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Medium- and Heavy-Duty Vehicle Electrification

An Assessment of Technology and Knowledge Gaps

(December 2019)

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Oak Ridge National Laboratory (ORNL) and National Renewable Energy Laboratory (NREL)

December 2019

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Acronyms

Acronym	**Definition**
BEV	battery electric vehicle
CAFE	Corporate Average Fuel Economy (regulations)
CNG	compressed natural gas
DC	direct current
DCFC	DC fast charger
DOE	US Department of Energy
EPA	US Environmental Protection Agency
EV	electric vehicle
FC	fast charger
FCEV	fuel cell electric vehicle
GHG	greenhouse gas
GPS	global positioning system
GVW	gross vehicle weight
GVWR	gross vehicle weight rating
HD	heavy duty
HEV	hybrid electric vehicle
HPC	high-performance computing
HRE	heavy rare earth
HV	high voltage
HVAC	heating, ventilating, and air-conditioning
ICCT	International Council on Clean Transportation
ICE	internal combustion engine
IEA	International Energy Agency
IGBT	insulated-gate bipolar transistor
LD	light duty
LDV	light-duty vehicle
LV	low voltage
MD	medium duty
MHDV	medium- and heavy-duty vehicle
MOSFET	metal-oxide semiconductor field-effect transistor
NACFE	North American Council on Freight Efficiency
NMC	lithium nickel manganese cobalt oxide (battery)
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
PM	permanent magnet
R&D	research and development
SOC	state of charge

Acronym	**Definition**
TCO	total cost of ownership
VMT	vehicle miles of travel
WBG	wide bandgap
WPT	wireless power transfer
XFC	extreme fast charging

Executive Summary

The objective of this assessment was to leverage current medium- and heavy-duty vehicle (MHDV) data and information to evaluate the state of commercial vehicle electrification technologies, including the following.

1. Assessment and inventory of current MHDV electrification architectures
2. Identification and assessment of MHDV component technologies
3. Assessment of potential performance and cost drivers
4. Identification of R&D gaps where appropriate R&D and technology would accelerate commercial vehicle electrification. These gaps include shortfalls in technology, gaps in data, and inadequate knowledge and understanding.

To inform this study, the National Renewable Energy Laboratory–Oak Ridge National Laboratory team examined the open literature; conducted workshops; assessed and analyzed data on more than 175 electrified MHDVs, including vehicle and powertrain specifications; and conducted one-on-one meetings with industry representatives. This systems-level information was concatenated and parsed with respect to key characteristics such as battery energy, power, and range compared across vehicle classes. Operational data of many conventional vehicles were also examined to help determine the requirements on electrified vehicle attributes such as range. Previous studies on the total cost of ownership of electrified MHDVs were reviewed to determine where improvements in technologies (efficiency, cost, maintenance) were needed to accelerate adoption. The team also assessed the state of the art in electric drivetrains for component specifications and challenges for the commercial vehicle sector, including electric machines, power electronics, and off-board high-power charging systems (extreme fast charging and beyond). The goal of this analysis was to identify the barriers to widespread adoption of commercial vehicle electrification technologies and prioritize the research and development gaps that need to be overcome to accelerate significant market penetration of these technologies.

MHDVs, defined as Class 2b–8, are critical to the US economy. Trucking accounts for more than 67% of freight movement by weight in the United States [1], with a revenue of $738.9B, 81.5% of the nation's total freight cost [2]. MHDVs are the second largest transportation energy-use sector, accounting for 22.7% of the total [3]. This is expected to grow to 24.7% of the total transportation energy consumption by 2050 while light-duty (LD) vehicle energy use is expected to fall 29% to 41.3% of the total in the same time frame. MHDVs represent about 4.6% of the total US vehicle fleet [4] and thus a large energy and economic improvement opportunity per vehicle. Because of the economic importance of freight costs, the growing energy use of MHDVs, and the large per vehicle opportunity, addressing MHDVs is important to helping the United States attain energy independence and helping the economy.

Electrification is a promising technology pathway for MHDVs because it has the potential to provide simultaneous gains in freight efficiency, emissions reductions, and performance improvements. Additionally, it provides energy source diversification, allowing energy production methods to change with technological and economic drivers. Hybrid electric vehicle (HEV) and plug-in electric vehicle (PEV) passenger cars have started to have market success; however, commercial-grade MHDV technology will require considerable R&D before broader market adoption can be achieved. Several demonstrations and market deployments for commercial PEVs have occurred, with mostly small volumes. Many of the vehicle technology providers have been small companies that have limited capability for providing long-term customer support/maintenance and have not established stable powertrain designs or consistent supply chains. Developers of many of the early electric vehicle powertrains have attempted to integrate "off-the-shelf" or "best available" battery systems, motors, and power electronics as opposed to purpose-built or optimized systems. Areas where MHDV electrification has made market progress are specialized applications such as transit buses, where other factors such as emissions and noise are also important and federal or state funding is available to incentivize zero-emissions technology. While technology advancement in LD vehicles can often benefit the MHDV market, key differences have resulted in R&D gaps that are limiting the electrification of commercial vehicles.

These key differences include the following.

- The life expectancy of a heavy-duty (HD) vehicle can exceed 1 million miles, and the *average* age of commercial trucks on the road is about 14 years. Often these miles are driven over more demanding duty cycles as defined by the vehicle vocational requirements. Therefore, many components and systems must be more durable than those intended for LD applications and the 15 years and 300, 000 miles in current industry LD targets.
- The power and energy flows in MHDV powertrains far exceed those of their LD counterparts: roughly twice the peak power, 4 times the peak torque, more than 5 times greater per-mile fuel consumption, and gross vehicle weights up to 80,000 lb for on-road (and higher for off-road). As shown in Figure ES1, PEV MHDV energy use ranges from 500 to 3,200 Wh/mile, while LD PEVs typically use 250 to 400 Wh/mile.
- The larger per-mile energy demands, along with daily driving distances, for MHDVs require much larger batteries. Today's MHDV PEV batteries have as much as 660 kWh, shown in Figure ES2, while near future concepts may exceed 1,200 kWh (100 kWh currently is about the largest battery pack found in LD vehicles). Fast charging these batteries will require substantially more power (greater than a megawatt) compared to current extreme fast charging for LD vehicles (350 kW).
- The MHDV market comprises a vastly diverse set of vocational uses compared to the passenger car market. MHDV purchases and market expansion will be driven largely by total cost of ownership (TCO). These vehicles must address a broad range of duty cycles and use cases. This often leads them to have highly customized options such as power takeoff, refrigeration, job-site power needs, and hotel/idle loads , which limits standardization. This also leads to a higher prioritization on reliability and lifetime cost than for LD vehicles.
- With high annual vehicle miles traveled in the MHDV sector and high fuel consumption per mile, fuel costs will typically exceed the purchase price of the vehicle in a few years. This places high priority on the overall vehicle efficiency and the efficiency of electrical components, even with electric vehicles, to accrue fuel savings that will pay back the very high cost of energy storage in 2–3 years.

- MHDVs are often located at centralized depots where the combined charging of PEVs may cause challenges with facility charging infrastructure and utility rate impacts such as demand charges. The annual sales volume of MHDV trucks is about a twentieth that of cars, and they can be purchased with options essentially specific to every vehicle. The resulting dilemma is that the volumes are low and the applications can be very diverse, resulting in the problem of how to cost effectively provide solutions across such diverse vocations, duty cycles, and missions.

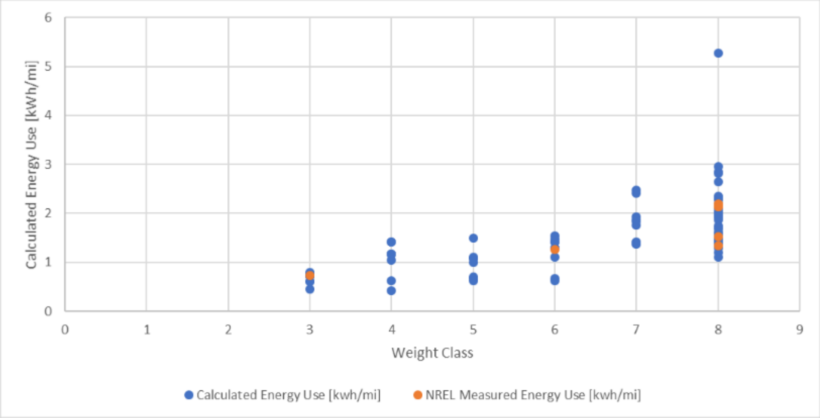

Figure ES1: Energy use by weight class for Class 3 through Class 8 battery electric vehicles.

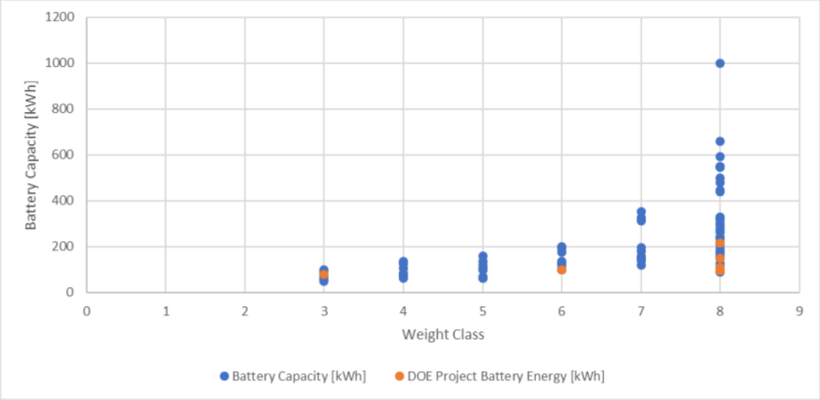

Figure ES2: Medium- and heavy-duty vehicle battery capacity by weight class for Class 3 through Class 8 battery electric vehicles.

Based on these differences, this study found the following important MHDV technology and knowledge gaps that need to be addressed.

- Research is needed to better understand how to apply electrified vehicle attributes to the broad range of on-road and off-road vehicle duty cycles and vocations. Larger and more comprehensive high speed (1 Hz or faster) data are required to get complete understanding of the diverse duty cycles and vocations in the MHDV sector and provide inputs to powertrain development. Advanced data analytics methods are then needed to organize and extract critical insights from these large data sets for design and operating algorithms.
- Given a robust database of operational requirements, there is a need expressed by industry to develop and apply simulation and optimization tools to enable development of electrified

vehicle drivetrains across multiple applications for scalability in an accelerated manner. Increased fidelity at the system level is now possible in today's high-performance computing systems instead of only at the component level. Optimization tools can be developed and augmented with hardware-in-the-loop data, validation, and codevelopment to provide a system-level understanding.

- Technology development targets specific to MHDV requirements are needed for MHDV systems and components. An assessment of the vehicle, vocation, infrastructure, and market is needed to understand R&D priorities for enabling MHDV electrification. New and expanded simulation and TCO analysis of the performance and costs of electrified vehicles are needed to help set targets for components.
- Development of ruggedized, scalable electrified powertrain components that meet the broad range of MHDV vocations, duty cycles, and missions is needed. Energy storage (battery) shortcomings remain a considerable barrier to electrification, with needs in the following areas: reducing costs, increasing energy density, improving performance at temperature extremes, achieving battery lifetimes (cycles) commensurate with commercial vehicle TCO requirements, and developing economical end-of-life solutions. Although additional data are needed, it is expected that commercial vehicles will more deeply discharge the batteries, which tends to shorten their life. The reasons for poor reliability seen in previous electric MHDV demonstrations need to be determined and corrected. More-specific targets and requirements for MHDV batteries are being assessed in ongoing TCO analyses.
- Freight efficiency must be preserved to the extent possible for electrification to make economic sense, so power and energy density of energy storage systems, motor efficiency, and power converter performance must be maximized in the MHDV design space. These components must meet performance and, in particular, durability criteria demanded by the commercial sector.
- To enable further market penetration, solutions need to be developed that optimize the powertrain system and controls for specific duty cycles that would benefit most from electrification. Methods to improve powertrain flexibility to achieve high efficiency at a wide range of operations are similarly needed. Defining new approaches to the missions that these vehicles must deliver from an energy efficient operations perspective could further exploit the electrification benefits and unlock systems-level efficiencies that might otherwise be lost due to conventional approaches. In addition, automation and connectivity are key focuses that could enable maximization of the benefits of electrification through optimized fleet control at the transportation systems level.
- Development of charging and infrastructure capable of providing fast charging for the larger batteries of MHDVs is needed. For the MHDV segment, the power levels necessary to rapidly recharge large capacity energy storage far exceed the current focus of LD extreme fast charging levels. Because of this, the need for reliable off-board charging system components (thermal considerations, very high bus voltages, etc.) is a critical gap to widespread adoption of electrification across the MHDV space.
- Impacts to the electric grid of even small increases in electrification of commercial fleets need to be understood and research into possible solutions identified. Business models and technology

solutions that avoid multipliers or surcharges on electricity price are needed (or else TCO will favor combustion vehicles).

- Especially for HEVs, tighter integration of electrified components with conventional MHDV powertrain architectures is also needed. Novel approaches to optimizing integration of power electronics and motors into existing MHDV powertrains will allow reduction of weight and losses due to reduced cabling needs (especially important for the six- and nine-phase electric machines prevalent in this space), additional functionality of electrified components (increased use for auxiliary systems required across many vocations), and multiple uses for single-power converter systems (combined inverter and charging operation). Innovative cofunction of electric and combustion processes has intriguing potential.
- Efficient electric accessories are needed to reduce their impact on vehicle energy consumption. Data are needed to develop innovative technologies and strategies to reduce the impacts of accessory loads, including HVAC; component thermal management; hoteling; and job-site power.
- Efficiency improvements are needed even for pure battery electric vehicles in that energy cost-savings are the primary means to recoup the high cost of batteries for overall affordable TCO. There are opportunities for efficiency gains within the electric drive system as well as at the vehicle level where constraints of engine-based configurations do not exist.

1 Introduction

1.1 Study Purpose

The objective of this assessment was to evaluate the status of commercial vehicle electrification technologies and identify the gaps and barriers that inhibit further development and deployment. More specifically, this report includes

1. Assessment of current medium- and heavy-duty vehicle (MHDV) electrification architectures
2. Identification and assessment of MHDV component technologies
3. Assessment of the potential performance and cost challenges that impact commercial acceptance
4. Identification of appropriate R&D gaps that need to be resolved for commercial vehicle electrification

The resources for this assessment of technology gaps and barriers to electrified commercial vehicles included the following:

- The open literature.

- Knowledge within the US Department of Energy (DOE) laboratories from R&D conducted for many years on components for electrified passenger vehicles.

- Extensive data collected from vehicles in fleet operation during various projects over the last 11 years.

- Input from industry in one-on-one visits to Cummins, Allison Transmission, Navistar, Eaton, and others.

- Focused workshops with participation by broad stakeholder representation. Two workshops were conducted during the Green Truck Summit meeting in March 2019.

- Industry and laboratory technical planning activities pertaining to the 21st Century Truck Partnership. (web and in-person meetings.)

1.2 Scope

This report assesses the status of electrification in commercial vehicle markets, covering weight classes 2b through 8 as defined in Section 2.1. However, more emphasis has been placed on Class 3 and higher weight classes in part due to data availability. Technologies within the report scope cover a broad spectrum from mild hybridization to full battery electric and fuel cell vehicles. These electrification architectures are described in Section 3.

1.3 Report Organization

This report is organized as follows. Section 2 provides an overview of the commercial vehicle industry and includes an inventory of electrified vehicle models. Section 3 reviews electrified vehicle architectures. Section 4 discusses the importance of total cost of ownership (TCO) and duty cycles in the design and market uptake of electrified solutions for the MHDV market. Section 5 summarizes industry perspectives on barriers to electrification. Section 6 provides a detailed discussion of the status of electrification component technologies. Finally, Section 7 presents study findings and conclusions and recommendations addressing the technology gaps.

2 Industry Overview

This section reviews the freight industry and its importance to the US economy, along with the various truck classifications used by the industry and regulatory agencies. The emergence of electrified MHDVs is covered, and an inventory of recent and current electrified vehicles is introduced.

2.1 Medium and Heavy-Duty Vehicle Industry Characterization

MHDVs, including trucks and buses, are the fastest growing fuel users and greenhouse gas (GHG) producers in the United States and, as such, are an important factor in energy independence and security. Affordable truck freight movement also is essential for the nation's economy. Trucks carry more than 70% of the nation's freight on a tonnage basis and 73% of freight on a value basis [5]. Virtually all goods consumed in the United States are shipped by truck for at least part of their trip to the consumer. There are more than 500,000 trucking companies in the United States with more than 13 million trucks on the road of which 2,900,000 are tractor trailers [6]. Of these trucking companies, 80% are regarded as small businesses, with six or fewer trucks.[1] While MHDVs account for 5% of the US vehicle population, they consume disproportionately more fuel than light-duty vehicles (LDVs) and account for more than 27% of on-road fuel use.

Separate regulations govern fuel consumption and emissions in MHDVs at both the vehicle and engine levels. Whereas passenger vehicles and light-duty (LD) trucks have been subject to Corporate Average Fuel Economy (CAFE) regulations for decades [7], MHDVs were not subject to fuel consumption and GHG regulations until 2011 [8]. Regulations at the vehicle level for MHDVs express standards in terms of fuel used or GHG produced per payload-distance (i.e. gallons per 1,000 ton-miles or grams CO_2 per ton-mile) in contrast to the simpler miles per gallon of the CAFE standards. In the context of fuel consumption and emissions, trucks are classified by gross vehicle weight rating (GVWR), shown in Figure 1. Figure 2 illustrates some typical vehicle types within each weight class. Further information that distinguishes LDVs from MHDVs and US Environmental Protection Agency (EPA) emissions classifications is available at the Alternative Fuels Data Center [9].

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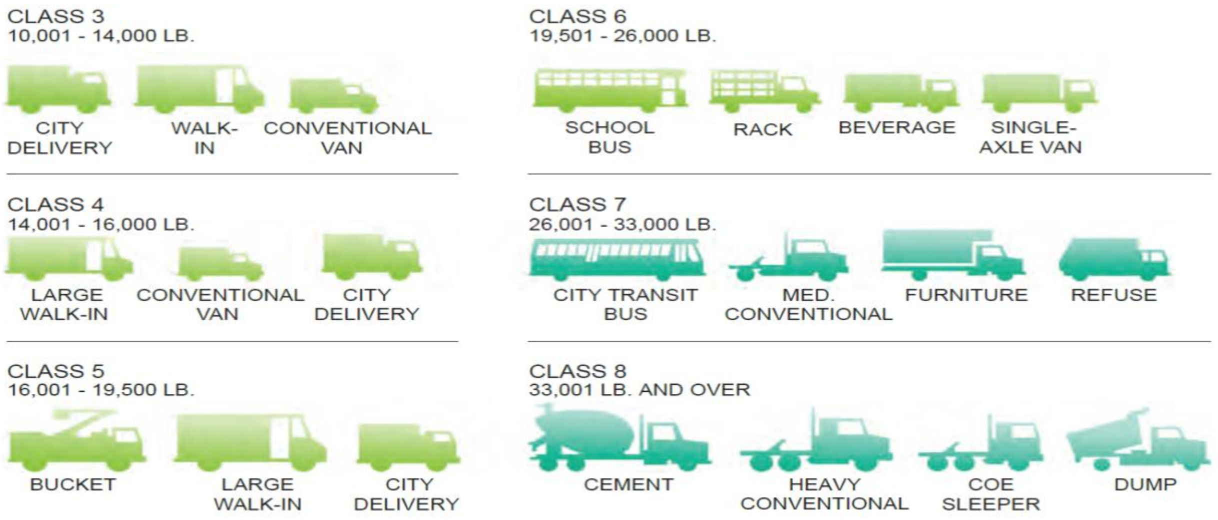
[1] Analysis of IHS 2013 vehicle registration data and Federal Motor Carrier Safety Administration 2019 carrier registration data.

Class	2b	3	4	5	6	7	8
GVWR (lb)	8,501–10,000	10,001–14,000	14,001–16,000	16,001–19,500	19,501–26,000	26,001–33,000	>33,000

Figure 1: Commercial vehicle weight classes (GVWR = gross vehicle weight rating).



Class 2b, 8501–10,000 lb

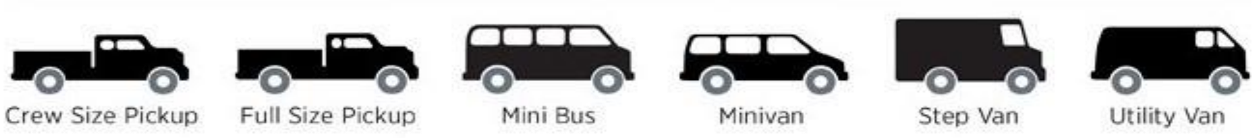


Figure 2: Classifications used for commercial vehicles (medium- and heavy-duty vehicles). (MED = Medium; COE = Cab Over Engine.) Source: National Academies of Sciences, Engineering, and Medicine. 2019. *Reducing Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two: Final Report*. Washington, DC: The National Academies Press; available at https://doi.org/10.17226/25542.

Class 2b is the part of Class 2 vehicles that are regulated as commercial vehicles, consisting of large pickup trucks and vans that are primarily used in commerce and have a GVWR of 8,501–10,000 pounds.

Class 3–8 trucks make up less than 5% of the total number of US on-road vehicles but represent a quarter of the annual vehicle fuel use. Commercial trucks in classes 3 through 8 used a total of about 45 billion gallons of fuel in 2016 [10]. Fuel consumption (meaning gallons per year) data specific to each category from 2b to 8 have not been updated in many years and represent a gap in the understanding of the sector. Fuel use data are aggregated for Class 3–6 and Class 7–8 [10]. MHDV total fuel consumption is dominated by Class 8 tractor trailers, which have the most annual vehicle miles of travel (VMT). Class 8 tractor trailer fuel consumption is followed by Class 2b because of the high numbers of relatively small Class 2b trucks and vans. Gasoline and diesel fuel account for well over 90% of MHDV fuel use. About half of Class 2b new vehicles are gasoline; the other half are diesel [11]. Natural gas is also finding use in Class 6–8 because, like electricity, it is cheaper on an energy basis than other fossil fuels.

The US market for new Class 3–8 MHDVs is relatively small, with sales in 2017 of about 732,000 compared to 16.8 million LDVs. While Toyota sold 387,000 Camrys in that year, sales of Class 7 and 8 tractor trailers by all manufacturers totaled only about 170,000. Sales of "vocational" vehicles, spread across all classes 3 through 8, all manufacturers, and the myriad of body styles illustrated in Figure 2, totaled 294,000, with pickup trucks and vans making up the remainder. The approximate distribution of newly purchased vehicles across weight classes is shown in Figure 3.

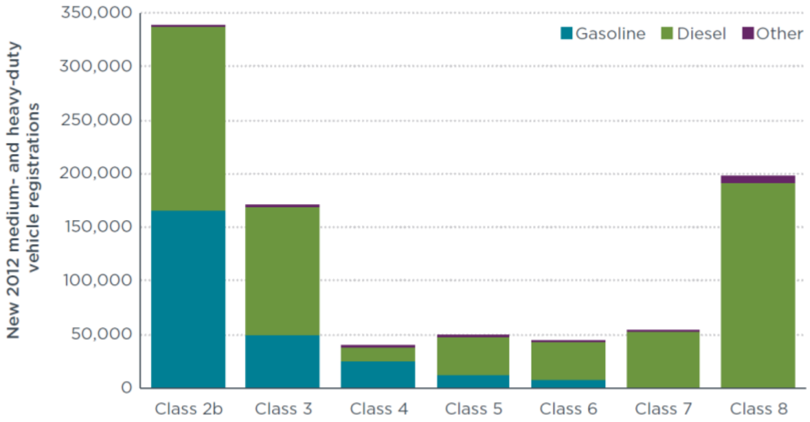


Figure 3: Approximate new sales of commercial vehicles across the weight classes 2b–8. Source: N. Lutsey, "Regulatory considerations for advancing commercial pickup and van efficiency technology in the United States," International Council on Clean Transportation (ICCT), White Paper, April 2015.

Similarly to the United States, MHDVs contribute disproportionally to emissions globally. Moultak et al. [12] summarized this perspective as follows:

> "Freight trucks, which primarily operate on diesel (and sometimes gasoline or natural gas), account for a large and growing share of local pollutant and greenhouse gas emissions. Despite representing merely 9% of the global vehicle stock and 17% of the total vehicle miles driven, freight trucks accounted for approximately 39% of the life-cycle road vehicle greenhouse gas emissions, with the share being even higher for other pollutants…."

2.2 Growth of Electrification in the Medium and Heavy-Duty Vehicle Sector

Electrification of MHDV powertrains has long been recognized as a potential path to reduced fuel costs and emissions for the nation's freight movement, yet development of a sustainable market for electrified commercial vehicles has lagged well behind LDVs. Electric delivery trucks were in use by the United Parcel Service in the 1930s. Over the last 10 years, battery performance has improved and battery costs have been reduced substantially, making electrification of MHDVs more attractive (Figure 4). Industry feedback has indicated that these low costs have not yet been realized in the MHDV sector due to low volume purchases and customized pack specifications. Electrified commercial vehicles are being reevaluated and are finding on-road applications in freight, package delivery, and buses. Heavy-duty (HD) off-road applications such as cargo handling equipment at seaports are being developed and demonstrated. Financial incentives such as the State of California's Hybrid and Zero and Bus Voucher Incentive Program are often available for vehicle conversions and purchases.

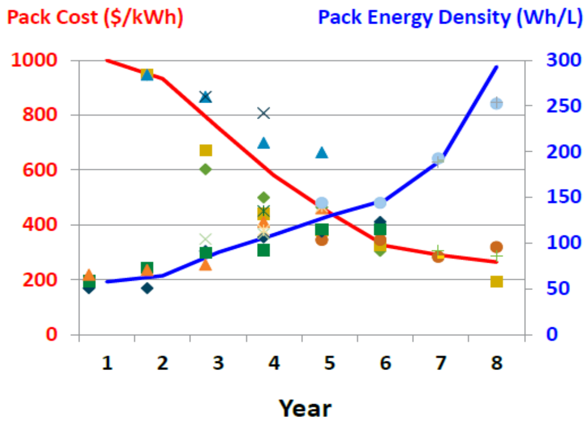


Figure 4: Reduction in battery costs enhances opportunities for electrified medium- and heavy-duty vehicles. Source: David Howell, "Electrochemical Energy Storage R&D Overview," US Department of Energy (DOE) Vehicle Technologies Office, Annual Merit Review, 2017; available at https://www.energy.gov/sites/prod/files/2017/06/f34/es000_howell_2017_o.pdf.

Globally, buses are the largest segment of electric commercial vehicles to date, with large numbers in China and Europe. The American Public Transit Association reported that in 2017, US transit fleets included 9,821 electrified buses of which 538 were battery electric vehicles (BEVs—i.e., battery only). Various incentives and regulations have stimulated this market. In 2018, the National Academies reviewed the status of battery electric buses in the United States, including a survey of 21 transit agencies experienced with electric bus deployment. They found that half of the agencies had implemented electric vehicles (EVs) due to board direction, environmental regulations, and sustainability programs and that 39% purchased the buses through federal or state grant opportunities such as the Federal Transit Administration Transit Investments for Greenhouse Gas and Energy Reduction program. The agencies used a variety of charging strategies, including installation of both depot and on-route charging infrastructures. While 33% of the agencies did not make any adjustments to operations, 60% had to adjust schedules, 40% adjusted layover times to accommodate charging, 20% used block scheduling, and 13% adjusted the number of buses serving a route. One agency reported that, through the use of on-route charging, it was able to operate 24/7 without returning to the depot to charge. However, the lack of depot charging infrastructure presents a significant risk in the event of service interruption at one charging location [13]. A study of electrification of buses in New York City found a notable monetary value from reducing health issues in the population among other advantages over diesel-powered buses [14].

Surveys of the growth in electrified MHDVs have reported 18–20 MHDV models in the commercialization process in 2018–2019, compared to 5–6 just 2 years ago [15, 16].

2.3 Summary of Available Electrified Commercial Vehicle Medium and Heavy-Duty Vehicle Electrification Inventory

Except for transit buses, the market for electrified commercial vehicles is very small, but a variety of electrified commercial vehicles that range from mild hybrid 48 V vehicles to Class 8 tractor trailer full BEVs have been developed and demonstrated and have achieved limited commercial sales. A recent survey by Synthesis Partners on behalf of DOE found the following population of electrified vehicles on the road in the United States [17].

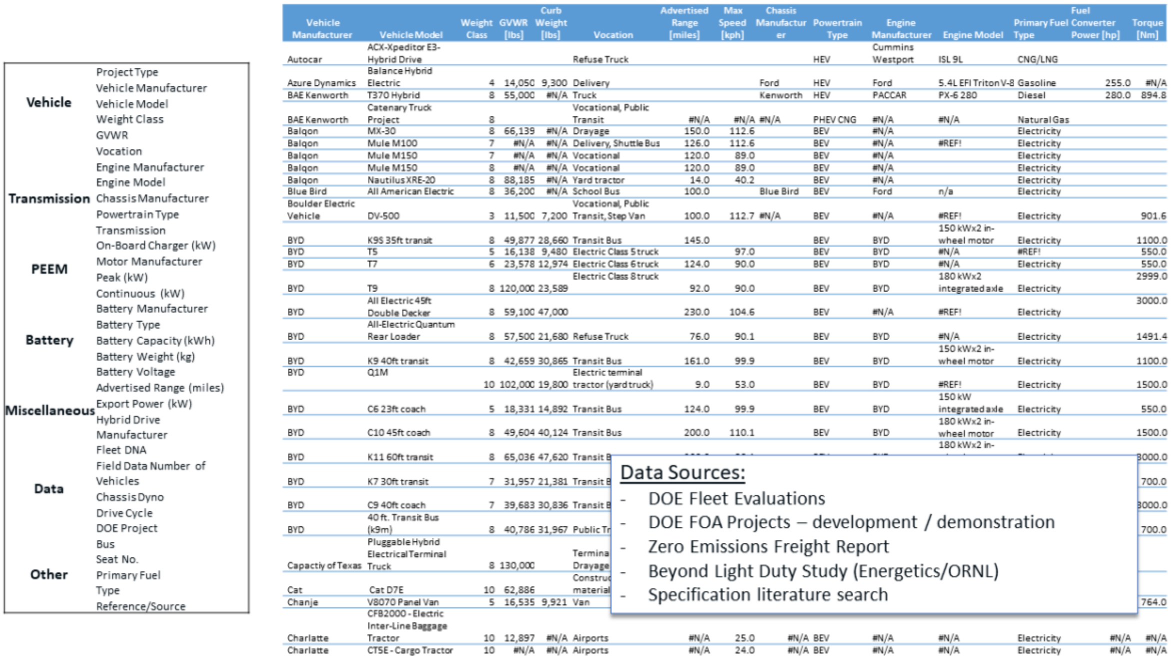
- 11,909 Class 3–8 trucks
- 13,826 buses
- 3187 upfitted vehicles

To better understand the small but growing MHDV electrification market, vehicle designs, and vehicle performance, an inventory of current and recent commercial EVs was created by NREL in this study. There are currently 178 vehicle models in the inventory, with 161 Class 3 or above. A summary of the Class 3–8a MHDVs found in this study through March 2019 is shown in Table 1 (for the entire inventory of electrified MHDVs, see https://app.box.com/s/04h4jqs50w88f5ziwvmf4o2sxbxpzhzg).

Table 1: Summary of Electrified Medium- and Heavy-Duty Vehicles Included in the Present Study Database

Weight Class	Total Number of Vehicle Models	Technology	Number of Vehicle Models	Battery Capacity (kWh)		Peak EM Power (kW)		Fuel Converter Power [kW]	
				Low	High	Low	High	Low	High
3	8	BEV	7	48.5	99.0	70.0	160.0		
		PHEV	1	14.0	14.0	92.0	92.0	138.0	138.0
4	15	BEV	10	61.0	136.0	20.0	188.0		
		HEV	3	1.8	60.0	44.0	100.0	156.6	190.2
		FCEV	1	28.0	28.0	120.0	120.0	30.0	30.0
		ICE	1					149.1	149.1
5	18	BEV	12	62.0	135.0	91.0	200.0		
		HEV	3	99.0	99.0	36.0	200.0	120.0	156.6
		EREV	2	60.0	60.0	200.0	343.0	25.0	50.0
		ICE	1					149.1	149.1
6	21	BEV	10	99.0	200.0	134.0	250.0		
		HEV	6	1.8	28.0	36.0	120.0	80.0	231.2
		FCEV	2	28.4	28.4	200.0	200.0	30.0	30.0
		PHEV	1	74.0	74.0	200.0	200.0	179.5	179.5
		ICE	2					205.1	223.0
7	15	BEV	10	120.0	352.0	103.0	360.0		
		HEV	4	1.8	28.0	44.0	71.0	186.4	242.4
		ICE	1					238.6	238.6
8	68	BEV	45	88.0	1000.0	103.0	770.0		
		HEV	8	1.8	28.0	44.0	265.0	149.1	227.4
		FCEV	7	12.0	700.0	85.0	746.0	29.8	100.0
		PHEV	5	80.0	175.0	168.0	300.0	29.8	238.6
		ICE	3					208.8	452.9
Off-Road Utility Vehicles	22	BEV	19	10.8	209.0	3.0	180.0		
		HEV	2	#N/A	#N/A	171.0	198.0	167.8	201.3
		FCEV	1	22.0	22.0	240.0	240.0	30.0	30.0

For each of these vehicles a wide range of metrics was collected when available. These included weight class, GVWR, powertrain type, electric machine power, battery size, battery type, advertised range, and others shown in Figure 5. Note that this inventory includes vehicles that were introduced and used in commerce going back to about 2012, so some are no longer available.



	Project Type
	Vehicle Manufacturer
Vehicle	Vehicle Model
	Weight Class
	GVWR
	Vocation
	Engine Manufacturer
	Engine Model
Transmission	Chassis Manufacturer
	Powertrain Type
	Transmission
	On-Board Charger (kW)
	Motor Manufacturer
PEEM	Peak (kW)
	Continuous (kW)
	Battery Manufacturer
	Battery Type
Battery	Battery Capacity (kWh)
	Battery Weight (kg)
	Battery Voltage
	Advertised Range (miles)
Miscellaneous	Export Power (kW)
	Hybrid Drive Manufacturer
	Fleet DNA
Data	Field Data Number of Vehicles
	Chassis Dyno
	Drive Cycle
	DOE Project
	Bus
	Seat No.
Other	Primary Fuel Type
	Reference/Source

Vehicle Manufacturer	Vehicle Model	Weight Class	GVWR [lbs]	Curb Weight [lbs]	Vocation	Advertised Range [miles]	Max Speed [kph]	Chassis Manufacturer	Powertrain Type	Engine Manufacturer	Engine Model	Primary Fuel Type	Fuel Converter Power [hp]	Torque [Nm]
Autocar	ACX-Xpeditor E3-Hybrid Drive				Refuse Truck				HEV	Cummins Westport	ISL 9L	CNG/LNG		
Azure Dynamics	Balance Hybrid Electric	4	14,050	9,300	Delivery			Ford	HEV	Ford	5.4L EFI Triton V-8	Gasoline	255.0	#N/A
BAE Kenworth	T370 Hybrid	8	55,000	#N/A	Truck			Kenworth	HEV	PACCAR	PX-6 280	Diesel	280.0	894.8
BAE Kenworth	Catenary Truck Project	8			Vocational, Public Transit	#N/A	#N/A	#N/A	PHEV CNG	#N/A	#N/A	Natural Gas		
Balqon	MX-30	8	66,139	#N/A	Drayage	150.0	112.6		BEV	#N/A		Electricity		
Balqon	Mule M100	7	#N/A	#N/A	Delivery, Shuttle Bus	126.0	112.6		BEV	#N/A	#REF!	Electricity		
Balqon	Mule M150	7	#N/A	#N/A	Vocational	120.0	89.0		BEV	#N/A		Electricity		
Balqon	Mule M150	8	#N/A	#N/A	Vocational	120.0	89.0		BEV	#N/A		Electricity		
Balqon	Nautilus XRE-20	8	88,185	#N/A	Yard tractor	14.0	40.2		BEV	#N/A		Electricity		
Blue Bird	All American Electric	8	36,200	#N/A	School Bus	100.0		Blue Bird	BEV	Ford	n/a	Electricity		
Boulder Electric Vehicle	DV-500	3	11,500	7,200	Vocational, Public Transit, Step Van	100.0	112.7	#N/A	BEV	#N/A	#REF!	Electricity		901.6
BYD	K9S 35ft transit	8	49,877	28,660	Transit Bus	145.0			BEV	BYD	150 kWx2 in-wheel motor	Electricity		1100.0
BYD	T5	5	16,138	9,480	Electric Class 5 truck		97.0		BEV	BYD	#N/A	#REF!		550.0
BYD	T7	6	23,578	12,974	Electric Class 6 truck	124.0	90.0		BEV	BYD	#N/A	Electricity		550.0
BYD	T9	8	120,000	23,589	Electric Class 8 truck	92.0	90.0		BEV	BYD	180 kWx2 integrated axle	Electricity		2999.0
BYD	All Electric 45ft Double Decker	8	59,100	47,000		230.0	104.6		BEV	#N/A	#REF!	Electricity		3000.0
BYD	All-Electric Quantum Rear Loader	8	57,500	21,680	Refuse Truck	76.0	90.1		BEV	BYD	#N/A	Electricity		1491.4
BYD	K9 40ft transit	8	42,659	30,865	Transit Bus	161.0	99.9		BEV	BYD	150 kWx2 in-wheel motor	Electricity		1100.0
BYD	Q1M	10	102,000	19,800	Electric terminal tractor (yard truck)	9.0	53.0		BEV	BYD	#REF!	Electricity		1500.0
BYD	C6 23ft coach	5	18,331	14,892	Transit Bus	124.0	99.9		BEV	BYD	150 kW integrated axle	Electricity		550.0
BYD	C10 45ft coach	8	49,604	40,124	Transit Bus	200.0	110.1		BEV	BYD	180 kWx2 in-wheel motor	Electricity		1500.0
BYD	K11 60ft transit	8	65,036	47,620	Transit B						180 kWx2 in-			3000.0
BYD	K7 30ft transit	7	31,957	21,381	Transit B									700.0
BYD	C9 40ft coach	7	39,683	30,836	Transit B									3000.0
BYD	40 ft. Transit Bus (k9m)	8	40,786	31,967	Public Tr									700.0
Capactiy of Texas	Pluggable Hybrid Electrical Terminal Truck	8	130,000		Termina Drayage									
Cat	Cat D7E	10	62,886		Construc material									
Chanje	V8070 Panel Van	5	16,535	9,921	Van									764.0
Charlatte	CFB2000 - Electric Inter-Line Baggage Tractor	10	12,897	#N/A	Airports	#N/A	25.0	#N/A	BEV	#N/A	#N/A	Electricity	#N/A	#N/A
Charlatte	CT5E - Cargo Tractor	10	#N/A	#N/A	Airports	#N/A	24.0	#N/A	BEV	#N/A	#N/A	Electricity	#N/A	#N/A

Data Sources:

- DOE Fleet Evaluations
- DOE FOA Projects – development / demonstration
- Zero Emissions Freight Report
- Beyond Light Duty Study (Energetics/ORNL)
- Specification literature search

Figure 5: Medium- and heavy-duty vehicle electrification inventory. Example characteristics and spreadsheet view.

To understand the trends in battery size, battery capacity was plotted by weight class (Figure 6). Note that data from the literature (blue circles) and from DOE-funded fleet evaluations (orange squares) have been included. This shows both the trend of increasing battery size with vehicle weight class and the large scatter in battery capacity found in the heavier vehicles, particularly Class 8. This variation may be due to range design decisions, duty cycle variations, and a distribution of vehicle efficiencies.

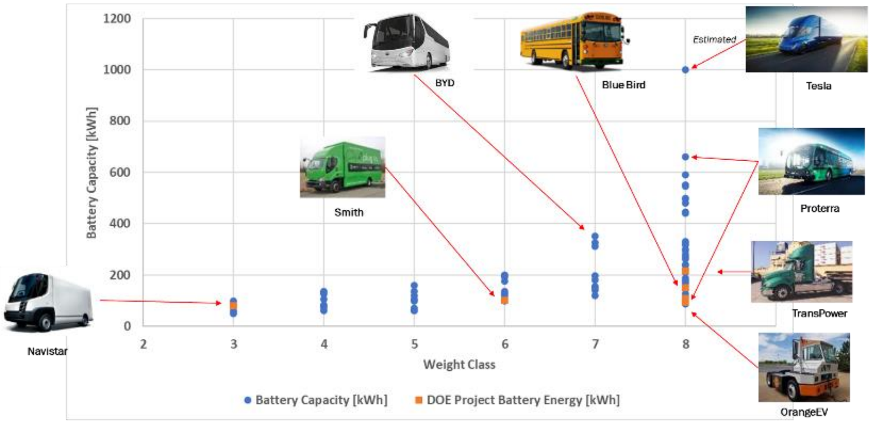
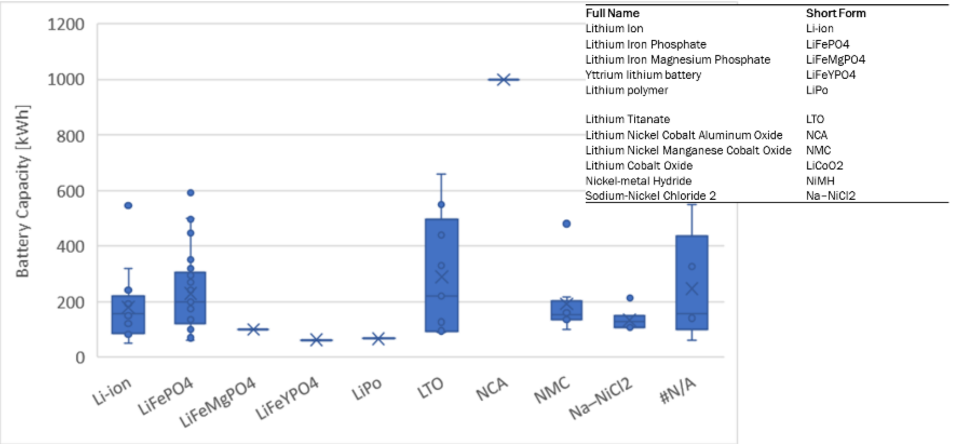


Figure 6: Battery capacity vs. weight class for select medium- and heavy-duty vehicles.

For each electrified vehicle in the inventory, battery chemistry was determined when possible. Figure 7 shows a box plot of the battery size vs. chemistry. Note that the one data point for NMC is an estimated battery size for the Tesla truck concept.



Full Name	Short Form
Lithium Ion	Li-ion
Lithium Iron Phosphate	LiFePO4
Lithium Iron Magnesium Phosphate	LiFeMgPO4
Yttrium lithium battery	LiFeYPO4
Lithium polymer	LiPo
Lithium Titanate	LTO
Lithium Nickel Cobalt Aluminum Oxide	NCA
Lithium Nickel Manganese Cobalt Oxide	NMC
Lithium Cobalt Oxide	LiCoO2
Nickel-metal Hydride	NiMH
Sodium-Nickel Chloride 2	Na–NiCl2

Figure 7: Inventory of medium- and heavy-duty vehicle battery chemistries. "Li-ion" includes batteries whose specific chemistries were not available. Source: NREL.

To better understand the vehicle efficiencies, the vehicle range was plotted against the battery size (Figure 8). The slope of this line is the energy use per mile for each weight class. For freight vehicles, the preferred figure of merit or metric for efficiency is the freight efficiency expressed in energy consumption per payload-mile. Fuel consumption standards for today's freight vehicles are expressed in gallons per 1,000 ton-miles, where the payload is the mass in tons. As electrified vehicles are further studied and characterized, their payloads in mass or perhaps volume of freight carried will need to be captured.

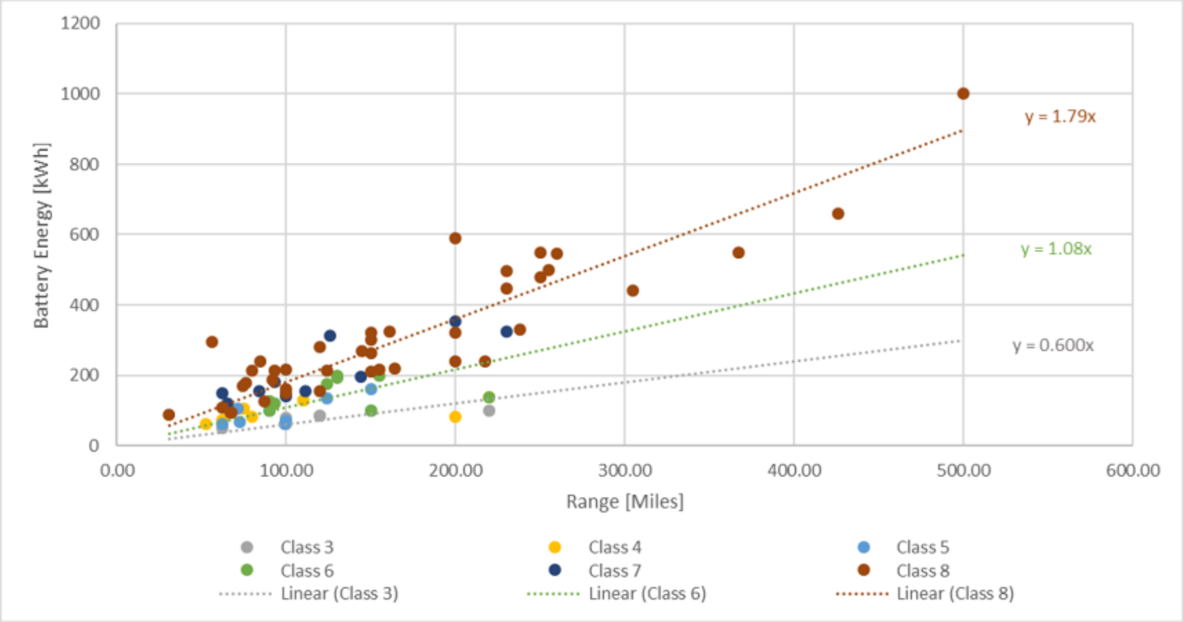


Figure 8: Range vs. battery energy for various classes of electrified medium-and heavy-duty vehicles.

Another way to look at the data is to plot the energy use (in kilowatt-hours per mile) against the vehicle weight class, as shown in Figure 9, which includes data from the literature and National Renewable Energy Laboratory (NREL) fleet evaluations. Good agreement can be seen between the measurements and inventory data, with measurements falling well within the inventory ranges.

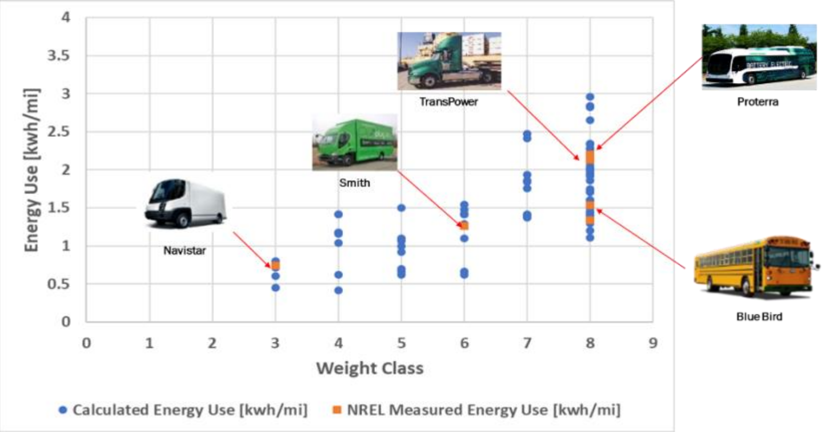


Figure 9: Energy use vs. weight class for medium-and heavy-duty vehicles. Source: NREL.

Expanding beyond BEVs, it is informative to plot the peak electric motor power against the fuel converter power for the full range of electrification architectures [BEVs, extended range electric vehicles, plug-in hybrid electric vehicles (PHEVs), fuel-cell electric vehicles (FCEVs), HEVs] as shown in Figure 10. This shows a spectrum of trade-offs in going from full electric to full conventional.

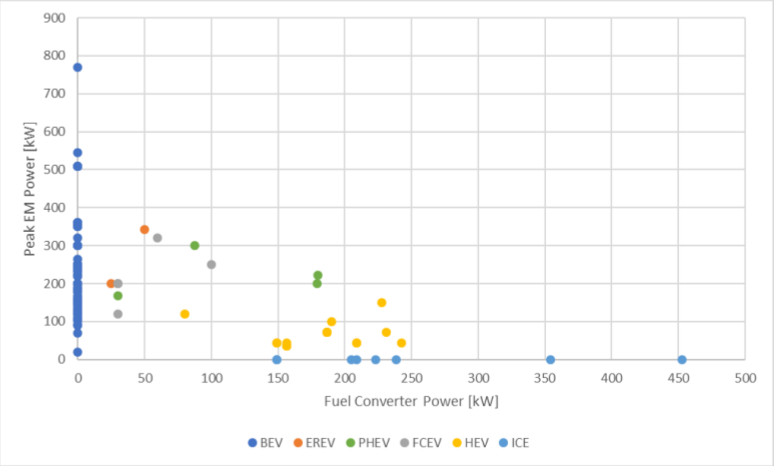


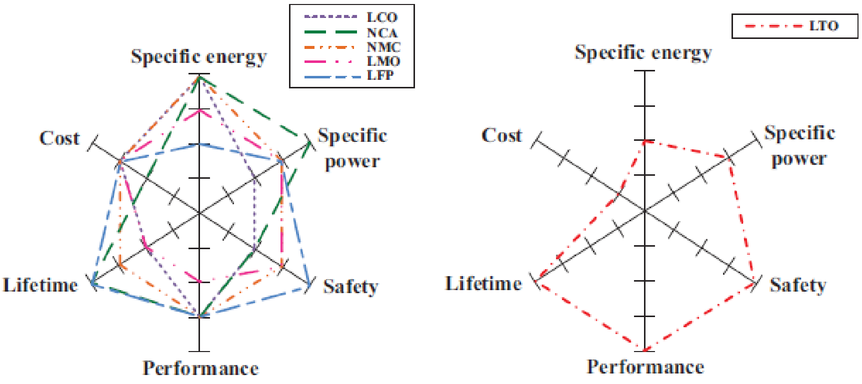
Figure 10: Peak electric motor power vs. fuel converter power for various electrification architectures and internal combustion engines. (BEV = battery electric vehicle, EREV = extended range electric vehicle, PHEV = plug-in hybrid electric vehicle, FCEV = fuel-cell electric vehicle, HEV = hybrid electric vehicle, and ICE = internal combustion engine.) Source: US Department of Energy.

Additional plots and the full database [18] may be found at https://app.box.com/s/04h4jqs50w88f5ziwvmf4o2sxbxpzhzg.

3 Medium- and Heavy-Duty Vehicle Hybrid and Electric Architectures

Given progress in reducing the cost of batteries for LDVs, along with market and regulatory drivers, electrification of the MHDV sector provides an opportunity to increase economic competitiveness and energy security while reducing environmental impact. However, the wide range of commercial vehicle operating weights, vocations, and duty cycles suggests that there may be no single solution to MHDV electrification. The following sections provide a summary of commercial vehicle electrified architectures: micro- or mild-HEV, full HEV, PHEV, FCEV, and BEV.

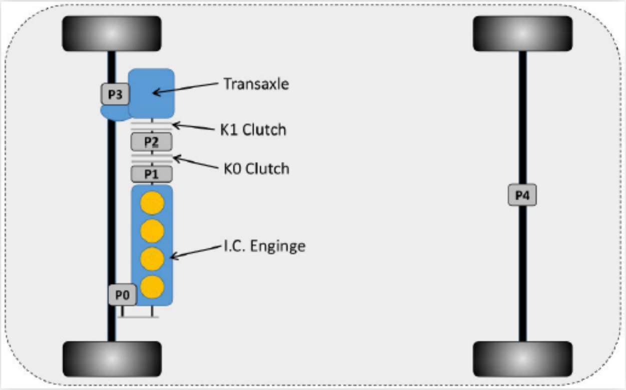
The various architectures of electrified vehicles incorporate different battery chemistries depending on trade-offs in duty cycle requirements, power density, energy density, safety, and cost. This variation can be seen in Figure 7, and Figure 11 shows a high-level overview of some of these trade-offs between lithium-ion chemistries.



(a) **(b)**

Figure 11: Trade-offs between common lithium ion chemistries. Image (a) shows Li-ion battery performance based on various cathode materials; (b) shows performance based on lithium titanate (LTO) anode material. (LCO = lithium cobalt oxide, NCA = lithium nickel cobalt aluminum oxide, NMC = lithium nickel manganese cobalt oxide, LMO = lithium manganese oxide, and LFP = lithium iron phosphate.) Source: Ana-Irina Stan et al., "Lithium Ion Battery Chemistries from Renewable Energy Storage to Automotive and Back-up Power Applications - An Overview," IEEE Conference Paper, DOI: 10.1109/OPTIM.2014.6850936. Used with the gracious permission of IEEE.

Simplified diagrams of powertrain architectures have been described in many literature sources, with examples shown in Figure 12 and Figure 13.



US Government / US Environmental Protection Agency

Figure 12: Schematic representation of the relative electric machine positioning (P_i) for different hybrid electric vehicle architectures. Source: S. Lee, J. Cherry, M. Safoutin, A. Neam, J. McDonald, and K. Newman, “Modeling and Controls Development of 48 V Mild Hybrid Electric Vehicles,” presented at the WCX World Congress Experience, 2018, SAE Technical Paper2018-01–0413; available at https://www.epa.gov/sites/production/files/2018-10/documents/sae-paper-2018-01-0413.pdf.

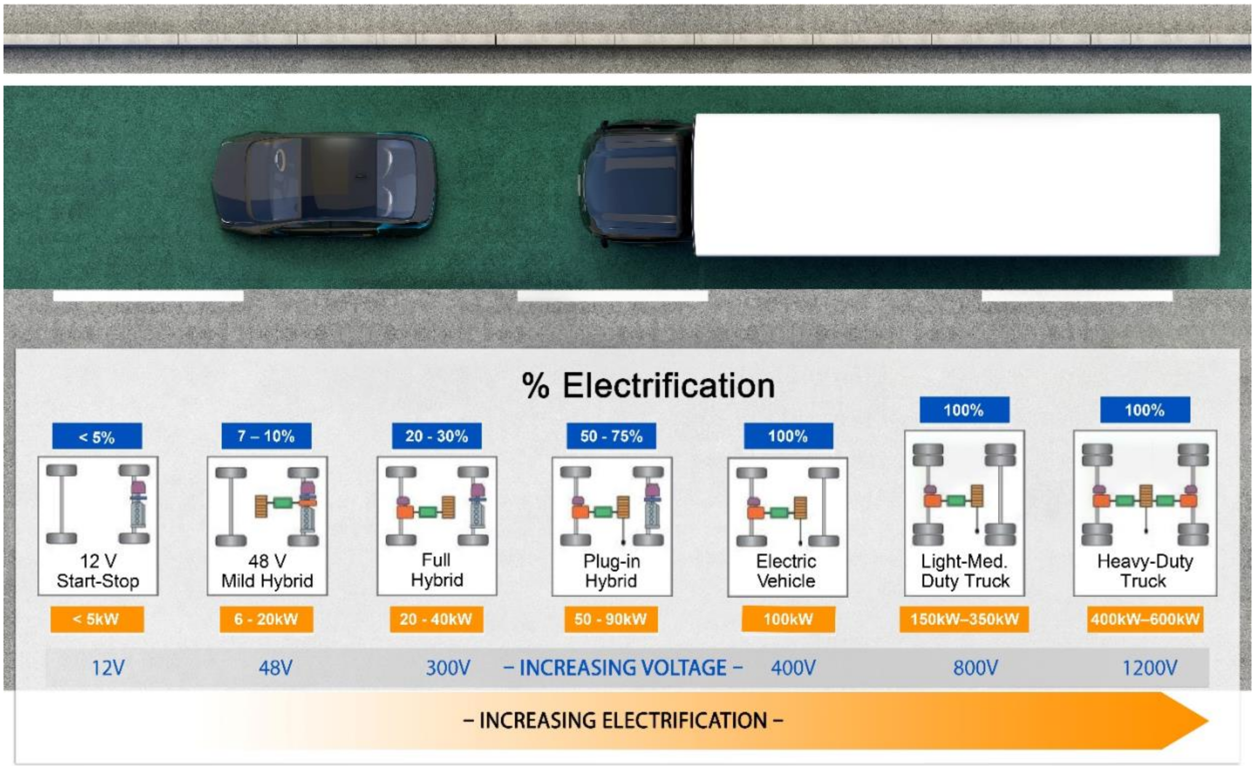


Figure 13: Various electric vehicle powertrain configurations with associated power levels and voltage requirements.

3.1 48 V Mild Hybrids

The 48 V micro- or mild-hybrid systems are among the fastest growing technologies for improving fuel efficiency in passenger vehicles, with limited applications in commercial vehicles. Mild-hybrid powertrains include a small electric drive and energy storage combined with a transmission and internal combustion engine (ICE). These systems are capable of limited low speed all electric operation, temporary boost, limited accessory load during engine-off operations and limited brake regeneration. This powertrain category also includes both micro-hybrids, which only provide stop-start functionality, and electric power takeoff systems that electrify the power takeoff functionality of MHDVs.

Mild-hybrid technology can be applied to medium-duty (MD) and HD trucks and buses, Class 2b through Class 8, but only a limited number of applications have been deployed in the US market.

The AVID 48 V mild-hybrid [19] is an example of a mild-hybrid delivery truck developed for the European market. It has a motor-generator connected to the engine for regenerative braking and engine torque augmentation.

The AVID system electrifies power steering, cooling fans, and the air compressor. For LDVs, 48 V systems are reported as likely the most cost-effective path to increasing miles per gallon by about 15% to meet fuel economy regulations. Further, 48 V is a low enough electrical potential to avoid the need for added electrical safety measures, which add cost. The 48 V systems can also be used in augmenting turbo- or supercharging boosting systems. The 48 V device usually replaces a conventional engine starter motor. Ricardo recently performed demonstrations of 48 V systems up through HD tractor-trailer rigs [20]. The Future Truck Committee of the American Trucking Associations' Technology & Maintenance Council released a study on 48 V systems for commercial vehicles in 2015 [21]. In vehicles equipped with engine shutoff, the added power of 48 V systems provided a smoother and more rapid restart. All of the five teams in DOE's Supertruck II project are investigating 48 V mild-hybrid technologies. As an example, the 48V system being developed in the Daimler Supertruck 2 is illustrated in Figure 14.

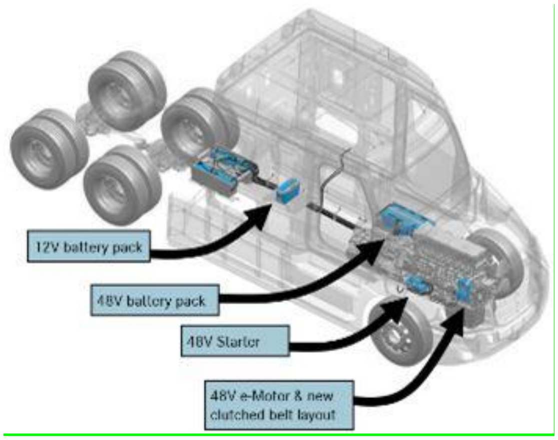


Figure 14: 48 V configuration for Daimler Supertruck 2. Source: Courtesy of Daimler Trucks, https://www.energy.gov/sites/prod/files/2019/06/f63/ace100_Rotz_2019_o_5.1_10.55am_jl.pdf.

The 48V motor-generator configuration replaces the customary alternator and can pull power off the engine in place of the alternator, or use battery power as an e-motor to assist powertrain and drive the starter, and can enable energy recovery as a mild hybrid.

A potential benefit of MHDV 48 V mild-hybrid systems that needs further consideration and analysis is augmented acceleration for traffic blending. Traffic congestion can be dominated by a small number of MHDVs because they cannot match the acceleration of LDVs on the same roads. The ability to boost the acceleration of MHDVs with mild-hybrid powertrains, even for short periods, conceptually may help save energy and money by mitigating congestion for all vehicles sharing the road. Additionally, 48 V systems may also improve vehicle gradeability.

3.2 High Voltage Full Hybrids, including Plug-In Hybrid Electric Vehicles

Full hybrid powertrains include an electric drive system capable of providing all or a substantial fraction of traction power (at some operating conditions) along with the required energy storage, combined with a transmission and ICE. These hybrid powertrains support multiple vehicle architectures (series, parallel, or power split). For at least part of the vehicle acceleration-speed range, they can sustain all vehicle traction needs on their own without any contribution from the ICE. A substantial portion of braking energy can be recuperated in the energy storage system.

Examples of current state-of-the-art full hybrids include the following [18]:

- Wrightspeed Fulcrum turbine generator (extended range series configuration)
- Hino diesel-electric parallel hybrid for Class 5
- Ford’s Qualified Vehicle Modifier program includes electric or hybrid vehicles such as by XL Hybrids, Motiv Power Systems, and Lightning Hybrids (now LightningElectric)

The key subsystems in a full HEV powertrain are illustrated in Figure 15. The complexity of deeply integrating the system for optimum performance over a diversity of duty cycles is self-evident, and the need for more powerful, flexible computational tools for integration and shortening (lowering cost) of the development cycle has been voiced by industry. The optimization may focus on fuel consumption, emissions, or TCO depending on the operating requirements and regulations. The benefits of the powertrain complexity are the increase in fuel efficiency and potential reduction in emissions without the need to locate and plug in to an electricity infrastructure.

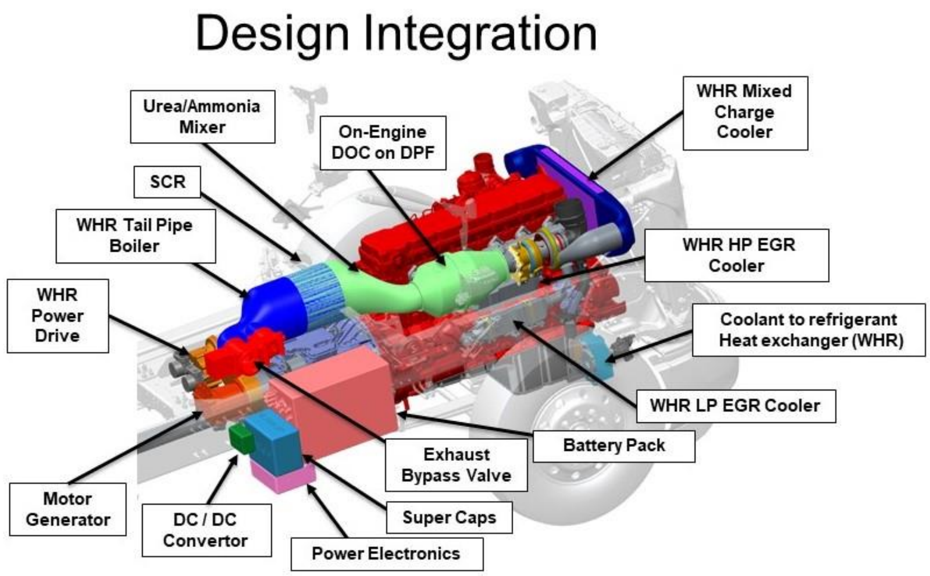


Figure 15: Hybrid electric-combustion powertrain requires deep integration and optimization of numerous subsystems. Illustration courtesy of Cummins, Inc. Used with permission.

Plug-In Hybrid Powertrain. A plug-in hybrid powertrain (whether mild or full) has the same features that a hybrid powertrain has, but it can also be recharged via an off-board source, most of the time the grid, whereas a hybrid relies on brake energy regeneration or the onboard ICE as the only energy source. Plug-in hybrids also tend to feature larger energy storage systems for prolonged all electric operation.

Examples of recent plug-in hybrid technology include the following [18]:

- Cummins PowerDrive 6000:
    - Demonstrated on a Class 6 Kenworth T370 with Cummins B6.7 diesel engine
    - 50-mile electric range, 300-mile hybrid range
    - Shifts between pure electric and hybrid (series or parallel)
    - 100 kW fast charge and 6.6 kW standard charge
    - Aftermarket add-on to a variety of MD and HD vehicles
- Ford Transit Cargo Van:
    - Class 2b PHEV
    - 31-mile electric range, 310-mile hybrid range
    - 1,000 kg payload capacity
    - 1.0-liter EcoBoost engine
- TransPower ElecTruck:
    - Class 8 drayage demonstration truck
    - Compressed natural gas (CNG) range extender engine
    - 60- to 120-mile electric range, 200-mile CNG hybrid range

3.3 Fuel Cell Hybrids

Fuel cell systems remain under active development for MHDVs as well as passenger vehicles. They are often integrated into a hybrid powertrain system with batteries. The DOE Fuel Cell Technologies Office has prepared a document of targets for fuel cell–powered freight trucks.

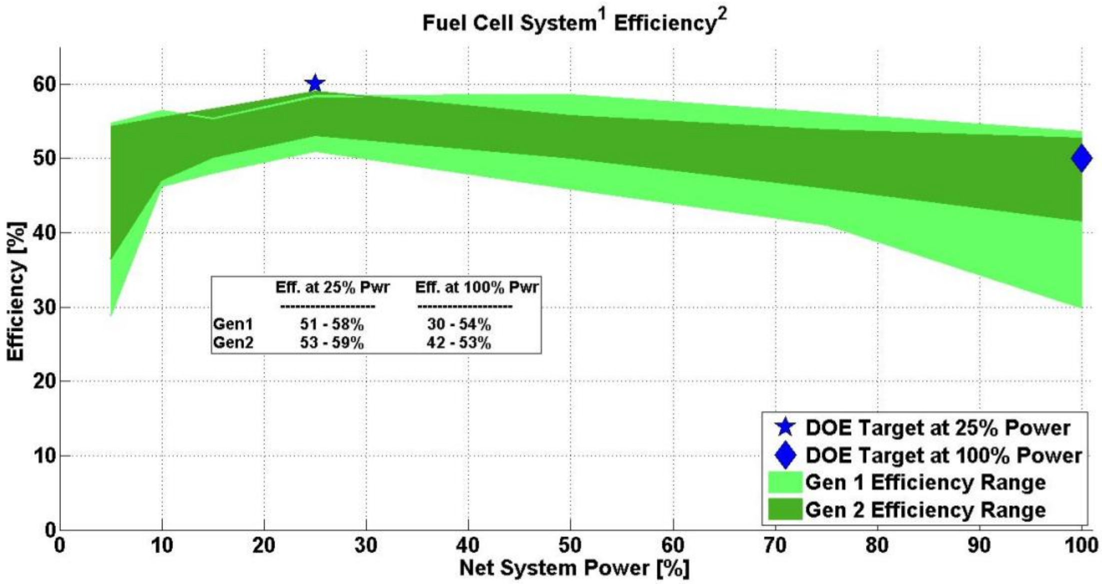
Most often fueled by hydrogen, fuel cells are advantageous in applications where there are requirements for zero emissions of carbon (CO_2), as well as zero emissions of NOx and hydrocarbon pollutants. When renewable hydrogen is available, the fuel cell vehicle is petroleum independent and essentially zero-carbon. Fundamentals of fuel cell operations and history can be found in numerous references and will not be repeated here. The National Academies reviewed and assessed fuel cells for MHDVs, noting progress in technology and numerous field trial vehicles [22], including the planned Nikola fuel cell Class 8 truck. Primary challenges for fuel cells are the cost, availability of hydrogen refueling, and volume and weight requirements of hydrogen storage.

Gangloff et al. [23] examined a number of packaging options and tank configurations for hydrogen MHDVs and concluded that “available packaging volumes onboard MD and HD vehicles appear sufficiently large to support deployment of FCETs [fuel cell enabling technologies] into a number of market segments.”

Kast et al. [24] concluded that “Onboard hydrogen storage is able to satisfy the vehicle range requirements for at least 90% of daily routes based on data collected from US census survey results and real world drive cycle data collection.” However, just considering the Class 8 over-the-road trucks, the hydrogen fuel cell systems could accommodate ~40% of trip requirements.

The efficiency of the most common vehicular fuel cell, the proton exchange membrane device, is somewhat higher than widely used ICEs because the direct conversion of chemical energy to electricity has lower losses than the integrated combustion and heat-to-work conversion (chemical energy to mechanical power) in ICEs. The efficiency advantage helps mitigate the hydrogen storage issue. However, fuel cells have their maximum efficiency at low load levels representative of low speed urban driving, whereas ICEs exhibit peak efficiency at medium to high loads that are more representative of hauling freight or highway speeds. The fuel cell efficiencies discovered in real vehicles, reported in Figure 16 [25] are furthermore not greatly higher than today’s production HD diesels at high loads.

DOE has a target cost for fuel cells of $45/kW for 2025 and estimates the present cost at roughly $200/kW [26]. Progress is being made on reducing the cost and the associated amounts of catalyst materials needed in the fuel cell. Fuel cell cars in 2017 can be purchased or leased by the public from Toyota, Honda, and Hyundai. Fuel cell buses are in operation as demonstration vehicles in several states, with numbers in transit fleet operation totaling 21 as of 2016 [27]. Kenworth recently announced a demonstration of a Class 8 fuel cell truck in partnership with Toyota. The press reports indicate they are not hybrids, having only small batteries for accessories



[1] Gross stack power minus fuel cell system auxiliaries, per DRAFT SAE J2615. Excludes power electronics and electric drive.

[2] Ratio of DC output energy to the lower heating value of the input fuel (hydrogen).

[3] Individual test data linearly interpolated at 5,10,15,25,50,75,and 100% of max net power. Values at high power linearly extrapolated due to steady state dynamometer cooling limitations.

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Figure 16: Fuel cell efficiencies. Source: K. Wipke, S. Sprik, J. Kurtz, T. Ramsden, C. Ainscough, and G. Saur, *National Fuel Cell Electric Vehicle Learning Demonstration Final Report*, NREL, NREL/TP-5600-54860, July 2012.

A recent vehicle analysis and simulation project carried out by Argonne National Laboratory investigated optimizing fuel cell trucks comparing range-extender hybrids to other hybrid fuel cell powertrains. Optimizing for lowest cost of ownership, the study showed that battery capacity was a pivotal parameter in the economics and overall total cost of ownership (TCO). Generally, the optimal battery size was much smaller than intuitive estimates [28].

The limited availability of hydrogen refueling remains a major barrier to expanded use of fuel cell vehicles. There were about 40 hydrogen fuel stations in the United States as of 2018, almost all in California, and they are built for passenger vehicles. Similar to the situation with natural gas, large freight fleets would likely establish hub fuel stations for hydrogen. Nikola has publicized plans to build hydrogen fueling facilities for trucks [29]. Nikola Motor Company has announced plans to offer a fuel cell–powered Class 8 truck as well as plans to construct a hydrogen refueling network across the United States. It will have a hybrid powertrain with a battery large enough for a 100–200 mile battery-only range.

3.4 Battery-Only Electric

BEVs do not include an ICE and rely solely on the electric drive and high-voltage (HV) battery for their traction needs. They include a transmission, but it is often a single-speed gear ratio—or direct drive, as electric machine torque and speed capabilities can be sufficient to cover most operating conditions (low speed on grade and high speed on highway) without a multispeed transmission. Multispeed transmissions can offer overall efficiency and performance gains by operating the electric motor in regions of higher efficiency or by improving drivetrain torque across the vehicle speed range. The energy storage system size is much larger than for hybrid vehicles to provide a range comparable with conventional vehicles. The absence of a conventional engine forces the electrification of all accessories such as brake, power steering, HVAC, and all electric loads on the vehicle in general.

This technology has been applied primarily to buses and MD vocational vehicles, Class 2b through Class 6, although it is beginning to be offered in larger Class 7–8 trucks and vocational vehicles. Field data obtained through research programs have provided insight and valuable fleet experience in a number of locations.

The data from a number of field deployments are available through “Fleet DNA” and have been presented on many occasions [30], but additional information based on the status of the prototypes and companies involved in testing them are available in the Inventory described in Section 2.

In 2017, the International Council on Clean Transportation (ICCT) listed about 40 worldwide demonstration projects for all-electric trucks, plus additional projects using in-road or catenary power (Figure 17). The zero-emission commercial vehicles in production are growing in number and span all of the weight classes. For example, the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) in California lists more than 60 zero-emission (electric) bus and truck models eligible for its program. A similar program in New York lists about 50 eligible vehicles from conversion companies and major original equipment manufacturers (OEMs).

In its annual outlook for electric vehicles, the International Energy Agency (IEA) provides the chart in Figure 18 showing planned and ongoing introductions of electrified MHDVs.

Table 2 shows further details of examples of current production and planned plug-in commercial vehicles.

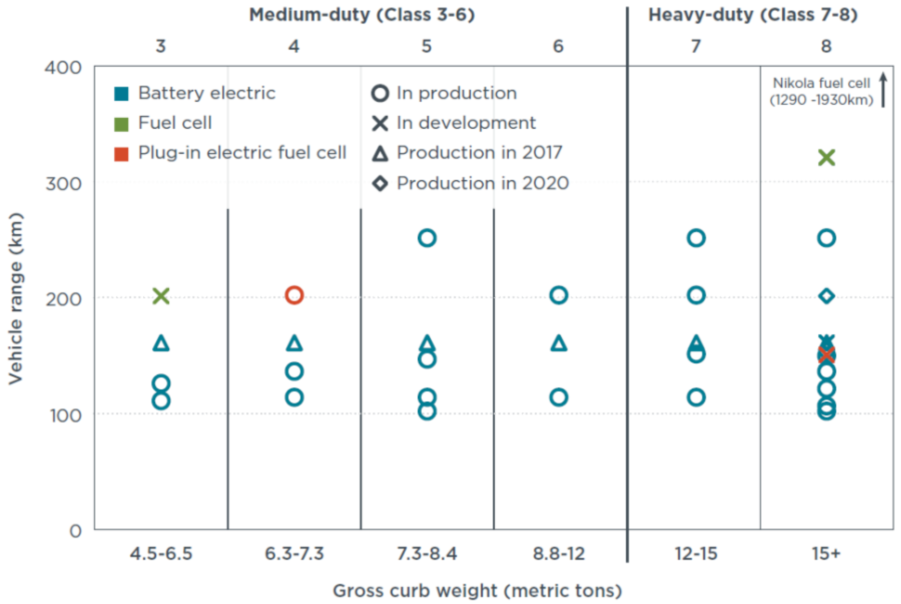

Figure 17: Recent and projected electric medium- and heavy-duty vehicles as described by the International Council on Clean Transportation. Source: M. Moultak, N. Lutsey, and D. Hall, "Transitioning to zero-emission heavy-duty freight vehicles," International Council on Clean Transportation (ICCT), Washington, DC, White Paper, September 2017.

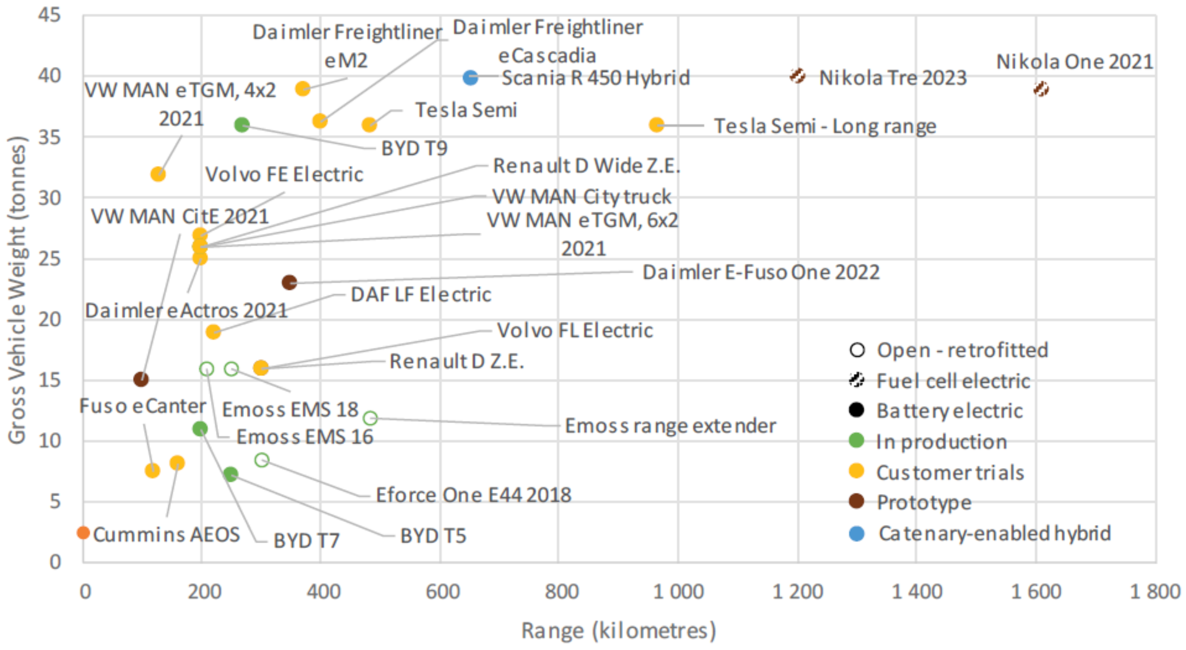

Figure 18: Illustration of trial, prototype, and production electric medium-and heavy-duty vehicles. Source: *Global EV Outlook 2019*, International Energy Agency, June 2019.

Table 2: Examples of Current, Planned, and Recent Class 3–8 Electrified Commercial Vehicles, Including Hybrids and All Electric

Vehicle Platform		Vocation	Powertrain Type	Motor Power (Peak/ Continuous) [kW]	Battery Capacity [kWh]	Battery Type	Range [miles]
	Proterra Catalyst[a]	Class 8 Transit Bus	Electric vehicle (EV)	110-165 kW cont	220-330	Li-ion NMC	136–193
	BYD[b]	Class 8 T9	EV	358	350	LFP	125
	Daimler[c]	Class 6/7 eM2	EV	358	325	NA	230
	Volvo[d]	Class 8 FL	EV	174 cont	100–300	NA	Up to 300
	Daimler[e]	Class 8e Cascadia	EV	540 peak	550	NA	250
	Blue Bird[f]	Class 8 School Bus	EV	235	150	$LiNiMnCoO_2$ (NMC)	100
	Daimler[g]	FUSO eCanter	EV	185	82	Li-ion NMC	80

Table 2 (continued)

Vehicle Platform		Vocation	Powertrain Type	Motor Power (Peak/Cont) [kW]	Battery Capacity [kWh]	Battery Type	Range [miles]
	Lion Electric[h]	Lion 8 Urban Class 8	EV	Up to 350	132-480	Li-ion NMC	Up to 250
	Odyne[i]	Powertrains for Class 6–8 Utility Trucks	Plug-in hybrid EV	95/56	14-28	Li-ion	Various

[a]Photo source: Proterra; available at https://www.proterra.com/vehicles/catalyst-electric-bus/.
[b]Photo source: BYD; available at https://en.byd.com/truck/.
[c]Photo source: Steve Martinez, “Daimler Delivers Electric eM2 Truck to Penske Truck Leasing, in *HDT Truckinginfo*, December 20, 2018; available at https://www.truckinginfo.com/321715/daimler-delivers-electric-em2-truck-to-penske-truck-leasing.
[d]Photo source: Volvo Trucks Global, “First electric Volvo trucks delivered to customers” [press release], 2/19/19; available at https://www.volvotrucks.com/en-en/news/press-releases/2019/feb/pressrelease-190219.html.
[e]Photo source: Freightliner [Daimler]; available at https://freightliner.com/e-mobility/.
[f]Photo source: Blue Bird Corporation; available at https://www.blue-bird.com/electric.
[g]Photo source: Daimler, “Daimler hands over FUSO eCanter to Penske Truck Leasing in the US [press release], undated; available at https://media.daimler.com/marsMediaSite/en/instance/ko/Daimler-hands-over-FUSO-eCanter-to-Penske-Truck-Leasing-in-the-US.xhtml?oid=42808954&ls=L2VuL2luc3RhbmNlL2tvLnhodG1sP29pZD0zMDAxMDQ1OSZyZWxJZD02MDgyOSZmcm9tT2lkPTMwMDEwNDU5JmJvcmRlcnM9dHJ1ZSZyZXN1bHRJbmZvVHlwZUlkPTQwNjI2JnZpZXdUeXBlPWxpc3Qmc29ydERlZmluaXRpb249UFVCTElTSEVEX0FULTImdGh1bWJTY2FsZUluZGV4PTAmcm93Q291bnRzSW5kZXg9NQ!!&rs=2.
[h]Photo source: Fred Lambert, “Lion unveils all-electric class 8 truck, will deliver emission-free booze,” *electrek*, March 12, 2019; available at https://electrek.co/2019/03/12/lion-electric-class-8-truck/.
iPhoto source: Odyne Systems, LLC; available at https://www.odyne.com/about-odyne/.

3.5 Distinguishing Aspects of Electrification of Commercial Medium- and Heavy-Duty Vehicles vs. Electric Passenger Cars

Market-success of electrified MHDVs will require development beyond merely scaling devices and designs from LD EVs for passenger travel. The critical distinguishing differences between these two sectors are summarized here. While technology advancement in LDVs can often benefit the MHDV market, key differences result in R&D gaps which are limiting the electrification of commercial vehicles.

- The life expectancy of an HD vehicle can exceed 1 million miles, and the *average* age of commercial trucks on the road is about 14 years. These miles are also often over more demanding duty cycles. Therefore, many components and systems must be more durable than those intended for LD applications of about 15 years and 150, 000 miles.

- Cost-effective freight movement has required vehicles with roughly twice the peak horsepower, up to 5 times greater energy consumption, and gross vehicle weights (GVWs) up to 80,000 lb, placing much greater loading upon both the mechanical and electrical components of MHDV powertrains compared to LD counterparts. The electrical power flowing to and from the battery (propulsion and regenerative braking modes) is much greater than that for passenger vehicles. As shown in Figure 19, PEV MHDV energy use is 500 to 5,200 Wh/mile, while LD PEVs typically use 250 to 400 Wh/mile. For the MHDVs, these extremes of energy consumption are due to the mass of the payload (and vehicle), the road grade, and other duty cycle factors.

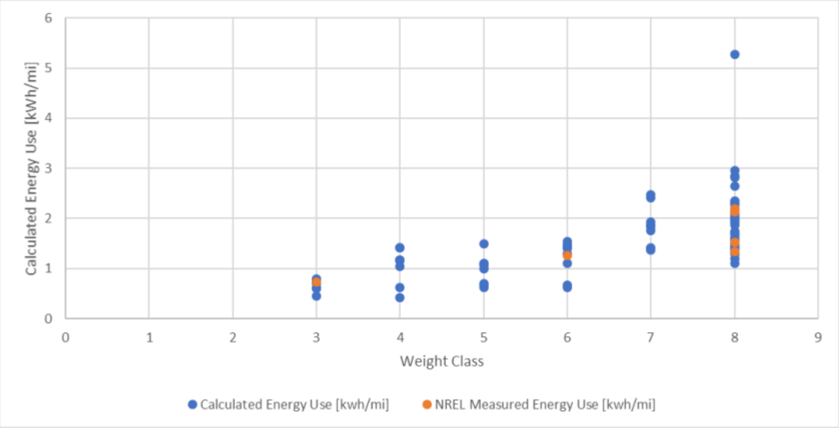

Figure 19: Energy use by weight class for Class 3 through Class 8 battery electric vehicles (NREL = National Renewable Energy Laboratory).

- Greater energy consumption for MHDVs requires much larger batteries if the same range as that for engine-powered trucks is approximately maintained with electric systems. Today's MHDV PEV batteries have as much as 660 kWh, while near future concepts may exceed 1,200 kWh. It is expected that freight duty cycles will result in deeper battery discharges than in LDV experience, tending to shorten the useful life of the batteries. Faster charging rates may impact cycle life as well. Goals for battery cycle lifetimes and TCO analyses should consider these effects. Fast charging these batteries will require substantially more power compared to current extreme fast charging (XFC) for LDVs (350 kW) at much greater than a megawatt. This presents new challenges and requires much higher power chargers, connectors, and infrastructure than currently considered for LDVs.
- The MHDV market comprises a diverse set of vocational uses that must be accommodated with competitive TCO. MHDVs are purchased based on business priorities such as TCO and corporate sustainability goals. These vehicles must address a broad range of duty cycles and use cases. This often leads them to have highly customized options and limits standardization.
- Commercial MHDVs are intended for a work function, that is, to carry volumes or masses of goods or people. As a result, they are expected to operate at total weights up to 2 times the unloaded weight, and their regulatory metrics are based on fuel used or emissions produced per payload-distance (ton-mile), not miles per gallon or per kilowatt-hour.
- With high annual VMT in the MHDV sector and high fuel consumption per mile, fuel costs will typically exceed the purchase price of the vehicle in a few years. This places high priority on the

overall vehicle efficiency, even with EVs, to accrue fuel savings that will pay back the very high cost of energy storage in 2–3 years.

- The annual sales volume of MHDV trucks is about a twentieth that of cars, and they can be bought in a thousand times more configurations. This results in the need to develop scalable component and system design that can address the broad range of MHDV vocations, duty cycles, and missions.

4 Important Factors in Design and Market Uptake of Electrified Commercial Vehicles

4.1 Total Cost of Ownership

Unlike passenger vehicles where consumer preferences for style and image are key factors in selecting among options, the choice decision for trucks and buses is largely driven by business case. Function is the primary consideration—commercial vehicles must be capable of meeting job requirements. After functional requirements, payback, return on investment, and TCO often serve as key criteria in the decision to adopt a new vehicle technology. TCO includes both the capital expense to purchase the vehicle and the operating costs (e.g., driver compensation, fuel, maintenance and repair, and insurance) over either the vehicle lifetime or the ownership period. If a business adds plug-in vehicles to its fleet and installs charging equipment, the amortized cost of the recharging system may be included in the TCO as well. TCO is a fundamental discriminator between electrification challenges for passenger vehicles vs. commercial MHDVs.

Cost parity occurs if the alternative technology TCO is the same or less compared to a conventional vehicle for a specified lifetime. A payback criterion compares the total cost cash flows for alternatives and determines the point when cost parity occurs—when the investment "pays back"—and compares this value to a threshold value that often falls between 2 and 3 years. A return on investment criterion compares the difference in lifetime TCO, i.e., the cash flow following payback, to the capital investment to determine the investment's yield, which is compared to either the "next best alternative" investment or to a threshold value.

While the concept of TCO seems straightforward, application is not simple and decision makers may struggle with questions about what cost elements to include and how to obtain reliable data. In addition, many elements are highly uncertain or unknown, including future fuel and electricity prices, future vehicle use and lifetime, new technology performance and reliability, and existing or pending incentives and tax policies. Parameters used for the analysis (e.g., the appropriate discount rate) can be controversial, though they may be dictated by policy.

TCO serves as an important calculation for selection, but it typically is not the only consideration. A number of "soft" costs and benefits, direct or indirect, are important but often hard to quantify and therefore not included in TCO. Examples include driver and maintenance technician training, improved driver comfort, and extended operating hours. Company image is another important soft cost, and fleet decisions may support corporate sustainability goals. Capital availability and fleet operational needs also must be considered. If a new technology has lower TCO but costs twice as much, purchasing the new technology may mean foregoing a second needed vehicle replacement. Finally, new powertrain technologies pose unique risks as parts and repair networks may be immature and, in the case of start-ups, manufacturer support may not be guaranteed.

4.1.1 Review of total cost of ownership analyses

Fleet managers may use TCO calculators to inform purchase decisions, and decision makers may also use them to guide research, investments, or policy. Trade associations and suppliers have developed TCO calculators and made them available to the public, though these calculators generally do not include cost data and users are required to provide their own. For this assessment, a number of techno-economic studies that compared costs for conventional commercial vehicles to battery electric and other alternative powertrains were reviewed, although there is variation in the vehicle applications, markets (e.g., United States, Europe, China), cost elements included, and assumptions.[2] Analysis coverage ranges from rough vehicle capital costs and fuel expenditures to detailed component and operational costs such as taxes and incentives. The North American Council on Freight Efficiency (NACFE) assessed EV TCO from the fleet owner perspective for the US MD market (10,001–26,000 lb GVWR) [31]. They concluded that, while electric trucks are a viable option in many operations, they are not the solution for every application and there are still a large number of unknowns. These uncertainties include economic, regulatory, and electric power issues, but key unknowns arise from the relative immaturity of the technology. Significantly, there are "insufficient field data to establish a baseline for comparison against alternative truck types," including maintenance and repair costs, battery and vehicle expected lifetime, and vehicle residual value. Each unknown represents a risk for fleet owners.

The following are key takeaways from commercial EV TCO studies.

- Driver compensation and fuel are the largest operational cost elements for conventional vehicles.
- Energy storage (batteries) is the largest cost element for PEVs.
- Fuel expenditures represent the largest cost savings for electrified vehicles.
- Electricity price projections are difficult due to utility demand charges. Electricity costs carry uncertainties such as whether there will be additional costs for trained personnel to operate high powered fast-charging systems.
- Annual mileage and vehicle lifetime are key determinants of cost parity.
- Specific applications in some markets may be at or near cost parity, especially when incentives are included in the analysis.
- Uncertainty remains a significant issue with TCO analysis.

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[2] Moultak, Lutsey, and Hall (2017), for example, review 13 quantitative analyses of medium-and heavy-duty vehicle electric drive and other advanced technologies, 12 of which provide cost analyses.

When fleet managers use TCO calculators, they have access to data on baseline vehicles specific to their operations. Decision makers, on the other hand, need to consider the market as a whole. Unfortunately, representative, complete, and current data on use are scarce. Analyses typically apply average vehicle mileage and lifetime from partial or outdated data sets and neglect variation among applications and users. This complicates interpretation of the results (e.g., do the findings apply to 50% of the market? 75%?).

4.1.2 Findings

Finding 1: Battery improvement via R&D remains a high priority

The cost and specific energy of battery packs generally are improving with time and are enabling a favorable TCO in some applications. Estimates of full-pack battery costs ranged from $155 to $360/kWh based on packs developed for LDVs [32], but MHDV-specific requirements such as high lifetime mileage, deeper discharges per cycle, overall ruggedness, and resistance to temperature extremes, along with low sales volumes, are likely push costs toward the upper end of this range. IEA noted that some attributes of MHDV battery packs could offset these cost-increase features. The relatively high daily range needed by commercial vehicles results in battery costs that drive vehicle incremental costs as high as 50%–100% of the price of a conventional truck.[3] In addition, large battery packs can reduce available cargo capacity in terms of weight and/or volume, effectively reducing revenue per mile. Significantly, the duty cycles that are best suited to electrification entail shorter trips with frequent stops that provide opportunities for regenerative braking, engine-off at idle, and ample time for recharging. Unfortunately, these duty cycles are also associated with lower annual mileage and therefore longer payback periods, resulting in a trade-off between battery capacity (range) and payback. While these duty cycles accrue low mileage relative to other MHDV applications, they still result in high annual mileage relative to LDVs, and lifetime mileage for long-haul tractor trailers can exceed 1 million miles. It is expected that TCO analysis will indicate the need for battery lifetimes exceeding current LD technology, or replacement costs must be considered during the life of the vehicle and disposal or recycling must be economical.

Finding 2: Charging infrastructure is key

A robust charging infrastructure could reduce range requirements and thus the need for large battery packs. However, this infrastructure would need to be convenient and high power to minimize the time the freight vehicle is out of service for recharging. It is uncertain whether the cost of recharging would include payment to skilled high-voltage operators.

Finding 3: EV energy efficiency should be an R&D focus

Because of the higher efficiency of electric powertrains and motors compared to diesel engines and geared transmissions, the energy consumption per mile for an electric truck may be one-quarter to one-half that of a modern conventional truck as shown in Figure 20. However, electricity still is a significant and highly uncertain operating cost for PEVs. For example, a long-haul truck driving 100,000 miles per

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[3] Example is 300 kWh battery pack in large truck at 200 $/kWh is $60,000. About half the cost of a conventional truck.

year with an average 2.0 kWh/mile energy demand (see Figure 19), paying 14 cents/kWh, would incur annual energy costs of $28,000. If the utility assesses demand fees for charging during peak hours, these costs could soar.[4] The cost contributions of electric motors, inverters, converters, and controls are much smaller than for the batteries for all EVs, such that R&D toward improving the efficiency and power density of the electric drive components is a higher priority than reducing their cost.

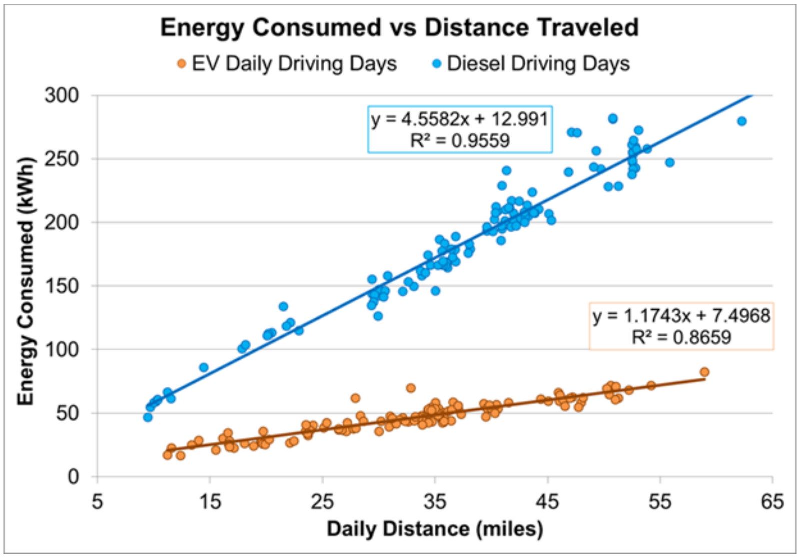

Figure 20: Energy consumption for medium-duty plug-in vehicles compared to conventional diesel. Source: Robert Prohaska et al. 2016. *Field Evaluation of Medium Duty Plug-in Electric Delivery Trucks*, NREL/TP 5400-66382, National Renewable Energy Laboratory, December 2016.

The energy efficiency of conventional engine-powered vehicles is the subject of continued worldwide research, yet the importance of efficiency is somewhat understated for electric trucks.

- The powertrain efficiency for EVs is much higher than for engine-powered vehicles, yet there is opportunity for improvement.
- The EV and charging system efficiencies influence not only the energy consumption cost, but also the all-important range and therefore the size of the costly battery pack.
- Vehicle attributes need not follow the paradigms of diesel vehicles and efficiencies may be uniquely available for EVs.

Vehicle powertrain simulation reveals the sources of the BEV efficiency advantage, and opportunities, in more detail. As shown in Figure 21 from a representative MD delivery truck simulation, about 75% of the available battery energy goes to propel and operate the vehicle, whereas in the analogous MD diesel engine powered truck, only about 35% of the fuel energy translates to useful work to propel the vehicle (Figure 22). This vehicle-level comparison does not include the losses incurred in generating and transmitting electric power. For completeness, we note that hybrid-electric powertrain simulations

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[4] Rapid Transit Denver reports that demand charges account for 82% of electricity costs to operate the electric shuttle buses that serve 16th Street Mall in downtown Denver. (John Aguilar, “RTD’S 16th Street Mall buses, Electric costs more than diesel.” *The Denver Post*, May 15, 2019.)

reveal reductions and redistributions of the engine losses for estimated fuel savings of about 30% for an average delivery truck drive cycle and 5%–10% for Class 8 vehicles. The impact of electrified powertrains on TCO is highly dependent on duty cycle, which is discussed further in Section 4.2.

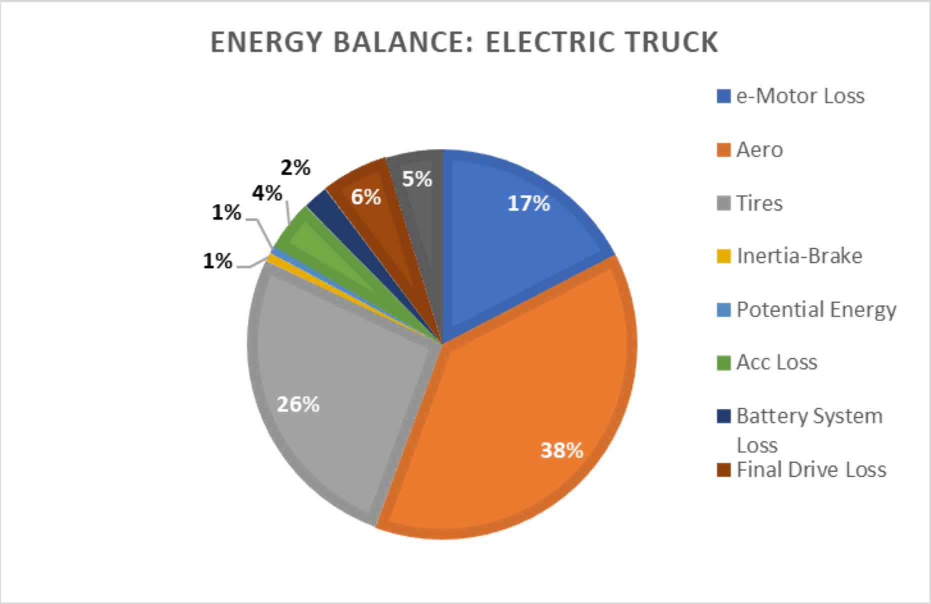

Figure 21: Energy audit of a battery electric delivery truck (34k lb) over a drive cycle derived from actual vehicle use. The modeled energy consumption is 1.44 kWh/km. Source of data: Gao, Zhiming et al., "Evaluation of Electric Vehicle Component Performance Over Eco-Driving Cycles," *Energy* 172 (2019) 823e839.

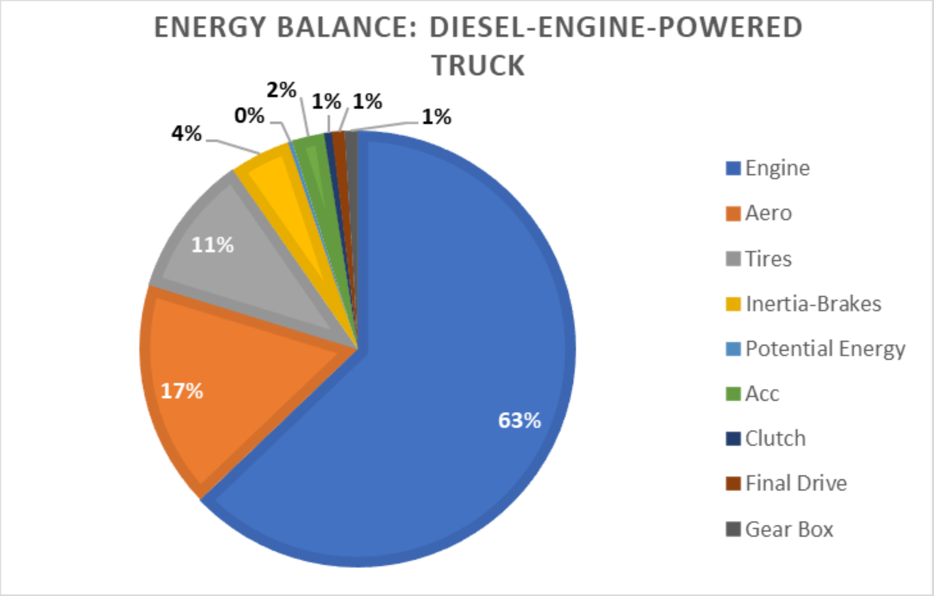

Figure 22: Energy audit from simulation of a diesel-engine–powered delivery truck with same overall configuration as in Figure 21. Via simulation, the overall energy consumption is 3.32 kWh/km. Source of data: Gao, Zhiming et al., "Evaluation of Electric Vehicle Component Performance Over Eco-Driving Cycles," *Energy* 172 (2019) 823e839.

For a fully electric truck, the efficiency of the electric drive system is doubly important because it impacts the vehicle range and size of the battery pack in addition to the energy consumption. For a Class

8 electric truck, for example, a 10% higher efficiency for the electric drive system could enable a 10% reduction in the needed battery pack capacity, favorably impacting TCO.

TCO benefits can accrue from any measure that improves the vehicle efficiency, including reducing weight, aerodynamic drag, and friction losses. New PEV designs for efficiency need not follow those of their conventional counterparts, but rather can take advantage of opportunities presented by relocation of the powerplant to the axles and elimination of components such as drive shafts, engine cooling, exhaust, and aftertreatment systems. Overall, the truck can be configured for maximum cargo volume with fewer constraints, and in most shipments volume limits are more frequently reached than weight limits. Clean-sheet electric freight designs may provide much greater opportunities for efficiency compared to overlaying electric drive systems on conventional vehicle designs.

Finding 4: Cost uncertainties and variability need to be addressed

Because EVs have fewer mechanical systems and have regenerative electric braking instead of only friction brakes, most studies assume lower maintenance costs. However, long-term field data are needed to quantify actual savings and confirm battery life. Real-world experiences with early MD electric delivery vehicles have revealed reliability issues, with as much as 30% downtime due to maintenance and repair and delays in obtaining parts and service. For example, Figure 23 shows the high sensitivity of payback period to assumptions about battery life and replacement, electricity price, and repair costs.

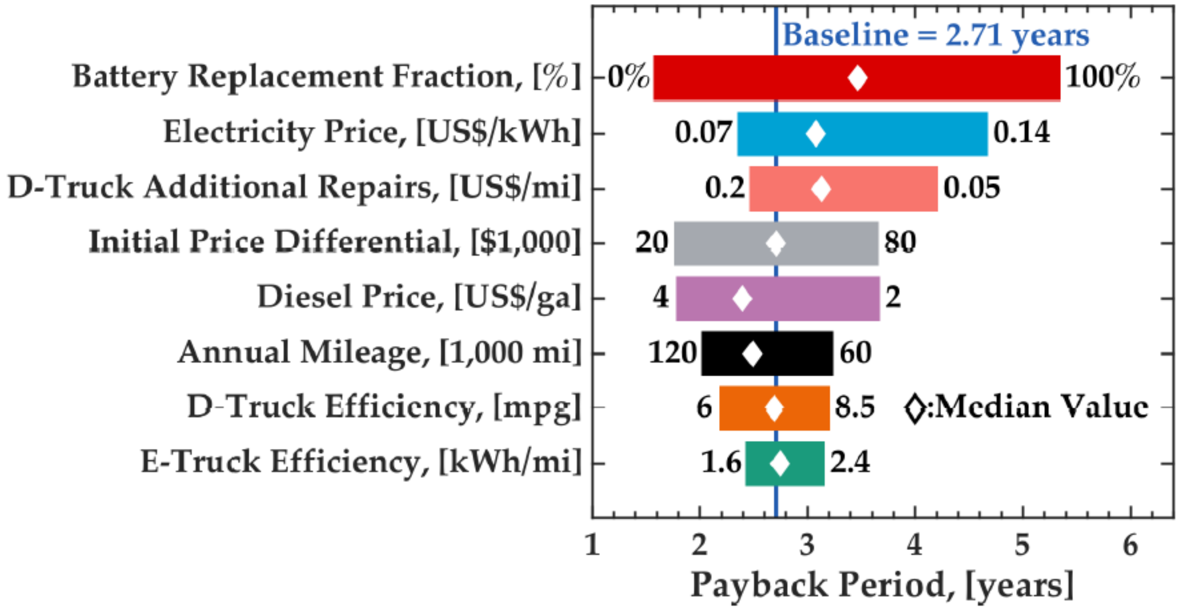

Figure 23: Impact of key contributors to total cost of ownership for electric medium- and heavy-duty vehicles (MHDVs) vs. diesel-powered MHDVs. Source: Shashank Sripad and Venkatasubramanian Viswanathan, "Quantifying the Economic Case for Electric Semi-Trucks," *ACS Energy Lett.*, 2019, 4 (1), pp 149–155) Used with permission.

In summary, TCO is a critical metric that provides insights for establishing research priorities and assessing technology suitability. Vehicle-level research priorities should target battery cost, energy efficiency, and reliability (uptime). Because of the demand for high daily range and lifetime mileage, battery performance is also key, including energy density, power density, and cycle life.

4.2 Duty Cycle Impact on Vehicle Design and Total Cost of Ownership

Duty cycles capture the vehicle operating conditions, including weight, route (speed, distance, and elevation), idling, and job-site power demands. The substantial impact of payload and the route/speed driving cycle on energy consumption is well understood from conventional vehicle experience, and some aspects carry over to electrified vehicles; for example, the following high-level duty cycle observations.

- For Class 8 trucks, the difference in fuel consumption between full weight and lightly loaded can be near 50%, depending on drive cycle.
- At any particular payload, the difference between predominantly urban and highway fuel consumption can be more than 50%.
- Even modest upward road grades of 3% can triple the power required to maintain speed in a fully loaded truck.

Urban cycles are particularly promising for reducing fuel consumption through deployment of electrified hybrid powertrains due to opportunities for engine-off at idle and regenerative braking. Urban cycles also highlight probable cost savings in EVs due to less wear of friction brakes. However, due to the weight and cost of energy storage, battery electric trucks present a distinctive multicriteria optimization challenge with trade-offs among energy consumption, payload mass capacity, cost, and range for various duty cycles. While increasing battery capacity will increase vehicle range, it increases per-mile energy demand and can reduce payload capacity, even after accounting for the weight of the conventional engine and aftertreatment systems, as illustrated in Figure 24. A simplified analysis (based on a detailed truck simulation), shown in Figure 25, further illustrates the impact of battery mass on payload and range.

For vehicles that are not loaded to full weight capacity, doubling the battery size (shown in Figure 25 as 8,000 lb vs. 4,000 lb) increases the operating range substantially but by less than a factor of 2 due to increased energy requirements for on overall heavier vehicle. However, the added battery weight does not greatly increase load-specific fuel consumption (fuel per 1,000 ton-miles) because, in most cases, the effect of vehicle mass on fuel consumption is only 1%–2% per 1,000 pounds. The impact on fuel consumption of increasing the payload is much more pronounced than the impact of a larger battery pack. It is significant to note that, for the assumptions used here, the vehicle GVWR limits total vehicle mass such that a 45,000-pound payload is not possible with an 8,000 lb battery.

Battery size and energy consumption, for any given payload and range, are impacted by the overall efficiency of the vehicle. Reducing aerodynamic drag and rolling resistance and improving the electric drivetrain efficiency can enable a smaller, lighter, and less costly battery pack. Figure 26 illustrates the effect on range of a 15% reduction in energy consumption via vehicle efficiency, without specificity on the source of the improvement (e-motor, aerodynamics, or rolling losses).

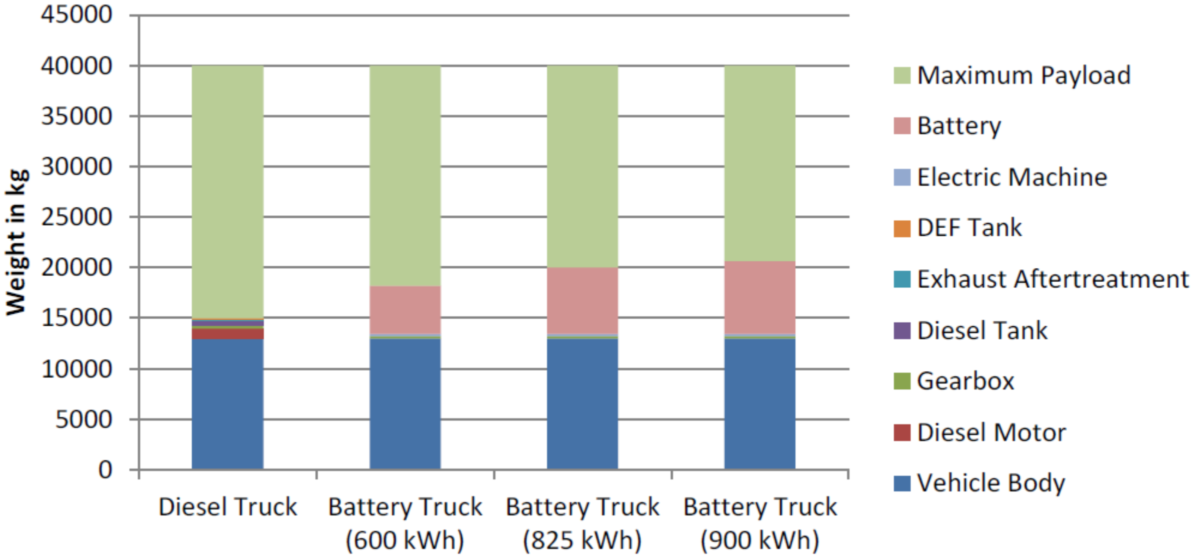

Figure 24: The mass of the batteries for longer range decreases the available payload capacity, thus increasing the load-specific fuel consumption. The battery weight is the third largest component of total vehicle weight in this example. Source: Mareev, Ivan et al., "Battery Dimensioning and Life Cycle Costs Analysis for a Heavy-Duty Truck Considering the Requirements of Long-Haul Transportation," *Energies* 2018, 11, 55; doi:10.3390/en11010055.

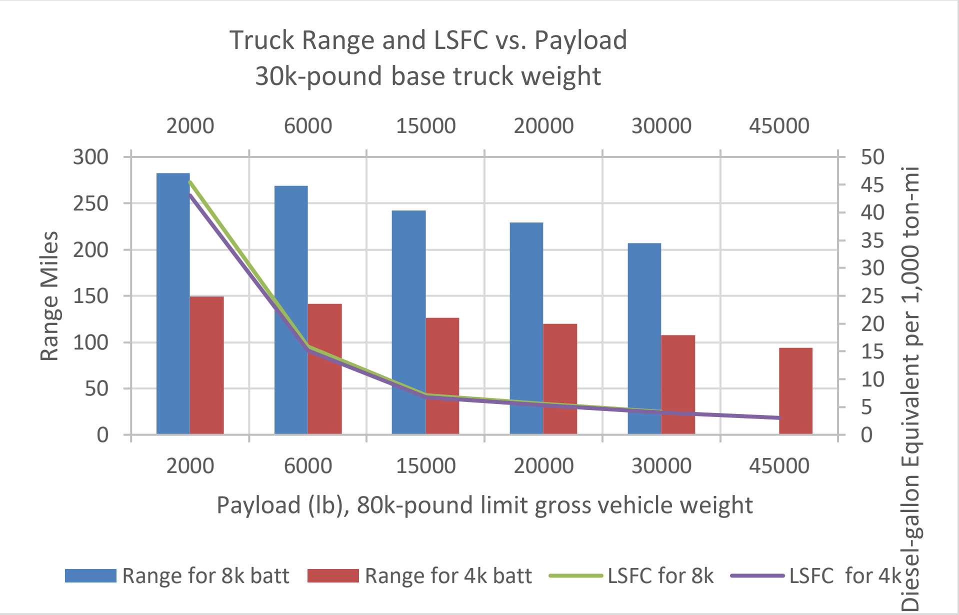

Figure 25: Interdependence of battery pack weight (pounds), range, and load-specific fuel consumption (LSFC) of an all-electric Class 8 truck. The duty cycle here approximates the California Air Resources Board drive cycle. The base vehicle efficiency was taken from typical field experience at 1.5 kWh/mile. In this analysis, the truck is not able to carry the maximum payload if the battery pack is large enough for 200+ miles.

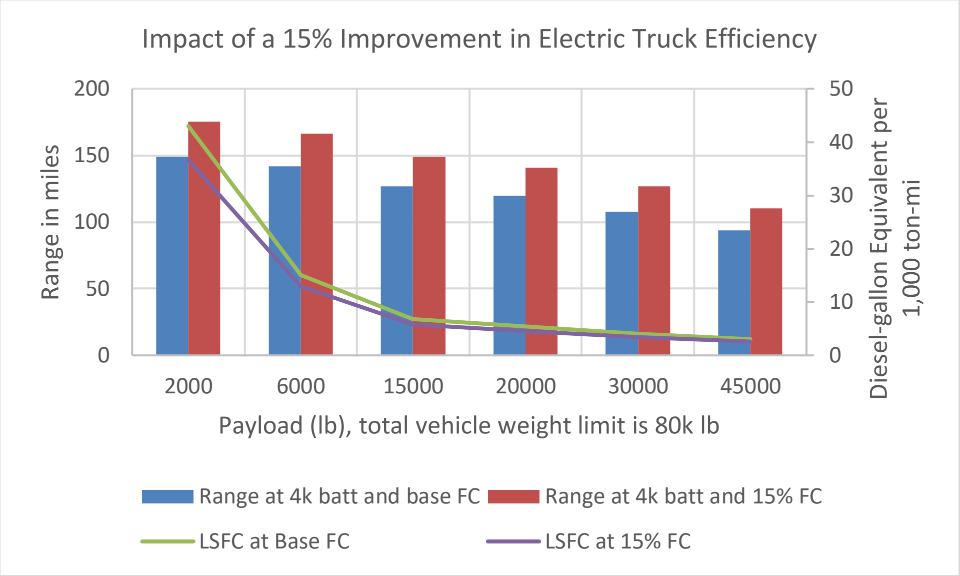

Figure 26: A 15% improvement in truck efficiency increases range by a similar quantity yet simultaneously yields a reduction in energy consumed per ton-mile. FC = fuel consumption; LSFC = load-specific fuel consumption.

The applicability of battery electric trucks to a particular use is considerably dependent on a threshold range, and data from Fleet DNA and other sources reveal the following trends.

- Although the average daily distance for Class 8 long-haul trucks is over 600 miles per day, many travel less than 200 miles before stopping for 30 minutes.
- Regional-haul trucks averaged 253 miles per day and 89% travelled less than 200 miles before a 30 minute stop.
- Other delivery vehicles and buses travel even fewer miles.
- More than 75% of Class 3–8 vehicles are operated on shift schedules where they are parked for more than 6 hours per day [33]. Miles traveled per shift were not cited.
- Even though these relatively short driving distances appear to favor use of BEVs, without knowledge of the details of the duty cycle (kinetic intensity, payload, etc.) and the efficiency of the electric drive system, the range cannot be assured. *This is a data and analysis gap.*

The trip distance data from the Fleet DNA project are summarized in Table 3.

For fleets and businesses engaged in local or regional product delivery, reports from personal contacts and interviews are that most trips are <100 miles and the overall trend is shorter trip length. These reports from a major fleet operator are consistent with studies of the Frito-Lay EV delivery vehicles published by NREL in 2016 [34].

Table 3: Fleet DNA Trip Distance Summary

Vocation	Avg. Daily Distance (miles)	Avg. Distance to 30 min. Stop (miles)	Avg. Distance to 2 hour stop (miles)	% Daily Distance <200 miles	Approx. 80th-percentile Daily Distance (miles)	VIUS 2002 Avg. Annual Fuel Consumption (gal)[a]
Long-Haul Tractors	675	181	537	13	600	14,552
Regional-Haul Tractor Trailers	254	76	198	39	400	8,189
Drayage Tractors	131	46	103	80	200	NA
Refuse Pickup	43	28	37	100	< 75	4,988
Beverage (Short)	14	2	9	100	< 30	NA
Beverage (Long)	62	10	35		100	2,052
Transit Bus	124	43	71	93	< 200	NA
School Bus	36	12	21	100	50	NA
Utility	16	5	10	99	< 30	1,540

[a] No current data on fleet size or energy use by vocation or body type other than tractor trailers. The tractor-trailer fleet has nearly doubled since 2002 (derived from 2013 IHS Polk registration counts by the National Renewable Energy Laboratory). Utility vehicles include both aerial and nonaerial utility vehicles and likely includes “utility body” service trucks. VIUS (the Vehicle Inventory and Use Survey) did not include data for drayage vocation or buses.

Recent surveys reported by NACFE and Advanced Clean Technology [33] somewhat augment and reinforce the trends in Table 3:

- For 98% of Class 3–6 trucks, the daily travel is 50–150 miles.
- For Class 7/8 regional haul, about 70% of daily use is more than 300 miles.
- For Class 7/8 long haul, 73% are more than 400 miles.

The justification for electrification of commercial MHDVs is heavily dependent on TCO and corporate sustainability targets, seemingly a simpler decision process than for an individual LDV purchase. However, there is a lack of sufficient information available to generate a complete evaluation for TCO combined with uncertain investment requirements for an OEM to design a vehicle best suited for a particular duty. A vehicle’s all-electric range has been highlighted as a critical requirement in relationship to the slow adoption of EVs in the North American LDV market. For an LDV, available range is quickly calculated based on state of charge (SOC) and the recent vehicle traveling efficiency; then charging infrastructure is considered when making a planned trip. For an MHDV there are many more trip attributes involved in both the available range calculation for the vehicle and the vehicle design requirements. An MHDV’s payload can be nearly triple the weight of the vehicle alone. The effect of this load parameter is multiplied when the route has aggressive topography or highly dynamic traffic accelerations, or even extreme temperatures. In the case of a BEV MDHD, the duty cycle must include charging considerations, not for typical drive cycle considerations but for the vehicle mission and daily use. Typically LD BEVs have no issue plugging in 4 plus hours a day, but when high percentage use cases of MHDVs are considered, the impact of charge time and charge rates (both in current flow of electricity and cost of the charge) become important variables that will impact componentry (even wiring) and will impact the cost of the electrified MDHD.

As stated earlier in this report, the production volumes for MHDVs are low when compared to the LDV market, and the number of vocations (or unique use cases) for each MHDV base platform is relatively high. The impact of TCO evaluations that a prospective fleet customer must consider will even impact the OEM decision to place a new vehicle into the development portfolio.

In addition to somewhat high-level duty-cycle characteristics that help determine the overall suitability of electric vs. conventional trucks, there are data with higher temporal fidelity that can be used to develop optimized electrified powertrains for a variety of vehicle missions. In the assessment of gaps and opportunities in the 21st Century Truck Program roadmap, vehicle and engine manufacturers expressed a need for data-driven analysis and detailed modeling tools to accelerate the design and optimization of powertrains for the diversity of duty cycles in the MHDV sector. The analysis can be started with data from current vehicles' CAN (controller area network) bus information on powertrain operations on a second-by-second basis, coupled with GPS and other environmental information. It is preferred that these data be treated to tractive energy analysis and filtered of driver behaviors to assess what is ultimately required of the drivetrain to complete the desired mission with minimum energy or time. The influence of surrounding traffic flows must be part of such analyses.

Information such as accelerations and stops (Figure 27), when merged with data such as grade and vehicle mass, can be used to determine powertrain requirements.

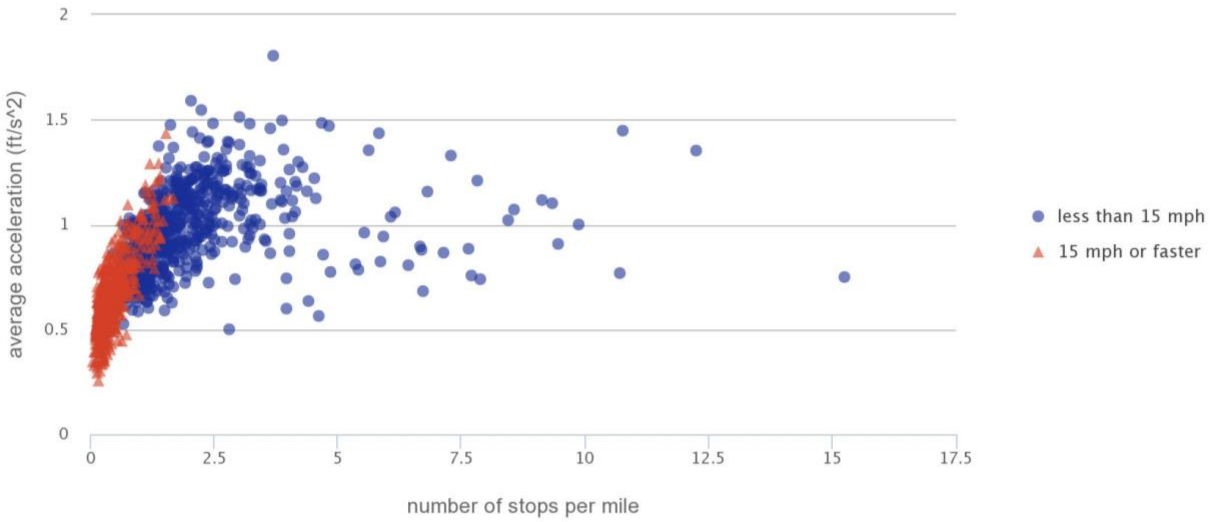

Figure 27: Example of average acceleration and number of stops by speed for tractor-trailer vehicles. Source: NREL FleetDNA, https://www.nrel.gov/transportation/fleettest-fleet-dna.html.

Data on acceleration and speed (Figure 28), when merged with other data, can be analyzed to determine energy storage and power levels for dominant duty cycles.

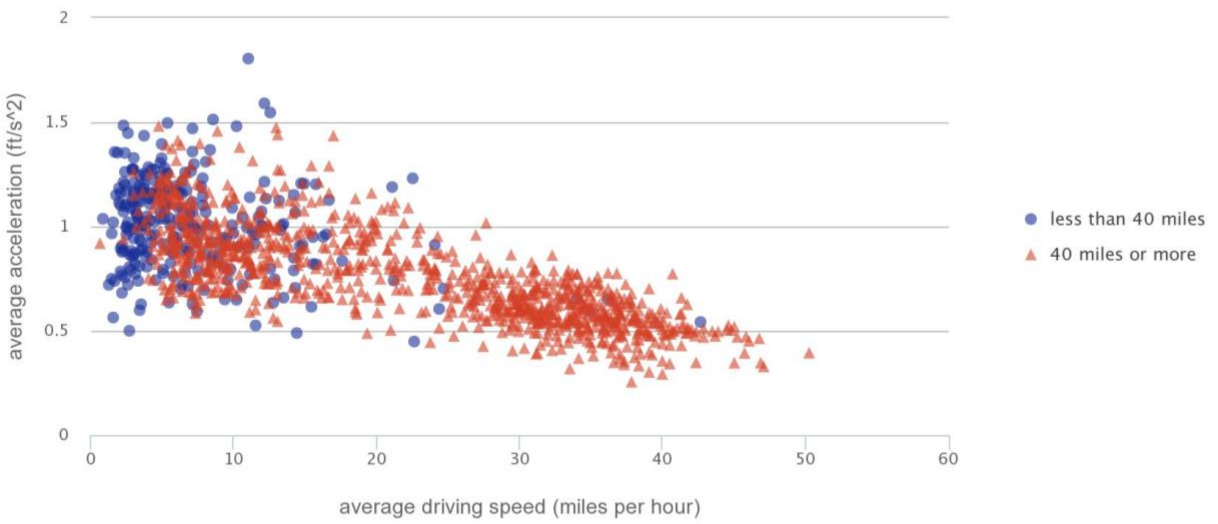

Figure 28: Average acceleration and driving speed by distance for tractor-trailer vehicles. Source: NREL FleetDNA, https://www.nrel.gov/transportation/fleettest-fleet-dna.html.

The important question of the range required for truck fleet operations can be considered with data collected in Fleet DNA, as shown in Figure 29 and Figure 30.

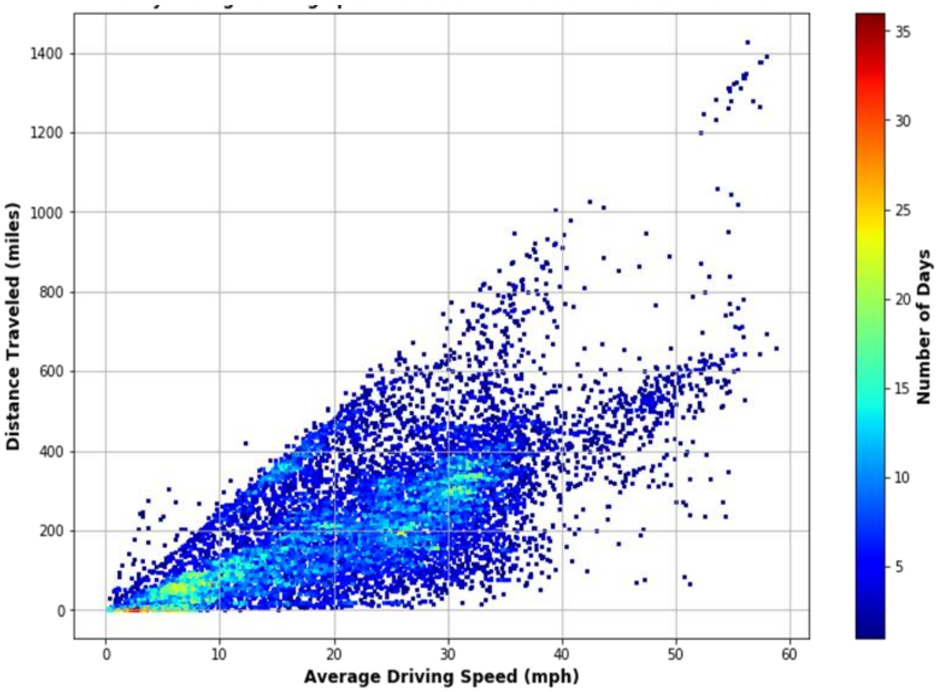

Figure 29: Daily average driving speed vs. distance traveled for Class 8 tractor trailers trucks (number of vehicles reporting = 343; generated on 11/08/2019; number of days included = 9,925). Source: NREL.

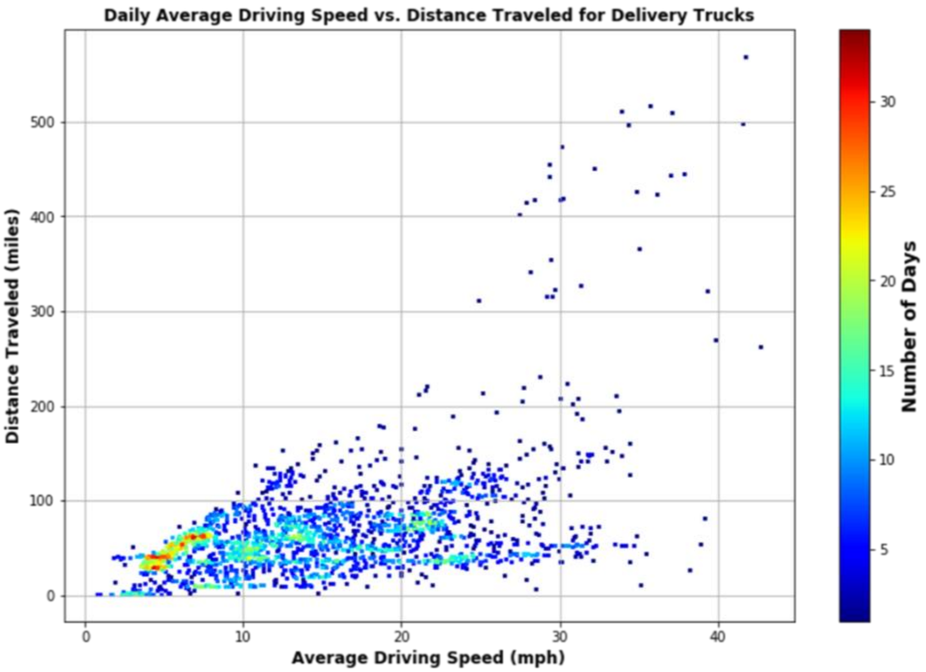

Figure 30: Daily average driving speed vs. distance traveled for delivery trucks (number of vehicles reporting = 119; generated on 11/08/2019; number of days included = 1,973). Source: NREL.

To support the design and specification of electrified powertrains, data collected from MHDV operations must include payload either directly recorded or derived from tractive power analysis. Most trucks are not weight limited, so batteries detract from payload capacity only part of the trips for part of the vehicles. However, weight does degrade energy efficiency, but electrified vehicles recapture some of the inertia losses via regenerative braking.

Speed and acceleration data are required to define the duty cycle. NREL and ORNL have compiled data on duty cycles for HD and MD trucks. Data on surrounding traffic/congestion are needed. To support back-calculation/modeling of powertrain requirements, it is better to perform tractive energy analysis of the required acceleration and speed for the route of interest at various payloads. Importantly, do not rely on real-world data that include the influence of drivers on vehicle speed, acceleration, and demanded output of the powertrain.

Additionally, the vehicle time at rest is important to record as an indicator of available recharging time.

5 Industry Perspectives on Technical Gaps and Barriers to Electrification

The perspectives from industry are divided into two groups:

- Perspectives of technology users, such as owners and operators of commercial vehicle fleets

- Perspectives of technology developers and suppliers, typically the engine and vehicle manufacturers and supply base.

These inputs were derived from one-on-one meetings, workshops, presentations, and literature reports. The list of gaps, as perceived by the stakeholders, includes shortfalls in technology and hardware and gaps in the knowledge and data necessary for further development, including the ability to deliver a low-cost, high performance product.

5.1 Gaps and Barriers Identified by Technology Users and Customers

- Primarily due to the battery, vehicle costs are often too high for the desired payback period. TCO drives choice of fleet vehicle purchase decisions. Corporate sustainability goals are impactful as well.
- The current battery recycling system is inadequate, with very high recycling costs (about $3 per pound according to one user interviewed).
- The batteries lose effectiveness at temperature extremes, limiting the applicability of electric trucks.
- Battery energy and power densities are (still) lower than desired (too heavy).
- So far, the reliability of electrified powertrains is notably inferior to ICE-based systems. In particular, battery management systems were noted as troublesome.
- A suitable charging infrastructure has not been developed, and anticipated costs and space requirements are a concern. Is battery exchange (instead of recharging) an option?
- As improved batteries come on the market, can they be retrofitted to existing MHDVs.
- It is not certain that electric powertrains can meet or exceed the life expectancy of MHDVs (the average age of Class 8 trucks on the road is 15 years, and the average age of all trucks is about 14 years).
- Uncertainty exists concerning the extent of local municipality bans on ICE-powered vehicles and the potential impact on the electric truck market.
- A gap exists between current design and analysis tools and the extreme capabilities of emerging high-performance computing (HPC) resources for data analytics of fleet and vehicle operations for overall transportation system improvement.

5.2 Gaps and Barriers Identified by Vehicle, Powertrain, and Component Manufacturers

- Duty cycle data and characteristics for design and optimization methods are lacking.

- The cost of large battery packs for trucks is still more than $200/kWh.

- Battery weight is inhibiting.

- The ultimate reliability of electrification components and systems is still very much in question, which has far reaching impacts, including on the need for replacement parts and how stocking them might be handled.

- A national-level solution for battery recycling and/or disposal is needed.

- Scalable components in high volume and at low cost are missing. Standardization of architectures or other means to increase production volumes of fewer component designs.

- Currently, climate extremes limit the performance of batteries and components and thus the applicability of electric trucks.

- More information is needed to efficiently electrify auxiliary devices over a range of duty cycles.

- There are shortfalls in the commercial high-voltage (~750 V needed for large trucks) component supply base, technology and product portfolio, powertrain interface, product and functional safety standards, technical/market/OEM platform fit, and new technology education.

- Charging devices and infrastructure are lacking, especially at the power levels needed for MHDVs in commercial freight.

- Suitable R&D technical targets and goals are incomplete.

    - Standardized “abuse cycles”—tests and lifetime.
    - Find the duty cycle commonalities that would lead to scalable components.
    - Carefully setting component targets that drive the system, when TCO could be lower with planned replacement (e.g., battery life).

- Safety pertaining to high-voltage systems. First responder concerns.

- Thermal management of electrified powertrain components is not fully resolved in this application.

- Understanding duty-cycle and vehicle mission across many vocations is a critical input to design. There is a need for more data and analysis to better understand vocations and provide requirements on vehicle designs.

- Design optimization and robust design methods for electrification are needed. This includes not only optimizing vehicle design to real-world duty cycle requirements but also understanding the robustness/trade-offs applying the design across the large diversity of potential applications. There is an opportunity and need to develop and apply HPC-enabled optimization tools to develop and evaluate electrified vehicle drivetrains and optimize performance while considering the robustness across multiple applications for scalability in an accelerated manner, augmented with hardware-in-loop validation and codevelopment.

- Data fusion of vehicle operational/duty cycle information with other data sets such as terrain, weather, traffic, etc.

- TCO comparisons between electricity, natural gas, and hydrogen MHDVs need to be updated as technology progresses.

- Although electrification is thought to be beneficial for connectivity and automated driving options, confirmation will require better understanding of the requirements on the electrified power systems and completion of technology.

- Gaps exist in development and manufacturing methods for high voltage electrification components, which impact cost.

6 Status of Components for Electrification

6.1 Introduction

Electrical components have a great impact on the ability of electrified MHDVs to be competitive with traditional ICE MHDVs. The components associated with the electric drivetrain, energy storage system, vehicle accessories, and charging infrastructure must be able to accommodate a higher power demand and perform over longer life cycles than seen in current passenger vehicles. The supply chain for electrified MHDV components has been surveyed and summarized by Whaling et al. [35] and is not repeated here.

Targets for EV components (battery, motors, power electronics) have not been fully defined for commercial vehicles and are needed to determine gaps for R&D focus. For example, the reliability or ruggedness of MHDV components may be more impactful on low TCO than weight. The following sections describe the current state of electrical components compared to what will be needed to electrify MHDVs.

6.2 Electric Drive Overview

The electric drive of an electrified vehicle primarily encompasses the power electronics and motor used to propel the vehicle, as well as the sensors and controller used to complete the closed loop system. Power electronics specifically include the passive and semiconductor devices used to convert the energy provided by the battery to drive the traction motor for the system. The current LDV technical targets for the US DRIVE partnership are shown in Table 4. The targets are goals that if achieved would make passenger vehicle electrification more economically feasible. Similar targets that are specific to MHDV TCO requirements have not been developed.

An example diagram of an electric drive for an electrified vehicle is shown in Figure 31. The battery connects to the power electronics (inverter) that then feeds the motor connected to the wheels of the vehicle. A controller receives inputs from motor measurements as well as driver input to control the power supplied to the motor.

Table 4: Technical Targets Set by USDRIVE for Passenger Vehicle Electrification

Electric Traction Drive System		
Year	**2020**	**2025**
Cost ($/kW)	8	6
Power Density (kW/L)	4	33
Power Electronics		
Year	2020	2025
Cost ($/kW)	3.3	2.7
Power Density (kW/L)	13.4	100
Electric Motor		
Year	2020	2025
Cost ($/kW)	4.7	3.3
Power Density (kW/L)	5.7	50
DC-DC Converter Targets		
Year	2020	2025
Cost ($/kW)	< 50	30
Specific Power (kW/kg)	> 1.2	4
Power Density (kW/L)	> 3.0	4.6
Efficiency	> 94%	98%
Onboard Charger Targets		
Cost ($/kW)	50	35
Specific Power (kW/kg)	3	4
Power Density (kW/L)	3.5	4.6
Efficiency	97%	98%

Source: USDRIVE, *Electrical and Electronics Technical Team Roadmap*, October 2017, https://www.energy.gov/sites/prod/files/2017/11/f39/EETT%20Roadmap%2010-27-17.pdf

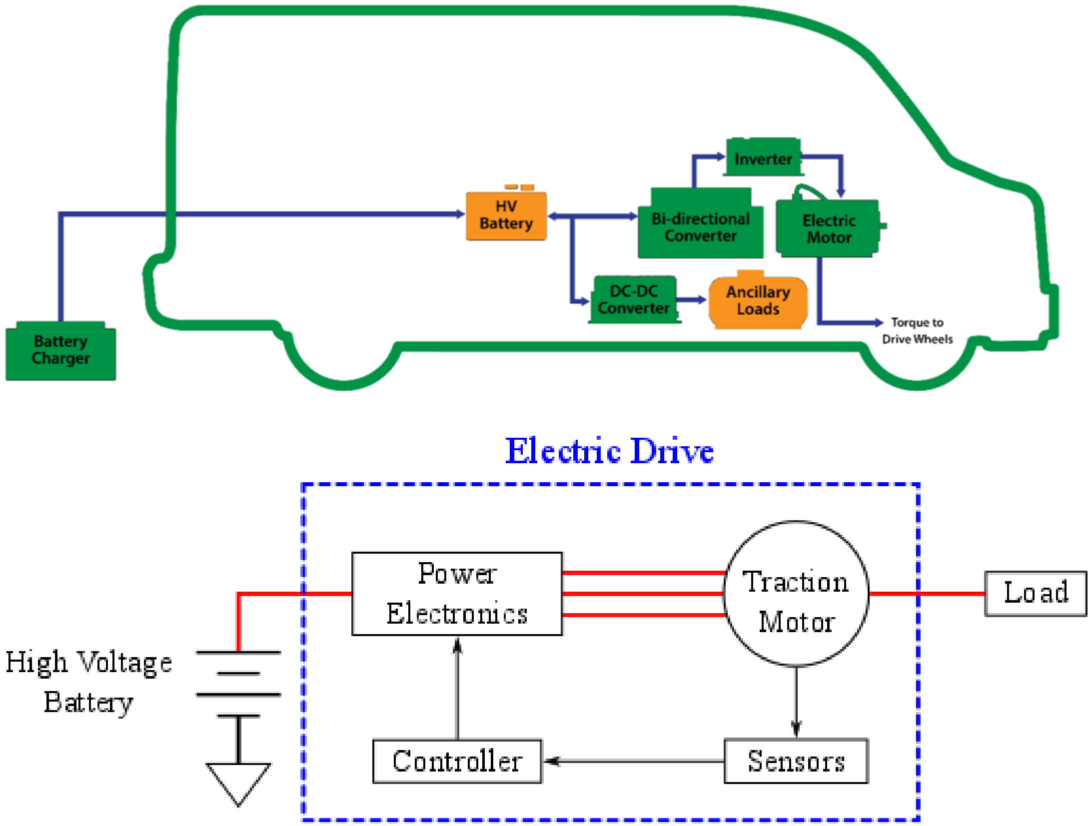

Figure 31: Electric drive system, with off-vehicle battery charger typical of medium- and heavy-duty vehicles (HV = high voltage; DC = direct current).

6.2.1 Major components

Power semiconductor devices are the core building blocks of power modules used in inverters which run the traction motor, DC-DC converters which distribute power to electric loads, and chargers. The following types of power devices are used in EV power converters.

- IGBTs (insulated-gate bipolar transistors)
- MOSFETs (metal-oxide semiconductor field-effect transistors)
- Diodes

Commercial IGBTs are silicon based and are used in low power onboard chargers. The diodes can be either silicon-based or SiC-based. Silicon IGBT- and diode-based Infineon power modules, shown in Figure 32, are used in the 2016 BMW i3.

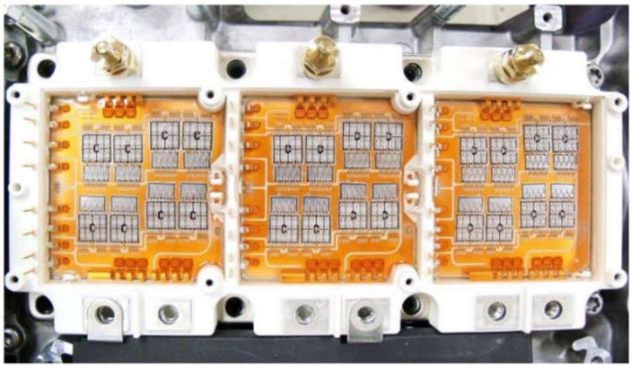

Figure 32: 2016 BMW i3 Infineon inverter power module. Source: DOE Office of Energy Efficiency and Renewable Energy, *FY 2016 Annual Progress Report for Electric Drive Technologies Program*, July 2017.

6.2.2 State of the art for electric power components

For battery electric LDVs, the inverter bus voltage can vary from 350 V to 700 V. Si IGBTs rated at 600 V can support inverter bus voltages of 325 V. IGBTs rated at 1,200 V can support bus voltages of 700 V. However, 1,200 V IGBTs are more cost effective than 600 V IGBTs [36]. A higher voltage also provides the opportunity to increase the combined motor-inverter efficiency and reduce the size of the electric drive for the same power level. In Figure 33, the peak efficiency is only 92%, and the maximum achievable power is 40 kW for a 300 V inverter bus voltage. On the other hand, the peak efficiency is more than 94% and the maximum achievable power is 124 kW for a 700 V inverter bus voltage (Figure 34). Maximum speed range is also increased with higher bus voltage. Therefore, for high power systems a higher voltage can reduce the maximum current requirement and losses.

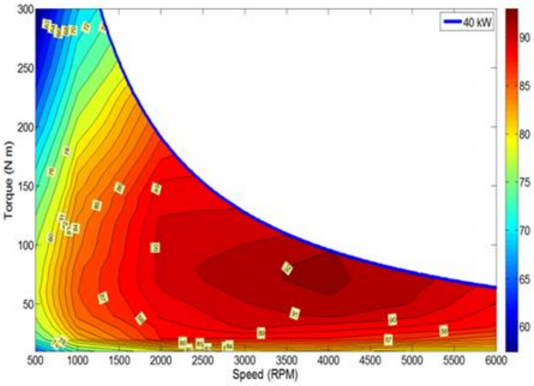

Figure 33: 2014 Accord motor-efficiency contour at 300 V inverter bus voltage. Source: Tim Burress. 2016. *Benchmarking EV and HEV Technologies*, presented at US Department of Energy, Vehicle Technologies Office, 2015 Annual Merit Review and Peer Evaluation Meeting, June 7, 2016; available at https://www.energy.gov/sites/prod/files/2016/06/f32/edt006_burress_2016_o_web.pdf.

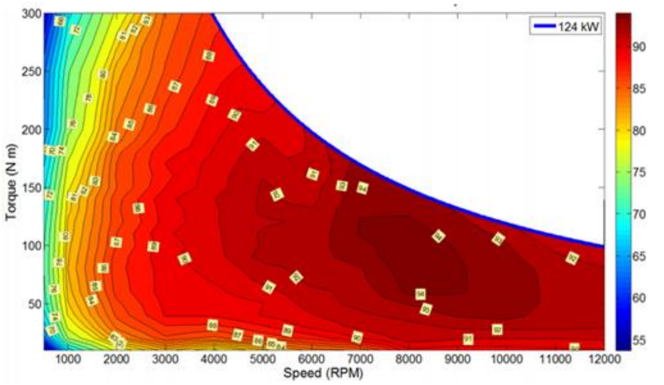

Figure 34: 2014 Accord motor-efficiency contour at 700 V inverter bus voltage. Source: Tim Burress. 2016. Benchmarking EV and HEV Technologies, presented at US Department of Energy, Vehicle Technologies Office, 2015 Annual Merit Review and Peer Evaluation Meeting, June 7, 2016; available at https://www.energy.gov/sites/prod/files/2016/06/f32/edt006_burress_2016_o_web.pdf.

The USDRIVE Electrical and Electronics Tech Team roadmap targets 800 V battery voltages to support XFC. To reduce the charging times and to increase the power density of the electric drive, even higher voltages might be needed. Increasing the battery voltage to 1,200 V would require 1,700 V rated devices, which are not currently as available as 600 V or 1,200 V rated devices.

For MHDV electrification, devices rated for 1.2 kV or higher are desirable to limit the bus bar, inductor, and motor winding size. Parallel devices are very common practice in industry to increase the current conduction capability. However, it comes with the challenge of parasitic reduction and higher switching loss. Instead of paralleling power modules, some commercial MHDV drive systems are using six- or nine-phase inverters and motors to achieve higher power levels without paralleling power modules. This also reduces the size of the bulky DC-link capacitor by half or more and improves fault tolerance.

Different OEMs are looking into incorporating wide-bandgap (WBG) SiC devices into EV converters. The Tesla Model 3 is the first EV to use SiC MOSFETs in the traction inverter. If the Tesla Semi uses Model 3 parts, that would be the first MHDV using SiC technology. Toyota has shown, in a benchtop prototype, that by adopting SiC devices, power control unit sizes can be reduced significantly (Figure 35). SiC devices can be operated at a higher temperature than IGBT devices. Thus, the cooling system requirements can be reduced which can eventually provide higher power density. SiC-based converters for auxiliary power can also be switched at higher switching frequencies without sacrificing converter efficiency. The size of the passive elements including the inductor and capacitor can be reduced. As a result, the overall system cost of the converter can be reduced.

(a) (b)

Figure 35: Toyota power control unit with silicon (a) and silicon carbide (b) devices. Source: Toyota Motor Corporation. 2014. "Toyota Develops New Silicon Carbide Power Semiconductor with Higher Efficiency," [press release], May 20, 2014. Permission to use requested.

6.2.3 Technology gaps in power electronics devices

HV (6.5 kV, 4.5 kV, 3.3 kV, 1.7 kV, 1.2 kV) IGBT die, power modules, and discrete devices are commercially available for MHDV electrification purposes. The major IGBT manufacturers are Infineon, Microswitch, Vishay, IXYS, Littelfuse, ST Microelectronics, ABB, Powerex, GE, and Global Power Devices. Most IGBT modules have matching gate drivers commercially available to make it easier to control these switches. For traction inverters, 1.7 kV and 1.2 kV rated devices would be preferred; higher rated devices would be preferred for XFC, with direct grid connection.

HV SiC dies and discrete devices are the new devices intended to replace silicon. SiC is commercially available in low current devices at this point in time. Larger commercially available cost-effective devices rated at 200 A at a 175°C junction temperature are needed at a minimum to support the growth of MHDV electrification with these high efficiency technologies to achieve the power density, efficiency, and specific power requirements. For a 1 MW application, the voltage rating of the SiC devices needs to be even higher than 1,700 V. However, no 1,700$^+$ V SiC dies or power modules are currently commercially available for on-highway applications. The silicon IGBTs would not be able to meet the electrification goals.

Wolfspeed has demonstrated 15 kV SiC devices which are currently in the research phase. However, as can be observed in Figure 36, the SiC MOSFET can be operated at a much higher switching frequency compared to an IGBT. As a result, the size of the passive components including the inductor and capacitor can be reduced. Figure 37 shows that the inverter loss can be reduced by 77% over the EPA city driving cycle (Federal Test Procedure or FTP-75) and by 85% over the EPA Highway Fuel Economy Test cycle. As a result, the heat sink size can be reduced significantly. For MHDV electrification, thermal management will be challenging considering the amount of cooling required for conventional IGBT-based solutions. Moving toward SiC devices can reduce vehicle weight and volume significantly through reduced component sizes and cooling requirements.

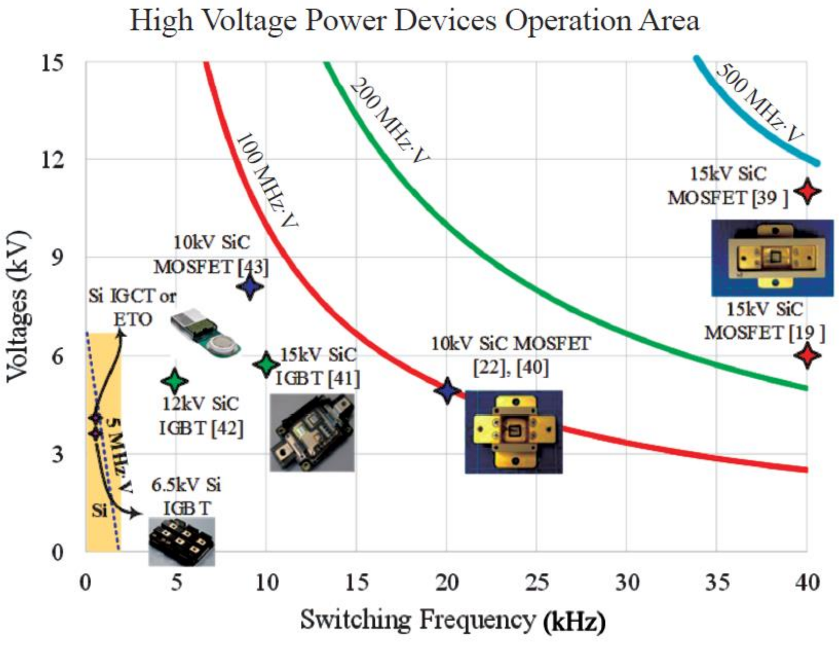

Figure 36: The medium-voltage SiC metal-oxide semiconductor field-effect transistor's (MOSFET's) voltage-frequency capability compared with that of silicon high-power devices such as insulated-gate bipolar transistors (IGBTs), integrated-gate commutated thyristors IGCTs), and emitter turnoff thyristors (ETOs). Source: A. Q. Huang, Q. Zhu, L. Wang, and L. Zhang, "15 kV SiC MOSFET: An enabling technology for medium voltage solid state transformers," ***CPSS Transactions on Power Electronics and Applications*****, vol. 2, no. 2, pp. 118–130, 2017.**

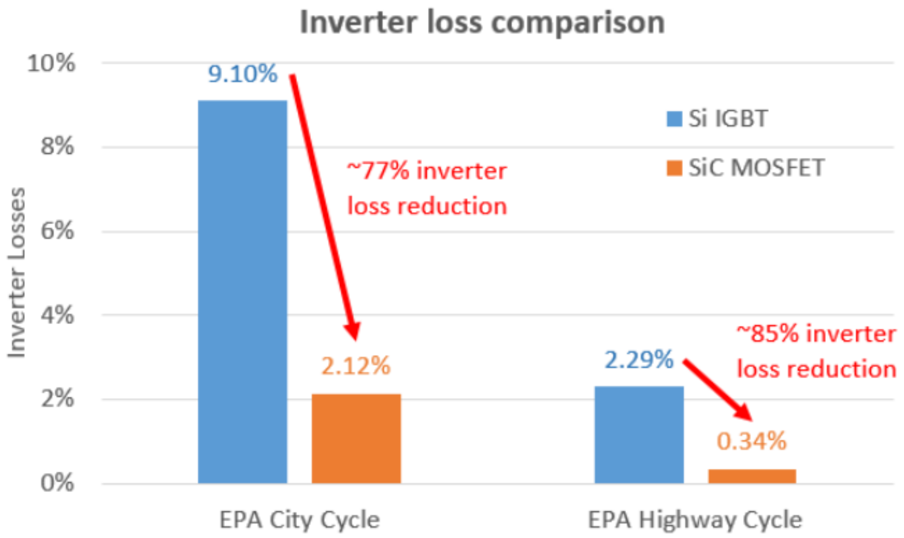

Figure 37: Inverter loss improvement with SiC device. (IGBT = insulated-gate bipolar transistor; MOSFET = metal-oxide semiconductor field-effect transistor; EPA = US Environmental Protection Agency.) Source: US Department of Energy. 2017. *FY 2016 Annual Progress Report for Electric Drive Technologies Program*, DOE Office of Energy Efficiency & Renewable Energy, July 2017; available at https://www.energy.gov/sites/prod/files/2017/08/f36/FY16%20EDT%20Annual%20Report_FINAL.pdf.

6.3 Motors-Inverters

Economically, the global EV inverter market is projected to reach about $16 billion by 2021 [37]. Technically, inverters are a compilation of components that manipulate electrical current to do useful work on board an EV and convert the battery DC power to AC power for use in motors or for other power requirements. Due to the higher power requirements and harsh working environments, MHDVs require a different set of inverters than LD EVs. Significant hardening of power electronics is therefore essential for the adoption of MHDVs [38].

The following sections comprehensively assess the current state of inverter technology in MHDVs.

Table 5 lists the currently available commercial inverters. All the products listed are relatively new to the market and have huge competition among the global electric truck inverter market. Some manufacturers do not disclose the metrics such as power density, continuous power rating, switch material, and thermal management for these products. For example, the only information available about the electric inverters used in the Tesla Semi is that the peak power of the electric inverter module is 350 kW. There are manufacturers who produce electric inverters for other manufacturers. For example, John Deere manufactures PD400 for Fuso eCanter developed by Daimler.

Table 5: Inverters Manufactured by Independent Vendors

Manufacturer/Model	Peak Power (kW)	Nominal Voltage (VDC)	Mass (kg)	Phases
Dana TM4 CO300 Inverter[a]	250–350	600	36	9
Dana TM4 CO200 Inverter[a]	230	350	26	6
Dana **TM4 CO200 Inverter**[a]	235–265	600	26	6
Dana TM4 CO150 Inverter[a]	162–220	600	26	3
John Deere PD400 Inverter[b]	280	700	17.3	N/A
Tesla Drive Inverter (Model 3)[c]	350	N/A	N/A	N/A

[a] Dana TM4 (no date), "Sumo [series] Electric Powertrain Systems for Medium & Heavy Duty Vehicles" (datasheet); available at https://www.danatm4.com/wp-content/uploads/2013/12/TM4_SUMO-Datasheet1.pdf.
[b] John Deere (no date), "PD400 Single" (factsheet); available at https://www.deere.com/en/power-electronics/pd400-single/.
[c] Fred Lambert, "Tesla Model 3 exclusive leaked specs: 300 kW+ inverter architecture putting its power capacity near Model S," *electrek*, June 29, 2016; available at https://electrek.co/2016/06/29/tesla-model-3-exclusive-leak-specs-300kw-inverter-architecture-power-capacity-model-s/.

6.3.1 Motors

Electric motors have basic characteristics well-suited for MHDV propulsion. They deliver high torque at zero speed and over a wide speed range; they are very efficient, are somewhat lower weight than a diesel engine, and can be readily used in multiples on a vehicle (such as one motor per wheel) for flexibility and better controllability. Rare earth permanent magnets (PMs) are preferred for use in motors for EV applications because of their high energy density and efficiency. However, with rare earth PM materials there are issues of high cost, supply availability, and, for MHDVs, brittleness of the magnets due to the harsh environment. Achieving the stated USDRIVE goals for electrical motors used in MHDVs in a sustainable manner will require motor designs that can withstand the harsh environments and that can match the heavy rare earth (HRE) PM motor performance without any HRE PMs or without any PMs at all.

6.3.1.1 Motor state of the art

The state-of-the-art electrical motors that might be used for MHDV electrification are shown in Table 6. The table lists the vehicle OEM, the vehicle type, the motor type and the physical and output electrical characteritics of the motors. In summary, electrical motors for MHDVs can be broadly categorised into PM and non-PM motors. For the non-PM motors, there is the AC synchronous motor, the induction motor, and the switched reluctance motor. This information is difficult to come by and depends on several other factors. The power density (kW/kg) for MHDV electric motors is provided (where data are available) with the upper value around 2 kWh/kg. In the context of conventional vehicles, the power density for a 2018 HD diesel engine with aftertreatment is much lower, about 0.37 kW/kg (about 1,000 kg for a 370 kW engine). The number of phases for some of the motors are indicated. While there are some three-phase motors, the general trend is toward a higher number of phases. More phases improve the torque and power profiles and the fault ride, and hence the reliability, through capabilities of the motor.

Table 7 shows some of the details for three additional electric motors finding application in electrified trucks.

Table 6: Characteristics of State-of-the-Art Electric Motors

Manufacturer	Vehicle Model	Electrification	Type	Number of Phases	Dimension (mm)	Peak Power (kW)	Continuous Power (kW)	Torque (Nm)	Weight (kg)	Power Density (kW/kg)
Tesla	Tesla Semi	BEV	PMSRM			808.339 (4 × 271 hp)				
BYD	K 11	BEV	AC SYCHRONOUS			2 × 180		1500 × 2		
	K 9	BEV	AC SYCHRONOUS			2 × 100		550 × 2		
	K9S	BEV	AC SYCHRONOUS			2 × 100		550 × 2		
	K 7	BEV	AC SYCHRONOUS			2 × 90		350 × 2		
	T9	BEV	PMSM			2 × 720.56		1499.535 × 2		
	Q1M	BEV	PMSM			179.7137		1499.535		
	T7	BEV	PMSM			149.886		550.4621		
	T5	BEV	PMSM			149.886		550.4621		
Allison	EP 50 / 40	HEV	IM			150				
BAE	Series - E / Series - ER	HEV	IM		629 × 613 × 569	200	160	5200 peak (2400 continuous)	352 (wet)	0.5682
		HEV	IM		653 × 613 × 569	230	180	6400 peak (3400 continuous)	388 (wet)	0.5923
		HEV	IM		554 × 615 × 595	195	120	2100 peak (1000 continuous)	192 (wet)	1.0156
			PM	6	452 diameter; length 478 (LSM200); 419 (LSM140)	265	155	2760 peak (970 continuous)	212 kg or 140 kg	1.25 / 1.8929
			PM	6	452 diameter; length 478 (LSM200); 419 (LSM140)	255	190	2355 peak (990 continuous)		1.2028 / 1.8214
			PM	9	572 diameter; 505 length	250	195	2700 peak (2060 continuous)	340	0.7353
			PM	9	572 diameter; 505 length	250	195	3400 peak (2060 continuous)		0.7353
BAE			PM	9	572 diameter; 505 length	350	260	3500 peak (1830 continuous)		1.0294
			PM	3	500 diameter; 200 length	200	160	915 peak (745 continuous)	100	2

Table 6 (continued)

Manufacturer	Vehicle Model	Electrification	Type	Number of Phases	Dimension (mm)	Peak Power (kW)	Continuous Power (kW)	Torque (Nm)	Weight (kg)	Power Density (kW/kg)
			PM		290 diameter; 230 length	135	80	320 peak (160 continuous)	50 dry	
			PM		390 diameter; 230 length	220	120	700 peak (350 continuous)	85 dry	
			PM		390 diameter; 230 length	145	100	950 peak (400 continuous)	85 dry	
			PM		390 diameter; 230 length	250	150	900 peak (350 continuous)	85 dry	
BAE			PM		80.4 length; 350 diameter	160	100	370 peak (300 continuous)		peak value of 6.7
			PM		98 length; 368 diameter	100	70	790 peak (400 continuous)	37	2.7
				3		about 290 peak	250	1700 peak(about 1500 continuous)	148	1.9595
					490 diameter; 202.76 length	about 290 peak	250	1100 peak (850 continuous)	98	1.9595

Acronyms used in the table: AC = alternating current, BEV = battery electric vehicle, HEV = hybrid electric vehicle, IM = induction motor, PM = permanent magnet, PMSM = permanent magnet synchronous motor, and PMSRM = permanent magnet synchronous reluctance motor.

Sources: http://en.byd.com/usa/ accessed on May 31, 2018; https://www.neweagle.net/support/wiki/index.php?title=EV-Components#UQM_Motors accessed on May 31, 2018; cdn.borgwarner.com/docs/default-source/default-document-library/remy-pds---hvh410-075-sheet-euro-pr-3-16.pdf?sfvrsn=a742cd3c_11 accessed on May 31, 2018; http://www.hybridrive.com/pdf/bus/MTS.pdf accessed on May 31, 2018; http://www.hybridrive.com/pdf/bus/DDTM-100.pdf accessed on May 31, 2018; www.tm4.com/wp-content/uploads/2018/04/TM4_SUMO-Product-Brochure.pdf accessed on May 31, 2018; Remy HVH 410 Series Electric Motors, 2010 http://www.doc88.com/p-4167665155293.html; Remy HVH410-150 Product Sheet, 2016. https://www.borgwarner.com/docs/default-source/default-document-library/remy-pds---hvh410-150-sheet-euro-pr-3-16.pdf?sfvrsn=a642cd3c_11

Table 7: Characteristics of Three State-of-the-Art Electric Motors

	UQM PowerPhase	TM4 Sumo	BorgWarner HVH 410
DC Voltage	425–750 V	750 V	650 V
Peak Efficiency	94–95%	95%	95%
Coolant Temperature		65°C	90°C
Motor Configuration	Inner rotor	Permanent magnet; outer rotor	Internal permanent magnet
# of phases	3	5	3
Peak Power Level	220–250 kW	250–350 kW	~130–300 kW
Motor Mass	85 kg	340 kg	98–148 kg
Inverter mass	40 kg	36 kg	NA
Drive Specific Power	1.76–2.0 kW/kg	0.66–0.93 kW/kg	Up to 3.0 kW/kg peak
Motor Volume	27 L	129 L	~30 L
Inverter Volume	40 L	41.45 L	NA
Drive Power Density	3.28–3.73 kW/L	1.46–2.05 kW/L	NA

Sources: http://en.byd.com/usa/ accessed on May 31, 2018; https://www.neweagle.net/support/wiki/index.php?title=EV-Components#UQM_Motors accessed on May 31, 2018; cdn.borgwarner.com/docs/default-source/default-document-library/remy-pds---hvh410-075-sheet-euro-pr-3-16.pdf?sfvrsn=a742cd3c_11 accessed on May 31, 2018; http://www.hybridrive.com/pdf/bus/MTS.pdf accessed on May 31, 2018; http://www.hybridrive.com/pdf/bus/DDTM-100.pdf accessed on May 31, 2018; www.tm4.com/wp-content/uploads/2018/04/TM4_SUMO-Product-Brochure.pdf accessed on May 31, 2018; Remy HVH 410 Series Electric Motors, 2010 http://www.doc88.com/p-4167665155293.html; Remy HVH410-150 Product Sheet, 2016. https://www.borgwarner.com/docs/default-source/default-document-library/remy-pds---hvh410-150-sheet-euro-pr-3-16.pdf?sfvrsn=a642cd3c_11

6.3.1.2 Motor technology gap

Motors for MHDVs are still largely PM-based despite the challenges with HRE PM materials. There are no commercial non-PM-based motors that can match the performance of the PM-based motors in terms of efficiency and power density. The motors developed for MHDVs are far away from meeting the USDRIVE LD power density target, and because they are hugely PM-based, the target for cost is not being met either.

6.3.2 Integrated traction drives and e-axles

Integrated traction drives and e-axles are out-of-the-box turn-key solutions for electrifying MHDVs. As complete solutions, integrated traction drives typically include several subsystems such as the inverter, electric motor, and transmission/gearing. E-axles are typically integrated traction drives included within an axle unit that also mechanically links to the wheels. Complete electrified chassis, marketed as complete powertrains, can also be alternatives to e-axles, and they usually include energy storage.

6.3.2.1 State of the art

Several integrated traction drives and e-axles are currently on the market. These are often used as retrofits and after-market solutions to electrify conventional MHDVs, but some are being developed for direct use within electrified chassis. Overall, these products have the potential to electrify company fleets, especially those that have start-stop uses. By hybridizing vehicle drivetrain architectures like this, higher energy efficiency and additional power can be gained compared to conventional vehicles. Regenerative braking allows braking energy previously wasted as heat to be used in movement. The market is already recognizing this benefit to some extent, and several large companies within the industry have launched or are launching their own product lines of e-axles and integrated traction drives. A few of these companies are listed in Table 8.

Table 8: Survey of Integrated Traction Drive and E-Axle Manufacturers

Company	Peak Power (kW)	Peak Torque (N-m)
US Hybrid	200	2,215
ZF	250	22,000
Meritor/UQM	200	N/A
Bosch	300	6,000
Hyliion	74	363
Workhorse/Dana Inc	220	700
AxleTech	265	20,424
Wrightspeed/AxleTech	186	17,626
US Hybrid	200	2,215

Note: The peak torque here is affected by gearing of the system, which varies across this market survey.

6.3.2.2 Integrated traction drives and e-axles technology gaps

Integrated traction drives and e-axles are limited by their constituent parts. When better motors, gearboxes, and inverters are made to suit MHDVs, integrated traction drives and e-axles will benefit. When fully mature, integrated traction drives and e-axles may replace engines altogether and allow MHDVs to use electrical energy exclusively, which would allow companies to save costs. However, many of the technology gaps of the constituent parts, as explored in other sections, are keeping this from happening.

Due to the recent influx of this sort of solution on the market, a few companies are using these for powertrain or electrified chassis as primary manufacturers. As mentioned before, several companies are simply retrofitting these solutions onto conventional vehicles. Eventually, as the market matures, primary MHDV manufacturers may design their powertrains to use these sorts of solutions in hybrid configurations. For function and reliability, current engine powertrains have a high standard for electrified systems to achieve.

6.4 Electrical Energy Storage

Electrical energy can be stored in many different forms; however, two methods have emerged as the primary solutions for vehicles: batteries and supercapacitors. Batteries work by converting stored chemical energy into electrical energy. Likewise, supercapacitors store energy by maintaining an electric potential across a dielectric. The supercapacitor is a type of capacitor specifically designed for energy storage and applications with high pulses of power. Batteries and supercapacitors have their own set of strengths and weakness. Batteries tend to have a higher specific energy than supercapacitors whereas supercapacitors have a higher specific power relative to batteries. Because of this, some vehicles have both of these types of storage to enable operation over a wider range.

6.4.1 Current state of the art

Most of the battery chemistries that have been used for energy storage within MHDVs are lithium-ion-based cells. The most common cathode chemistries are lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide, and lithium iron phosphate, while graphite and lithium titanate constitute the anodes [39]. Table 9 captures the specific energy and lifespan of each of these chemistries. Figure 38 compares other characteristics of these batteries.

Table 9: Characteristics of Common Chemistries Used in Traction Batteries

Battery Chemistries	Specific Energy (Wh/kg)	Life Span (cycles)	Application in Transportation
Nickel Manganese Cobalt Oxide (NMC)	150–220	2,000$^+$	Nissan Leaf, Lion 8, Proterra, New Flyer
Nickel Cobalt Aluminum (NCA)	200–260	<1,000	Toyota Prius, Tesla
Lithium Titanate (LTO)	70–80	3,000–7,000	Honda Fit, Proterra
Lithium Iron Phosphate (LFP)	90–120	1,000–2,000	BYD, TransPower, Siemens, Nova Bus, Volvo

Source for specific energy and life span:
https://batteryuniversity.com/learn/article/bu_216_summary_table_of_lithium_based_batteries.

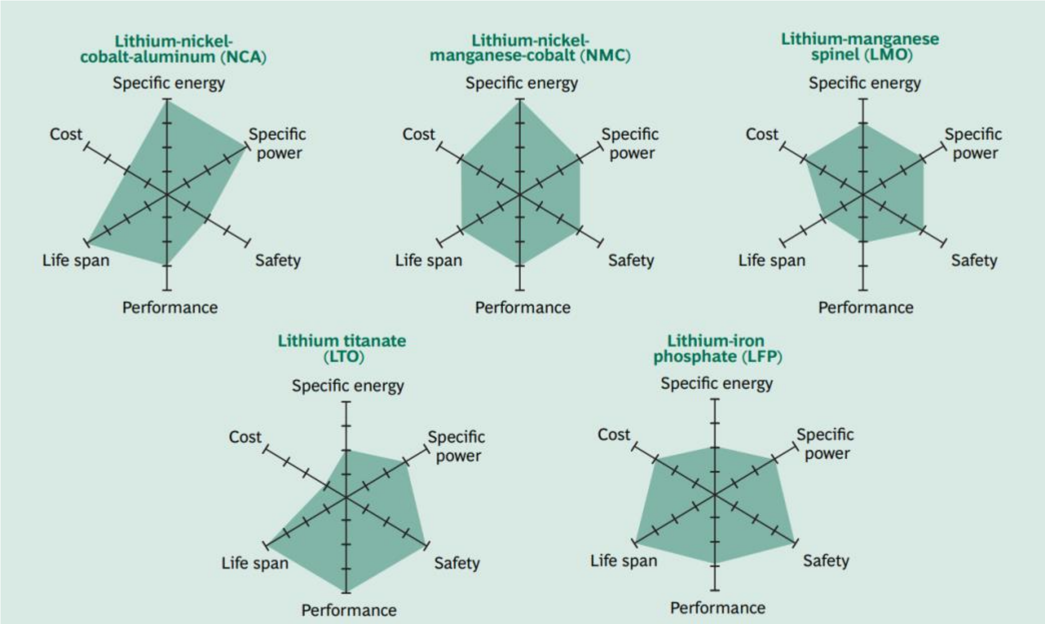

Figure 38: Trade-offs between lithium-ion battery chemistries. Source: Boston Consulting Group [BCG], 2010, *Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020*; available at www.bcg.com/documents/file36615.pdf [last accessed May 2018].

The battery performance values that are essential for favorable TCO are dependent on the MHDV application and are being studied. An important consideration for MHDV batteries is the impact of depth of discharge on the cycle lifetime, recognizing that the depth of discharge may be greater than in LDVs. Discharging a battery pack completely, instead of to a 50% level for example, is reported to reduce the cycle life by about 50% [40]. This is an area needing more data from field experience or laboratory simulation. Lion Electric has estimated a battery life of 11 years and 4,000 cycles [41]. Recently published results on a new Li-ion NMC formulation indicate the potential for 1 million miles and 20 years of use [42]. The authors advise that numerous EV categories may deeply discharge the batteries on a daily basis, including ride-hailing, truck transport, and buses. It is customary for fleets to place older trucks in shorter annual-mile functions, which may lessen the impact of the gradual reduction in charge capacity.

Most of the information about the price of MHDV battery packs on the market comes from customers reporting the cost of battery replacements and occasional estimates given by manufacturers. Battery pack cell construction and chemistry are areas of fierce competition among companies, and innovations are reducing costs. Tracking and forecasting the cost and price of battery packs is well-publicized. Results of a recent survey by ICCT are shown in Figure 39. In support of rulemaking for GHG emissions of LDVs, EPA exercised the BatPac[*] analysis tool to project battery costs, which were within the range of the ICCT report [43, 44]. As of the date of this report, the battery pack cost is estimated to be slightly below $200 per kilowatt-hour.

Although most indications are for a gradual decline in battery costs, there are some concerns regarding the future cost and availability of critical materials such as cobalt, nickel, and lithium [45] and how this may impact cost. Recognizing this situation, DOE Vehicle Technology Office is investing in research to eliminate the need for cobalt in particular.

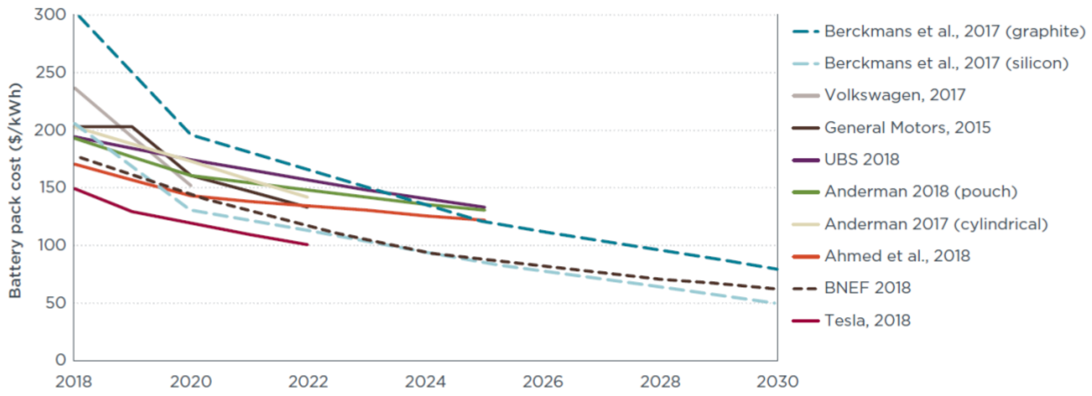

Figure 39: Projection of battery pack costs compiled by the International Council on Clean Transportation. Source: Nic Lutsey and Michael Nicholas, "Update on electric vehicle costs in the United States through 2030," Working Paper 2019-06, International Council on Clean Transportation, April 2019.

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[*] Additional information on BatPac is available at https://www.anl.gov/tcp/batpac-battery-manufacturing-cost-estimation

Supercapacitors can charge extremely quickly without impacting their lifetimes, but they do not have the energy capacity of batteries. Nevertheless, there are several commercial supercapacitors available that are intended for use on vehicles as seen in Table 10. So far, these devices have been used in China and the United States in hybrid electric transit buses and other start-stop transportation applications [46]. Most of the time they are used in tandem with a battery pack, but in some instances, they have been used alone in applications where buses can charge very frequently at stops. Compared to typical lithium ion batteries, the supercapacitors exhibit long cycle lifetimes and high specific power but with much higher cost and weight per energy stored.

Table 10: Market Assessment of Current Supercapacitors

Company	Cost ($)	$/kW	$/kWh	Specific Power (W/kg)	Specific Energy (Wh/kg)	Mass (kg)
Maxwell	1,266	21.95	47,274	5,600	2.6	10.3
Maxwell	1,821	18.73	32,634	5,400	3.1	18
Maxwell	2,212	20.58	30,510	4,300	2.9	25
Maxwell	5,474	24.93	39,016	3,600	2.3	61
Eaton	1,450	20.98	20,833	4,319	4.35	16
Vinatech	N/A	N/A	N/A	1,085	3.5	0.054
Ioxus	N/A	N/A	N/A	923	0.54	0.37
Skeleton Technology	N/A	N/A	N/A	2,796	0.8	0.145
Yunasko	N/A	N/A	N/A	2,919	0.9	0.078
Ness	N/A	N/A	N/A	975	0.55	0.38
LSCable	N/A	N/A	N/A	1,400	0.25	0.63

Note: Several companies do not produce entire modules and only produce individual components.

6.4.2 Energy storage technology gaps

The 2017 USDRIVE "Electrochemical Energy Storage Technical Team Roadmap" [47] sets the goals for EV energy storage as shown in Table 11. These goals were set primarily with LDVs in mind. Some MHDV OEMs are already citing battery life much higher than these LDV goals.

Table 11: 2017 USDRIVE Roadmap Electrochemical Energy Storage Goals

System Level Energy Storage Goals	
Cost ($/kWh)	100
Power Density (W/kg)	470
Usable Specific Energy (Wh/kg)	235
Energy density (volumetric), Wh/liter	500
Calendar Life (years)	15
Life Span (cycles)	1,000

The energy storage requirement heavily depends not only on the range, but also on the energy use per ton-mile to account for the particular payload being moved. With an assumed typical payload, Class 7 or 8 vehicles using on average 2 kWh/mile would need battery capacities of about 1,500 kWh to cover the upper end of trips without recharging. From Figure 8, we see that none of the currently available vehicles accommodate such extreme trip lengths. For a common 200-mile trip between charging opportunities, the battery pack can be a more affordable ~500 kWh, which is seen for several planned vehicles. A robust analysis to set targets for MHDV batteries is not fully complete for the wide range of duty cycles and applications. This represents a gap in knowledge.

Cost Targets/Gaps. The cost of adding even a 500 kWh battery pack is significant. Using the $100/kWh goal set by USDRIVE, the pack would cost $50,000, adding about 35% to the cost of a conventional truck. Although the cost of electrical energy per mile of operation may be lower than diesel prices, this potential base price increase represents a technology gap. Currently, the cost of batteries appears more than double the current goal. An HD powertrain OEM recently stated that the cost of batteries still exceeds $200/kWh for MHDV applications. However, in a recent article it was noted that battery packs for electric cars currently cost about $150/kWh [48]. Considering the goal of $100/kWh, future advances in active battery materials are needed as well as improvements in pack design and manufacturing.

Specific Energy Targets/Gaps. It is questionable that the specific energy goal of 235 Wh/kg for LDVs is adequate for commercial vehicles where payload capacity will be compromised by the added vehicle weight (refer to Figure 24 and Figure 25). With batteries meeting a goal of 235 Wh/kg, this would result in a 500 kWh pack weight of 2,127 kg or 4,680 lb. For a typical Class 8 truck, the maximum legal payload is about 50,000 lb to stay under the US Department of Transportation legal GVW limit of 80,000 lb, so the batteries would effectively reduce that by nearly 10% (we use an oversimplified example . . . other parts of an electric truck have lower mass). Analysis to set suitable targets for specific energy and other battery characteristics are in progress through DOE Vehicle Technologies Office programs.

Battery Cycle Life. There is an optimization challenge between pack size, cycle life, depth of discharge, and TCO. The cycle life of batteries may need to increase well beyond the 1,000-cycle goal, which has already been met by most commercial batteries, with battery chemistries accommodating 5,000$^+$ cycles. Even at 5,000$^+$ cycles, there are some fleet business cases that might require much longer life or need to replace the batteries once during the vehicle life. Batteries could possibly be cycled twice daily in over-the-road applications, and trucks are often used more than 15 years, yielding roughly 10,000 cycles The overall lifetime of batteries must either increase to approach the useful lifetime mileages of Class 8 trucks, which routinely reach over 1 million miles, or exhibit the affordability to be replaced during the vehicle life. Supercapacitors could help with this, as they have been shown to have high cycle lifetimes. However, their low energy density bars them from being used for large-scale energy storage and can keep them from helping with battery lifetime.

Volumetric Energy Density. Volumetric energy density goals have been set for LDV batteries to accommodate space for passengers and luggage. Looking at the example of a 24-foot Class 6 box truck, the total available payload space is about 38,000 L or 1,350 ft^3. For a 200 kWh battery pack at 500 Wh/L, the batteries require 400 L or only about 1% of the payload space. Typically, the battery weight will be a much greater fraction (10% or higher) of the mass-based payload capacity. The volumetric energy density of batteries is thus not seen as a significant barrier to electrification of MHDVs.

The large battery packs in MHDVs present significant challenges for charging systems if there are needs to apply XFC objectives from passenger vehicles (200 mile recharge in 10 minutes). A technology assessment for XFC is found in [49], but it primarily addresses LDVs. Assessments for MHDV battery charging are included later in this report and in NACFE's review of charging infrastructure [50].

New and higher goals for MHDV electrical energy storage are needed. In this area, significant advances are needed for battery-powered vehicles to adequately compete with conventional vehicles, especially in over-the-road freight applications. Commercial vehicle use is demanding in general, and the conventional technology market is relatively mature and competitive. Using electricity will result in a lower cost per mile for electrified vehicles compared to diesel-powered vehicles, but electrical storage technology must become better in a myriad of ways to overcome all the roadblocks and be seen in the market.

Worldwide attention is being given to solid state batteries that have the potential to make EV batteries inherently safe, increase energy density dramatically, and reduce volume and cost [15, 51]. Solid state batteries reduce the amount of inactive materials and host matrices for lithium ions by replacing bulky anode materials with dense and light metallic lithium. Most safety incidents with lithium ion batteries can be traced back to uncontrolled reactions of the organic electrolyte solvents which are flammable and form flammable gases that can burst cell housings. Solid state batteries will eliminate these problems. They have been shown to operate safely even after having been exposed to very high temperatures or high degree of mechanical deformation. The missing piece for solid state batteries are low cost roll to roll manufacturing procedures which enable lithium metal incorporation and seamless solid-solid interfaces between electrodes and electrolyte. The required development time to commercialization of cells large enough for vehicles is speculative, but likely over 10 years.

6.5 Electrified Accessories

The architecture of EVs comprises at least one low-voltage (LV) subnetwork, with LV energy storage and multiple electrical loads, and one HV subnetwork, with HV energy storage. The purpose of the auxiliary HV/LV DC-DC converter is to enable bidirectional energy flow between these two electrical subnetworks [52].

The DC-DC converter effectively replaces the alternator on an ICE car. Instead of taking energy from the rotation of the ICE motor to charge the 12 V battery, it pulls power from the main HV battery pack and converts it down to 12 V. DC-DC converters can transfer energy between the traction system and energy source (such as battery, fuel cell, ultracapacitor bank, or mechanical generator) running at different voltage levels [53]. The 12 V systems (headlights, stereo, seat heaters, etc.) use a lot of power and would quickly drain the onboard 12 V battery if it were not charged while driving.

Additionally, in the future, vehicles equipped with highly automated driving systems will consume more power through additional auxiliary loads. The additional loads include sensors such as lidar, radar, and

GPS, along with computer processors to interpret sensor data and drive the vehicle. Industry reviewers note that power requirements for accessories in general are likely to increase in future vehicles, probably needing relatively high voltage.

A basic wiring diagram for an electrified vehicle is given in Figure 40.

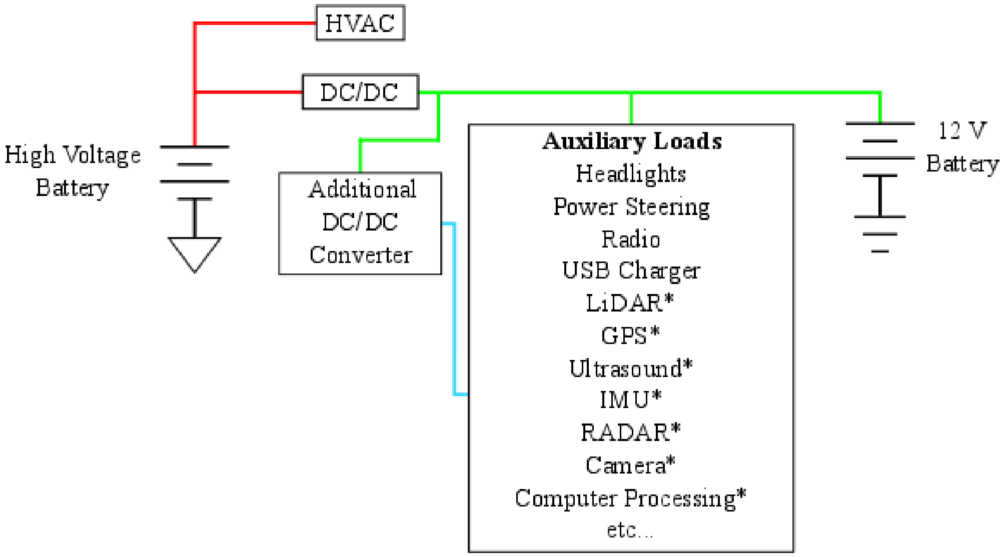

Figure 40: Auxiliary load wiring diagram for an electrified vehicle. Note: Loads associated with automated driving systems are shown with an asterisk.

6.5.1 State of the art

The typical commercially available auxiliary DC-DC converter on the market has a power rating from 1 to 3 kW, and the current rating may be as high as 120 A. The efficiency ranges from 90% to 96%, which is a decent number considering the high efficiency in DC-DC technologies. Currently, auxiliary power DC-DC converters commonly use the isolated topology. Table 12 shows the characteristics of some commonly available commercial DC-DC converters.

Table 12: Characteristics of Commercially Available Auxiliary DC-DC Converters

Manufacturer or Source	Power Rating (kW)	Power Density (kW/L)	Weight (kg)	Cost ($/KW)	Efficiency (%)
BRUSA BSC6XX-12	2.8/3.5 (nom/max)	0.89	4.8	1,600–2,100	93.5–94.7
BRUSA BSC6XX-24	2.8/3.5 (nom/max)	0.89	4.8	1,600–2,100	95.9–96.0
Elcon DC-DC Converter	0.4/0.48 (nom/max)	0.26	N/A	572	92
Denso	N/A	N/A	2.7	N/A	96
OEM DELPHI	2.2	0.42	5	634	90
OEM Chevrolet Volt Accessory Power Control Module (GM24262765)	2	0.3	N/A	498	92
THQ1200-14	1.2	0.2	8.1	612	92
JCD175	1	0.17	6.5	449	90
HWZ6	1.2	0.145	7	662	90

6.5.2 Electrified accessories technology gap

The technology gaps for electrified accessories are discussed below in relation to auxiliary DC-DC converters.

- Power requirements. When applied in MD/HD vehicles, the power requirements for auxiliary DC-DC converters increase dramatically. In LDVs, the auxiliary loads are typically rated less than 3 kW. However, in the MD/HD scenario, the power rating can go up to at least 10 kW. The reasons can be (1) greatly increased power use by air conditioning and heating, (2) high power for electric steering system, (3) more lighting requirements, and (4) special needs for various duties.

- Higher DC bus voltage. Typically, the LV DC bus in LD vehicles is rated at 12 V. However, the trend for MD/HD EVs is to increase the LV bus voltage to 24 V or 48 V. The auxiliary DC-DC converter should be adjusted and improved based on different low-side voltage.

- Multiple DC output voltages. It is highly likely that in MHDVs there exists a hybrid of LV DC voltages, i.e., 12 V and 48 V. This requires a DC-DC converter that has multiple output ports rated at different voltage levels.

- Need for auxiliary energy management system. When more and more auxiliary electric loads are used in MD/HD vehicles, the energy distributed among these loads should be dispatched optimally for minimum loss. This is a problem that should be addressed through the controller of auxiliary DC-DC converters.

6.6 Chargers

Charging requirements and infrastructure for MHDVs will depend heavily on business use and duty cycle. For some MD vocations and buses, there are one-shift operations that have hours of nonoperational time to recharge. For regional- or long-haul trucking, with the size of MHDV batteries usually exceeding 200 kWh, DC fast chargers (FCs, also referred to as DCFCs) or extreme FCs would likely become a dominant EV charging method. Having access to these fast charge stations can help truck fleet operators retain routing and business models similar to those experienced with conventional vehicles.

DCFC charging rates are estimated in a recent NACFE guidance report [50] as

- 30–40 minutes for a 100 kWh panel van to 80% charge.
- 2.5–3.5 hours for a Class 8 truck with 550 kWh storage to 80% charge.

These convert to charging rates of 125–150 kWh.

DOE defined XFC as the ability to charge an electric LDV to a 200-mile range in 10 minutes or at a rate of about 400 kW [49]. To address the electrification technology gap for MHDVs, further analysis of truck owner-operator practices and duty cycles may be needed to augment the DOE summary on gaps in XFC. For example, as noted in Table 3, even many tractor-trailer rigs travel less than 200 miles before stopping for 30 minutes, but this would still indicate the need for greater than 400 kW charging rates. (Note: The use of onboard low-power charging in MHDVs is not anticipated and is not covered here.)

6.6.1 Current state of the art

Overall, a battery charger must be efficient and reliable, with high power density, low cost, and a small footprint. Its operation depends on components, control, and switching strategies. Charger control algorithms are implemented through analog controllers, microcontrollers, digital signal processors, and specific integrated circuits depending upon the rating, cost, and types of converters. An EV charger must ensure that the utility current is drawn with low distortion to minimize power quality impact and at high power factor to maximize the real power available from a utility outlet. IEEE1547 [54], SAE-J2894 [55], IEC 61000-3-2:2018 and IEC 61000-3-12:2018 (for Europe) [56], and the US National Electric Code (NEC) 690 [57] standards limit the allowable harmonic and DC current injection into the grid, and EV chargers should be designed to comply.

Moreover, as mentioned, DCFCs are likely to become a dominant EV charging method from an MHDV perspective. As DCFCs targeting MHDVs are just emerging, a detailed survey of FCs for LD EVs was investigated to evaluate the technology gap, as shown in Table 13. Most off-board chargers have a power range from 50 kW to 150 kW with 90% overall efficiency.

On the other hand, wireless power transfer (WPT) appears suitable for the EV charging application. In contrast to traditional plug-in charging systems, WPT systems achieve the advantages of electrical and mechanical isolation, safe operation in harsh environments, and fully automatic charging [58]. An

abundance of research has been conducted on WPT EV charging applications to improve the transfer efficiency, distance, and optimization of coil size.

Table 14 gives an overall survey of stationary and dynamic wireless charging systems describing power rating, coil distance, switching frequency, and system efficiency.

Table 13: Current Research in Electric Vehicle Off-Board Chargers

Manufacturer	Output Power (kW)	Output Current (A)	Output DC Voltage Range (V)	Efficiency (%)
Blink DC Fast Charger	60	200	200–450	>90
eVGO DC Fast Charger	150	N/A	N/A	N/A
Chargepoint Express 250	62.5	156	200–1,000	96
Chargepoint Express plus	500	400	200–1,000	96
Greenlots	60	125	480	N/A
Bosch	25	65	200–500	94
Delta EV DC Quick Charger	50	125	50–500	94.6
BTC Power EVP-FC-50-001	50	100	50–500	>90
Schneider Electric	58	125	50–500	N/A
Tesla Super Charger	120	N/A	N/A	N/A
ABB Terra 54 HV Charger	50	125	200-920	95
ABB Terra HP	160	375-500	150-920	94

Table 14: Current Research in Electric Vehicle Wireless Chargers

Research Group	Output Power max (kW)	Distance (cm)	f_o (kHz)	Efficiency (end-end) (%)
Stationary Charging				
Oak Ridge National Laboratory	120	15	22	97
Mojo Mobility	10	20	80–90	92
Evatran Plugless	7.2	10	N/A	90
WiTricity	11	up to 25	80–90	91–94
Momentum Dynamics	200 (Combined four coils and power supplies)	30	N/A	“Equal to conductive”
ETH Zurich	50	16	85	N/A
WAVE Inc	50	17.8	23.4	92
NYU and HEVO Power	25	21	85–88	91
Showa Aircraft Co	30	15	22	91
Dynamic Charging				
KAIST	22/27	20	100	97
Korea Railroad Research Institute (KRRI)[a]	818 (rail-type system)	5	60	82.7
INTIS	30	15	35	90

Research Group	Output Power max (kW)	Distance (cm)	f_o (kHz)	Efficiency (end-end) (%)

[a] J. H. Kim, B.-S. Lee, J.-H Lee. S.-H. Lee, C.-B. Park, S.-M. Jung, S.-G. Lee, K.-P. Yi, J. Baek, "Development of 1-MW Inductive Power Transfer System for a High-Speed Train," *IEEE Transactions on Industrial Electronics*, Vol. 62(10), 6242–6250 (October 2015).

6.6.2 Other charging systems

Other systems to energize electric trucks include catenary overhead power lines and in-ground rails, both of which rely on direct contact between a power rail and receiving wire. These systems have been studied and advocated for zero-emission corridors and bus loops. They both pose difficulties when vehicles need to pass one another on the dedicated powered lane, and they impose a high degree of visual degradation to the landscape. At the present, the following studies are cited for background wherein the catenary systems were found to be comparable to diesel power on life-cycle cost in spite of the rather high infrastructure cost ([12],[59], [60]).

6.6.3 Charging technology gap

To charge an MHDV quickly, improvements must be made to chargers and the associated grid infrastructure. The current availability of FCs is indicated in Table 13, with the goal of an extreme FC at 350 kW or greater. DOE's study of technology gaps for XFC [49] covers the subject thoroughly, but summarized here are areas of particular importance on MHDVs.

- Component level needs for chargers are consistent with those shown previously for WBG devices. Pack configuration, size, rated voltage, and battery chemistry can vary by MHDV manufacturer, which may lead to different or unique charging protocols [49]. Considering higher power rating and reliability concerns, different battery SOCs, states of health, and battery temperatures at charge time may require different charging rates and charging voltages. Interoperability across all existing and new charging architectures must be a requirement.

- Additional barriers to achieving high power charging (or XFC) are the improvement of compatibility between charging equipment and charging networks. In terms of hardware connectivity for conductive charging, several factors should be considered to ensure appropriate cables are selected to support 1,000 V and 400 A XFC [49]. The connector shapes and interfaces should be standardized to ensure interoperability with MHDVs. Existing connectors that manufacturers are offering at the maximum current rating of 250 A and with convective cooling cannot support 400 A XFC. One option is to integrate a liquid cooling circuit into the cables and connectors. With a liquid-cooled cable and connector system, a constant charging current of 350 A and short-term events up to 400-A DC maximum appear possible while still providing a flexible, small-diameter and low-weight cable solution. Even higher power connectors (>1 MW) are in development for some applications. Without active cooling, at high charging power levels (i.e., 300^{+} kW), the required DC cabling and connector would be too heavy to physically manipulate and would be prohibitive for most consumer applications. Although integrating liquid cooling for the wire could be an option, it must be robust and not bring reliability concerns due to possible leaks, additional insulation, and periodic maintenance requirements at the charging stations. Moreover, several challenges need to be considered for establishing XFC systems, including logistics and infrastructure requirements (at truck stops for example); design and deployment of the grid interface converters; grid power quality (power factor and harmonic distortions); availability of the power (integration with renewable energy or energy storage systems if needed); distribution voltage level at the point of grid connection; and architecture limitations, thermal management systems, and the vehicle side power delivery architectures. To achieve a high charge rate, such as 3C, a collective approach considering all the challenges and requirements listed above should be taken into consideration.

- High-power stationary wireless charging can alleviate some of the cable and connector issues described above and can enable convenient and automated fast recharging. Additionally, high-power dynamic wireless charging can significantly alleviate range anxiety while concurrently reducing the required on-board battery storage leading to reduced weight, volume, and cost of the EV. Wireless charging-based solutions also have the inherent benefits of electrical and mechanical isolation, immunity to inclement weather, and are more suitable to automated charging. This is a significant advantage as automated vehicles cannot reach their full potential unless the charging process is automated.

  For MD/HD vehicle wireless charging applications, the ground clearance and thus power transfer distance is greater than that of the LD vehicles. It is also desirable to have a compact onboard wireless receiver assembly. The requirement to transfer a large amount of power (>1 MW) efficiently across a large air gap (> 25 cm) to a relatively small secondary coil necessitates high voltages and/or currents in the resonant network and couplers. Consequently, this can lead to higher electromagnetic emissions. One promising solution could be polyphase wireless charging architectures that reduces the passive component size and leads to reduced peak electromagnetic fields compared to the single-phase counterpart. Polyphase systems also reduce passive component sizes in the ground side DC/AC and vehicle side AC/DC converters, further improving power density and efficiency [61]. Advanced control and shielding techniques such as active shielding may need to be investigated to avoid interference with the environment. Co-optimization and co-design methodologies considering particular vehicle form factors are needed to meet power density, efficiency, and safety requirements for high-power wireless charging of MD/HD vehicles.

6.7 Summary of Electrification Component Technology, Knowledge Gaps, and R&D Needs

Overall, most of the technology gaps outlined in the previous section point to a lack of availability of components and technologies that will be able to handle the needs of an electrified HD or MD vehicle. The R&D needs begin with established goals and research to address the obstacles and gaps of MHVD electrification. More capable power electronics, packaging, components, and enabling materials for these components are needed.

7 Conclusions

Market Status

- Trucks move more than 70% of the nation's freight and account for 27% of on-road fuel consumption.

- The current US population of electrified MHDVs is small and fewer than 29,000 are currently registered, nearly half of them buses.

- Despite the small market, 161 electrified MHDV products, available and in development, were identified by the study team, covering a broad range of applications and architectures across weight classes 3 through 8.

- Product specifications claim vehicle ranges up to 500 miles, but most offerings fall under 250 miles. No Class 3–7 and only a handful of Class 8 vehicles claimed ranges of 250 miles or greater, all buses except for the Tesla Semi.

    - ➢ *Vehicles needing ranges above 250 miles represent a market gap*

Factors in Vehicle Design, Technology, and Market Uptake

- TCO is an important criterion in vehicle adoption and includes more factors than purchase cost and future fuel expenditures. However, many costs and benefits are unknown or uncertain and others are difficult to quantify.

    - ➢ *To achieve market success, MHDV R&D goals should move electrification technology toward a lower TCO than conventional trucks.*

    - ➢ *R&D that addresses maintenance, reliability, performance at extreme temperatures, efficiency, and component life will reduce uncertainties in cost analysis.*

- The battery has a greater impact on TCO than other technologies. Cost, energy density (weight), recyclability, durability, and safety are all important. The loss of battery performance at temperature extremes points to a need for more analysis of the impact and effectiveness of pack heating/cooling measures. Operational cost of MHDV has a greater impact on TCO than acquisition cost. Operational cost is dependent on vehicle up time, energy cost, usable load, maintenance, end of life cost, etc. For example, vehicle energy storage ability to charge quickly and not derogate over time or operational conditions is a key contributor to TCO.

- In addition to TCO, the benefits in sustainability, environment, and health are expressed by industry, transportation agencies, and various municipal groups as motivation to adopt electrified MHDVs.

- Overall vehicle efficiency is critical to minimizing energy costs and battery requirements.

  - *Efficiencies of motors, inverters, and chargers are all important.*

  - *Purpose built, "clean-slate," designs, optimized for specific vocations will likely achieve greater efficiency compared to those that begin with conventional vehicle configurations.*

- MHDV design is a complex optimization problem with trade-offs among many objectives, including power, energy, range, performance in extreme temperatures, component life, reliability, weight, payload capacity, and cost.

  - *MHDV duty cycles and the need for TCO parity result in unique requirements that should be considered in setting technical targets at the component, vehicle, and system level.*

  - *Commonization of architectures along with critical components will be necessary to increase production volumes of components for electrified vehicles, reduce cost, and increase reliability. Scalable components and subsystems are expected to aid cost-effectiveness and affordability.*

- Hybrid EVs are advantageous for some duty cycles and need technology and system optimization to satisfy common requirements and be affordable in low-volume markets.
- Additional analysis is needed to set technology targets.
- Accelerating and economizing the optimization of highly integrated powertrain architectures will aid market robustness and expand deployment. Data and analysis on duty cycles and mission requirements are needed, and more powerful simulation tools and data analytics will enable the accelerated technology development.
- Development of charging devices and infrastructure capable of providing fast charging for the larger batteries of MHDVs are needed. For the MHDV segment, the power levels necessary to rapidly recharge large capacity energy storage far exceed the current focus of LD extreme fast charging levels.

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Appendix A

Partial listing of electrified medium- and heavy-duty vehicles (MHDVs). (See full inventory at this site: https://app.box.com/s/04h4jqs50w88f5ziwvmf4o2sxbxpzhzg.)

Company	Name of the Electric Truck	Reported Battery Size and Range	Tractive Power	Source
Tesla*	Class 8 truck Semi	500–1000 kWh, 300–500 miles		
Lion Electric	Class 8 truck for urban areas	132-480 kWh, 100-250 miles	Up to 470 hp	Manufacturer
Nikola*	Class 8 truck Nikola One			
Daimler^	Class 4 Fuso eCanter	82.8 kWh, 80 miles	248 hp	Original equipment manufacturer literature
Daimler*	Class 8 eCascadia	550 kWh, 250 miles	730 hp	Daimler Literature
Daimler^	Class 6/7 eM2	325 kWh, 230 miles	480 hp	“
Daimler*	Class 6 eActros	240 kWh, 125 miles	335 hp	“
E Force*	Class 8 truck E-Force one			
Cummins*	Class 7 truck Aeos	140 kWh, 100 miles	300 hp continuous	Cummins press
Thor trucks*	Class 8 truck ET One	Up to 1000 kWh, 100–300 miles	300-700	Various web sources
BYD^	Class 8 truck T9	188 kWh, 92 miles		
BYD	Class 8 truck T9	350 kWh, 125 miles	~480 hp	BYD literature
BYD^	Class 6 truck T7	175 kWh, 124 miles		
BYD^	Class 5 truck T5	150 kWh, 155 miles		
Volvo FL	Class 8 truck	100–300 kWh, up to 300 miles	174 hp continuous	
Orange EV^	Class 8 truck T-series			
Typical Transit Bus. BYD, Proterra	Class 8 Bus (C10 BYD) Proterra XR	420 kWh, 225 miles 220–330 kWh, 81–218 miles	180 kW 150–220 hp continuous	