Public Workshop,” California Air Resources Board (California ARB or CARB), August 31, 2017, https://www.arb.ca.gov/msprog/onroad/caphase2ghg/20170831_workshop_presentation.pdf

212. EPA, “Regulatory Impact Analysis, Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2,” EPA-420-R-16-900, U.S. Environmental Protection Agency, Aug. 2016, https://nepis.epa.gov/Exe/ZyPDF.cgi/P100P7NS.PDF?Dockey=P100P7NS.PDF

213. “Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles— Phase 2 ,” Federal Register, Rules and Regulations, Vol. 81, No. 206, Tuesday, October 25, 2016, https://www.gpo.gov/fdsys/pkg/FR-2016-10-25/pdf/2016-21203.pdf

214. Pelletier, S., et al, "Battery Electric Vehicles for Goods Distribution: A Survey of Vehicle Technology, Market Penetration, Incentives and Practices," Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT), CIRRELT-2014-43, Sep 2014, https://www.cirrelt.ca/DocumentsTravail/CIRRELT-2014-43.pdf

215. Gallo, J., Tomic, J., "Battery Electric Parcel Delivery Truck Testing and Demonstration," CALHEAT Research Center/ CALSTART Inc., Aug 2013, http://www.calstart.org/Libraries/CalHEAT_2013_Documents_Presentations/Battery_Electric_Parcel_Delivery_Truck_Testing_and_Demonstration.sflb.ashx

216. Loveday, E., "Navistar begins commercial production of eStar electric cargo van, first four going to FedEx," Autoblog, May 15, 2010, https://www.autoblog.com/2010/05/15/navistar-begins-commercial-production-of-estar-electric-cargo-va/

217. Lambert, F., "Royal Mail unveils new electric truck made by Arrival," electrek, Aug 23, 2017 https://electrek.co/2017/08/23/royal-mail-new-electric-autonomous-truck-arrival/

218. Heisler, Y., "UPS' new trucks look straight out of a Pixar movie," New York Post, May 11, 2018, https://nypost.com/2018/05/11/ups-new-trucks-look-straight-out-of-a-pixar-movie/amp/

219. Arrival website, https://arrival.com/

220. BYD website, http://en.byd.com/usa/truck/

221. Chanje website, https://chanje.com/ and Chanje V8100 product brochure https://chanje.com/wp-content/uploads/2018/08/Chanje-V8070-2018-brochure.pdf

222. "Ryder Reserves 500 Chanje Electric Panel Vans," Transport Topics (TT), Jun 8, 2018, https://www.ttnews.com/articles/ryder-reserves-500-chanje-electric-panel-vans

223. "Ryder Expands Leadership in Commercial Electric Vehicles, Places Reservation for Additional 500 Chanje Electric Vans," Chanje press release, Jun 7, 2018, https://chanje.com/press/ryder-expands-leadership-commercial-electric-vehicles-places-reservation-additional-500-chanje-electric-vans/

224. Edwards, J. et al, "Daimler Trucks North America Unveils Two Freightliner Electric Vehicle Models and Freightliner Electric Innovation Fleet," Daimler Trucks North America (DTNA) press release, Jun 6, 2018, https://daimler-trucksnorthamerica.com/influence/press-releases/#daimler-trucks-north-america-unveils-two-2018-06-06

225. Lockridge, D., "Daimler Trucks North America to Build Electric Cascadia, M2 Trucks," Heavy Duty Trucking (HDT), Jun 6, 2018, https://www.truckinginfo.com/303913/daimler-trucks-north-america-to-build-electric-cascadia-m2-trucks

226. "Daimler Trucks North America Announces Penske Truck Leasing and NFI as Partners for Freightliner Electric Innovation Fleet ," Cision PR Newswire, Jun 27, 2018, https://www.prnewswire.com/news-releases/daimler-trucks-north-america-announces-penske-truck-leasing-and-nfi-as-partners-for-freightliner-electric-innovation-fleet-300673138.html

227. Frightliner website, https://freightliner.com/e-mobility/

228. EForce One AG website, https://eforce.ch/index.html and product brochures https://eforce.ch/downloads.html

229. EForce, “18-44t eLkw,” Specifications, https://eforce.ch/uploads/1/1/7/1/117106312/e44_fact_sheet_e.pdf

230. Einride website, https://www.einride.tech/

231. Hyatt, K., “Swedish startup Einride prepares to drop the T-Pod at Detroit,” Road Show by CNET, Jan 3, 2018, https://www.cnet.com/roadshow/news/swedish-start-up-einride-prepares-to-drop-the-t-pod-at-naias/

232. “New Ford eQVM Program Electrifies Work Trucks,” Ford Media Center, Mar 14, 2017, https://media.ford.com/content/fordmedia/fna/us/en/news/2017/03/14/new-ford-eqvm-program-electrifies-work-trucks.html

233. LightningElectric website, **https://lightningsystems.com/lightningelectric**

234. “Lightning Systems Electric Ford Transit: 61 MPGe in the City,” Heavy Duty Trucking, Apr 4, 2018, https://www.truckinginfo.com/279472/lightning-systems-electric-ford-transit-61-mpge-in-the-city

235. “Lightning Systems Electric Ford Transit: 61 MPGe in the City,” Automotive Fleet, Apr 4, 2018, https://www.automotive-fleet.com/279472/lightning-systems-electric-ford-transit-61-mpge-in-the-city

236. “Orders Open for Electrified Transit Van Conversion,” GreenFleet, Oct. 26, 2017, https://www.greenfleetmagazine.com/142779/orders-open-for-lightningelectric-system

237. Motiv website, https://www.motivps.com/

238. “Heavy Duty Technology and Funding Showcase,” Clean Cities Sacramento, Jun 6, 2016, http://www.cleancitiessacramento.org/uploads/2/7/8/6/27862343/consolidated_deck_v3.0.pdf

239. Motiv Upfit Packages, Motiv website, http://www.motivps.com/motivps/wp-content/uploads/2017/12/Motiv_M102_BR_F59_E450_Class8_UpfitPackagesBifold_20171031.pdf

240. Marsh, A., “Isuzu testing out electric trucks,” Fleet Owner, May 9, 2018, https://www.fleetowner.com/running-green/isuzu-testing-out-electric-trucks

241. “ISUZU TO DISPLAY ELECTRIC TRUCK AT NTEA,” Isuzu press release, Mar 7, 2018, https://www.isuzucv.com/app/press/doc/5453

242. Middleton, G., “Isuzu announces electric truck program,” Truck Sales, May 11, 2018, https://www.trucksales.com.au/editorial/details/isuzu-announces-electric-truck-program-112541/

243. Lambert, F., “A new lineup of all-electric trucks and buses is now emerging in Quebec,” electrek, May 7, 2018, https://electrek.co/2018/05/07/all-electric-trucks-lion-electric/

244. Lion Electric website, https://thelionelectric.com/en

245. Mitsubishi Fuso eCanter website, https://www.mitsubishi-fuso.com/content/fuso/en/truck/ecanter/lp.html

246. “eCanter,” Mitsubishi Fuso product specifications brochure, http://www.mitfuso.com/en-us/models/ecanter

247. Lambert, F., ”Renault Trucks unveils new generation of all-electric trucks,” electrek, Jun 27, 2018, https://electrek.co/2018/06/27/renault-trucks-new-generation-electric-trucks/

248. “Renault Trucks unveils its second generation of electric trucks: a complete Z.E. range from 3.1 to 26t ,” Renault Trucks press release, Jun 26, 2018, https://corporate.renault-trucks.com/en/press-releases/2018-06-26-renault-trucks-unveils-its-second-generation-of-electric-trucks.html

249. Kane, M., “The Electric Renault Truck D On The Streets Of Paris,” InsideEVss, Jul 19, 2014, https://insideevs.com/the-all-electric-renault-trucks-d-on-the-streets-of-paris/

250. Hanley, S., “UPS Will Test Medium-Duty Class 6 Electric Trucks From Thor,” CleanTechnica, Aug 2, 2018, https://cleantechnica.com/2018/08/02/ups-will-test-medium-duty-class-6-electric-trucks-from-thor/

251. Abt, N., UPS working with Thor on electric Class 6 truck,” FleetOwner, Aug 1, 2018, https://www.fleetowner.com/powertrain/ups-working-thor-electric-class-6-truck

252. Thor Trucks website, https://www.thortrucks.com/

253. “UPS to Test New Electric Vehicle,” UPS Pressroom, Jul 31, 2018, https://pressroom.ups.com/pressroom/ContentDetailsViewer.page?ConceptType=PressReleases&id=1532964104882-384

254. Lambert, F., “VW receives massive order for 1,600 all-electric trucks,” electrek, Aug 21, 2018, https://electrek-co.cdn.ampproject.org/c/s/electrek.co/2018/08/21/vw-massive-order-all-electric-trucks/amp/

255. “Ambev Brewery will have more than 1/3 of its third-party fleet composed by electric trucks by 2023,” Volkswagen Press Release, Aug 21, 2018, https://www.volkswagenag.com/en/news/2018/08/ambev_electric_trucks.html

256. Clevenger, S., “Volvo Pushes Forward With Electric Trucks,” Transport Topics (TT), Jun 21, 2018, http://www.ttnews.com/articles/volvo-pushes-forward-electric-trucks

257. O’Dell, J., “Volvo Will Sell Electric Trucks in Europe Next Year, North America to Follow,” Trucks.com, Jan 23, 2018, https://www.trucks.com/2018/01/23/volvo-electric-trucks-europe-north-america/

258. Kane, M., “Volvo Unveils Second Electric Truck – FE Electric, It’s Bigger, Badder,” InsideEVss, May 22, 2018,https://insideevs.com/volvo-unveils-second-electric-truck-fe-electric-its-bigger-badder/

259. Workhorse website, https://workhorse.com/

260. Cannon, J., “Workhorse electric van showcasing fuel efficiency equivalent of up to 75 mpg,” Commercial Carrier Journal (CCJ), Jul 30, 2018, https://www.ccjdigital.com/workhorse-electric-van-showcasing-fuel-efficiency-equivalent-of-up-to-75mpge/

261. Kane, M., "Workhorse, together with its distribution and service partner, Ryder System, put on the road the first of its N-GEN new all-electric vans in the San Francisco Bay Area," InsideEVs, Mar 30, 2018, https://insideevs.com/workhorse-n-gen-electric-van-hits-the-road/

262. Workhorse Group SEC Edgar Fiscal Year 2017 10-K filing, Mar 14, 2018, https://www.sec.gov/Archives/edgar/data/1425287/000121390018002957/f10k2017_workhorsegroup.htm#a_003

263. Wrightspeed powertrain website, https://www.wrightspeed.com/the-route-powertrain

264. Carpenter, S., "Electric Supercar Builder Xing Mobility Plans Light-Duty Truck," Trucks.com, May 15, 2018, https://www-trucks-com.cdn.ampproject.org/c/s/www.trucks.com/2018/05/15/electric-xing-mobility-light-duty-truck/amp/

265. XING Mobility website, https://www.xingmobility.com/vehicles

266. XING Mobility Modular Battery System, brochure, https://docs.wixstatic.com/ugd/a4e211_0ca55bc2b2d14a2286070bffd6a088c2.pdf

267. Chateua website, http://chateaues.com/how-we-do-it/renewables-energy-storage/electric-vehicle-infrastructure/

268. Nicholas, M., Hall, D.," Lessons Learned on Early Electric Vehicle Fast-Charginng Deployments," International Council on Clean Transporation (ICCT), Jul 2018, https://www.theicct.org/publications/fast-charging-lessons-learned

269. "Opening Brief of Southern California Edison Company (U 338-E) on the Priority Review Transportation Electrification Proposals from San Diego Gas & Electric Company, Southern California Edison company, and Pacific Gas and Electric Company," State of California PUC, Application 17-01-020, Filed Jan 20, 2017, http://www3.sce.com/sscc/law/dis/dbattach5e.nsf/0/23A245BBF648CD5788258141008086C5/$FILE/A1701021-SCE%27s%20Opening%20Brief%20on%20the%20Priority%20Review%20TE%20Proposals.pdf

270. Transportation Electrification Activities Pursuant to Senate Bill 350," California Public Utilities Commission (PUC), website http://www.cpuc.ca.gov/sb350te/

271. "Application of Sand Diego Gas & Electric Company (U 902-E) for Approval of Senate Bill 350 Transportation Electrification Proposals Regarding Medium and Heavy Duty Electric Vehicles and Vehicle-to-Grid Pilot," State of California PUC, Application No. A.18-01, Filed January 22, 2018, https://www.sdge.com/sites/default/files/regulatory/A.%2018-01- %20Application%20-MD%20and%20HD%20EVs.pdf

272. Roberts, J., "What's Hot in Medium Duty for 2018," Heavy Duty Trucking (HDT), Oct 18, 2017, https://www.truckinginfo.com/157750/whats-hot-in-medium-duty-for-2018

273. FCA US Fleet website, https://www.fcausfleet.com/commercial-vans.html

274. Chevrolet Commercial Trucks website, https://www.chevrolet.com/commercial/

275. Commercial Truck Trader website, https://www.commercialtrucktrader.com/

276. Kenworth Trucks website, https://www.kenworth.com/trucks/

277. Peterbilt Medium Duty website, https://www.peterbilt.com/products/medium-duty/

278. ABB website, https://new.abb.com/ev-charging/products/depot-overnight-charging

279. ChargePoint website, https://www.chargepoint.com/products/commercial/

280. Chateau Energy Solutions website, http://chateaues.com/how-we-do-it/renewables-energy-storage/electric-vehicle-infrastructure/

281. ClipperCreek website, https://www.clippercreek.com/fleet/

282. Cole, J., "Eaton Leaves the Commercial EV Charging Station Game," InsideEVs, Sep 3, 2015, https://insideevs.com/eaton-leaves-ev-charging-station-game/

283. EV Connect website, https://www.evconnect.com/business/

284. EVgo website, https://www.evgo.com/ev-charging-business/other-business-types/

285. "ChargePoint Takes Over Management of GE's Electric Vehicle Charging Network," ChargePoint press release, Jun 27, 2017, https://www.chargepoint.com/about/news/chargepoint-takes-over-management-ges-electric-vehicle-charging-network/

286. Rhombus Energy Solutions website, https://www.rhombusenergysolutions.com/

287. Siemens website, https://w3.usa.siemens.com/powerdistribution/us/en/product-portfolio/electricvehicle/versicharge/Pages/ev-charging-station.aspx

288. Tritium website, https://www.tritium.com.au/

289. Garcia, C., "Electric Vehicle Charger Selection Guide," Energy Efficiency Coordinator (EEC), Nov 10, 2017 http://eecoordinator.info/electric-vehicle-charger-selection-guide/

290. "Electric Vehicle Charger Selection Guide," ShareAlike, updated Jan 2018, http://eecoordinator.info/wp-content/uploads/2018/01/EV_Charger_Selection_Guide_2018-01-11.pdf

291. Davis, S., Xue, D., "Financing Low and Zero-Emission Freight Transportation Technologies in California," Goldman School of Policy, University of California Berkeley, Aug 2018, https://gspp.berkeley.edu/assets/uploads/page/Funding_Programs_Summary_final_August_29.pdf and press release at https://gspp.berkeley.edu/news/news-center/the-roadmap-to-electric-truck-incentives

292. "Second Quarter 2018 Report to the California Air Resources Board," Electrify America, Aug 10, 2018, https://www.electrifyamerica.com/downloads/get/1036154

293. Lightning Systems Lands Launch Order for Electric Truck Powertrain," Trucks.com, Aug 27, 2018, https://www.trucks.com/2018/08/27/lightning-systems-lands-launch-order-for-electric-truck-powertrain/

294. ZEEM Solutions website, https://www.zeemsolutions.com/

295. UD Trucks website, https://www.udtrucks.com/en-us/home

296. Ryan, J., "Zero Emission, All-Electric Buses Take to Louisville Streets," WFPL 89.3 News, http://wfpl.org/zero-emission-electric-buses-take-louisville-streets/

297. Gilpin, L., "These City Bus Routes are Going Electric – and Saving Money," Inside Climate News, Oct. 23, 2017, https://insideclimatenews.org/news/18102017/these-city-bus-routes-are-going-all-electric

298. "Fast-Charging, all electric ZeroBus," U.S. Department of Energy (DOE), video, https://vimeo.com/180798047

299. Reid, G., "Why we will electrify trucking faster than you think (and it has nothing to do with Tesla)," Energy and Carbon, May 2, 2018, http://energyandcarbon.com/will-electrify-trucking-faster-think-nothing-tesla/

300. Meyer, D., "Meet Ford and Deutsche Post DHL's First Electric Delivery Van: StreetScooter Work XL," Fortune, Aug 17, 2017, http://fortune.com/2017/08/17/ford-deutsche-post-dhl-electric-van/

301. StreetScooter DHL website, https://www.streetscooter.eu/en/

302. Kane, M., "StreetScooter Opens 2nd Manufacturing Facility, Doubles Production Capacity," Inside EVs, Jun 19, 2018, https://insideevs.com/streetscooter-opens-second-manufacturing-facility-and-doubles-production-capacity/

303. "StreetScooter opens new factory to meet demand," SMMT TNB News, Jun 13, 2018, https://www.smmt.co.uk/2018/06/streetscooter-opens-new-factory-to-meet-demand/

304. Girifallco, L., "Dynamics of Technological Change," University of Pennsylvania, Van Nostrand Reihnold, New York, 1991, ISBN-13: 978-1-4684-6511-2, DOI: 10.1007/978-1-4684-6509-9 available digitally through SpringerLink

305. Churella, A., "Corporate Culture and Marketing in the American Railway Locomotive Industry: American Locomotive and Electro-Motive Despond to Dieselization," The Bisuiness History Review, Vol. 69, No. 2, Summer 1995, pp. 191-229, The President and Fellows of Harvard College, DOI: 10.2307/3117099 available digitally from https://www.jstor.org/stable/3117099

306. Iden, M., "U.S. Freight Rail Fuel Efficiency 1920-2015 & Beyond," Union Pacific, 19th Railroad Environmental Conference, Oct 25, 2017, http://railtec.illinois.edu/RREC/presentations/2017RREC/9.1.pdf

307. Schramm, J., "Black diamonds no more : a technological history of the dieselization of the Lehigh Valley Railroad," Lehigh University Theses and Dissertations, 1995, https://preserve.lehigh.edu/cgi/viewcontent.cgi?article=1349&context=etd

308. "CityFreighter investment opportunity," startengine.com, www.startengine.com/cityfreighter

309. Everett, R., "Rogers, E. (1962) Diffusion of innovations," Free Press, London, NY, USA, ISBN 0-02-926650-5, https://teddykw2.files.wordpress.com/2012/07/everett-m-rogers-diffusion-of-innovations.pdf - 5th Edition available through Simon & Schuster at http://www.simonandschuster.com/books/Diffusion-of-Innovations-5th-Edition/Everett-M-Rogers/9780743222099

310. Roeth, M., et al, "Annual Fleet Fuel Study," North American Council for Freight Efficiency (NACFE), Aug 2018, https://nacfe.org/annual-fleet-fuel-studies/

311. Mihelic, R., "Envisioning Future Commercial Vehicles," presentation for Stifel Transportation Equipment Equity Research, Mihelic Vehicle Consulting, Aug. 30, 2017. (available from author, or through Stifel at https://stifel2.bluematrix.com/sellside/EmailDocViewer?encrypt=8fe7415e-801a-48c0-ade6-3a8e7418dddc&mime=pdf&co=Stifel&id=null&source=mail) http://www.stifel.com/

312. Graphic from https://en.wikipedia.org/wiki/Diffusion_of_innovations

313. Manthey, N.,"MAN presents wide-ranging electric truck portfolio," Electrive.com, Sep 19,2018, https://www.electrive.com/2018/09/19/man-presents-wide-ranging-electric-truck-portfolio/

314. MAN website, https://www.truck.man.eu/de/en/man-etruck.html and https://www.truck.man.eu/de/en/cite.html

315. Kane, M., "Volkswagen Unveils e-Crafter Electric Van: 124 Mile Range, Arrives In 2017," InsideEVs, Sep 22, 2016, https://insideevs.com/volkswagen-unveils-e-crafter-electric-van-124-mile-range-arrives-in-2017/

316. Yoney, D., "Volkswagen e-Crafter Electric Van: Test Drive Review," InsideEVs, Sep 3, 2018, https://insideevs.com/volkswagen-e-crafter-review/

317. Traton website, https://traton.com/en.html

318. "Electric Mobility Guide IAA Commercial Vehicles," Electrive.com, Sep 2018, https://www.iaa.de/fileadmin/user_upload/2018/deutsch/downloads/besucher/Electric_Mobility_Guide_IAA_2018.pdf

17 Appendix A: MD CBEV Products and Relevant Others In Production or Near Production

The growth in medium-duty electric truck platforms has been significant. A 2013 CALSTART study highlighted there were four electric vehicle parcel delivery platforms [215]. A 2017 ICCT study on Zero Emission vehicles identified 19 medium-duty electric truck platforms [209]. Press releases from medium-duty manufacturers in 2018 show that truck makers have further added medium-duty CBEV platforms to their product offerings. The September 2018 Hanover International Automotive Exhibition (IAA) listed fifteen brand names making electrified trucks and fifteen showing electrified vans [318]. NACFE compiled the following list in September 2018 for vehicles either in North American production, near production, or relevant developments from other regions of the world. New announcements on vehicle offerings, however, seem to come nearly weekly, so this is just a starting point for review.

17.1.1 Arrival

The Arrival, according to a 2017 Electrek article, has an "optimized the maximum range-to-weight ratio for inner city deliveries with battery packs enabling up to 100 miles of range on 3.5, 6 and 7.5 tonne trucks [217]." A 2018 *New York Post* article states, "The electric vehicles boast a range of more than 150 miles and will include an Advanced Driver Assistance System [218]." The Arrival website does not yet have details [219]. The product and technology may be relevant to the North American market.

Figure 86. Arrival Delivery Truck (Arrival) [218][219]

17.1.2 BYD

BYD is an established electric truck manufacturer dating from 1995 [220]. Their website lists Class 5 and Class 6 truck offerings with detailed specifications. The Class 6 model has a battery capacity of 221 kWh with a fully loaded range of 124 miles. Charge times vary between 1.5 hours fast charging and 4.5 hours. The Class 5 product has a battery capacity of 145 kWh, a half loaded range of 155 miles, and a charging time of 5 hours. The company is a significant manufacturer of batteries and offers static storage systems.

Figure 87. BYD Class 5 and Class 6 (BYD) [220]

17.1.3 Chanje

Chanje offers "an electric medium-duty panel van designed and built from the ground up to meet the specific needs of the last mile industry." The company offers the V8100 medium-duty panel van with a 150 mile range with 2,000 lbs. payload (per testing on the Heavy-Duty Urban Dynamometer Driving Schedule). The V8100 product brochure also states a maximum freight payload of 6,000 lbs. and GVWR of 16,535 lbs. [221]. Chanje offers turnkey vehicle systems including arrangements with Ryder Service for maintenance support. The turnkey solution also includes providing fully integrated electric vehicle infrastructure [221]. A June 2018 *Transport Topics* article states the vehicle can haul 6,000 lbs. and "has a 100-mile range on a single charge [222]." These numbers originate from a Chanje press release [223].

Figure 88. Chanje V8100 (Chanje) [221]

17.1.4 Chevrolet

Chevrolet does not produce its own electric medium-duty products. However, Lightning systems and Zeem Solutions teamed up in August 2018 to produce the first Class 6 Chevrolet electric medium-duty truck [293].

17.1.5 CityFreighter

An example of a start-up in the early stages for commercial battery electric vehicle space is CityFreighter, which is pursuing funding to develop the CF1 light duty delivery van (Class-1-3) [308]. The company stresses the modular approach indicative of the nature of electric vehicles.

Figure 89. CityFreighter concept vehicle (CityFreighter) [307].

17.1.6 Daimler

Daimler announced in June 2018 the eM2 106, stating, "The eM2 has up to 480 peak horsepower. The batteries provide 325 Kwh of usable capacity, a range of up to 230 miles, and have the ability to charge up to 80% (providing a range of 184 miles) in about 60 minutes [224][227]." The objective duty cycle is to "meet customer needs for electrified commercial vehicles serving dedicated, predictable routes where the vast majority of daily runs fall between 45 and 150 miles [224]." *Heavy Duty Trucking* editor Deborah Lockridge quoted that, "Daimler emphasized that this rollout is part of a global effort, and in fact the goal is to develop a single proprietary electric system that will be used on its products around the world. EMG (electric mobility group) will define the strategy for everything from electrical components to completely electric vehicles for all brands and all business divisions, while also working to create a single global electric architecture [225]."

DTNA also announced "that Penske Truck Leasing and NFI have agreed to partner in operating the Freightliner Electric Innovation Fleet of eCascadia™ heavy-duty trucks and eM2 106 medium-duty trucks [226]." DTNA said production start would be in 2021 [226].

"DTNA plans to offer customers consulting services to assist with site selection based on truck applications, available government incentives, infrastructure deployment and route identification as part of a preliminary review prior to commercial electric vehicle business proposals [226]."

Figure 90. DTNA eM2 106 (DTNA) [227]

17.1.7 DHL

The Deutsche Post DHL Group working with Ford has gone into production with a light-duty battery electric delivery van named the StreetScooter Work XL [299][300]. DHL "designed and built by a delivery firm because it couldn't find a vehicle on the market to suit its needs and has doubled its production capacity thanks to external demand [303]." The product is initially intended for the German market. It is based on the Ford Transit chassis. Mark Kane in an Inside EVs article in 2018 stated "The new 78,000 m^2 facility in Düren, Germany will be able to produce up to 10,000 StreetScooters annually, so together with the main factory in Aachen, production capacity will be 20,000 [302]." While the vehicle is a light-duty vehicle and only available in Germany, NACFE has included it here to show the ability of innovators to quickly go into production with battery electric vehicles.

Figure 91. StreetScooter Work XL (DHL) [300]

17.1.8 E-FORCE

E-Force (or alternatively EFORCE or E-Force One AG) is a German company with product technology relevant to the North American market. The E-Force One specification sheet states a city drive cycle range of up to 186 miles (300 km) or up to 111 miles (180 km) on highway. Battery packs come in four capacities, "Mini 120 kWh, Midi 190 kWh, Maxi 260 kWh, Maxi S 310 kWh." Recharge times are 6 hours with AC @ 44 kW for the Midi battery, and less than 2 hours at 150 kW with the Midi battery. The vehicle weighs in at approximately 19,000 lbs. (8600 kg) and is based on the Iveco Stralis chassis [228][229].

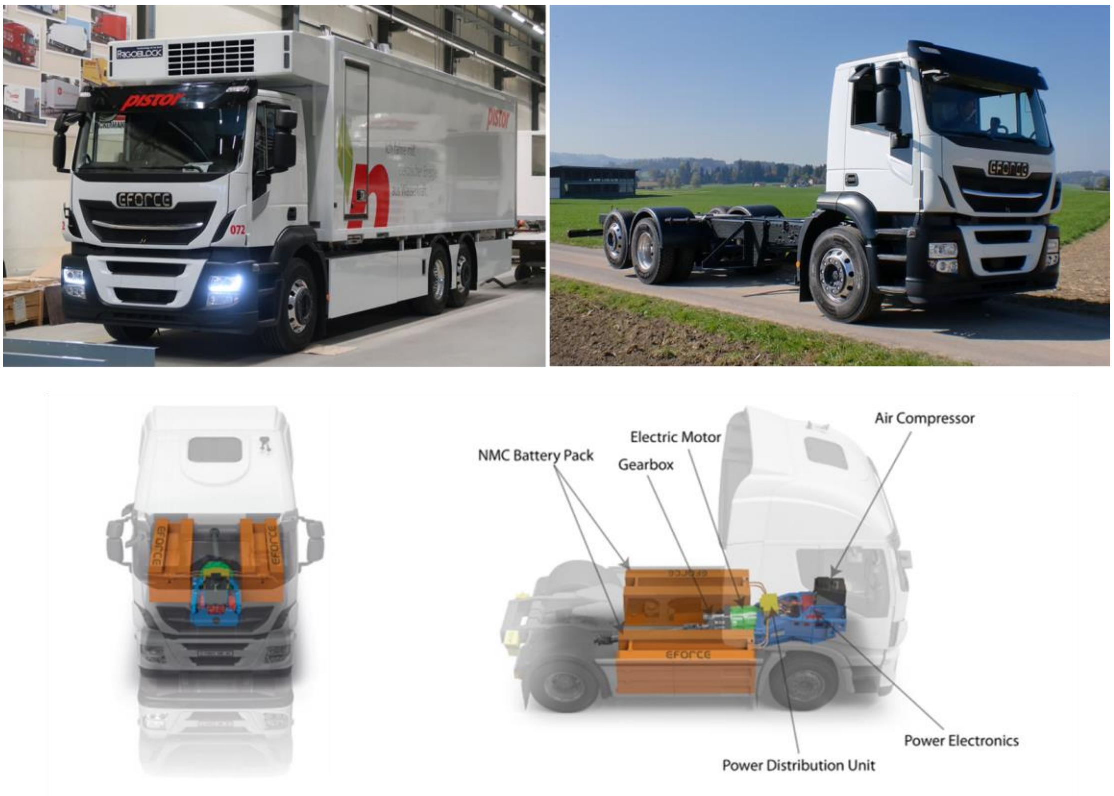


Figure 92. E-Force 18-44t eLkw (EForce) [228][229]

17.1.9 Einride

Einride (alternatively E/NRIDE), is a Swedish start-up with a fully autonomous T/Pod driverless cargo carrier that has relevance to North American technology development. The company's website states a range of 125 miles (200 km) with a 200 kWh battery pack and GVW of up to 26 tons fully loaded [230]. The vehicle was shown in North America at the Detroit Auto Show in 2018 [231].

Figure 93. E/NRIDE T/Pod Fully Autonomous CBEV (Einride) [230]

17.1.10 Ford

Ford's Qualified Vehicle Modifier (QVM) program includes electric vehicles (eQVM). In 2017 a Ford press releases discussed using three developers, XL Hybrids, Motiv Power Systems and Lightning Hybrids (now LightningElectric) [232]. The eQVM developers take production Ford chassis systems and modify them for electric or hybrid drives. Ford does not yet produce its own electric vehicles, but benefits from these technology partnerships and fielded vehicle experience [201].

17.1.11 Isuzu

Isuzu began announcing an electrified Class 4 cab based on the NPR-HD in 2017 and showed a prototype at the 2018 Work Truck Show [240]. The company teamed with Nordresa in Quebec, Canada to modify the N-Series truck for electrification [240]. Two other prototypes based on an NQR and an FWR were shown in Australia. Those two had energy storage ranging from 100 kWh to 135 kWh [242].

Figure 94. Isuzu Prototype Electric NPR-HD (Isuzu) [241]

17.1.12 Lightning Systems

Lightning Systems produces alternative drive train vehicles including buses, vans and trucks. The business model adapts a production chassis available from Ford, Chevrolet or potentially others. End products are finalized with a body builder such as Morgan.

17.1.12.1 Lightning Systems - Ford Based

Lightning offers the Class 6 LEV100 low cab forward product specifications with a stated 110 mile range, with 160 kWh battery capacity and a charging time of 20 hours (level 2) or 3-4 hours (DC fast charging). The Lightning E-450 has a GVWR of 14,500 lbs., an electric range of 100 miles with 128 kWh battery capacity and charges in 15.5 hours (Level 2) or 2 hours (DC fast charging). The Ford Transit LEV chassis has a GVWR of 10,360 lbs., and three battery pack configurations giving ranges of 50 miles (32 kWh), 100 miles (64 kWh), and 150 miles (96 kWh). Charge time for the 32 kWh pack is 4.5 hours (level 2) or 33 minutes (DC fast charge). The 64 kWh pack charge time is 9 hours (level 2) or 1 hours (DC fast charge). The 96 kWh pack charges in 13 hours (level 2) or 2 hours (DC fast charge). The Ford Transit HD Cargo Van has a GVWR of 10,360 lbs. and three battery pack ranges 50 miles (67 kWh), 100 miles (64 kWh) and 150 miles (96 kWh) with similar charge times to the Transit LEV Chassis [233].

Figure 95. LightningElectric Electric Trucks (LE) [233]

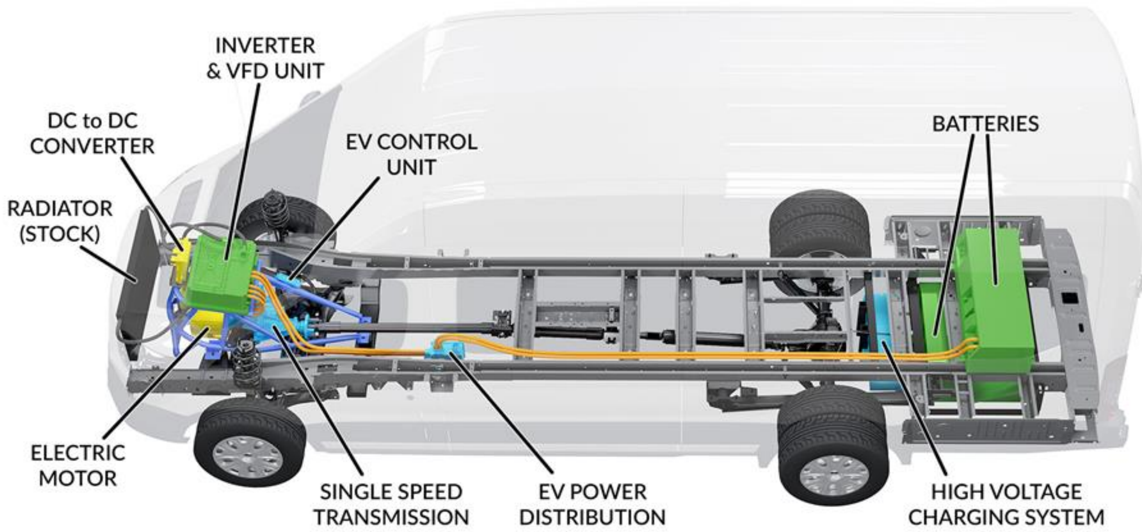


Figure 96. LightningElectric Transit 350 Cutaway View (LE) [233]

Various media outlets reported in April 2018 that, "the Ford Transit 350HD equipped with the zero-emissions LightningElectric drivetrain achieved 61 MPGe on EPA City routes and 66 MPGe on EPA Highway routes, compared to 13 and 15 MPG respectively for the identically configured gasoline Ford Transit 350HD, according to the company [234][235]." Details of the duty cycle and operating period were not included in discussing this over 4:1 performance ratio. A *Green Fleet* article stated that, "In the United States, the electric-vehicle conversion is $69,000 for vehicles with an electric range of 50 miles and $89,000 for vehicles with a range of 100 miles [236]."

17.1.12.2 Lightning Systems - Chevrolet Based

Lightning systems teamed with Zeem to produce the first Chevrolet based Class 6 electric truck announced in August of 2018. "The new Lightning powertrain, which provides 295 horsepower and up to 110 miles of range per charge, will be fitted into the Chevrolet 6500XD Low Cab Forward chassis [293]."

Figure 97. Chevrolet Class 6 Electric Truck (Lightning Systems) [293]

17.1.13 Lion Electric Co.

Lion Electric has been a bus maker in Quebec, Canada, but announced in 2018 they were expanding into manufacturing a full line of electric trucks [243]. There initial entry is a Class 8 product named Lion8 but they have shown medium-duty concepts as well [244]. The specifications include up to 480 kWh battery capacity, but does not specify ranges. Charging is an on-board 19.2 kW J1772 charger and there is capability for DC fast charging with the SAE Combo plug.

Figure 98. Lion Electric Class 8 Truck and Possible Medium-duty Trucks (Lion) [244][243]

17.1.14 MAN

MAN introduced, at the 2018 Hanover International Automobile Exhibition (IAA), the eTGE electric panel van based on their TGE Panel Van platform which MAN's website states has a total weight up to 5.5 tonnes (12,125lb) [314]. The eTGE is reportedly going into series production produced in Poland with deliveries possibly in 2018. The eTGE has a 36 kWh battery capacity that weighs approximately 340 kg, and provides a range up to 173 kM using the New European Driving Cycle (NEDC) [314]. MAN also has the CitE, a 15 tonne (33,000 lb) electric concept. Nora Manthy reported in Electrive.com that "the CitE, …which was developed in just 18 months, was designed for inner cities and has a range of 100 km. The low entry height and especially wide doors allow for easy access in crowded conditions [313]." A third electric truck discussed was the eTGM, a 26 tonne (57.300 lb) vehicle. While the CitE and the eTGM have GVWR's greater than U.S. Class 3-6, the eTGE panel van would be a Class 3. These products are not for North American use, but the rapid development and testing of these vehicles for the European may have relevance to North American product development.

Figure 99. eTGE, eTGM and CitE Trucks (MAN)[313][314]

17.1.15 Mitsubishi Fuso

Mitsubishi Fuso announced in 2017 that they would have the electric eCanter in use in the U.S. in mid-2018. These 500 initial trucks are being used world-wide with fleets on a temporary basis to collect field experience. The trucks are on a two-year lease and will be returned to Mitsubishi Fuso engineering for analysis. Fuso's website states, "Large scale production is intended to start in 2019 [245]." Service personnel, spares and service equipment have been located in the urban areas where these test fleets are being operated. These initial eCanter vehicles have a GVWR of 15,995 lbs. and are estimated to have a range of 62 miles (100 km) using six lithium-ion liquid-cooled battery packs each at 13.8 kWh for a total of 82.8 kWh [245][246]. NACFE did a specification comparison in its Guidance Report: Electric Trucks – Where They Make Sense in May 2018 comparing the eCanter to its comparable FE180 Diesel from the same manufacturer and it is provided again here [1].

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 100. Diesel and Battery Electric Comparison (from Mitsubishi Fuso data) [1]

Figure 101. Mitsubishi Fuso eCanter (MFTBC) [246]

17.1.16 Motiv

Motiv produces battery electric drive train chassis based on Ford production chassis systems under the product name Electric Powered Intelligent Chassis (EPIC). They partner with body builders to produce a variety of trucks. Motiv maintains ownership of any emissions credits. The business model has Motiv delivery kits to upfitters to modify the Ford chassis, then the vehicle goes on to a body builder to complete the vehicle as shown in Figure 102 [237][238]. Motiv chassis are used in box trucks, walk-in vans, work trucks, buses and specialty vehicles [237].

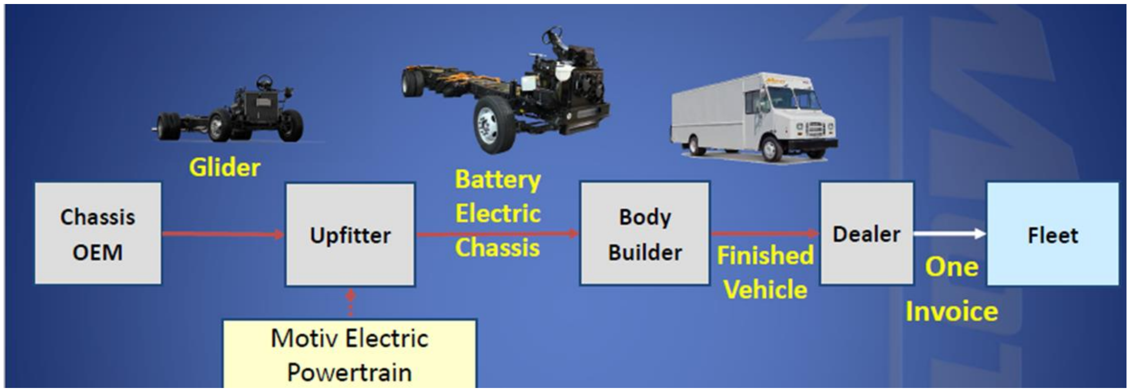


Figure 102. Motiv Business Model (Motiv) [238]

Motiv offers three variations, EPIC 4, EPIC 5 and EPIC 6. The EPIC 4 is based on the Ford E-450 chassis with a GVWR of 14,500 lbs. It has three battery pack options 85 kWh, 106 kWh and 127 kWh giving it an estimated range of up to 90 miles and 100% recharge time of 8 hours. Recharge time for 75% charge is 4 hours, and 50% charge is 2 hours [239]. The Epic 5 is based on the Ford F-59 chassis with a GVWR of 22,000 lbs. The EPIC 6 is similarly based but with GVWR of 26,000 lbs. It has two battery pack options of 106 kWh and 127 kWh again with range up to 90 miles and the same charge times as with the EPIC4. Charging is stated as 208V, 25 kW [239].

Figure 103. Motiv EPIC Chassis Offerings (Motiv) [237]

Figure 104. Example of Motiv EPIC Based Vehicles (Motiv) [239]

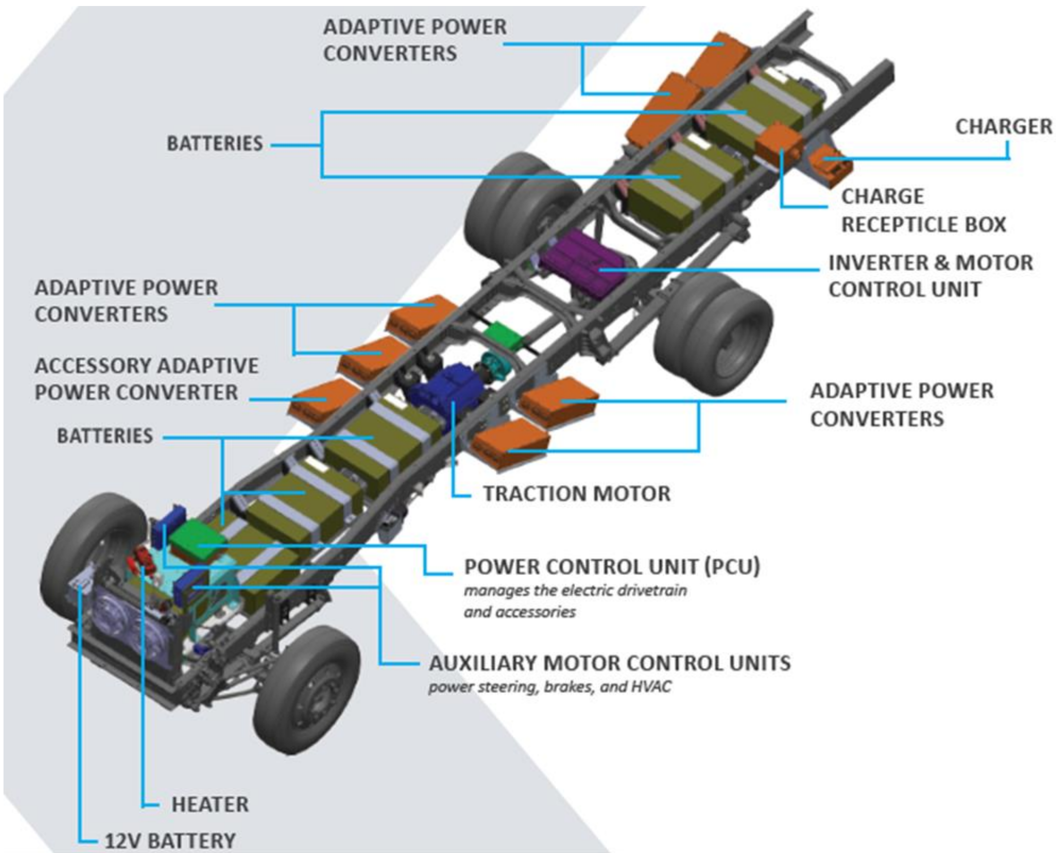


Figure 105. Typical Motiv Class 6 Chassis Details (Motiv) [239]

17.1.17 Renault

Renault announced a new line of electric trucks in June of 2018 but the offerings do not appear to fit the U.S. definition of medium-duty [247]. The Master Z.E. has a GVW of 6,800 lbs. (3.1t) using a 33 kWh capacity battery pack with an operating range on NEDC cycle of 124 miles (200 km). The Renault D Z.E. with a GVWR of 36,000 lbs. (16.7t) uses a 200-300 kWh lithium-ion battery with a range up to 186 miles (300 km). The Renault D Wide Z.E. has a GVWR of 59,500 lbs. (27t) and uses a 200 kWh battery for a range of up to 124 miles (200 km) [248][249]. Renault has been experimenting with electric trucks for a decade [248][249]. Manufacturing is to start in 2019 in France. The technology and urban operating experience may be relevant to the North American market.

Figure 106. Renault Electric Trucks (Renault) [248]

17.1.18 Thor

Thor is a new startup capturing headlines and investment for its Class 8 electric vehicle. In August 2018 it announced plans to build a Class 6 electric truck for UPS with a 100 mile range powered by a Thor designed battery pack that can be charged in 1 hour [250][251]. Thor indicates the platform can have a 200+ mile range on one charge [252]. The bodies are by Morgan. Vehicles are expected to be in testing in Los Angeles in late 2018 [253].

Figure 107. Thor Class 6 Electric Truck (Thor) [252]

17.1.19 Volkswagen (Traton)

Volkswagen announced in 2017 a $1.7B investment to bring electric trucks and buses to the market [254]. An initial offering is the e-Delivery with a 179kWh battery pack providing an estimated range of 124 miles (200 km). The vehicle is made in Brazil. The first major customer, Ambev, said that the vehicle likely "is sufficient for a vast number of its delivery routes and ordered 1,600 electric trucks to convert one-third of its delivery fleet by 2023 [254]." The pilot vehicles will be delivered in late 2018 with production starting in 2020 and the full 1,600 vehicles delivered by 2023. AMbev said, "About 35% of the fleet serving the brewery will consist of clean energy-powered vehicles [255].” VW did not state the availability of this model for North America.

Figure 108. Volkswagen e-Delivery (VW) [254]

Volkswagen also is producing the e-Crafter, reported by Mark Kane in 2016 InsideEVs article, a panel van with a planned 43 kWh battery pack and estimated range of 208 km (129 mi), but speed limited to 80 km/h (50 mph) [315]. A September 2018 article by Domenick Yoney for InsideEVs states that about 40 have been put in service in Europe, and updates the specifications with a city range of about 107 miles, computer-limited top speed of 56 mph, a 3.5-tonne (7,716 lb) and a 35-kWh battery pack [316]. Yoney states pricing in England is $81,420 versus the ICE version at $48,019. These two Volkswagen products are under the new Traton corporate organization [317]. This product is not stated as intended for North America, but experience in actual fleet use may be pertinent to North American product development.

Figure 109. e-Crafter (Volkswagen) [315]

17.1.20 Volvo FL

Volvo introduced a Class 7 FL Electric in April 2018 for testing in Europe. *Transport Topics’* Seth Clevenger cited Volvo stating the vehicle can be equipped for different ranges with 50 kWh lithium-ion battery packs each weighing 1,146 lbs. [256]. “With the full complement of six batteries, the FL Electric will offer a maximum range of up to 186 miles in ideal conditions, while the FE will offer a range of up to 125 miles.” Simulation testing suggests the batteries will last for the life of the truck. The truck is equipped with a two-speed Volvo transmission and an electric driveline as shown in Figure 110. The vehicle can recharge overnight or in 1.5 hours with fast charging [256]. Volvo has also announced plans for an FE based electric platform and has shown prototypes [258]. These vehicles are not yet planned for the North American market. However, the technology and field experience are relevant to the North American market.

Figure 110. Volvo Electric FL with Electric Driveline (Seth Clevenger) [256]

17.1.21 Workhorse

Workhorse dates to 2007 under the name AMP Electric Vehicles. They were contracted under a development agreement with Navistar and delivered a prototype in 2012 of a 1,000 cubic foot delivery van. Management and priority changes at Navistar at that time put the project on hold. AMP began working directly with an end customer and completed a 4,000-mile durability test. AMP absorbed the Workhorse brand and custom chassis plant in 2015 with the capability to build Class 4 through Class 6 trucks, and changed their name to Workhorse [259].

The Workhorse E-100 is an all-electric Class 6 delivery van with a 123 kWh battery pack and GVWRs of 14,500, 19,500 and 23,500 lbs. The vehicles have ranges up to 100 miles. They are equipped for J1772 Level 2 charging with an onboard 22 kW charger, and are capable of DC fast charging. The batteries are provided by Panasonic and carry an eight-year warranty. The body comes from Morgan Olson. Service is provided through a Ryder's national network [259].

Figure 111. Workhorse E-100 (Workhorse) [259]

Workhorse also has developed the N-GEN 450 and N-GEN 1000 delivery vans. The N-GEN 450 has a GVWR of 10,001 lbs. with an estimated electric range of 100 miles. The N-GEN 1000 has a GVWR of 14,500 lbs. and also an estimated range of 100 miles. Specifications on the battery packs is not apparent on the Workhorse website or in media releases, but InsideEVs' Mark Kane reported the battery pack is 60 kWh in the smaller Workhorse test vehicle [261]. Workhorse asserts they have demonstrated a 50 MPGe for the N-GEN 450 and N-GEN 1000 platforms [259]. In July 2018, *CCJ's* Jason Cannon reported a 200 cubic foot version as achieving 75 MPGe [260]. The details on the specific duty cycles and evaluation methods are not discussed. The manufacturer is optimizing the production design and the production line around specific configurations in order to obtain economies of scale, with a goal of producing 2,000 units in 2018 [261][262].

Workhorse has also manufactured range extended E-GEN vehicles that include gasoline engines with battery packs [262].

Figure 112. Workhorse N-GEN Configurations (UPS & Workhorse) [259]

17.1.22 Wrightspeed

Wrightspeed is a startup manufacturing range extended vehicles with electric powertrains paired with an onboard turbine generator to reduce range anxiety issues. The Route 250 has a GVWR of 16,000 lbs. for Class 3 and 4 use, with a pure electric range of 20 miles and unlimited range with refueling for the turbine generator. The generator can burn diesel, CNG, LNG, gasoline and biogas. Wrightspeed estimates the MPGe at 17.9 [263].

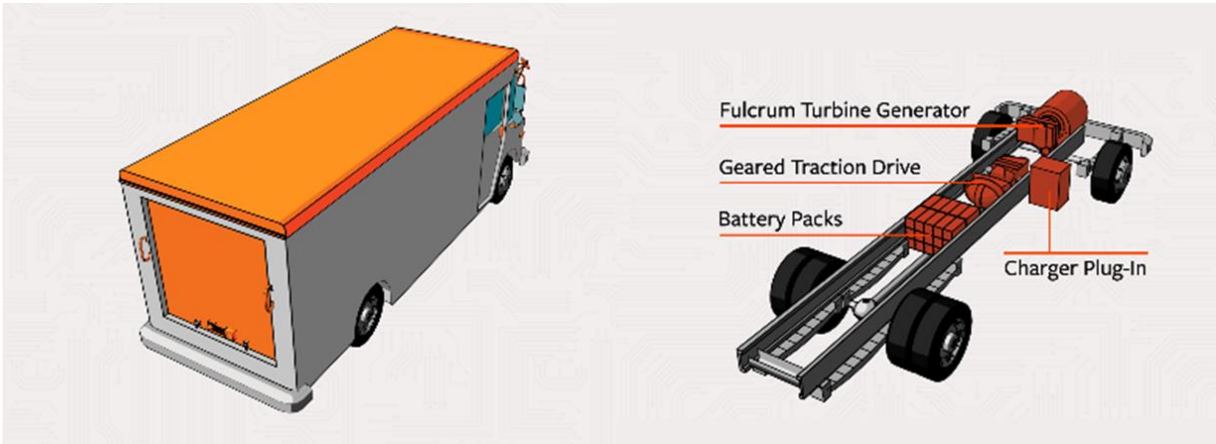


Figure 113. Wrightspeed Route 250 (Wrightspeed) [263]

17.1.23 XING Mobility

In May 2018, XING Mobility showed a prototype 3.5-ton light truck which has an innovative stacking battery pack system [264][265][266]. While this is outside the medium-duty definition for this report, the technology may be relevant to North American product development.

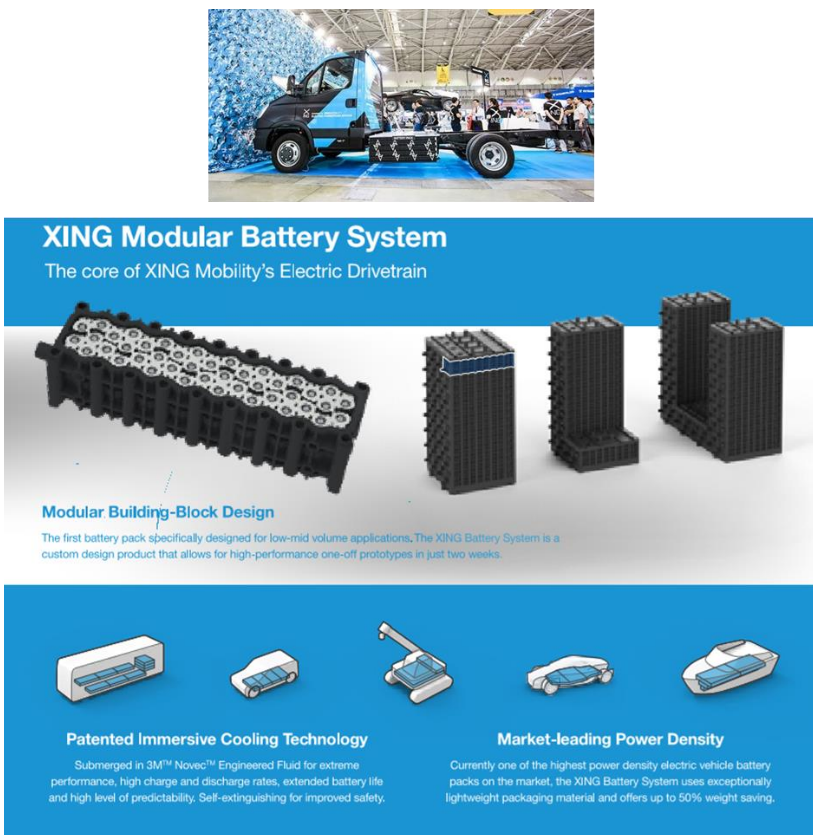


Figure 114. XING Mobility Modular Battery Concept and Prototype (XING) [266]

17.1.24 Zeem Solutions

Zeem Solutions is a company with a mission to provide “turnkey solution for fleet owners looking to buy an electric truck or bus [294].” They teamed with Lightning Systems to produce the first Chevrolet based Class 6 electric truck announced in August of 2018 [293]. While not strictly a vehicle OEM, this team highlights a growing opportunity for start-ups to innovate vehicle production, energy infrastructure, service and maintenance outside the realm of established vehicle OEMs.

18 Appendix B - Charging Infrastructure Suppliers

A growing list of twenty-seven potential charging system suppliers updated in January 2018 titled Electric Vehicle Charger Selection Guide is available from the Energy Efficiency Coordinator (EEC) website [289][290]. NACFE is in the process of developing a detailed Guidance Report on Commercial Vehicle Charging Infrastructure to be published in the spring of 2019. The following suppliers have been identified as relevant to past and present commercial truck applications, so are singled out here for additional discussion regarding their electric vehicle supply equipment (EVSE). However, as the EEC document shows, there are a considerable number of competing offerings that may be applicable to trucks due to commonality in connectors and charging levels.

18.1 ABB

ABB offers HVC-overnight charging products capable of charging larger fleets of electric buses and trucks during the night. This EVSE solution is scalable and can help enable smaller and cheaper grid connections. The chargers also offer remote diagnostics and management through ABB Ability. These chargers are compliant with CCS and OCPP standards and have a flexible design to allow for roof and floor mounting. ABB has years of experience in creating, installing and maintaining charging infrastructure, including several nationwide charger networks [278].

18.2 ChargePoint

ChargePoint began by focusing on the light-duty passenger vehicle market and has made a name for themselves as one of the most popular EVSE suppliers, with a built-out nationwide network of electric car chargers. They have recently broadened their scope to include charging solutions for medium- and heavy-duty fleets as well. ChargePoint stations include 24/7 driver support, cloud-based software with features and plans specific to various industries, and service and maintenance. ChargePoint's team is able to work with customers to help them through the entire infrastructure process, including engaging their utility company and determining whether Level 2 or DC fast charging makes the most sense for their fleet. ChargePoint offers an entire range of solutions. All of their chargers are UL listed and some are ENERGY STAR® certified. Their DC fast chargers all use CHAdeMO connections and are available with CCS1 (SAE J1772™ Combo) and CCS2 (IEC 61851-23) connectors. Their DC ultra-fast charging solution is modular and easily scalable so that it can grow with demand and accommodate the battery technologies of today's and tomorrow's CBEVs [279].

18.3 Chateau Energy Solutions

Chateau Energy Solutions provides customized, turnkey electric vehicle infrastructure charging solutions for commercial, military, federal fleets, as well as state and local municipalities. This includes the design, installation, project management, and maintenance services of electric vehicle charging stations, also known as EVSE. Their EV experts will provide strategic insight into how the additional load will impact your facility and how to best integrate into your system. In addition to EV infrastructure deployment, Chateau also offers EVSE maintenance as well as EV controls, metering integration, and analytics [280].

18.4 ClipperCreek

ClipperCreek chargers are popular for residential and workplace charging, but they also offer commercial charging stations for fleets at a variety of power levels. Their stations are capable of electrical load management, and optional data tracking is available [281].

18.5 Eaton

Eaton used to supply both Level 2 and DCFC stations, however in 2015 they announced they would focus on producing other components for CBEVs. That said there are still Eaton chargers available in the marketplace [282]. Their Pow-R-Stations and other charging products may still be available in the market or encountered in the field.

18.6 EV Connect

EV Connect offers scalable, flexible, and comprehensive industry-specific solutions for EV charging, including charge stations, software, and 24/7 support [283].

18.7 EVgo

In addition to owning, operating, and maintaining the largest public fast charging network, EVgo builds dedicated EV fast charging stations for their fleet partners. They handle the entire process, from site acquisition, construction, procurement, network management, and customer service [284].

18.8 GE

ChargePoint acquired GE's EV charging network in June 2017 with support for GE's Durastation and Wattstation chargers. These devices may still be available on the open market under the GE brand and may be encountered in the field [285].

18.9 Rhombus Energy Solutions

Rhombus Energy Solutions' charging station portfolio has thus far been focused on electric bus charging (they supply chargers for Proterra), but their chargers are capable of charging electric trucks as well. Rhombus' chargers are smart grid ready, offering bi-directional power flow for future vehicle-to-grid (V2G) capability and meet UL requirement 1741 SA. They utilize a standard J1772-CCS plug-in system [286].

18.10 Siemens

Siemens supplies electric vehicle charging stations for municipalities, corporations, fleets and utilities. Their VersiCharge line of Level 2 chargers use an SAE J1772 connector [287].

18.11 Tritium

Australian-based company, Tritium offers award-winning DC fast charging stations and has partnered with ChargePoint to install these Veefil stations across the U.S. The fast charging stations are able to charge all vehicles equipped for DC fast charging, using the included SAE-Combo connector or a CHAdeMO connector [288].

19 Appendix C - Diesel Product Baselines

Baseline diesel and gasoline medium duty trucks for the North American market are produced by a wide range of manufacturers with a number of body builders. Estimates for box and step van production in the U.S. is 100,000 vehicles per year, while medium duty in general is estimated at 400,000 to 500,000 vehicles per year.

- Chevrolet
- Daimler
- Dodge
- Ford
- Freightliner
- GMC
- Mitsubishi Fuso
- Hino
- Hyundai
- Isuzu
- Kenworth
- Navistar
- Nissan
- Peterbilt
- UD

Figure 115 Medium Duty Baselines (Connor Mihelic) [200]

Figure 116. Medium Duty Baselines (Chevrolet, Kenworth, FCAUSFleet, Peterbilt, Daimler, UD) [207][273]274][275][276][277][295]

20 APPENDIX D. CALCULATORS

NACFE is providing in this report background on a select sampling of calculators that illustrate a range of uses and approaches to assisting fleets in decision making on battery electric technology investment. NACFE is providing its own downloadable calculator based on the research NACFE has done in preparing this report and the prior Guidance Report: Electric Trucks – Where They Make Sense [1]. The calculator is available at www.NACFE.org.

There are TCO, fuel use and emissions calculators available from private companies and organizations, for example, Fleet Advantage's Advanced Truck Lifecycle Analytics and Administrative Software (ATLAAS) [142]. Another is available from Vincentric [188]. These commercial or proprietary tools may be of use to fleets. NACFE is not discussing these in this report as they may involve proprietary data sources, proprietary methods or require working through sales offices for access.

20.1 CARB

The California Air Resources Board (CARB) Fleet Calculator is "an Excel spreadsheet created to assist fleet owners in evaluating various compliance strategies to comply with the truck and bus regulation. It allows the user to input the engine model year, and emission control technology assumptions to determine what compliance options may be available to comply with the regulation for each calendar year [122]." The tool is not suited for comparison of diesel to electric vehicles.

20.2 EPA GREENHOUSE GAS EQUIVALENCIES CALCULATOR

The EPA's Greenhouse Gas Equivalencies Calculator has a simple one-field entry to convert kilowatt-hours of electricity into carbon dioxide equivalents with a range of comparisons as shown in Figure 117.

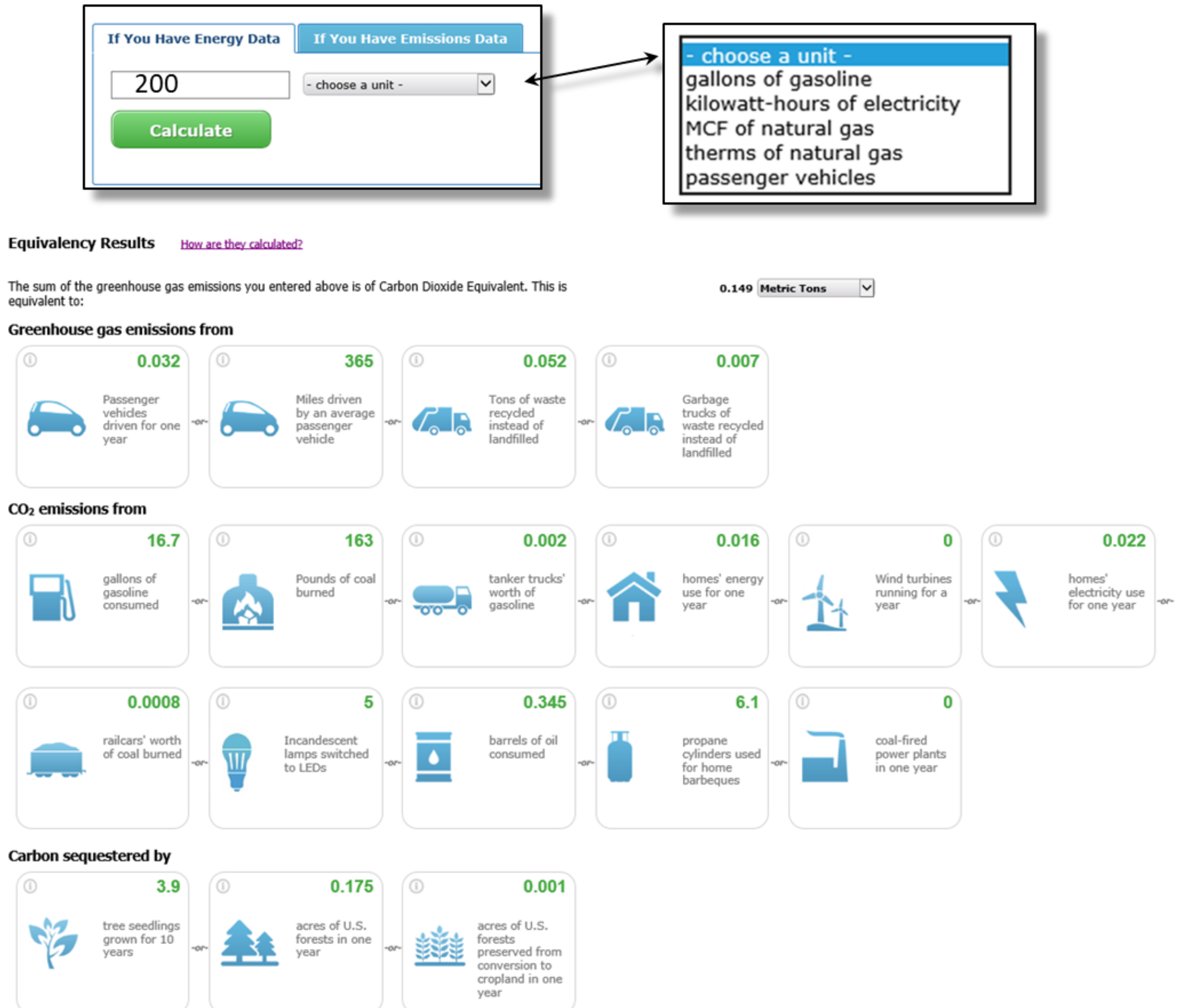


Figure 117. U.S. EPA Emissions Equivalency Calculator (EPA) [123]

NACFE found that a common question was what does a kWh of energy mean in terms of other metrics. This tool and more importantly, the reference material cited by EPA on how calculations are made can help with understanding conversions for emissions factors. Unfortunately, the tool does not yet include diesel fuel as an input. A second tab also allows inputting for reverse calculations where the emission values are known.

20.3 BSR Fuel Sustainability Tool

BSR is a global non-profit organization with a focus on building a just and sustainable world. Their Future of Fuels initiative produced and maintains Fuel Sustainability Tool (Fuel Tool). The tool "allows decision-makers to compare fuel pathways within types of fuels used in medium- and heavy-duty trucks in North America. These fuels include diesel, biofuels, natural gas, electricity and hydrogen, as well as options within fuel types that decision-makers can take to engage suppliers and improve impacts [124]." BSR provides granularity in energy pricing by dividing electricity into the U.S. grid regions and providing the regional diesel pricing as shown in Figure 118.

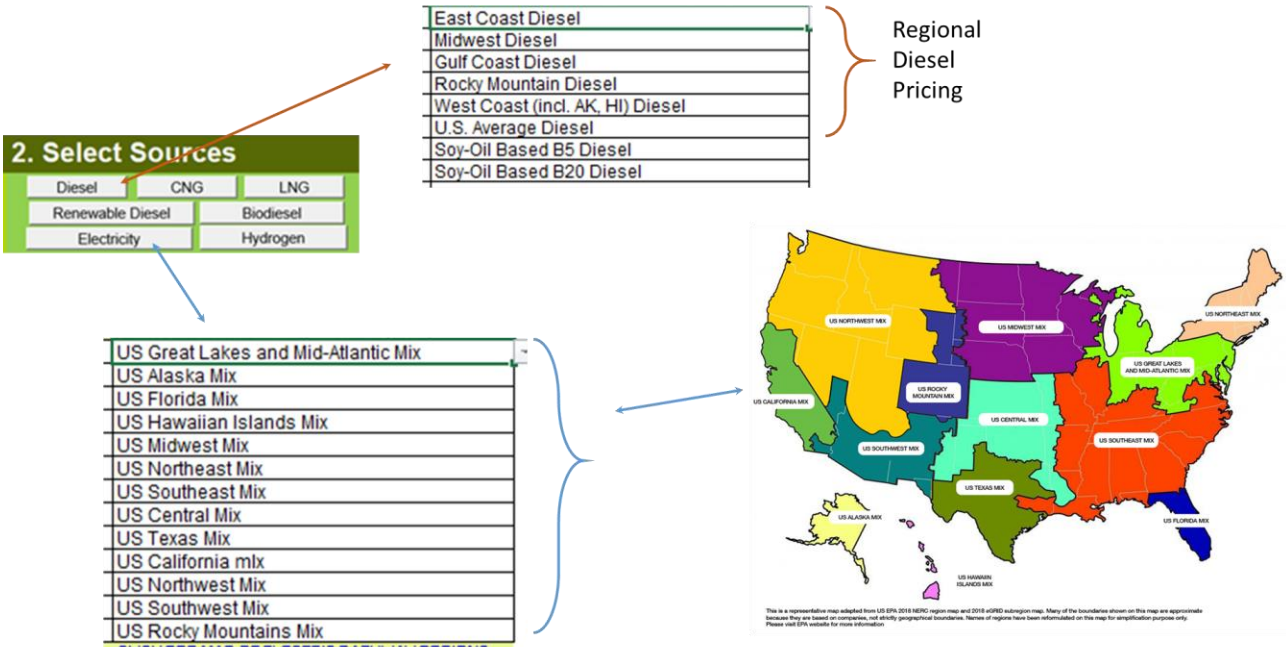


Figure 118. BSR Future of Fuels Tool (BSR) [124]

The BSR Fuel Tool has simple inputs for miles driven and users can override default average MPGs as shown in Figure 119. The background on calculations is well documented in the tool and in a companion guide. The tool is the result of BSR consulting with a broad group of industry and government groups. Results are graphical side-by-side comparisons of the chosen energy (fuel) types and presented in two graphs of well-to-wheel (WTW) Estimated Per-Mile Emissions and Average Diesel Gallon Equivalent (DGE) Emissions segmented into the well-to-pump (WTP) and pump-to-wheel (PTW) portions. The data is also conveniently rank ordered (Pareto format). The power of this tool is it allows for equivalent cross comparison between fuel types and breaks emissions down into well-to-pump and well-to-wheel components. NACFE discovered that fleets and OEMs want access to this differentiation.

Instructions

Add estimate of miles or adjust vehicle efficiency to customize results to specific fleet characteristics, vehicle technologies, and duty cycles.

Add Miles	Adjust Vehicle Efficiency (Optional)		
Estimated Miles	**Average Engine Efficiency**		
Miles per Fuel Type	Engine Type	MPDGE Default	Adjust MPG
	Diesel Engine	7.3	
	Biodiesel	7.3	
	CNG	6.6	
	LNG	6.9	
	Electricity	29.2	
	Hydrogen	13.9	

Figure 119. BSR Fuel Tool Inputs (BSR) [124]

The background calculations and references are well documented. The tool is a common Excel format. The tool is focused on emissions comparisons so there are no financial TCO evaluations.

20.4 Argonne National Laboratory GREET

The Argonne National Laboratory GREET calculator (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) was developed to help fleet managers determine well-to-wheel petroleum use and greenhouse gas emissions. The tool included use for Clean Cities Program stakeholders to estimate values [125]. The tool began as a downloadable Excel spreadsheet, which is still available for use. The latest iteration is an online application titled GREET.NET.

20.4.1 GREET 2012 EXCEL Version

The Excel spreadsheet version of GREET allows the user to enter data on an entire mixed fleet of vocations and technologies to determine the net impact of the fleet on petroleum use and GHG emissions [125]. Users populate five tables of information about their fleets as seen in Figure 120:

- Number of vehicles by vocation and type of fuel (energy)
- Average annual miles travelled for each
- Average fuel economy (in miles per gasoline gallon equivalent)
- Annual total fuel (energy) used in the appropriate units of measure
- Fuel production sourcing assumptions

The results are conveniently tabulated, as shown in Figure 121, for On-Road Petroleum Usage (barrels) and then Greenhouse Gas Emissions (short tons CO2-equivalent). The results are presented for each vocation and fuel type, and also the net fleet values in each vocation.

On-Road Fleet Petroleum Use and GHG Footprint

1. Method to Calculate On-Road Fleet's Petroleum Energy Use and GHG Footprint

1	1 - Fleet size, vehicle miles traveled, and fuel economy
	2 - Fuel use (skip to question 5)

2. The Number of Each Type of Vehicle in On-Road Fleet

	Gasoline	Diesel	Diesel HEV	Biodiesel (B20)	Biodiesel (B100)	Ethanol (E85)	Compressed Natural Gas (CNG)	Liquefied Natural Gas (LNG)	Liquefied Petroleum Gas/ Propane (LPG)	Electricity	Gaseous Hydrogen (G.H2)	Liquid Hydrogen (L.H2)
School Bus	0	0	0	0	0	0	0	0	0	0	0	0
Transit Bus	0	0	0	0	0	0	0	0	0	0	0	0
Shuttle/Paratransit Bus	0	0	0	0	0	0	0	0	0	0	0	0
Waste Hauler	0	0	0	0	0	0	0	0	0	0	0	0
Street Sweeper	0	0	0	0	0	0	0	0	0	0	0	0
Delivery Step Van	0	0	0	0	0	0	0	0	0	0	0	0
Transport/Freight Truck	0	0	0	0	0	0	0	0	0	0	0	0
Medium/Heavy Duty Pickup Truck	0	0	0	0	0	0	0	0	0	0	0	0
Maintenance Utility Vehicle	0	0	0	0	0	0	0	0	0	0	0	0
Other	0	0	0	0	0	0	0	0	0	0	0	0

3. The Average Annual Vehicle Miles Traveled by Each Vehicle Type

	Gasoline	Diesel	Diesel HEV	B20	B100	E85	CNG	LNG	LPG	Electricity	G.H2	L.H2
School Bus	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000	12,000
Transit Bus	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000
Shuttle/Paratransit Bus	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000
Waste Hauler	23,400	23,400	23,400	23,400	23,400	23,400	23,400	23,400	23,400	23,400	23,400	23,400
Street Sweeper	12,600	12,600	12,600	12,600	12,600	12,600	12,600	12,600	12,600	12,600	12,600	12,600
Delivery Step Van	16,500	16,500	16,500	16,500	16,500	16,500	16,500	16,500	16,500	16,500	16,500	16,500
Transport/Freight Truck	80,000	80,000	80,000	80,000	80,000	80,000	80,000	80,000	80,000	80,000	80,000	80,000
Medium/Heavy Duty Pickup Truck	11,400	11,400	11,400	11,400	11,400	11,400	11,400	11,400	11,400	11,400	11,400	11,400
Maintenance Utility Vehicle	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
Other	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000	30,000

4. The Average Fuel Economy for Each Vehicle Type in the On-Road Fleet (miles per gasoline gallon equivalent)

	Gasoline	Diesel	Diesel HEV	B20	B100	E85	CNG	LNG	LPG	Electricity	G.H2	L.H2
School Bus	6.0	7.0	8.5	7.0	7.0	6.0	6.0	6.0	6.0	20.5	12.0	12.0
Transit Bus	2.5	3.0	3.8	3.0	3.0	2.5	2.5	2.5	2.5	8.5	5.0	5.0
Shuttle/Paratransit Bus	7.0	8.0	10.0	8.0	8.0	7.0	7.0	7.0	7.0	24.0	14.0	14.0
Waste Hauler	2.0	2.5	3.0	2.5	2.5	2.0	2.0	2.0	2.0	7.0	4.0	4.0
Street Sweeper	3.0	4.0	5.0	4.0	4.0	3.0	3.0	3.0	3.0	10.0	6.0	6.0
Delivery Step Van	12.0	15.0	18.5	15.0	15.0	12.0	12.0	12.0	12.0	41.0	24.0	24.0
Transport/Freight Truck	5.0	6.0	7.5	6.0	6.0	5.0	5.0	5.0	5.0	17.0	10.0	10.0
Medium/Heavy Duty Pickup Truck	9.0	11.0	13.5	11.0	11.0	9.0	9.0	9.0	9.0	31.0	18.0	18.0
Maintenance Utility Vehicle	20.0	25.0	31.0	25.0	25.0	20.0	20.0	20.0	20.0	68.0	40.0	40.0
Other	2.5	3.0	3.8	3.0	3.0	2.5	2.5	2.5	2.5	8.5	5.0	5.0

5. The Annual Total Fuel Use by On-Road Fleet Vehicles (gallons, cubic feet, or kilowatt-hours)

	Gasoline (gallons)	Diesel (gallons)	Diesel HEV (gallons)	B20 (gallons)	B100 (gallons)	E85 (gallons)	CNG (cubic feet)	LNG (gallons)	LPG (gallons)	Electricity (kilowatt-hours)	G.H2 (cubic feet)	L.H2 (gallons)
School Bus	0	0	0	0	0	0	0	0	0	0	0	0
Transit Bus	0	0	0	0	0	0	0	0	0	0	0	0
Shuttle/Paratransit Bus	0	0	0	0	0	0	0	0	0	0	0	0
Waste Hauler	0	0	0	0	0	0	0	0	0	0	0	0
Street Sweeper	0	0	0	0	0	0	0	0	0	0	0	0
Delivery Step Van	0	0	0	0	0	0	0	0	0	0	0	0
Transport/Drayage/Freight Truck	0	0	0	0	0	0	0	0	0	0	0	0
Medium/Heavy Duty Pickup Truck	0	0	0	0	0	0	0	0	0	0	0	0
Maintenance Utility Vehicle	0	0	0	0	0	0	0	0	0	0	0	0
Other	0	0	0	0	0	0	0	0	0	0	0	0
Gasoline Gallon Equivalent Total	0	0	0	0	0	0	0	0	0	0	0	0

6. Fuel Production Assumptions

Biodiesel Feedstock Source	1	1 - Soy 2 - Algae
Ethanol Feedstock Source	1	1 - Corn 2 - Switchgrass
CNG Feedstock Source	1	1 - North American NG 2 - Non-North American NG 3 - Landfill Gas
LNG Feedstock Source	1	1 - North American NG 2 - Non-North American NG 3 - Landfill Gas
North American NG Feedstock So	Conventional 77%	Shale 23%
LPG Feedstock Source	NG 60%	Petroleum 40%
Source of Electricity for On-Road Electric Vehicles and H2 Electrolysis	14	1 to 13 - EIA Regions 1 through 13 Mix (see map) 14 - Average U.S. Mix 15 - User Defined (go to 'Specs' sheet)
G.H2 Production Process	1	1 - Refueling Station SMR (On-site) 2 - Central Plant SMR (Off-site) 3 - Refueling Station Electrolysis (On-site)
L.H2 Production Process	1	1 - Refueling Station SMR (On-site) 2 - Central Plant SMR (Off-site) 3 - Refueling Station Electrolysis (On-site)

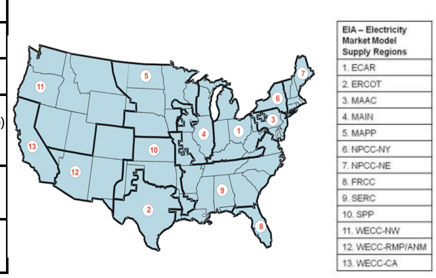


Figure 120. ANL GREET Excel Based Calculator (ANL) [125]

7. Results of On-Road Fleet's Petroleum Usage (barrels)

	Gasoline	Diesel	Diesel HEV	B20	B100	E85	CNG	LNG	LPG	Electricity	G.H2	L.H2	Vehicle Total
School Bus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Transit Bus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Shuttle/Paratransit Bus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Waste Hauler	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Street Sweeper	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Delivery Step Van	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Transport/Freight Truck	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Medium/Heavy Duty Pickup Truck	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maintenance Utility Vehicle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fuel Total	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

On-Road Fleet Total **0.0 barrels of oil**

8. Results of On-Road Fleet's Greenhouse Gas Emissions (short tons CO2-equivalent)

	Gasoline	Diesel	Diesel HEV	B20	B100	E85	CNG	LNG	LPG	Electricity	G.H2	L.H2	Vehicle Total
School Bus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Transit Bus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Shuttle/Paratransit Bus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Waste Hauler	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Street Sweeper	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Delivery Step Van	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Transport/Freight Truck	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Medium/Heavy Duty Pickup Truck	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maintenance Utility Vehicle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fuel Total	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

On-Road Fleet Total **0.0 short tons of GHG emissions**

Figure 121. ANL GREET Excel Version Petroleum Use and GHG Emissions Results (ANL) [125]

The ANL GREET Excel based tool is focused on emissions comparisons so there are no financial TCO evaluations. The tool does a good job presenting information for entire mixed fleets. Back-up information tables are provided in the spreadsheet and instructions are found both in the spreadsheet and in a companion document.

20.4.2 GREET.NET 2017 Version

The 2017 and later versions of GREET moved to a more point-and-click user interface in a Microsoft.NET application with supporting databases that can be updated at each use. It includes more than 100 fuel production pathways. According to ANL, "GREET® 2017 provides the user with an easy to use and fully graphical toolbox to perform life cycle analysis simulations of alternative transportation fuels and vehicle technologies in a matter of a few clicks. This new tool includes the data of the GREET model, a fast algorithm for processing it and an interactive user interface. The interface allows faster development using graphical representation of each element in the model, and drag & drop editing approach to add and modify data [126]."

GREET is designed to do a Life Cycle Assessment (LCA). Argonne provides a video on how to use the GREET.NET tool [126]. Argonne's definition of LCA differentiates obtaining the raw source energy, well-to-pump, pump-to-wheel, and includes the end of life recycling and disposal of the vehicle as illustrated in Figure 122. For more information on a definition of LCA Argonne points to ISO 14040 Environmental management — Life cycle assessment — Principles and framework [127]. Argonne summarizes the ISO definition as "the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its lifecycle [126]."

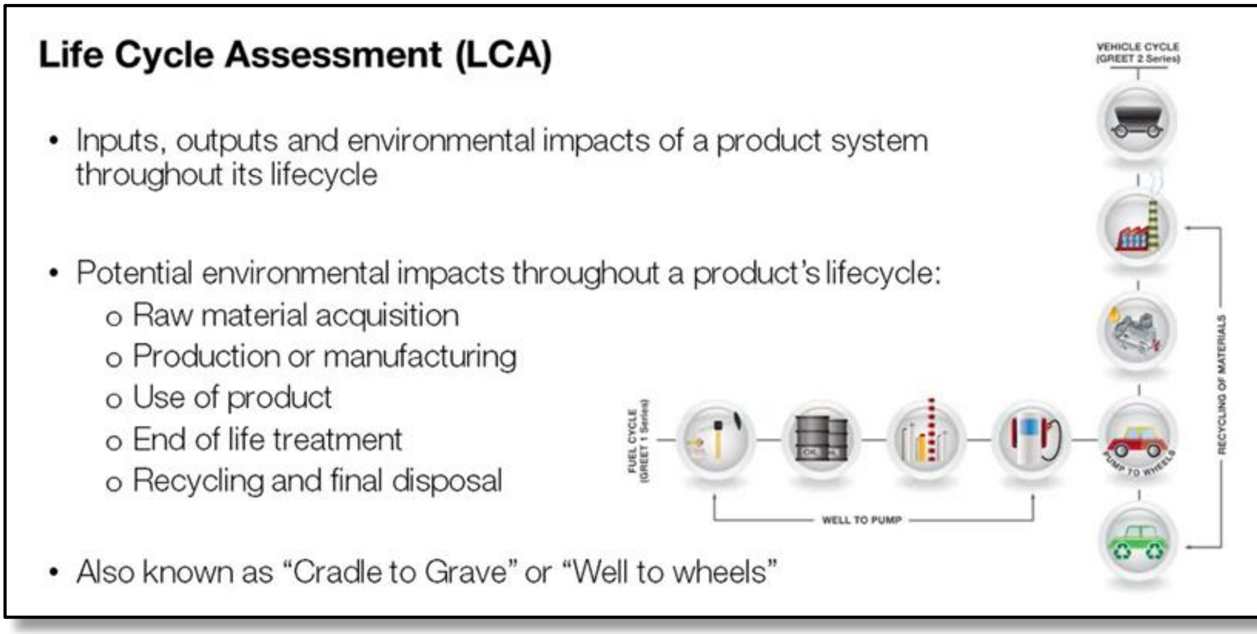


Figure 122. Life Cycle Assessment (LCA) segments (ANL) [126]

Argonne uses a system boundary diagram, shown in Figure 123, to explain the methodology used in developing the LCA model, creating a boundary that encompasses the system, then defining the various inputs, outputs and processes in the model.

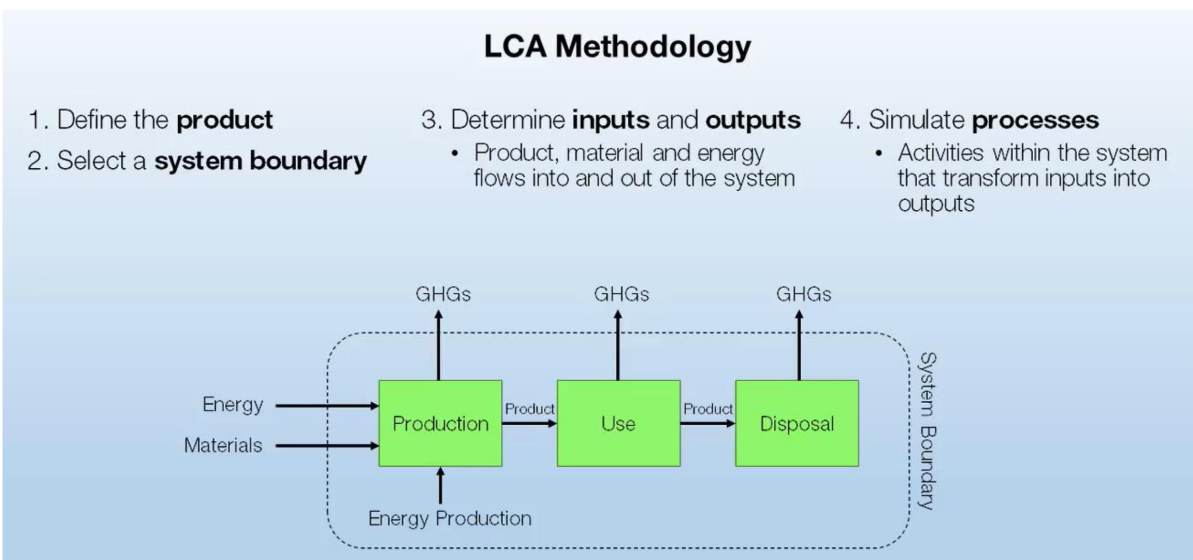


Figure 123. System Boundary Diagram LCA methodology (ANL) [126]

Argonne's example of a conventional gasoline vehicle to demonstrate the system boundary diagram approach is shown in Figure 124.

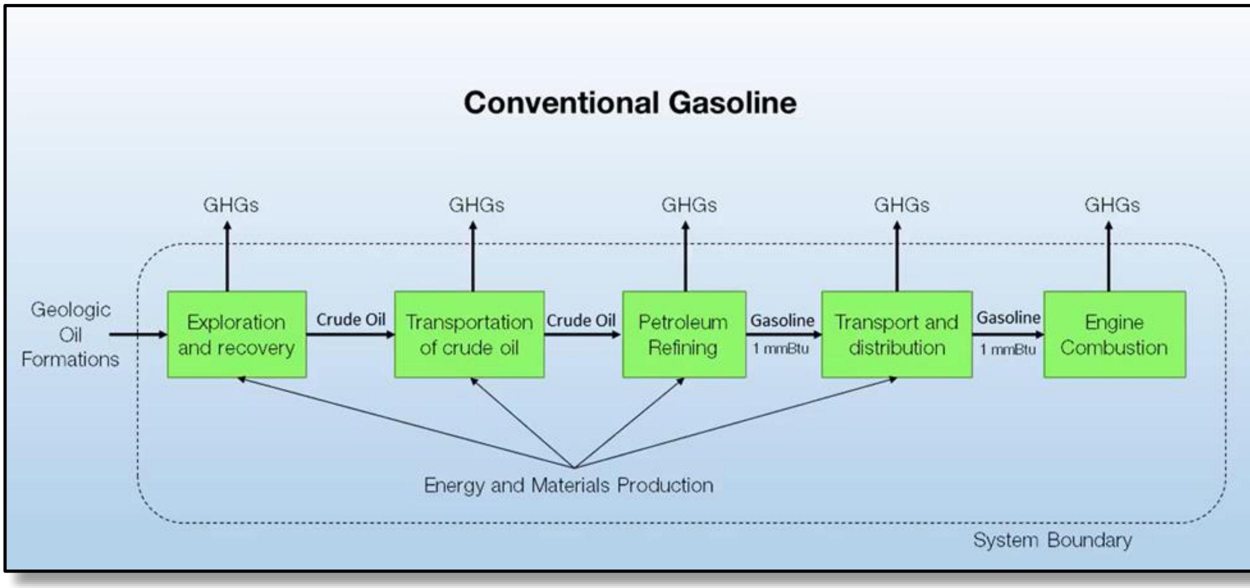


Figure 124. Example System Boundary Diagram for LCA with Conventional Gasoline Vehicle (ANL) [126]

Outputs of the tool include both tabular data and graphs, with an ability to transfer to Excel based worksheets.

The Argonne GREET.NET tool is significantly more sophisticated than their 2012 Excel based version. The tool has very granular control of nearly all of the variables involved in the system modeling. Values can also be entered as time based trends in curves. The tool evolved out of demands for greater detail and control of emissions modeling variables. With greater detail comes greater complexity. The tool represents over 20 years of development into providing more representative estimation of life cycle emissions. Argonne has provided an extensive collection of video tutorials to assist users.

NACFE found in interviews with fleets and OEMs frequent questions and observations about whether electric vehicles actually reduce emissions when you factor in the entire process of getting energy to the vehicle. The ANL GREET.NET tools provide the ability to dive deeply into answering that question for each of the many energy pathways involved in getting energy to the vehicle. Since the databases supporting GREET.NET are actively maintained and updated, the tool adapts to new information.

The ANL GREET Excel based tool is focused on emissions comparisons so there are no financial TCO evaluations.

20.5 Argonne AFLEET Tool

The Argonne AFLEET tool (Alternative Fuel Life-Cycle Environmental and Economic Transportation) is an Excel spreadsheet based application which estimates total cost of ownership values from simple user inputs and pre-defined values for an entire fleet with mixed vocations and mixed fuel (energy) types [128]. The tool is similar to the GREET 2012 Excel based tool but with a focus on the economics comparing different powertrain types, in addition to the emission aspects.

The AFLEET tool is separated into two primary input sections of Light-Duty and Heavy-Duty. Light-duty consists of passenger car, passenger truck and light commercial truck. Heavy-duty consists of [128]:

- School Bus = Passenger vehicles with a capacity of 15 or more persons used primarily for transport of students for school.
- Transit Bus = Passenger vehicles with a capacity of 15 or more persons primarily used for transport within cities.
- Refuse Truck = Trucks primarily used to haul refuse to a central location.
- Single Unit Short-haul Truck = Single unit trucks with more than four tires with a range of operation of up to 200 miles.
- Single Unit Long-haul Truck = Single unit trucks with more than four tires with a range of operation of over 200 miles.
- Combination Short-haul Truck = Combination tractor/trailer trucks with more than four tires with a range of operation of up to 200 miles.
- Combination Long-haul Truck = Combination tractor/trailer trucks with more than four tires with a range of operation of over 200 miles.

The AFLEET tool includes 15 fuel (energy) types under the heavy-duty group. There are 14 for the light-duty group. Users populate tables for number of vehicles for a particular vocation, annual miles, fuel economy (expressed in MPG Gallon Gasoline Equivalents) and the purchase price per vehicle. The program pre-populates many values from tables located in the program so that users can accept defaults or can override them and put in their own values. Figure 125 shows the heavy-duty vehicle information where the vehicle type is Single Unit Short-Haul Truck and the vocation is Delivery Step Van. The yellow areas on vehicles by fuel (energy) type are pre-populated with default values but can be overridden by user-entered values.

23	**Heavy-Duty Vehicle Information**				
24	Vehicle Type	Single Unit Short-Haul Truck			
25	Vocation Type	Delivery Step Van			
26	**Heavy-Duty Fuel Type**	**Number of Heavy-Duty Vehicles**	**Annual Vehicle Mileage**	**Fuel Economy (MPDGE)**	**Purchase Price ($/Vehicle)**
27	Gasoline	0	0	6.2	$0
28	Diesel	0	16,500	7.4	$65,000
29	All-Electric Vehicle (EV)	0	16,500	18.9	$145,000
30	Gaseous Hydrogen (G.H2) Fuel Cell Vehicle (FCV)	0	0	12.4	$0
31	Diesel Hybrid Electric Vehicle (HEV)	0	16,500	9.4	$83,000
32	Diesel Hydraulic Hybrid (HHV)	0	0	9.5	$0
33	Biodiesel (B20)	0	16,500	7.4	$65,000
34	Biodiesel (B100)	0	16,500	7.4	$65,000
35	Renewable Diesel (RD20)	0	16,500	7.4	$65,000
36	Renewable Diesel (RD100)	0	16,500	7.4	$65,000
37	Ethanol (E85)	0	0	6.2	$0
38	Propane (LPG)	0	16,500	6.2	$73,000
39	Compressed Natural Gas (CNG)	0	16,500	6.3	$105,000
40	Liquefied Natural Gas (LNG)	0	16,500	6.3	$95,000
41	LNG / Diesel Pilot Ignition	0	0	7.0	$0

Figure 125. AFLEET Heavy Duty Vehicle Information Inputs (ANL) [128]

The AFLEET tool includes which type of fueling station, either private or public. Recognizing that fuel prices do change, the AFLEET tool allows the user to include fuel price sensitivity as a percent of default price or enter specific values as shown in Figure 126. The tool also includes Diesel Exhaust Fluid (DEF) as one of the consumables. Again, yellow areas are pre-populated but can be overridden by the user's own value.

42	**Refueling Information**			
43	Fueling Type	Private Station	Infrastructure costs (go to 'Payback')	
44	Fuel Price Sensitivity	No	Enter fuel price range (go to 'Payback')	
45	**Fuel and DEF Price**			
46			**Public Station**	**Private Station**
47		**Fuel Unit**	**($/Fuel Unit)**	
48	Gasoline	gasoline gallon	$2.29	$2.35
49	Diesel	diesel gallon	$2.27	$1.67
50	Electricity	kWh	$0.13	$0.13
51	G.H2	hydrogen kg	$12.18	$12.68
52	B20	B20 gallon	$2.33	$1.80
53	B100	B100 gallon	$2.81	$3.25
54	RD20	RD20 gallon		
55	RD100	RD100 gallon		
56	E85	E85 gallon	$2.18	$2.19
57	Propane	LPG gallon	$2.61	$1.76
58	CNG	CNG GGE	$2.38	$1.93
59	LNG	LNG gallon	$2.70	$2.28
60	Diesel Exhaust Fluid (DEF)	DEF gallon	$2.80	$2.80

Figure 126. AFLEET Fueling inputs (ANL) [128]

The AFLEET tool includes the ability to make inputs to manage the scope of the TCO calculations as shown in Figure 127. These include the expected ownership period of the vehicle and also the infrastructure. The financing method is also selectable including loan, loan term, interest rate, down payment and discount factor.

62	**Total Cost of Ownership Inputs**			
63	**Light-Duty Vehicle Information**			
64	Years of Planned Ownership	years	15	
65	**Heavy-Duty Vehicle Information**			
66	Years of Planned Ownership	years	15	
67	**Infrastructure Information**			
68	Years of Planned Ownership	years	15	
69	**Financial Assumptions**			
70			**Vehicles**	**Infrastructure**
71	Loan	yes/no	No	No
72	Loan Term	years	5	5
73	Interest Rate	%	3.21%	3.21%
74	Percent Down Payment	%	0.00%	0.00%
75	Discount Factor	%	1.42%	

Figure 127. AFLEET TCO Input Parameters (ANL) [128]

The AFLEET tool includes greater choices in where the energy originates so for example the regional pricing of electricity or how ethanol is sourced as shown in Figure 128.

The analysis can be done three ways:

- 1 - Well-to-Wheels Petroleum Use and GHGs & Vehicle Operation Air Pollutants
- 2 - Well-to-Wheels Petroleum Use, GHGs, and Air Pollutants
- 3 - Well-to-Wheels & Vehicle Production* Petroleum Use, GHGs, Air Pollutants (*LDVs only)

Where Vehicle Production (or Vehicle Cycle) is defined as “raw material recovery, material processing, vehicle component production, vehicle assembly, disposal, and recycling [128].”

77	**Fuel Production Assumptions**			
78	Biodiesel Feedstock Source	1 - Soy	1	
79		2 - Canola		
80		3 - Corn		
81		4 - Tallow		
82	Renewable Diesel Feedstock Source	1 - Soy	1	
83		2 - Tallow		
84		3 - Palm		
85	Ethanol Feedstock Source	1 - Corn	1	
86		2 - Switchgrass		
87		3 - Sugarcane		
88		4 - Grain Sorghum		
89	CNG Feedstock Source	1 - North American NG	1	
90		2 - Landfill Gas		
91		3 - AD Gas of Animal Waste		
92		4 - AD Gas of Wastewater Sludge		
93		5 - AD Gas of MSW		
94	LNG Feedstock Source	1 - North American NG	1	
95		2 - Landfill Gas		
96		3 - AD Gas of Animal Waste		
97		4 - AD Gas of Wastewater Sludge		
98		5 - AD Gas of MSW		
99	North American NG Feedstock Source		Conventional	Shale
100			66%	34%
101	LPG Feedstock Source		NG	Petroleum
102			69%	31%
103	Source of Electricity for PHEVs, EVs, and FCVs (Electrolysis)		7	
104		1 - Average U.S. Mix		
105		2 to 11 - EIA Region Mix (see map)		
106		12 - User Defined (go to 'Background Data' sheet)		
107	G.H2 Production Process	1 - Refueling Station SMR (On-site)	1	
108		2 - Central Plant SMR (Off-site)		
109		3 - Refueling Station Electrolysis (On-site)		

Number	Grid Mix
1	U.S.
2	ASCC
3	FRCC
4	HICC
5	MRO
6	NPCC
7	RFC
8	SERC
9	SPP
10	TRE
11	WECC
12	User Defined

Figure 128. AFLEET Fuel Assumptions (ANL) [128]

The spreadsheet for AFLEET includes inputs for idle reduction methods, percent time idling, and time hoteling. These even include breaking down the annual portions of vehicle interior heating and cooling, engine heating and percent for electrical loads. Users can input or accept defaults for the types of idle reduction technology used.

Outputs for AFLEET include tabulated and graphical data for payback, total cost of ownership, idle reduction and net fleet footprint (with petroleum used and emission constituents) in both quantities and dollars. NACFE interviews reinforced that the AFLEET tool is a valuable asset for groups dealing with Clean Cities initiatives. The tool is well documented with comment fields in Excel cells, and background on the default values, as well as a companion user guide.

20.6 ACT Research Truck Fuel Calculator

ACT Research launched a truck fuel calculator and keeps it maintained as an online tool shown in Figure 129 . It has pre-inserted default values that users can override. It includes comparing financing, lease and cash buy of a vehicle. It includes grants and subsidy provisions. Also included are insurance costs and tire costs, and users estimate their own annual service costs. User entries can be simple by accepting default values, or more involved with user specified values, for example you can key in MPG for your baseline vehicle, pricing on fuel and Diesel Emission Fluid (DEF), your DEF ratio to fuel. The output results show you a cost per mile, annual vehicle cost, fuel cost, maintenance/operating cost, and a TCO value [129].

The tool can automatically compare annual cost of ownership for diesel, natural gas, fuel cell, electric, propane and gasoline vehicles in a convenient side-by-side tabular manner. A useful output is cost per mile, along with annual vehicle cost, annual fuel cost, annual maintenance/operating cost.

The ACT Research Truck Fuel Calculator has pop-up explanatory comments over the fields. The calculator is an online tool, so likely to be maintained. The tool dispenses with much of the complexity found in GREET.NET and AFLEET

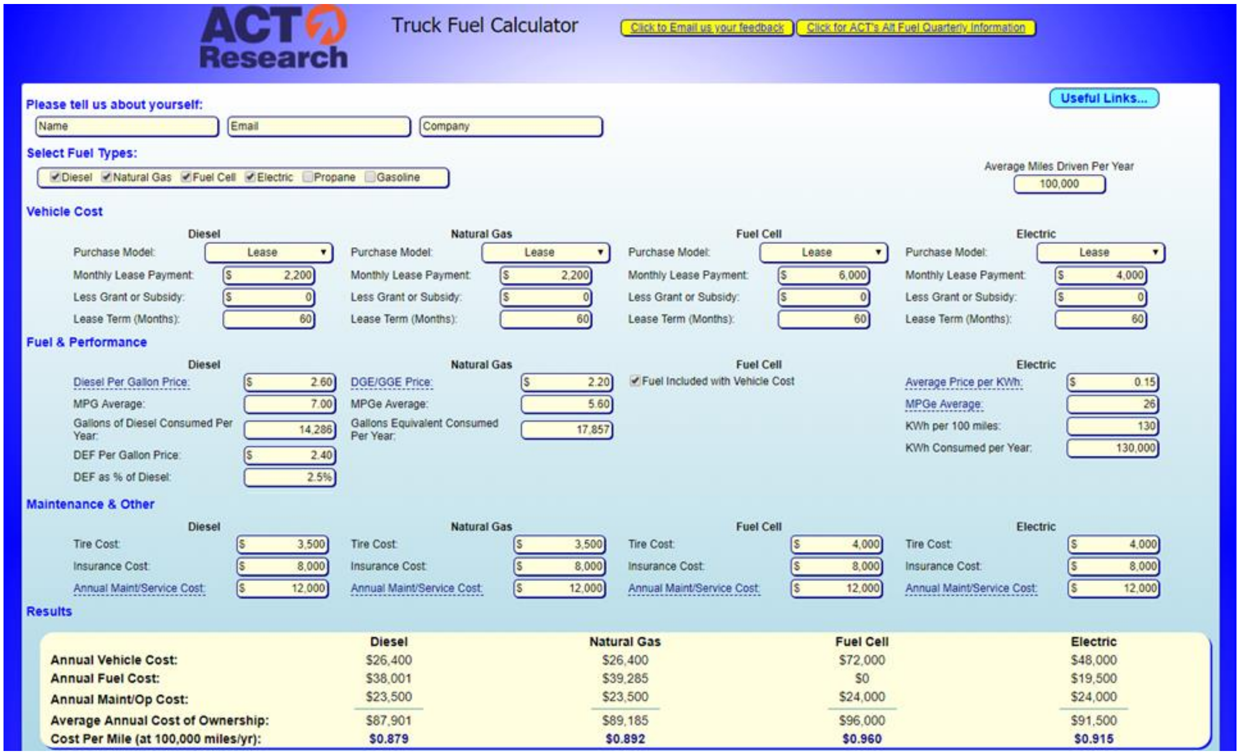


Figure 129. ACT Research Truck Fuel Calculator [129]

The ACT Research Truck Fuel Calculator is useful for quick side-by-side comparison of individual vehicles where duty cycle and infrastructure costs are not considered. The inclusion of grants and subsidies recognizes the reality that these are currently a part of the TCO equation for alternative fueled vehicles.

20.7 NREL Battery Second-Use Repurposing Cost Calculator

The National Renewable Energy Laboratory is funded by the U.S. Department of Energy to "investigate the feasibility of and major barriers to the second use of modern lithium-ion PEV batteries [135]." Vehicle batteries can decrease in capacity with use based on many factors including charging cycles, charging rates, depth of discharge, environmental factors, etc. An industry target for use in vehicles is that batteries that are below 80% of original capacity when fully charged should be replaced. Those batteries are still of use for a number of other applications called repurposing. Batteries below the 80% vehicle threshold may even be remanufactured for vehicle re-use. Repurposing or remanufacturing are less cost intensive than recycling, so are a preferable next step in the battery's life. Ultimately, batteries that are no longer suitable for repurposing or remanufacturing would need to be scrapped or recycled. These life cycles are illustrated in a flow chart from NREL in Figure 130.

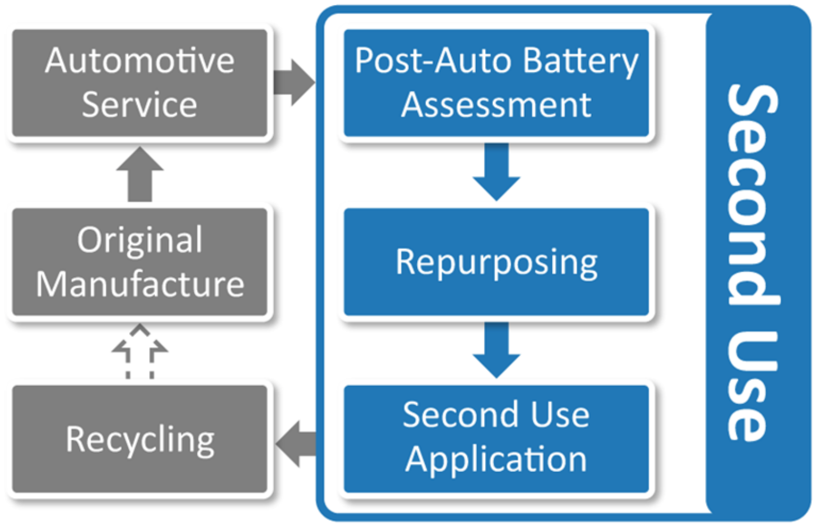


Figure 130. Battery Second Use Options (NREL) [135]

NREL has developed an Excel spreadsheet tool for exploring the impacts of various factors relevant to "repurposing strategies and assumptions on economics [134]." The tool is titled Battery Second Use Repurposing Calculator (B2U). Outputs of the tool itemize the components business metrics, seen in Figure 131, for repurposing the batteries based on the extensive set of inputs and assumptions.

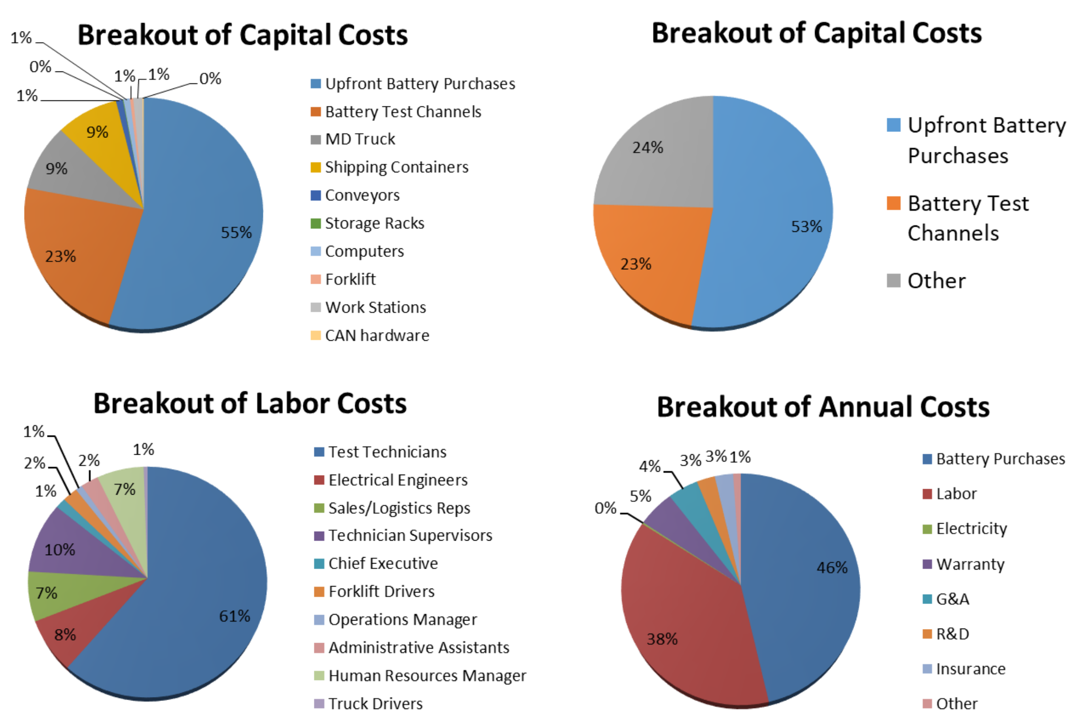


Figure 131. Example of Battery Repurposing Business Metrics (NREL) [134]

The NREL B2U tool shows that modeling costs for repurposing batteries involves a significant number of assumptions and inputs. The tool is intended to show there are positive business cases for repurposing, while the actual markets may not yet have developed. Estimating the salvage value of used batteries at the 80% threshold should be included in estimating total cost of ownership of commercial battery electric vehicles planned to be held for an extended period.

20.8 NREL Battery Lifetime Analysis & Simulation Tool

A key factor in estimating total cost of ownership for commercial battery electric vehicles is predicting the battery lifespan. Vehicle manufacturers offer warranties on vehicle systems and components. The warranty is essentially a bet placed by the manufacturer that the system will survive for a period of time without failure. There are costs associated with making perfect systems. There are also unknowns and uncontrolled factors. In the real world, the manufacturer has made some trade-offs and expects some level of failure under warranty. To some degree, the manufacturer has hedged this risk by allocating some portion of the vehicle sales price paid by the purchaser to cover warranty costs later in the vehicle's life. On the purchaser's side, the warranty is a bet on his part that the system will fail in the warranty period. Warranty period may or may not be a good estimate of battery life as it is tied to a number of business economic trade-offs and not strictly tied to performance factors.

The National Renewable Energy Laboratory has developed a suite of tools to estimate battery lifetimes called the Battery Lifetime Analysis and Simulation Tool (BLAST) Suite [136][138]. They have also developed a Battery Ownership Model (BOM) to estimate battery costs related to performance and lifespan [137]. The tool set also permits several alternatives for "behind the meter" alternatives that include various load leveling choices, solar, storage, etc. The user inputs to the BLAST tool suite include:

- **"Hardware options** — Input data for defining the battery performance and cost values employed by the simulation. Enter four factors: upfront installed cost, incentives, operational and maintenance costs, and hardware parameters. The latter defines the search space for system optimization. (See Figure 132).
- **Demand and PV options** — Select facility demand and PV production profiles. Choose between preloaded demand profiles from EnerNOC and PV profiles from PVWatts, or provide unique data via CSV document. See the BLAST documentation PDF for proper CSV formatting.
- **Rate structure values** — Define demand charges and energy costs to best represent your utility rate structure of interest. Demand charges and energy costs are divided between off-, mid-, and on-peak periods of the day, as well as season of the year. (See Figure 133).
- **Internal rate of return (IRR)** — Specify the term in years of IRR by which the economic performance of energy storage systems will be evaluated [137]."

The BLAST tool includes a user manual that contains the details of the calculations and meaning of the various factors. One key factor to consider with battery life is that lithium-ion batteries tend to live longer lives when not fully discharged. This is similar to always holding some diesel fuel in reserve in a vehicle's tanks. The "E" meaning empty generally includes some reserve. That reserve for diesel or gasoline fueled vehicles is meant to allow the driver to have enough fuel to get to a station to refill. That reserve takes on added meaning for battery electric vehicles, where the battery capacity may decrease more rapidly when depth of discharge consistently falls below 10% or 20% of capacity. This highlights that in sizing battery packs for CBEVs, additional capacity should be included to ensure minimum state of discharge stays above the 10% or 20% value, plus additional capacity to address long-term battery degradation expectations so the required duty cycle ranges are met for the life of the vehicle.

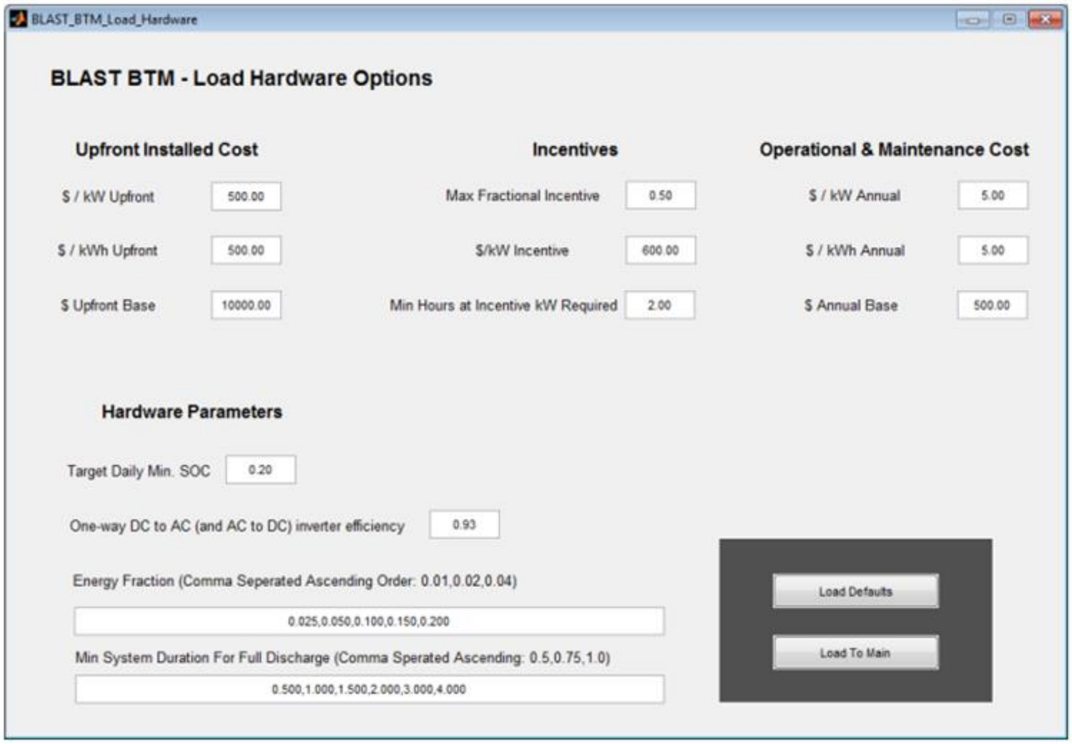


Figure 132. Battery Lifetime Calculator Hardware Inputs (NREL) [136][138]

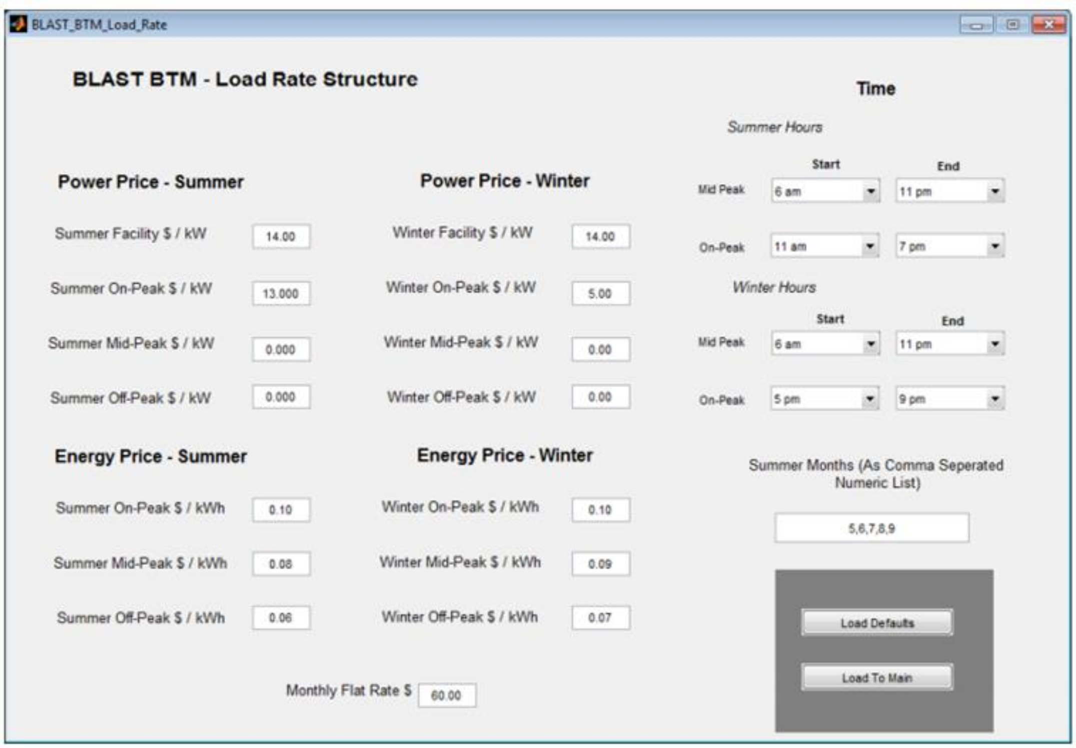


Figure 133. Battery Lifetime Calculator Rate Structure Inputs (NREL) [136][138]

Discussion of the NREL BLAST tool suite is included here to illustrate the complexity of estimating the costs associated with batteries in the absence of any significant volume of production field experience of commercial battery electric trucks and charging infrastructure. With time and new volumes of production vehicles entering use, the field experience can be used to refine and validate predictive battery life models. Standardization of battery packs will also help the industry have confidence in life predictions as the systems will not be all-new each year or for each model vehicle.