Medium- & Heavy-Duty Vehicles

Market structure, Environmental Impact, and EV Readiness



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Contents

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This report summarizes an analysis of the U.S. medium and heavy-duty in-use truck fleet to identify the most common vehicle types/uses, estimate the environmental impact of each, and assess near-term readiness for greater adoption of electric vehicles based on typical usage patterns and market status. For this analysis we have included all vehicles with gross vehicle weight rating (GVWR) above 8,500 pounds, encompassing vehicle classes from Class 2b (8,500 – 10,000 lb GVWR) to Class 8 (>33,000 lb GVWR).

Totaling 22.8 million vehicles that annually travel more than 430 billion miles and consume more than 55 billion gallons of fuel, this is a very diverse group, ranging from heavy-duty pickups and vans to transit and school buses, freight and work trucks, and tractor-trailers. Most of these vehicles are used commercially, rather than for personal transportation.

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About M.J. Bradley & Associates

MJB&A, an ERM Group company, provides strategic consulting services to address energy and environmental issues for the private, public, and non-profit sectors. MJB&A creates value and addresses risks with a comprehensive approach to strategy and implementation, ensuring clients have timely access to information and the tools to use it to their advantage. Our approach fuses private sector strategy with public policy in air quality, energy, climate change, environmental markets, energy efficiency, renewable energy, transportation, and advanced technologies. Our international client base includes electric and natural gas utilities, major transportation fleet operators, investors, clean technology firms, environmental groups and government agencies. Our seasoned team brings a multi-sector perspective, informed expertise, and creative solutions to each client, capitalizing on extensive experience in energy markets, environmental policy, law, engineering, economics and business. For more information we encourage you to visit our website, www.mjbradley.com.

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Executive Summary

This report summarizes an analysis of the U.S. medium and heavy-duty (M/HD) in-use truck fleet to identify the most common vehicle types/uses, estimate the environmental impact of each, and assess readiness for greater adoption of zero emitting technologies over the next decade, based on typical usage patterns and market status. It is intended to help inform the Environmental Protection Agency's deliberations involving future criteria and greenhouse gas emissions standards and policies for medium- and heavy-duty engines and vehicles.

This analysis focuses on prospects for electric vehicle penetration because all scenarios for avoidance of detrimental future climate warming point to the need for significant reductions in emissions from the transportation system, coupled with further decarbonization of the electric sector. Net reductions in transportation emissions could come from a range of zero-emitting vehicle types including battery-electric vehicles and hydrogen fuel cell electric vehicles. For this study, MJB&A evaluated the current state of battery electric vehicles for each M/HDV market segment, to assess prospects for near-term (through 2025) and medium-term (through 2030) uptake of zero-emission vehicles within each segment. While fuel cell vehicles could also play a role in transforming the transportation system within this timeframe, the focus of this report on battery electric vehicles is based on the relatively greater commercial maturity of this technology in the U.S. market

Also, while comprising less than 10 percent of all vehicles on the road, M/HD trucks account for more than 60 percent of tailpipe nitrogen oxide (NOx) and particulate (PM) emissions from the onroad fleet[1]; these emissions contribute to poor air quality in many urban areas, including areas with vulnerable populations. Deploying zero-emitting vehicles coupled with greater use of renewable electricity will provide significant public health benefits by reducing urban air pollution. A recent study indicates that eliminating tailpipe emissions from new medium- and heavy-duty vehicles by 2040 could provide up to $485 billion in health and environmental benefits as a result of pollution reductions (2020$)[2].

For this analysis we have included all vehicles with gross vehicle weight rating (GVWR) above 8,500 pounds, encompassing vehicle classes from Class 2b (8,500 – 10,000 lb GVWR) to Class 8 (>33,000 lb GVWR).

Totaling 22.8 million vehicles that annually travel more than 430 billion miles and consume more than 55 billion gallons of fuel, this is a very diverse group, ranging from heavy-duty pickups and vans to transit and school buses, freight and work trucks, and tractor-trailers. Most of these vehicles are used commercially, rather than for personal transportation.

While very diverse, approximately 80 percent of the fleet can be grouped into 17 market segments each with broadly similar vehicle configuration and usage patterns; these 17 market segments are the focus of this analysis[3].

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[1] Per EPA MOVES model emissions inventory.

[2] EDF, *Clean Trucks, Clean Air, American Jobs*, March 2021; https://www.edf.org/sites/default/files/2021-03/HD_ZEV_White_Paper.pdf

[3] The remaining 20 percent of the fleet encompasses a wider diversity of vehicle types and uses, some of which includes a relatively small number of vehicles. This includes Fire Trucks, ambulances and other emergency vehicles, Motor Homes, and trucks used in Forestry and Mining. It also includes vehicles that could not be classified based on VIN-defined vehicle type or the type of company that registered them. See Appendix A for more information about how the market segments were determined and number of vehicles in each was estimated.

For each market segment the number of vehicles in the segment was estimated using registration data collected from all 50 states by IHS Markit [1]. EPA's MOtor Vehicle Emissions Simulator (MOVES3) model [2] was used to estimate the environmental impact of each market segment – from both a climate and air quality perspective.

Various resources and considerations were then used to evaluate prospects for near-term uptake of battery-electric vehicles within each market segment, as a proxy for uptake of zero-emission vehicles more generally.

Each market segment was evaluated based on four relevant factors that will significantly impact truck owner decisions about whether to purchase an electric vehicle: availability of electric models from major manufacturers (Commercial EV Market), infrastructure requirements for vehicle charging (Charging), the ability of current EV models to meet operating requirements (Technical Feasibility), and prospects for cost parity with current diesel and gasoline vehicles (EV Business case). See the appendix for a full discussion of the methodology and data sources used for the EV market readiness analysis.

Figure 1 M/HD Market Segments

MARKET SEGMENT	Weight Class
Heavy Duty Pickup & Van	Class 2B Class 3
Regional Haul Tractor	Class 7 - 8
Long Haul Tractor	Class 8
Transit Bus	Class 8
School Bus	Class 7
Shuttle Bus	Class 3-5
Delivery Van	Class 3-5
Delivery Truck	Class 6-7
Service Van	Class 3-5
Service Truck	Class 6-7
Refuse Hauler	Class 8
Box Truck (freight)	Class 3-5
Box Truck (freight)	Class 6-7
Box Truck (freight)	Class 8
Stake Truck (construction)	Class 3-5
Stake Truck (construction)	Class 6-7
Dump Truck	Class 8

The analysis finds that there are a large number of market segments that have favorable ratings across at least 3 of the 4 relevant factors, which indicates strong potential for near-term EV uptake[4]. Representing approximately 66 percent of the current in-use fleet, these market segments include Heavy-duty Pickups and Vans, Local Delivery and Service Trucks and Vans, Transit and School Buses, Class 3 - 5 Box Trucks, Class 3 – 7 Stake Trucks, Dump Trucks, and Refuse Haulers. Electrifying these vehicles would deliver significant public health benefits – including up to 1,500 fewer premature deaths, 1,400 fewer hospital visits, and 890,000 incidents of exacerbated respiratory conditions and lost or restricted workdays annually. Additional major take-aways from the full analysis are summarized below and are discussed more fully in the following sections.

[4] While not formally evaluated, other zero-emitting technologies such as hydrogen fuel cell electric vehicles could also play an important role in many market segments.

Climate	While less than 15% of vehicles, long- and regional-haul tractor-trailers have the greatest climate impact - accounting for 60% of greenhouse gases - due to their high annual mileage. The second most important market segment is heavy-duty pickups and vans (Class 2b – 3) which account for more than 20% of GHGs because there are so many of them.	**80% of Climate impact is from three of the 17 market segments**
Air Quality	Market segments with the highest relative impact on urban air quality – NOx and PM emissions relative to the number of vehicles and miles traveled – include buses of all types, tractor-trailers, refuse trucks, heavy freight trucks, and construction trucks	**Air quality impact is less concentrated among market segments than climate impact**
EV Market	The market segments that can be considered fully mature in 2021 with respect to commercial EV offerings are transit and school buses. While most other M/HDV market segments currently have few commercial EV models from key market actors, they are seeing rapidly increasing activity from established players and well-financed start-ups. Virtually all market segments have the potential to be fully mature by 2025, with EV models available from multiple companies, including the majority of major OEMs that currently have 90% market share of the in-use fleet. A number of companies have near-term plans to launch light-duty electric pickups and vans (<8,500 lb GVWR), including the market leader Ford. Developments in this market can help to advance electrification of the heavier Class 2B (8,500 – 10,000 lb GVWR) segment of the M/HD market	**In Most market segments the EV market is emerging with the potential to be fully commercially mature by 2025.**
Charging	The majority of M/HDVs have relatively modest charging needs (<20 kW/vehicle) and can do most if not all charging overnight at their "home base" Developing additional fueling infrastructure is needed for wide adoption of zero-emitting long-haul freight trucks, as those vehicles will require a nation-wide network of high-power shared (public) chargers (for battery electric trucks) or hydrogen fuel stations (for fuel cell electric trucks).	**Most M/HD EVs can be charged overnight at their "home base" and will not need public chargers**

EV Business Case	The current cost of M/HD EVs present some challenges for the business case, but projected cost reductions will substantially improve EV economics in all market segments over the next 10 years. Increased EV sales volumes will accelerate expected cost reductions. EVs in the majority of market segments have the potential to achieve life-cycle cost parity with internal combustion engine vehicles by model year 2025 or earlier if M/HD battery costs follow a similar trajectory as battery costs for light-duty EVs.	**For most Market Segments the EV business case remains challenging but is improving rapidly in a very dynamic market**
Policy Implications	Vehicle segments for near-term ZEV policy focus include *School and Transit buses* – mature ZEV market, high urban air quality impact, high visibility *Urban delivery and service fleets (Class 3 – 5), to include vans and box trucks of variuous sizes* – duty cycle matches EV capability, low charging barriers, large number of vehicles which can advance techical and commercial development H*eavy-duty Pickups and Vans (Class 2B)* – duty cycle generally matches EV capability, generally low charging barriers, large number of vehicles which can advance techical and commercial development *Construction trucks, including Class 3 -7 Stake Trucks, and Dump Trucks* – high urban air quality impact, generally low charging barriers *Refuse Haulers* - high urban air quality impact, high visibility	

M/HDV In-Use Fleet: Vehicle Types & Uses

This section discusses the composition of the current M/HD fleet, including the number of vehicles of each type/use, the percentage of vehicles by fuel type, and manufacturer market shares.

Under EPA's Phase 2 rules, GHG emissions are regulated both from new engines and from new vehicles [3]. Engine standards are separated into three categories: those applicable to light-heavy duty engines (LHD) used in Class 2b – Class 5 trucks, those applicable to medium-heavy duty engines (MHD) used in Class 6 – 7 trucks, and those applicable to heavy-heavy duty (HHD) engines used in Class 8 trucks. Vehicle regulations are separated into three vehicle categories: those applicable to Heavy-duty Pickups and Vans (Class 2b – 3), those applicable to Combination Truck tractors (Class 7 – 8), and those applicable to all other trucks that are not in either of the first two categories, which are called Vocational Vehicles. The vocational vehicle category is very diverse, covering vehicles from Class 3 to Class 8 with a wide range of uses, from freight trucks, to buses, to construction and other work trucks; see Figure 2

Figure 2 Vehicle Weight Classes and EPA Regulatory Categories

Weight Class	2b	3	4	5	6	7	8
Example Vehicles							
GVWR (lb)	8,500 to 10,000	10,001 to 14,000	14,001 to 16,000	16,001 to 19,500	19,501 to 26,000	26,001 to 33,000	>33,000
Engine Regulatory Category	Light Heavy-Duty				Medium Heavy-duty		Heavy Heavy-Duty
Vehicle Regulatory Category	Heavy Duty Pickup & van						
		Vocational Trucks					
						Combination Trucks	

Source: U.S. Environmental Protection Agency

Given the diversity of the Vocational Vehicle Category it is further divided by the characteristics of the duty cycle seen by "typical" vehicles. The defined duty cycles are Urban (low speed, frequent stops), Regional (higher speeds, less frequent stops) and Mixed Use (a combination of Urban and Regional duty cycles). Vehicles regulated under the different duty cycles are subject to different regulatory test cycles that reflect the chosen duty cycle and subsequently have different numerical emission limits. Manufacturers are allowed to specify the duty cycle used to certify each Vocational Vehicle model.

See Figure 3 for a summary of the M/HDV market segments analyzed here, and the estimated number of in-use vehicles in each. Each market segment is identified by vehicle type and weight class range. Also included is information on the EPA vehicle and engine regulatory category that the vehicles in the segment are covered by, for the purposes of regulating new engine and vehicle fuel economy and greenhouse gas emissions.

For most market segments the estimated number of vehicles shown in Figure 3 is based on an analysis of state vehicle registration data collected by IHS Markit [1]. For this analysis all in-use vehicles were categorized based on manufacturer-defined vehicle type[5] and weight class, plus the "registration vocation" assigned by IHS Markit based on the company that registered each vehicle (i.e. construction, sanitation, freight, services). The market segmentation summarized in Figure 3 is an organic outcome of the in-use vehicle analysis, and the market segment names are intended to be illustrative of the vehicle configuration and use for the majority of vehicles in each segment, based on vehicle configuration and using company. Within each segment there is some variation in vehicle configuration and daily/annual usage patterns. See Appendix A for a full discussion of how the in-use vehicle segmentation analysis summarized in Figure 3 was conducted.

Figure 3 U.S. In-use Medium- & Heavy-duty Fleet by Market Segment

MARKET SEGMENT	Weight Class	EPA Phase 2 Regulatory Category		Estimated In-use Vehicles	
		Engine	Vehicle	Number	% of Fleet
Heavy Duty Pickup & Van	Class 2B	LHD	HD Pickup & Van	8,951,335	39.3%
	Class 3	LHD	HD Pickup & Van	2,330,763	10.2%
Regional Haul Tractor	Class 7 - 8	MHD, HHD	Combination Trucks	1,094,056	4.8%
Long Haul Tractor	Class 8	HHD	Combination Trucks	2,057,164	9.0%
Transit Bus	Class 8	HHD	Vocational Ve Urban	77,720	0.3%
School Bus	Class 7	MHD	Vocational Ve Urban	497,201	2.2%
Shuttle Bus	Class 3-5	LHD	Vocational Ve Urban	149,773	0.7%
Delivery Van	Class 3-5	LHD	Vocational Ve Urban	500,110	2.2%
Delivery Truck	Class 6-7	MHD	Vocational Ve Urban	400,969	1.8%
Service Van	Class 3-5	LHD	Vocational Ve Urban	808,802	3.5%
Service Truck	Class 6-7	MHD	Vocational Ve Urban	296,999	1.3%
Refuse Hauler	Class 8	HHD	Vocational Ve Urban	101,401	0.4%
Box Truck	Class 3-5	LHD	Vocational Ve Regional	162,731	0.7%
Box Truck	Class 6-7	MHD	Vocational Ve Regional	172,354	0.8%
Box Truck	Class 8	HHD	Vocational Ve Regional	153,776	0.7%
Stake Truck	Class 3-5	LHD	Vocational Ve Mixed Use	391,348	1.7%
Stake Truck	Class 6-7	MHD	Vocational Ve Mixed Use	191,925	0.8%
Dump Truck	Class 8	HHD	Vocational Ve Mixed Use	247,475	1.1%
OTHER	Class 3 - 8	LHD,MHD,HHD	Vocational Ve Mixed Use	4,216,527	18.5%
				22,802,427	100.0%

Source: IHS Markit, M.J. Bradley & Associates

[5] This information is encoded in the vehicle identification number (VIN) assigned by the original equipment manufacturer (OEM). Other data encoded in the VIN and included in the IHS Markit database for each vehicle includes manufacturer name, vehicle model, and weight class.

Weight Class 2 (VIN-defined) does not identify the sub-set of vehicles in Class 2b (8,500 – 10,000 lb GVWR), so the IHS Markit data could not be used to estimate the number of these vehicles in the fleet; the estimate of Class 2b vehicles in Figure 3 is from EPA's MOVES3 model [2].

As shown, as of December 2020 there were an estimated 22.8 million medium- and heavy-duty vehicles (Class 2b – 8) registered in the U.S. Almost 50% of these vehicles are heavy-duty pickups and vans (Class 2b – 3), 13% are combination trucks (tractor-trailers), and 37 percent are various types of vocational vehicles. Of the vocational vehicles about 33 percent have a primarily urban duty cycle, 6 percent have a primarily regional duty cycle, and 61 percent have a mixed duty cycle.

Based on analysis of in-use tractor characteristics, MJB&A estimates that approximately one third of tractor-trailers are primarily used for local or regional freight hauling (return-to-base) and two thirds are primarily used to deliver freight across much longer distances, with vehicles not returning to the same location every day.[6] Some examples of local/regional hauling using tractor trailers include beverage delivery and shuttles between major regional warehouses or logistics centers.

The market segmentation analysis is most helpful in breaking down the diverse group of vocational vehicles into different use cases. Almost 9% of vocational vehicles are buses of different types, and another 11% are construction trucks. Approximately 16% of vocational vehicles are single-unit freight delivery vans and trucks primarily used for local and regional freight deliveries (return-to-base) and 14% are vans and single unit trucks used in the delivery of various local services – including by electric and gas utility companies, telecom companies, and local contractors (plumbers, electrician, landscapers, etc.).

The last category in Figure 2, labeled "other" includes a diverse mix of vocational vehicles, none of which individually make up more than 0.5% of the fleet. These vehicle types include fire trucks and other emergency vehicles, motor homes, and mining and forestry trucks. Most of the trucks in this category, however, are trucks that could not be identified as belonging in one of the other market segments due to a lack of data – because they were registered to individuals rather than companies (and therefore have no registration vocation), or because they were registered by companies which could not be easily categorized by IHS Markit (see the Appendix).

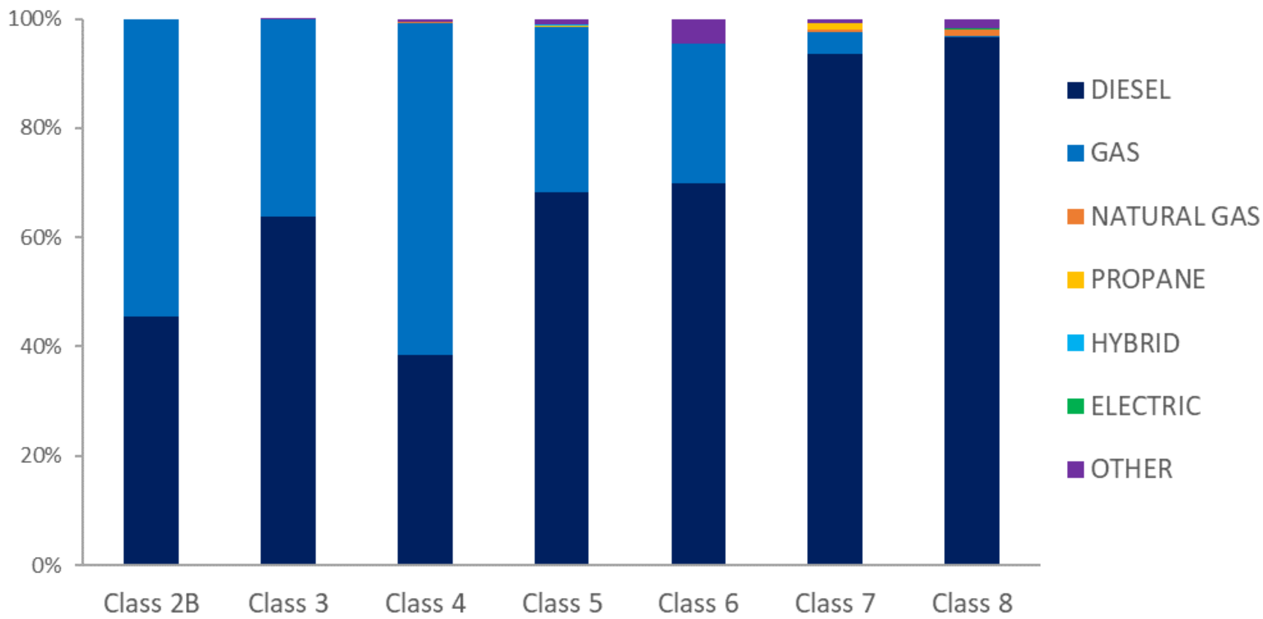
As shown in Figure 3, most of the market segments used to frame this analysis map directly to a single combination of EPA engine and vehicle regulatory categories – i.e., Transit Bus is HHD/Vocational Vehicle/Urban Duty Cycle, and Delivery Van is LHD/Vocational Vehicle/Urban Duty Cycle. However, multiple market segments may map to the same combination of EPA regulatory categories – for example Delivery Van, Shuttle Bus and Service Van all map to LHD/Vocational Vehicle/Urban Duty Cycle.

See Figure 4 for a summary of the in-use M/HDV fleet by weight class and fuel type[7]. Today, less than one percent of the M/HDV fleet are hybrid-electric or battery-electric vehicles and less than 2% are alternative fuel vehicles (natural gas, propane, other). Over 95% of the largest Class 7 and Class 8 trucks have diesel engines. A much larger percentage of smaller vehicles have gasoline engines, especially Class 2B and Class 4 trucks – over 50% of these vehicles have gasoline engines, with most of the rest diesel.

[6] As discussed more fully in Appendix A the estimate of regional versus long-haul tractor trailers is based on characteristics of vehicles in the registered in-use fleet, including engine displacement, number of driven wheels, and cab style.

[7] Data for Class 3 – 8 in this his figure is based on IHS Markit registration data; the fuel type distribution for Class 2b trucks is based on EPA's MOVES3 model.

Figure 4 U.S. In-use Medium- & Heavy-Duty Fleet by Fuel Type



Source: IHS Markit

See Figure 5 for a summary of the in-use M/HDV fleet by manufacturer; as shown, 12 companies account for 90% of the fleet. The remaining 10% of the fleet ("Other" in Figure 5) was primarily produced by small specialty manufacturers, including those that exclusively make transit buses, fire trucks, and motor homes.

The twelve primary manufacturers of M/HDV trucks can be divided into three groups – those that primarily make smaller vehicles (Class 3 – 6), those that almost exclusively make the largest Class 8 trucks, and those that have significant market share across the entire size range. Manufacturing of the smallest vehicles is dominated by the "big 3" US car companies – Ford, General Motors, and Chrysler (Dodge)[8]. There are only two companies that have significant market share from Class 4 through Class 8 – International and Freightliner. The companies that primarily produce the largest Class 8 trucks – most of which are combination truck tractors and construction trucks – include PACCAR (which owns Kenworth, and Peterbilt), Volvo (Volvo also owns Mack), and Freightliner (which owns Sterling Truck and Western Star). Note that the manufacturers shown in Figure 5 produce their own engines, but typically also offer engines from Cummins in many of their models. Cummins is the only large fully independent engine manufacturer in North America (it produces only engines and not full vehicles)[9]; over the past three years Cummins has had a 25 percent market share of engines in new Class 3 -8 vehicles, with engine sales across all weight classes[10].

For new vehicles registered in the last three years (2018 – 2020) manufacturer market shares are very similar to those shown in Figure 5 for the full in-use fleet, with the exception that for smaller vehicles

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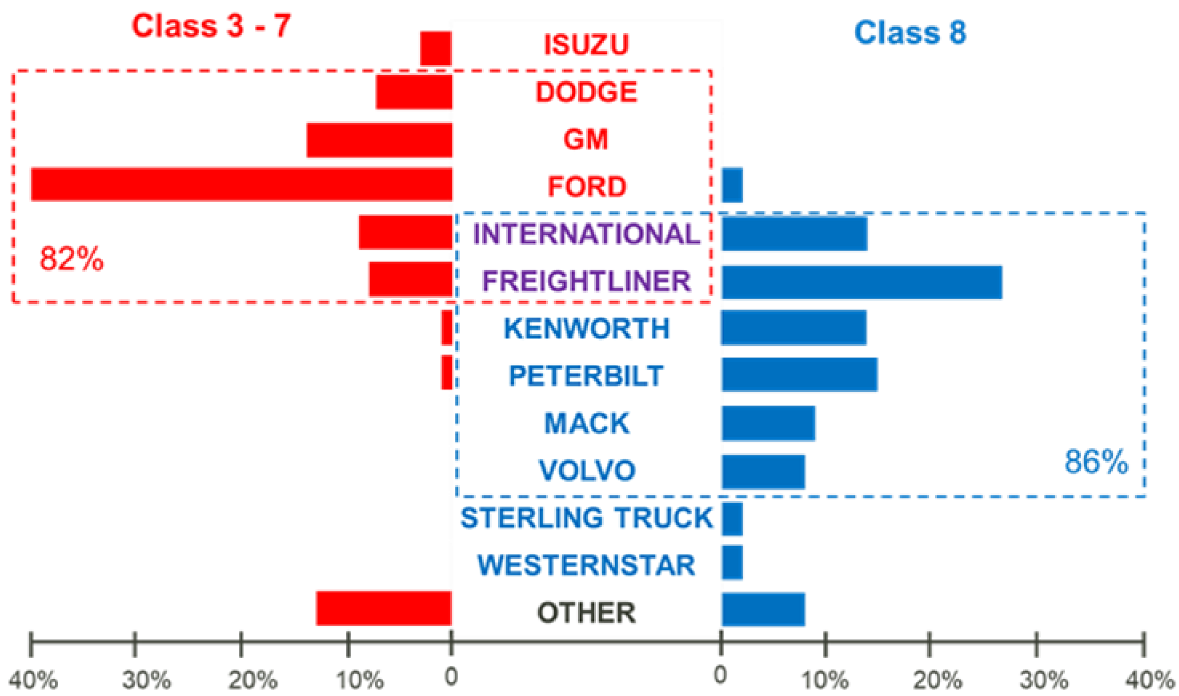
[8] Though not included in Figure 3, these companies also dominate manufacturing of Class 2b trucks, which are primarily heavy-duty pickups and vans, as well as a small number of large SUVs.
[9] Detroit Diesel is also an independent engine manufacturer but is a subsidiary of Freightliner.
[10] IHS Markit, new Class 3 – 8 vehicle registrations 2018 – 2020.

(Class 3 - 7) Mercedes and Hino each have about 1.5% market share of recent truck sales, and Sterling Trucks has less than 1% market share of recent Class 8 truck sales. [4]

Figure 5 U.S. In-use Medium- & Heavy-Duty Fleet by Manufacturer



"Other" manufacturers are mostly specialty vehicle manufacturers (i.e. bus, motor home, fire truck, etc.)

Source: IHS Markit

M/HDV In-Use Fleet: Environmental Impact

EPA estimates that in 2020 the M/HDV fleet consumed 55.3 billion gallons of fuel and emitted 561 million metric tons (mill MT) of greenhouse gases (GHG), 1.5 million MT of nitrogen oxides (NOx) and 38,000 MT of particulate matter (PM)[11] [2]. Almost 60% of NOx and PM exhaust emissions from the M/HDV fleet were in urban areas. NOx and PM emissions from the M/HD fleet are currently responsible for up to 4,550 premature deaths, 4,290 hospital visits, and 2.7 million incidents of exacerbated respiratory conditions and lost or restricted workdays annually. The monetized cost of these public health impacts from the M/HD fleet are estimated to exceed $53 billion annually[12].[5]

In their 2021 Annual Energy Outlook the Energy Information Administration estimates that national M/HD VMT will grow by 29 percent through 2050[13], a compound annual average growth rate of 0.75 percent [6]. Projected regional growth rates vary, with higher projected growth in the Southeast and Mountain West than in most other parts of the country, mirroring projected regional population growth. Based on EIA VMT growth projections, and current EPA new engine fuel economy and emission standards, MJB&A estimates that annual M/HDV fuel use and GHG emissions will fall by 18 percent through 2050 as the fleet turns over to new, more efficient vehicles [7]. Through 2045 annual fleet NOx and PM exhaust emissions are projected to fall by 43 percent and 72 percent respectively, as the fleet turns over to new vehicles with engines that meet more stringent emission standards. After 2045 annual fleet NOx and PM emissions are projected to start rising again due to continued VMT growth.

See Figure 6 for a summary of the estimated relative environmental impact of the different M/HDV market segments in 2020, as a percentage of total M/HD fleet impact. For each segment Figure 6 includes the estimated percentage of total in-use M/HD vehicles included in the segment, the percentage of total M/HD fleet miles (VMT) driven by these vehicles, and the percentage of M/HD fleet total GHG, urban NOx, and urban PM[14] produced by the segment. These estimates were developed by mapping MOVES3 data, delineated by vehicle type and regulatory category, to the vehicle types in each segment. See the appendix for a full discussion of how this mapping was conducted.

As shown, almost 50% of GHGs from the entire M/HDV fleet are emitted by combination truck tractors used in long-haul service. This market segment also accounts for over 40% of M/HDV tailpipe NOx and PM emitted in urban areas. Regional haul tractors account for another 12% of GHGs and a similar percentage of urban tailpipe NOx and PM emissions. From both a climate and air quality perspective the third most important market segment is heavy duty pickups and vans, which contribute 16% of GHGs, 17% of tailpipe NOx emissions, and 23% of tailpipe PM emissions from the M/HD fleet. These three market segments together account for greater than three quarters of the climate and air quality impact of the M/HDV fleet.

As a group Class 3 – 8 vocational trucks account for 27 percent of fleet VMT, 25 percent of fleet GHGs, 23 percent of urban tailpipe NOx and 26 percent of urban tailpipe PM. Within the vocational vehicle

[11] This is estimated direct exhaust emissions of PM with mean aerodynamic diameter less than 2.5 microns ($PM_{2.5}$). It does not include PM emissions from brake and tire wear, or secondary PM emissions formed in the atmosphere from exhaust gases such as NOx.
[12] This is based on EPA's Co-Benefits and Risk Assessment (COBRA) screening tool. Values are national estimates of health impacts due to the contribution of M/HD vehicle exhaust to ambient PM concentrations. Hospital visits includes hospital admissions and emergency room visits.
[13] EIA's AEO 2021 includes the effects and projected recovery from the COVID-19 pandemic and includes slower near-term M/HD VMT growth than had been projected by EIA in recent years.
[14] Direct exhaust PM, not including secondary PM or PM from brake and tire wear.

category approximately 17 percent of urban air quality impact (tailpipe NOx and PM) comes from buses of different types, 17% comes from construction trucks, 17% comes from single-unit freight trucks primarily used for local and regional freight deliveries (return-to-base) and 9% comes from vans and single unit trucks used in the delivery of various local services.

Figure 6 U.S. In-use Medium- & Heavy-duty Fleet Environmental Impact by Market Segment

MARKET SEGMENT	Weight Class	SEGMENT IMPACT				
		% of Fleet	% of VMT	% of GHG	% Urban NOx	% Urban PM
Heavy Duty Pickup & Van	Class 2B	39.2%	22.7%	11.7%	14.6%	18.8%
	Class 3	10.2%	6.0%	4.0%	2.8%	4.0%
Regional Haul Tractor	Class 7 - 8	4.8%	9.0%	11.9%	12.7%	10.6%
Long Haul Tractor	Class 8	9.0%	35.8%	47.8%	46.5%	41.0%
Transit Bus	Class 8	0.3%	0.6%	0.7%	0.9%	0.5%
School Bus	Class 7	2.2%	1.2%	1.1%	1.3%	1.9%
Shuttle Bus	Class 3-5	0.7%	1.0%	1.3%	1.6%	1.9%
Delivery Van	Class 3-5	2.2%	1.4%	1.0%	0.7%	1.1%
Delivery Truck	Class 6-7	1.8%	2.8%	2.7%	2.2%	2.7%
Service Van	Class 3-5	3.5%	2.3%	1.7%	1.2%	1.8%
Service Truck	Class 6-7	1.3%	0.8%	0.8%	0.7%	0.8%
Refuse Hauler	Class 8	0.4%	0.4%	0.6%	1.0%	1.4%
Box Truck (freight)	Class 3-5	0.7%	0.5%	0.3%	0.2%	0.2%
Box Truck (freight)	Class 6-7	0.8%	0.6%	0.5%	0.4%	0.5%
Box Truck (freight)	Class 8	0.7%	1.8%	1.9%	2.2%	1.7%
Stake Truck (construction)	Class 3-5	1.7%	1.0%	0.7%	0.5%	0.8%
Stake Truck (construction)	Class 6-7	0.8%	0.5%	0.5%	0.4%	0.5%
Dump Truck	Class 8	1.1%	2.3%	2.6%	3.4%	2.8%
OTHER	Class 3 - 8	18.5%	9.5%	8.1%	6.6%	7.2%
		100%	**100%**	**100%**	**100%**	**100%**

Source: IHS Markit, EPA MOVES3, M.J. Bradley & Associates

For most market segments climate and air quality impact is generally proportional to the miles traveled by vehicles in the segment (VMT). There are a few segments however, with air quality impact higher than their proportion of fleet VMT - these segments include both regional and long-haul tractors; transit, school, and shuttle buses; refuse trucks, the largest (Class 8) freight hauling box trucks, and dump trucks.

It is also worth noting that a long-term trend in the M/HD fleet is the increasing importance of smaller Class 3 vehicles, most of which are pickup trucks, or are vans and small box trucks used for local services and deliveries. In 1990 only 7 percent of new M/HD truck sales were Class 3, but by 2000 this had risen to 20 percent, and since 2010 it has averaged 40 percent; see Appendix B [8]. In 2020 384,000 new Class

3 vehicles were registered, an increase of 42 percent compared to the previous year. By comparison, in 2020 registrations of new Class 4 – 8 trucks were down 19 percent compared to 2019, likely due to the effects of the COVID 19 pandemic [4].

See Figure 7 for a summary of relative market segment impact for Vocational trucks (the market segments other than Heavy-duty Pickup and Van, and tractors).

Figure 7 Market Segment Impacts – not Including Tractors and Heavy-Duty Pickups and Vans

MARKET SEGMENT	Weight Class	RELATIVE SEGMENT IMPACT				
		% of Fleet	% of VMT	% of GHG	% Urban NOx	% Urban PM
Transit Bus	Class 8	0.9%	2.1%	2.9%	3.8%	1.8%
School Bus	Class 7	5.9%	4.4%	4.6%	5.6%	7.5%
Shuttle Bus	Class 3-5	1.8%	3.8%	5.3%	6.9%	7.5%
Delivery Van	Class 3-5	6.0%	5.2%	4.2%	3.2%	4.2%
Delivery Truck	Class 6-7	4.8%	10.5%	11.0%	9.6%	10.6%
Service Van	Class 3-5	9.7%	8.5%	6.8%	5.1%	6.8%
Service Truck	Class 6-7	3.5%	3.1%	3.2%	2.8%	3.1%
Refuse Hauler	Class 8	1.2%	1.6%	2.3%	4.4%	5.4%
Box Truck	Class 3-5	1.9%	1.7%	1.3%	0.7%	0.9%
Box Truck	Class 6-7	2.1%	2.3%	2.2%	1.7%	1.9%
Box Truck	Class 8	1.8%	6.7%	7.6%	9.5%	6.5%
Stake Truck	Class 3-5	4.7%	3.8%	3.0%	2.3%	3.0%
Stake Truck	Class 6-7	2.3%	1.8%	1.9%	1.7%	1.9%
Dump Truck	Class 8	3.0%	8.7%	10.6%	14.4%	10.9%
OTHER	Class 3 - 8	50.4%	35.8%	33.1%	28.3%	28.1%

Among the Vocational truck market segments, the most impactful are dump trucks, Class 8 box trucks, Class 6-7 delivery trucks, Class 3 -5 service vans, and school and shuttle buses.
Note that the “other” category at the bottom of Figure 7 includes a wide range of vehicles. As discussed above, some vehicles in this segment are known specialty vehicles with very low total numbers in the fleet (i.e. ambulances, forestry trucks) but the majority of vehicles in this segment could not be fully characterized by type and usage due to a lack of data[15]; it is likely that a significant percentage of these vehicles actually belong in one of the other market segments.

The analysis summarized in Figure 6 is based on the current 2020 in-use fleet. As described above, EPA projects that total annual GHG, NOx, and PM emissions from the M/HD fleet (Class 2B-8) will fall by 2030 due to turnover of the in-use fleet to new, cleaner vehicles. However, estimated reductions

[15] This is because they were registered by individuals or by companies that could not be characterized by business type. See the Appendix for a full discussion of the data and methods used to apportion vehicles to market segments.

in average emissions (g/mi) are generally consistent across different vehicle types, and the relative environmental impact of the different market segments is expected to remain consistent with the values in Figure 6, with only minor shifts based on changes in the fleet vehicle mix (see Appendix B). For example, if the trend of increasing Class 3 vehicle sales continues this would slightly increase the relative impact of market segments such as Heavy-duty Pickup and Van, Delivery Van and Service Van.

M/HDV ZEV Market Readiness

In the last two years there has been significant activity in the M/HD ZEV market, with a number of fleets making commitments to electrification, and vehicle manufacturers introducing prototype vehicles and pilot fleets, and announcing commercial launch dates [9]. Volvo and Freightliner are operating ZEV demonstration fleets across the country and have both begun taking commercial orders for their e-models. Kenworth has developed a prototype Class 6 electric truck and plans to produce up to 100 of them in 2021.

Both Navistar (NEXT) and General Motors (Bright Drop) have launched new business units to focus on electric mobility solutions, including vehicles, software, and services. Navistar, Volvo, and Freightliner have all announced major investments to build or upgrade U.S. factories to produce zero emitting vehicles. Cummins will invest more than $500 million into its Electrified Power technology, and, by 2050, has committed to powering its products using carbon neutral technologies that address air quality. Ford will soon begin taking pre-orders for an electric version of their Transit commercial van, to be introduced in Model Year 2022; the electric version of Ford's F150 pickup – the bestselling vehicle in the U.S. – will also launch in Model Year 2022[16].

In addition to these major market players there are several smaller players and start-ups already selling M/HD ZEVs into the market or planning to launch vehicles in the next three years. These include Lion Electric, Workhorse, Tesla, Nikola, Rivian, and UK-based Arrival. Roush CleanTech also recently announced a collaboration with electric bus maker Proterra and Penske Truck Leasing to develop a next generation all-electric commercial truck build on the Ford F-650 chassis.

Fleets that have already made significant commitments to electrification include Amazon (100,000 electric delivery vans ordered from Rivian), UPS (950 electric trucks ordered from Workhorse and 10,000 electric vans from Arrival), Pride Group (6,400 electric vehicles ordered from Workhorse, Tesla, and Lion), FedEx (500 electric delivery trucks ordered from Bright Drop), Montgomery Maryland Public Schools (326 electric school buses from Thomas Built), and PepsiCo (100 electric semi-trucks ordered from Tesla).

In addition, there are over 2,000 electric transit buses in-service or on order at over 160 U.S. transit agencies in 45 different states. Agencies that have already made major commitments to electric buses include Los Angeles Metro and Los Angeles Department of Transportation (369 electric buses), and the Antelope Valley and Foothill transit systems in California (80+ buses each). Many other private and public fleets have made public commitments to electrify their entire fleets by 2030 but have yet to order a significant number of vehicles; see Appendix B [9].

For this analysis MJB&A evaluated the current state of electrification for each M/HDV market segment, to assess prospects for near-term (through 2025) and medium-term (through 2030) uptake of battery-

[1616] Neither the Ford e-Transit or F150 Lightning electric vehicles are expected to initially be available with GVWR above 8,500 pounds; as such they are "light-duty" vehicles but are prevalent in many commercial fleets.

electric vehicles within the segment. This analysis focused on prospects for electric vehicle penetration, as a proxy for uptake of all zero-emitting technologies, because all scenarios for avoidance of detrimental future climate warming point to the need for significant pollution reductions from the transportation system, coupled with further decarbonization of the power sector. In addition, as described above, medium- and heavy-duty vehicles are a significant source of health harming air pollution, which ZEVs would likewise help to eliminate.

Each market segment was evaluated based on four relevant factors that will significantly impact truck owner decisions about whether to purchase an electric vehicle:

- **Charging -** infrastructure requirements for vehicle charging, including required charging capacity (kW/vehicle) and location (at vehicle home base or shared public charging)
- **Technical Feasibility -** the ability of current and future EV models to meet operating requirements of the segment, primarily based on range per charge compared to typical daily mileage accumulation,
- **Commercial EV Market** – current and announced availability of electric models from major manufacturers in the short (through 2025) and medium (through 2030) term, and
- **EV Business Case -** prospects for lifetime cost parity with current diesel and gasoline vehicles in the short (through 2025) and medium (through 2030) term. Potential cost parity was evaluated based on incremental EV purchase cost – compared to a diesel or gasoline vehicle – compared to life-time projected discounted fuel cost savings.

See the appendix for a full discussion of the methodology and data sources used to evaluate each of these metrics for each M/HDV market segment. The results of the analysis are discussed below.

Charging

Charging needs in each market segment were evaluated based on the likely/feasible location of charging for most vehicles in the segment, and the typical charging capacity required (kW/vehicle). Charging location is assessed as "Home Base" or "Public". Home Base charging means that a significant majority of vehicles in the segment are primarily used during day light hours and return to the same location every afternoon/evening, allowing for overnight charging at the home base. Public charging means that a significant percentage of vehicles in the segment are used for long-haul freight operations and do not routinely return to the same location for overnight parking. These vehicles will need to have access to a shared (Public) network of chargers.

Required charging capacity for vehicles in each segment was estimated based on typical daily energy use (kWh/day) and available charging time (hours); estimated daily energy use is based on typical daily usage patterns (miles driven) and the average energy use (kWh/mi) of vehicles in the segment.

For some market segments required charging capacity is low enough (<19 kW/vehicle) that many vehicles in the segment can use relatively inexpensive Home Base Level 2 chargers, similar to "home chargers" used with many light-duty EVs[17]. Other market segments will require more expensive Level 3 chargers for home-base charging due to higher typical daily energy needs[18].

See Figure 8 for a summary of estimated charging needs of vehicles in each market segment; details of how these charging needs were determined is in the Appendix.

Figure 8 Charging Needs by Market Segment

Home Base, Level 2	Home Base, Level 3	Public
• Heavy-duty Pickup & Van	• Heavy-duty Pickup	• Long Haul Tractor
• School Bus	• *Regional Haul Tractor*	• *Regional Haul Tractor*
• Delivery Van	• Transit Bus	• *Box Truck (Class 6 – 7)*
• Service Van	• Shuttle Bus	• *Box Truck (Class 8)*
• Service Truck	• Delivery Truck	
• Box Truck (Class 3 – 5)	• Refuse Hauler	
• Stake Truck (Class 3 – 5)	• *Box Truck (Class 6 – 7)*	
• Stake Truck (Class 6 – 7)	• *Box Truck (Class 8)*	
	• Dump Truck	

As shown in Figure 5, the vehicles in fifteen of the market segments – which include more than 60% of all vehicles in the M/HDV fleet - will generally be able to use Home Base charging. Of these vehicles that can use home base charging, for more than 80% of them their charging requirements can likely be met by an inexpensive Level 2 charger. For these vehicles, charging is not a significant barrier to EV adoption, either in terms of cost or practicality. Note that the charging needs of many Heavy-duty Pickups can be met using a Level 2 charger, but for those that regularly tow trailers a Level 3 charger might be required due to higher daily energy demand.

There is only one market segment – Long Haul Tractor – for which virtually all vehicles will require access to a public charging network. There are three other market segments – Regional Haul Tractors and Class 6-7 and Class 8 Box Trucks – for which a large number of vehicles (but not the majority) will likely require access to a public charging network on a regular basis if not every day (these market segments are therefore shown in Figure 8 as requiring both Home Base, Level 3 and Public charging).

For these market segments charging requirements are a greater near-term barrier to EV adoption than for the other segments that can primarily use home base charging[19]. This is primarily because charger

[17] Level 2 chargers have 240-volt input voltage and provide alternating current (AC) output to the vehicle; these chargers typically have a maximum charge rate of 19 kW or less.
[18] Level 3 chargers require 480-volt input voltage and deliver direct current (DC) output to the vehicle. Level 3 chargers can be designed with maximum charge rate between 25 kW and 600 kW.

[19] Other zero-emitting technologies – such as hydrogen fuel cell electric vehicles – will also require development of new public fueling infrastructure to support adoption in these market segments.

siting/availability is outside of the span of control of any individual company or fleet. To keep charging time low (<2 hr/day/vehicle) public chargers will need to have high charge rates (>500 kW) and will therefore be expensive. However, they will be a shared resource with one charger able to support 12 – 20 vehicles in the medium and long term, so average charging capacity (kW/vehicle) will be similar to that required for home base charging of a similar vehicle[20].

Technical Feasibility

The near-term technical feasibility of electric vehicles in each market segment was evaluated by comparing the estimated range per charge (miles) of currently available vehicles to average daily usage (accumulated miles) of vehicles in the segment; see Figure 9 for a summary of this analysis, and Appendix A for a more detailed discussion of how the analysis was conducted[21].

Figure 9 EV Usability by Market Segment

Range > Average Daily Mileage	60% <Range <100% of Average Daily Mileage	Range < 60% of Average Daily Mileage
• Heavy-duty Pickup and Van	• Regional Haul Tractor	• *Long Haul Tractor*
• Transit Bus	• Delivery Truck (Class 6 – 7)	• *Shuttle Bus*
• School Bus	• Dump Truck	• *Box Truck (Class 8)*
• Delivery Van		
• Service Van		
• Service Truck		
• Refuse Hauler		
• Box Truck (Class 3 - 5)		
• Box Truck (Class 6 – 7)		
• Stake Truck (Class 3– 5)		
• Stake Truck (Class 6 – 7)		

As shown, there are 11 market segments, representing 63% of the fleet, for which current commercially available battery electric models have large enough batteries to power an average day's driving for vehicles in the segment; in most cases the range is sufficient to go at least 50% further than the average. For these market segments, currently available EV models could meet operational needs for the majority of in-use vehicles in the segment.

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[20] In the short term when the percentage of in-use vehicles that are electric is low more chargers will likely be required in order to achieve necessary geographic network coverage.

[21] Hydrogen fuel cell electric vehicles do not have the same limitations of on-board energy storage as battery electric vehicles so "range between fueling events" is generally not a significant barrier to their adoption for any market segments.

Current EV models available for another three market segments, representing an additional 8% of the fleet, have large enough batteries to cover at least 60% of average daily driving for vehicles in the segment. For these market segments there will be some individual vehicles for which current EVs can meet fleet operational needs, while for other vehicles they cannot.

There are only three market segments for which range limits of current commercially available EVs pose a significant operational challenge – however two of these segments (Long Haul Tractor and Class 8 Box Truck) also require public charging, which could alleviate some or all the range constraints.

The evaluation summarized in Figure 9 indicates that currently available electric vehicles could replace diesel and gasoline vehicles for 40 – 60% of the M/HDV fleet while meeting all operational needs.[22] It is important to note that this estimate is based on current commercially available EVs. Projected improvements in battery energy density over the next 5 – 7 years should increase vehicle range and increase the total number of vehicles in the fleet for which EVs can replace diesel and gasoline vehicles while meeting all operational requirements.

Commercial EV Market

The maturity of the commercial EV Market in each market segment was evaluated based on the number of electrified models currently available for purchase, and those projected to be available in the next five years based on announcements already made by manufacturers [10]. Also important is whether the major full line manufacturers that currently dominate M/HD truck sales (see Figure 5) offer EV models, or whether they are only offered by small start-up or specialty manufacturers (e.g., ZEV only manufacturers or retrofitters).

The only market segments that are fully mature in 2020 with respect to EVs are the Transit Bus and School Bus markets. For both of these vehicle types, EV models are already fully commercially available from more than one manufacturer that has significant market share in the segment. In the case of Transit buses every bus manufacturer that sells diesel buses in North America also offers an electric version; in addition, there are two electric-only manufacturers that have already made a large number of sales.

For other market segments current (2021) commercial EV models are limited and generally produced only by small start-up manufacturers. However, there is growing and accelerating interest from the 12 major OEMs shown in Figure 5 which account for 90% of the current in-use fleet. Most of these manufacturers have prototype EV models under development or have in-use pilot or demonstration fleets under test. Several have announced they will begin limited production or full commercial introduction of one or more electric models in 2021 or 2022 [11]. The announced model introductions from major OEMs include vehicles across the M/HD spectrum, from Class 3 vans to Class 6 box and work trucks, to Class 8 tractors. There are also a number of well-funded start-up companies entering the market specifically to produce electric trucks – primarily for short- and long-haul freight deliveries.

Several major manufacturers have recently announced plans to introduce light-duty (<8,500 lb GVWR) electric delivery vans, and two major OEMs and four start-up companies have announced the launch of light-duty electric pickups in the next three years. No companies have yet announced any plans for electrification of heavy-duty vehicles in this segment (Class 2b-3), though the announcements from manufacturers like Ford and Rivian in the light duty truck space may pave the way for manufacturing opportunities in the heavier duty truck space in the next few years.

[22] Hydrogen fuel cell electric vehicles could potentially meet the operational needs of virtually all M/HD vehicles if supported by depot-based and public hydrogen fueling infrastructure.

Figure 10 summarizes the number of companies with at least one EV model in either production (i.e. currently available for sale in 2021), pre-production (i.e., vehicles with an announced production/availability date from 2022 - 2025), or concept (i.e., prototypes and/or pilot fleets with no announced commercial launch date)[23]. In table 10, Company Type “Major OEM” refers to established players in the U.S. with significant market share of diesel and gasoline vehicles; “EV Manufacturer” refers to established and start-up companies making only purpose-built EV; and “EV Retrofit” refers to manufacturers that purchase incomplete vehicles from major OEMs and up-fit them to EV.

There are currently 30 companies with at least one EV model for sale commercially. An additional nine companies have announced they will begin production of EV models between 2022 and 2025, including 5 of the 12 OEMs that currently hold 90% of the M/HD market share (Figure 5). Based on existing manufacturer announcements there will be multiple companies selling EV in virtually all MHD market segments by 2025, including 58% of the major OEMs.

[23] There are also a small number of hydrogen fuel cell vehicle models in-service, under test, and in development by several manufacturers.

Figure 10 Announced and Available M/HD Electric Vehicles

<table>
<tr><th rowspan="2">Vehicle Type</th><th rowspan="2">Regulatory Category (Vehicle, Engine)</th><th rowspan="2">Company Type*</th><th colspan="3">Number of Companies with at least one ZEV Model</th></tr>
<tr><th>Production</th><th>Pre-production</th><th>Concept</th></tr>
<tr><td rowspan="3">Transit Bus</td><td rowspan="3">Vocational Urban, Heavy Heavy-Duty Engine</td><td>Major OEM</td><td colspan="2">4</td><td></td></tr>
<tr><td>EV Manufacturer</td><td>4</td><td></td><td>2</td></tr>
<tr><td>EV Retrofit</td><td colspan="3">3</td></tr>
<tr><td rowspan="3">School Bus</td><td rowspan="3">Vocational Urban, Medium Heavy-Duty Engine</td><td>Major OEM</td><td>2</td><td></td><td></td></tr>
<tr><td>EV Manufacturer</td><td>2</td><td></td><td></td></tr>
<tr><td>EV Retrofit</td><td colspan="3">2</td></tr>
<tr><td rowspan="3">Coach Bus</td><td rowspan="3">Vocational Urban, Heavy Heavy-Duty Engine</td><td>Major OEM</td><td></td><td></td><td></td></tr>
<tr><td>EV Manufacturer</td><td colspan="2">3</td><td></td></tr>
<tr><td>EV Retrofit</td><td colspan="3">1</td></tr>
<tr><td rowspan="3">Shuttle Bus</td><td rowspan="3">Vocational Urban, Light Heavy-Duty Engine</td><td>Major OEM</td><td></td><td>5</td><td></td></tr>
<tr><td>EV Manufacturer</td><td>2</td><td></td><td></td></tr>
<tr><td>EV Retrofit</td><td colspan="3">6</td></tr>
<tr><td rowspan="3">Class 2b-3</td><td rowspan="3">Heavy Duty Pick-up and Van/ Vocational Trucks, Light Heavy-Duty Engine</td><td>Major OEM</td><td colspan="2">3</td><td></td></tr>
<tr><td>EV Manufacturer</td><td colspan="3">11</td></tr>
<tr><td>EV Retrofit</td><td colspan="3">4</td></tr>
<tr><td rowspan="3">Class 4</td><td rowspan="3">Vocational Trucks, Light Heavy-Duty Engine</td><td>Major OEM</td><td>1</td><td></td><td></td></tr>
<tr><td>EV Manufacturer</td><td>2</td><td></td><td>4</td></tr>
<tr><td>EV Retrofit</td><td colspan="3">6</td></tr>
<tr><td rowspan="3">Class 5-6</td><td rowspan="3">Vocational Trucks, Light Heavy-Duty /Medium Heavy-Duty Engines</td><td>Major OEM</td><td></td><td>3</td><td></td></tr>
<tr><td>EV Manufacturer</td><td colspan="2">7</td><td></td></tr>
<tr><td>EV Retrofit</td><td colspan="3">7</td></tr>
<tr><td rowspan="3">Class 7-8 Single Unit</td><td rowspan="3">Combination Trucks, Medium Heavy Duty Engine</td><td>Major OEM</td><td></td><td colspan="2">6</td></tr>
<tr><td>EV Manufacturer</td><td>7</td><td></td><td>2</td></tr>
<tr><td>EV Retrofit</td><td colspan="3">1</td></tr>
<tr><td rowspan="3">Class 7-8 Tractor</td><td rowspan="3">Combination Trucks, Medium Heavy Duty/ Heavy Heavy-Duty Engine</td><td>Major OEM</td><td></td><td colspan="2">9</td></tr>
<tr><td>EV Manufacturer</td><td>3</td><td></td><td>2</td></tr>
<tr><td>EV Retrofit</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Terminal Tractor</td><td rowspan="3">Combination Trucks, Medium Heavy Duty/ Heavy Heavy-Duty Engine</td><td>Major OEM</td><td></td><td></td><td></td></tr>
<tr><td>EV Only</td><td>5</td><td></td><td></td></tr>
<tr><td>EV Retrofit</td><td></td><td></td><td></td></tr>
</table>

EV Business Case

While electric M/HD vehicles are currently more expensive than their diesel counterparts, several studies have indicated that costs are anticipated to fall dramatically within the next 10 years as manufacturers introduce more models, and as increased vehicle volumes enable manufacturers to move down the learning curve in electric vehicle production.

One reason for expected M/HD EV cost reductions are projected continuing reductions in the cost of batteries, which are a significant contributor to the current increased cost of M/HD EVs compared to diesel and gasoline vehicles. Light-duty EV battery costs have fallen from over $1,100/kWh in 2010 to $156/kWh in 2019 [12]. Many analysts are projecting costs will continue to fall, to as low as $61/kWh in 2030; several major car companies have endorsed these estimates [11].

While average battery costs for M/HD EVs have also fallen in the last 10 years they currently remain higher than costs for light-duty EVs, at approximately $375/kWh [12]; this implies that there is currently about a 5-year lag between cost reductions for LD EV and M/HD EV batteries. Even if this lag continues, M/HD EV battery costs should still fall below $90/kWh by 2030 (76% reduction from today). It is likely that increased production volumes will cause this cost gap to close such that M/HD EV battery costs could fall below $70/kWh by 2030 (81% reduction). As noted above in Figure 5, the manufacturers that dominate Class 3 – 7 trucks sales also dominate US car and light truck sales and may therefore be well positioned to apply to the M/HD segment cost reduction strategies developed for the much higher volume light-duty segment.

A 2019 study conducted by ICF that evaluated costs of M/HD ZEVs in California estimated that between 2020 and 2030 the purchase cost of most M/HD EVs would fall by almost 50% [13]. ICF assumed that in 2030 M/HD EV battery costs would average $157/kWh; as such, this study's conclusions are likely conservative, and M/HD EV purchase costs will likely fall even further over the next 10 years if the current trend of LDV battery cost reductions is mirrored in the M/HDV market.

For this study MJB&A used the ICF M/HD EV cost estimates for different vehicle types but adjusted them downward based on an assumed continued 5-year cost lag between LD EV and M/HD EV battery costs ($132/kWh in 2025, $86/kWh in 2030). The resulting incremental EV purchase costs were then compared to an estimate of life-time discounted fuel cost savings for M/HD EVs in each market segment (compared to equivalent diesel vehicles), to identify when EVs in different market segments might reach "cost-parity" with diesel vehicles over their lifetime.[24]

See Figure 11 for a summary of the analysis. As shown, there are nine market segments ‑ which account for approximately 72% of the in-use fleet ‑ in which EVs could reach life-time cost parity with diesel and gasoline vehicles by 2025 based on discounted lifetime fuel savings and projected incremental purchase costs. EVs in an additional three market segments (4% of the fleet) could reach cost parity by 2030. Note that neither Transit Buses nor School Buses are shown in Figure 11 due to significant uncertainty around the ICF future EV cost projections for these two vehicle types. ICF 2030 cost estimates ‑ even when adjusted for lower battery costs ‑ indicate that neither Transit nor School buses will achieve life cycle cost parity with diesel vehicles by 2030. However, these cost

[24] When evaluating the EV Business case this analysis used U.S. average fuel prices (diesel, electricity), as projected by the Energy Information Administration [6]. Estimated annual fuel cost savings for an EV compared to a diesel vehicle over the full vehicle life were discounted at a 7% discount rate and compared to the projected incremental EV purchase cost. The vehicle life used for this calculation varied from 10 years for Class 2b-5 vehicles, to 14 years for Class 6-7 vehicles, and 18 years for Class 8-vehicles.

estimates indicate much higher cost reductions by 2030 for electric tractors and Class 8 single unit trucks than for electric transit and school buses, despite having similar power and energy requirements. The reason for the difference is not clear. If relative cost reductions for electric transit and school buses match projected reductions for other Class 8 electric trucks, these market segments could also achieve life-cycle cost parity with diesel buses by 2030.

Figure 11 Projected EV -ICE Cost Parity by Market Segment

Projected EV Life-Cycle Cost Parity with Diesel & Gasoline Vehicles		
By 2025	**By 2030**	**After 2030**
• Heavy-duty Pickup and Van • Regional Haul Tractor • Long Haul Tractor • Delivery Van • Delivery Truck • Service Van • Refuse Hauler • Box Truck (Class 8) • Dump Truck	• Shuttle Bus • Service Truck	• Box Truck (Class 3 - 7) • Stake Truck (Class 3– 7)

Note also that this analysis does not assume any local, state, or federal EV purchase incentives nor does it take into consideration the potential for more stringent NOx emission standards – currently under consideration by EPA – to increase purchase costs for new diesel and gasoline vehicles, and thus reduce net incremental purchase costs for M/HD EVs.

Given significant uncertainties as to future EV incremental purchase costs, the EV-ICE cost parity projections in Figure 11 are a first order estimate; additional work to refine future EV cost estimates based on recent and on-going market developments is warranted to refine this preliminary understanding of how the M/HD EV business case will evolve in the short- and medium-term.

Policy Implications

There are a large number of medium- and heavy-duty applications that have favorable ratings for early deployment of ZEVs in all four categories evaluated (Heavy-duty Pickup and Van, Refuse Hauler, Delivery Van, and Service Van) or three of four categories (Transit Bus, School Bus, Service Truck Delivery Truck, Dump Truck, Box Truck (Class 3-5), Stake Truck (Class 3-5) and Stake Truck (Class 6-7)). Collectively, these segments represent 66 percent of the fleet and account for 28 percent of GHGs, 30 percent of urban NOx and 37 percent of urban PM emitted by the fleet. Eliminating tailpipe pollution from these vehicles would deliver significant public health benefits – including up to 1,500 fewer premature deaths, 1,400 fewer hospital visits, and 890,000 incidents of exacerbated respiratory conditions and lost or restricted workdays annually[25]. Together these segments represent a large number of vehicles which can also advance the technical and commercial development of all M/HDV market segments.

This analysis is based on the current landscape and does not consider future technological improvements or policy interventions that might further enhance the near-term attractiveness of zero-emitting medium and heavy-duty vehicles across all applications. For instance, policies could support the development of high-volume commercial ZEV markets and improving the ZEV value proposition for fleet owners. Specific policy interventions that could address both barriers include low interest loans or tax credits for ZEV research and development and for development of U.S. manufacturing facilities. Direct ZEV purchase subsidies for fleets could also significantly strengthen the near-term ZEV business case, which would advance development of the commercial market by creating more demand from customers. President Biden has put forward proposals along these lines as part of his American Jobs Plan[26]

[25] These values are based on the estimated public health impact of the current in-use M/HD fleet in 2020, using exhaust emissions estimates from MOVES3 and EPA's CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA). Annual public health impacts from the entire M/HD fleet, and from this segment of the fleet, are projected to fall over time as the fleet turns over to newer vehicles with engines that meet more stringent emission standards. However, electric vehicles have lower annual and life-time public health impact than even the newest diesel and gasoline vehicles, even after accounting for emissions from generating the electricity used to charge them.

[26] See https://www.whitehouse.gov/briefing-room/statements-releases/2021/05/18/fact-sheet-the-american-jobs-plan-supercharges-the-future-of-transportation-and-manufacturing

Appendix A – Methodology & Data Sources

M/HDV In-Use Fleet: Vehicle Types & Uses

The number of M/HD vehicles in each market segment was estimated using vehicle registration data collected by IHS Markit [1]. For each registered vehicle IHS uses data encoded in the vehicle identification number (VIN) to identify vehicle attributes. The VIN-defined attributes used for this analysis include Gross Vehicle Weight Class, Fuel Type, Vehicle Type, and Manufacturer. In addition, IHS assigns a Registration Vocation based on the entity that registered the vehicle.[27]

Certain VIN-defined vehicle types map directly to the market segments used here – for example PICKUP, VAN CARGO, BUS SCHOOL, and TRACTOR TRUCK – because they are definitively descriptive of the final vehicle configuration. Others are more ambiguous and provide little information about the actual vehicle configuration and use – examples include CAB CHASSIS, STRAIGHT TRUCK, and INCOMPETE (STRIP CHASSIS).

For this project, assignment of vehicles to each market segment is therefore based on a combination of VIN-defined Vehicle Type and, if necessary, IHS-defined Registration Vocation and weight class. See Figure A1, which shows how these attributes were mapped to market segments to estimate the number of vehicles in each segment. Single unit trucks with indeterminate VIN-defined vehicle type were assigned to the different market segments based on the type of company that registered them (Registration Vocation) – as an indication of the vehicle configuration/use based on the work performed by the owning company.

For example, there are many types of buses in the fleet, but only School Buses are definitively identified by VIN-defined vehicle type. As shown in Figure A1 the other types of buses in the fleet (Transit, Coach, Shuttle) were assigned to the bus market segments based on the registering company having Registration Vocation "Bus Transportation".

Similarly, Class 3 – 5 single-unit trucks with indeterminate VIN-defined vehicle type were assigned to the Delivery Van market segment if the registering company had a registration vocation of Wholesale/Retail, Beverage Processing and Distribution, or Food Processing and Distribution as these types of companies typically use Class 3-5 vehicles to make local deliveries of the products they manufacture and sell. In addition, 75% of the vehicles of this type that were registered by companies with registration vocations characterized as General Freight delivery companies were also put into this market segment. The remaining 25 percent of Class 3 – 5 vehicles registered by General Freight companies were classified as small Box Trucks.

Note that Registration Vocation is based on the type of company that registered the vehicle, and is not directly based on vehicle attributes, so the mapping shown in Figure A1 produced a first order estimate of market segment population subject to some uncertainty. For example, not all trucks with Registration Vocation "Sanitation/Refuse" are necessarily refuse-hauling trucks. Similarly, not all vehicles with Registration Vocation "Wholesale/Retail" are necessarily box trucks used to deliver freight.

[27] The IHS VIO database that includes Registration Vocation over-estimates the number of in-use vehicles in Arizona and California, because these states have non-expiring registrations for some vehicles. MJB&A used IHS estimated in-use vehicle totals from their statistical database for AZ and CA (which includes scrappage assumptions) to adjust for this overcount when developing national total estimates presented here. At the national level the VIO database overcount is approximately 4%.

Figure A1 M/HD Vehicle Attribute Mapping to Market Segments

MARKET SEGMENT	VIN-Defined Vehicle Type	IHS-Defined Registration Vocation	Weight Classes
Heavy Duty Pickup & Van	PICKUP SPORT UTILITY VEHICLE STEP VAN VAN CARGO VAN PASSENGER	ALL	Class 2b[1] & 3
Regional Haul Tractor & Long Haul Tractor	GLIDERS TRACTOR TRUCK	ALL	Class 7 - 8
Transit Bus	BUS NON SCHOOL	ALL	Class 8 [2]
School Bus	BUS SCHOOL	ALL	Class 7 - 8
Shuttle Bus	BUS NON SCHOOL	ALL	Class 3 - 5
	CAB CHASSIS CUTAWAY INCOMPLETE (STRIP CHASSIS) INCOMPLETE PICKUP STRAIGHT TRUCK UNKNOWN	BUS TRANSPORTATION	
Delivery Van	CAB CHASSIS CUTAWAY INCOMPLETE (STRIP CHASSIS) INCOMPLETE PICKUP STRAIGHT TRUCK UNKNOWN	WHOLESALE/RETAIL, BEVERAGE PROCESSING & DISTRIBUTION, FOOD PROCESSING & DISTRIBUTION, and 75% of General Freight [5]	Class 3 - 5
Delivery Truck	Same vehicle types as delivery van	Same registration vocations as Delivery Van	Class 6 - 7
Service Van	Same vehicle types as delivery van	SERVICES UTILITY SERVICES UTILITY/HAZARDOUS MATERIAL GOVERNMENT/MISCELLANEOUS LANDSCAPING/HORTICULTURE	Class 3 - 5
Service Truck	Same vehicle types as delivery van	Same registration vocations as Service Van	Class 6 -7

Figure A1 M/HD Vehicle Attribute Mapping to Market Segments

MARKET SEGMENT	VIN-Defined Vehicle Type	IHS-Defined Registration Vocation	Weight Classes
Refuse Hauler	Same vehicle types as delivery van	SANITATION/HAZ MATERIAL SANITATION/REFUSE	Class 8
Box Truck (small)	Same vehicle types as delivery van	VEHICLE TRANSPORTER, MOVING AND STORAGE, PETROLEUM, SPECIALIZED/HEAVY HAULING, HAZARDOUS MATERIALS, PETROLEUM/HAZARDOUS MATERIAL, and 25% of General Freight [5]	Class 3-5
Box Truck (medium)	Same vehicle types as delivery van	Same registration vocations as other Box Trucks	Class 6 - 7
Box Truck (large)	Same vehicle types as delivery van	Same registration vocations as other Box Trucks	Class 8
Stake Truck (small)	Same vehicle types as delivery van	CONSTRUCTION ROAD/HIGHWAY MAINTENANCE	Class 3 - 5
Stake Truck (large)	Same vehicle types as delivery van	Same registration vocation as small stake trucks	Class 6 - 7
Dump Truck	Same vehicle types as delivery van	Same registration vocation as stake trucks	Class 8
OTHER	All other [3]	ALL [4]	Class 3 - 8

[1] IHS database does not include Class 2b; Class 2b estimate from MOVES model

[2] Transit Bus estimate is 69% of total; remainder are estimated to be Coach buses

[3] Includes MOTOR HOME and FIRE TRUCK

[4] Includes vehicles in weight classes from above registration vocations not otherwise assigned, plus all vehicles in registration vocations FORESTRY/LUMBER PRODUCTS, MINING/QUARRYING, AGRICULTURE, MANUFACTURING, EMERGENCY VEHICLES, DEALER, INDIVIDUAL, MISCELLANEOUS, and UNCLASSIFIED

[5] The General Freight category includes registration vocations: GENERAL FREIGHT, GENERAL FREIGHT/HAZARDOUS MATERIALS, LEASE/FINANCE, LEASE/MANUFACTURER SPONSORED, and LEASE/RENTAL

For Tractor Trucks, the estimated number of vehicles used in long-haul versus regional haul service is based on supplemental data from IHS which included additional attributes for each registered tractor, including engine displacement, axle/wheel configuration, and cab style. Using these attributes MJB&A estimated the number of tractors equipped with day cabs as opposed to sleeper cabs. The estimated number of regional haul tractors includes 100% of estimated day-cab equipped trucks and 5% of estimated sleeper-cab equipped trucks. Individual tractors were assumed to have day cabs if:

- Engine displacement is less than 10 liters,

- Engine displacement is greater than 10 liters but there are only two driven wheels (4x2 and 6x2 configuration), or
- Engine displacement is greater than 10 liters, and there are more than two driven wheels, but cab style is any of the following: Low Tilt Cab, High Tilt Cab, Cab Forward, Short Conventional Cab, Medium Conventional Cab, or Half Cab.

Based on this analysis, 30% of in-use Tractor Trucks are estimated to be used for regional haul operations and 70% for long-haul operations.

The IHS VIO database cannot be used to estimate the number of Class 2b trucks in the fleet, which are a subset of VIN-defined Class 2 trucks[28]. To estimate the number of these vehicles, MJB&A used EPA's MOVES3 model [2]. The Class 2b estimate includes vehicles identified in MOVES as Source Type equals "Light Commercial Truck" or "Passenger Truck", and Registration Class equals "41-LHD2b3". Definitive data on the composition of the Class 2b fleet is unavailable but the limited data that is available indicates that the majority of these vehicles are "heavy duty" pickups and vans, with a small percentage large SUVs [14] [29]

The IHS VIO database also cannot distinguish Transit Buses from other "BUS NON SCHOOL" vehicles (VIN-defined) or based on registration vocation. The estimated number of vehicles in the Transit Bus market segment is 69% of registered Class 8 vehicles with vehicle type BUS NON SCHOOL; the other 31% are estimated to be intercity coach buses. These relative percentages of transit and coach buses are based on vehicle populations reported in the National Transit Database (transit bus) [15], and the ABA Coach Census (coach bus) [16].

[28] VIN-defined Class 2 includes vehicles with GVWR 6,000 – 10,000 lbs. Class 2b includes vehicles with GVWR 8,500 – 10,000 lbs.

[29] Class 2B examples for model year 2017 include Chevy Silverado 2500HD; Ford F250, F350 and E350; Ford Transit; GMC Sierra 2500, and GMC Yukon 2500. Typically, only a portion of total sales of these models would be Class 2b, with other vehicles of the same model classified as Class 2 or Class 3 depending on actual vehicle configuration.

M/HDV In-Use Fleet: Environmental Impact

To estimate the environmental impact of each market segment, MJB&A calculated total annual fuel use by the segment (diesel equivalent gallons) using the estimated number of vehicles in the segment, average fuel economy for vehicles in the segment (MPG), and average annual miles driven per vehicle (VMT). See Figure A2 for the MPG and VMT assumptions used.

Figure A2 M/HD Vehicle MPG and VMT Assumptions by Market Segment

MARKET SEGMENT	Weight Class	AVG MPG	VMT	
			mi/yr/veh	% urban
Heavy Duty Pickup & Van	Class 2B Class 3	15.10 11.50	10,900 11,000	58% 58%
Regional Haul Tractor	Class 7 - 8	5.85	35,332	50%
Long Haul Tractor	Class 8	5.83	75,000	42%
Transit Bus	Class 8	6.19	30,947	65%
School Bus	Class 7	8.16	10,219	58%
Shuttle Bus	Class 3-5	6.06	29,144	62%
Delivery Van	Class 3-5	10.50	12,000	60%
Delivery Truck	Class 6-7	8.10	30,000	60%
Service Van	Class 3-5	10.50	12,000	60%
Service Truck	Class 6-7	8.10	12,000	60%
Refuse Hauler	Class 8	5.72	17,847	58%
Box Truck (freight)	Class 3-5	11.50	12,000	50%
Box Truck (freight)	Class 6-7	8.70	15,000	45%
Box Truck (freight)	Class 8	7.50	50,000	40%
Stake Truck (construction)	Class 3-5	10.50	11,000	59%
Stake Truck (construction)	Class 6-7	8.10	11,000	59%
Dump Truck	Class 8	6.90	40,000	59%
OTHER	Class 3 - 8	9.10	9,700	58%

For each market segment average MPG and average VMT/vehicle was estimated using a number of different sources, including EPA's MOVES model, data collected by California Air Resources Board in the context or their regulatory activities [17], and MJB&A engineering judgement based on project experience. In general MPG and VMT assumptions from MOVES were used directly, for MOVES vehicle types that could be directly mapped to the vehicles in each market segment (see below discussion of MOVES vehicle segmentation and development of emission factors). For some market segments MOVES MPG and/or VMT assumptions were adjusted to better reflect the vehicle type/use case of the segment.

For example, MOVES VMT assumptions are averages for a wide range of vehicle configurations in the same weight class range. For some market segments variations were made around this average to reflect a greater percentage of vehicles in the segment used for long- or short-haul operations. The resulting total annual fleet VMT and fuel use, including for vehicles in the "other" (uncategorized) market segment, match the 2020 MOVES national totals +/-1%.

MOVES was also used to develop NOx and PM emission factors (grams per gallon of fuel use, g/gal) for each combination of Source Type and Regulatory Category in the model. This was done by dividing MOVES' estimate of total emissions (g) by MOVES' estimate of total fuel use (gal) for each combination of source type and regulatory category. These emission factors represent average emissions of each group of vehicles in the current in-use fleet (calendar year 2020).

In MOVES "Source Type" represents the type of vehicle, and "Regulatory Category" represents the vehicle's size (Weight Class). Each vehicle (source) type includes a range of vehicle sizes (regulatory category), including Light Heavy-Duty Class 2b-3, Light Heavy-Duty Class 4 – 5, Medium Heavy-Duty Class 6-7, and Heavy Heavy-Duty Class 8. See Figure A3 for how MOVES vehicle types were mapped to market segments, and the MOVES in-use average NOx and PM emission factors for each. Emission factors were calculated separately for diesel and gasoline vehicles of each type. To calculate total NOx and PM emissions attributed to each market segment total estimated fuel use (gallons) for the segment was multiplied by a weighted average emission factor (g/gal), which was based on the percentage of the vehicles in the segment that are diesel vs gasoline (IHS data). The percentage of emissions for each market segment that is emitted in urban areas was also estimated based on the percentage of total VMT projected by MOVES to be operated on roadway types "Urban Restricted" and "Urban Unrestricted" for relevant vehicle types.

Figure A3 MOVES Emission Factors by Market Segment

MARKET SEGMENT	Weight Class	MOVES CY2020						IHS
		Source Type	Regulatory Category	NOx (g/gal) Gas	NOx (g/gal) Diesel	PM (g/gal) Gas	PM (g/gal) Diesel	% gas
Heavy Duty Pickup & Van	Class 2B	Pass Truck, Light Comm Truck	41 LHD2b3	23.48	34.35	0.38	1.62	55%
	Class 3	Single Unit Short-haul Truck	41 LHD2b3	7.18	20.47	0.19	0.80	36%
Regional Haul Tractor	Class 7 - 8	Combination Short-haul Truck	47 HHD8		27.79		0.60	0%
Long Haul Tractor	Class 8	Combination Long-haul Truck	47 HHD8		30.28		0.69	0%
Transit Bus	Class 8	Transit Bus	48 Urban Bus		25.41		0.35	0%
School Bus	Class 7	School Bus	46 MHD67		26.55		1.00	0%
Shuttle Bus	Class 3-5	Other Buses	42 LHD45	4.09	40.96	0.19	1.22	40%
Delivery Van	Class 3-5	Single Unit Short-haul Truck	42 LHD45	7.74	21.53	0.27	0.83	38%
Delivery Truck	Class 6-7	Single Unit Short-haul Truck	46 MHD67	6.62	20.45	0.13	0.65	10%
Service Van	Class 3-5	Single Unit Short-haul Truck	42 LHD45	7.74	21.53	0.27	0.83	38%
Service Truck	Class 6-7	Single Unit Short-haul Truck	46 MHD67	6.62	20.45	0.13	0.65	10%
Refuse Hauler	Class 8	Refuse Truck	47 HHD8		40.57		1.41	0%
Box Truck	Class 3-5	Single Unit Long-haul Truck	42 LHD45	3.81	16.57	0.15	0.57	38%
Box Truck	Class 6-7	Single Unit Long-haul Truck	46 MHD67	5.06	18.17	0.06	0.57	10%
Box Truck	Class 8	Single Unit Long-haul Truck	47 HHD8		26.88		0.52	0%
Stake Truck	Class 3-5	Single Unit Short-haul Truck	42 LHD45	7.74	21.53	0.27	0.83	38%
Stake Truck	Class 6-7	Single Unit Short-haul Truck	46 MHD67	6.62	20.45	0.13	0.65	10%
Dump Truck	Class 8	Single Unit Short-haul Truck	47 HHD8		29.69		0.63	0%
OTHER	Class 3 - 8	Single Unit Short-haul Truck	42, 46, 47	5.81	22.22	0.15	0.63	22%

M/HDV EV Market Readiness

To evaluate M/HD EV market readiness for each market segment, MJB&A developed estimates for the following key evaluation factors for vehicles in each market segment: 1) daily vehicle use (range of hours, miles, fuel), 2) battery size and range per charge (current commercial EV models), 3) incremental EV purchase cost (compared to diesel vehicles - current and projected through 2030), 4) EV fuel cost savings (compared to diesel vehicles), and 5) EV charging location and average demand. These estimates were developed using the data sources and methodology described below.

To calculate the average daily usage (miles driven) for vehicles in each market segment MJB&A used the average annual VMT shown in Figure A2 divided by 250 days per year, since most M/HD vehicles are used commercially. High and low estimates of daily VMT for vehicles in each market segment were taken from the California Air Resources Board Advanced Clean Truck Market Segment Analysis spreadsheet ("ARB ACT Spreadsheet") and previous project experience [17]; the Truck and Engine Manufacturer Association battery electric route information from the ARB ACT Spreadsheet was used to determine the "high" and "low" estimated daily miles traveled.

Figure A4 Vehicle Daily Use Analysis

MARKET SEGMENT	Weight Class	TYPICAL DAILY USE								
		MILES			HOURS		AVG EV	EV KWh/day		
		low	*AVG*	*high*	*low*	*high*	*kWh/mi*	*low*	*AVG*	*high*
Heavy Duty Pickup & Van	Class 2B Class 3	30	44	150	8	10	1.09	33	47	163
Regional Haul Tractor	Class 7 - 8	100	141.3	200	8	10	2.14	214	302	428
Long Haul Tractor	Class 8	200	300	600	10	12	2.15	429	644	1,288
Transit Bus	Class 8	100	123.8	300	8	15	2.02	202	250	607
School Bus	Class 7	30	40.88	125	4	7	1.53	46	63	192
Shuttle Bus	Class 3-5	70	116.6	150	6	12	2.06	145	241	310
Delivery Van	Class 3-5	30	48	150	8	10	1.19	36	57	179
Delivery Truck	Class 6-7	80	120	150	8	10	1.55	124	185	232
Service Van	Class 3-5	30	48	75	8	10	1.19	36	57	89
Service Truck	Class 6-7	30	48	75	8	10	1.55	46	74	116
Refuse Hauler	Class 8	40	71	80	4	8	2.19	88	156	175
Box Truck (freight)	Class 3-5	30	48	150	8	10	1.09	33	52	163
Box Truck (freight)	Class 6-7	40	60	175	8	10	1.44	58	86	252
Box Truck (freight)	Class 8	150	200	500	10	12	1.67	250	334	834
Stake Truck (construction)	Class 3-5	30	44	100	8	10	1.19	36	52	119
Stake Truck (construction)	Class 6-7	30	44	100	8	10	1.55	46	68	155
Dump Truck	Class 8	100	160	250	8	10	1.81	181	290	454

For vehicles in each market segment average EV energy use (EV kWh/mile) was calculated based on average diesel MPG for vehicles in the segment (Figure A2) assuming an EV chassis efficiency of 95 percent compared to diesel vehicles and average diesel engine efficiency of 35 percent[30]. Average, high, and low daily mileage estimates were then multiplied by the average EV energy use (kWh/mile) to

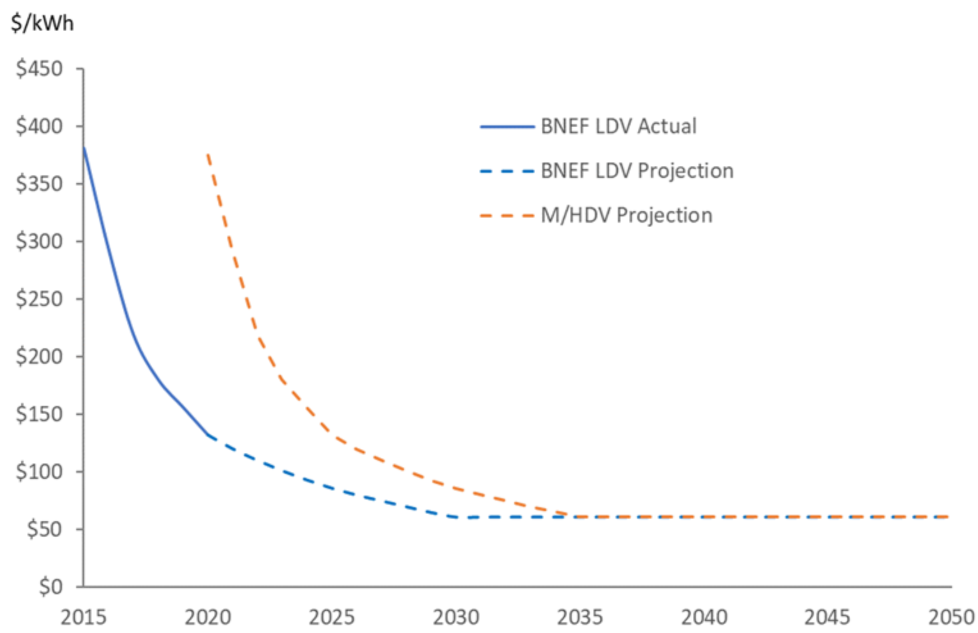
[30] EV Energy [kWh/mi] = (Diesel Energy Content [kWh/gal] x Engine Efficiency [%] x Chassis Efficiency [%]) ÷ MPG. Diesel Energy Content = 128, 450 btu/gal = 37.6 kWh/gal

determine the range of typical daily energy use for EVs in each market segment (EV kWh/day); see Figure A4.

To calculate the high and low range per charge (miles) for MY 2020 EVs in each market segment and to determine the EV incremental purchase cost, MJB&A used the 2019 Medium- and Heavy-Duty California Trucking Report produced by ICF ("ICF Truck Report"), previous project experience, and an EDF Electric Truck and Bus Commercial Database ("EDF Truck Database") [10] [13]. The ICF Report was the primary source used to determine typical installed battery size by market segment. In situations where the battery size data was not listed for a particular market segment, MJB&A used previous project experience and the EDF Truck Database to estimate battery size. For vehicles in each market segment MJB&A calculated the range per charge (miles) using estimated average EV daily energy use from Figure A4 (kWh/day +/- 10%) and assuming that only 85 percent of installed battery capacity is usable.

For each market segment MJB&A calculated the EV incremental purchase cost by subtracting the estimated purchase cost of a diesel truck from the cost of an electric truck (2020$), using 2020 and 2030 estimated purchase prices from the ICF Truck Report, adjusted for assumed lower future battery costs. Average battery costs for EVs have fallen dramatically in the last 10 years, and they are projected to continue to fall through at least 2030 [12]. However, at $375/kWh average battery costs for M/HD EVs remain higher than costs for light-duty EVs ($132/kWh); current relative prices imply that there is currently about a 5-year lag between cost reductions for LD EV and M/HD EV batteries. If this lag continues, M/HD EV battery costs should fall below $90/kWh by 2030 (76% reduction from today); if increased production volumes cause this cost gap to close M/HD EV battery costs could fall below $70/kWh by 2030 (81% reduction). See figure A5.

Figure A5 Battery Cost Projections



Source: Bloomberg New Energy Finance; MJB&A

The 2019 ICF Truck Report assumed that in 2030 M/HD EV battery costs would average $157/kWh. This study's EV cost estimates are therefore likely conservative, and M/HD EV purchase costs will likely fall even further over the next 10 years than ICF estimated if the current trend of LDV battery cost reductions is mirrored in the M/HDV market.

For this study the ICF 2030 M/HD EV purchase cost estimates for different vehicle types were adjusted downward based on the M/HD battery cost projections shown in Figure A5 ($86/kWh in 2030). Estimates for 2025 EV purchase costs were also developed from the 2020 and 2030 estimates assuming that average battery costs will be $132/kWh in that year. Finally, the ICF 2020 estimates for Class 2B and Class 3 EVs were also adjusted downward based on recently announced pricing for the model year 2022 Ford F150 Lightning electric pickup truck and the Ford eTransit electric delivery van; the base model F150 Lighting targeted toward fleets has an announced MSRP of $40,000 - $49,000 depending on battery size. This compares to an MSRP of $34,000 for the base gasoline model[31] [18]

The resulting estimated battery size, range per charge, and EV incremental purchase costs for EVs in each market segment are summarized in Figure A6.

Figure A6 Estimated EV Range and Incremental Purchase Cost

MARKET SEGMENT	Weight Class	MY2020 EV Battery Size *kWh*	MY2020 EV Range per Charge *miles* *low*	MY2020 EV Range per Charge *miles* *high*	EV INCREMENTAL PURCHASE COST (2020$) *ICF* 2020	EV INCREMENTAL PURCHASE COST (2020$) *ICF Adjusted* 2025	EV INCREMENTAL PURCHASE COST (2020$) *ICF Adjusted* 2030
Heavy Duty Pickup & Van	Class 2B Class 3	100	70	86	*$25,000*	$5,250	$5,200
Regional Haul Tractor	Class 7 - 8	250	89	109	$187,000	$93,500	$49,250
Long Haul Tractor	Class 8	500	178	218	$215,000	$50,000	-$16,500
Shuttle Bus	Class 3-5	100	37	45	$150,000	$79,600	$28,900
Delivery Van	Class 3-5	100	64	78	*$40,000*	$12,750	$5,200
Delivery Truck	Class 6-7	150	74	91	$103,667	$43,693	$13,268
Service Van	Class 3-5	150	96	118	*$40,000*	$6,050	$1,650
Service Truck	Class 6-7	150	74	91	$103,667	$43,693	$13,268
Refuse Hauler	Class 8	500	175	214	$202,500	$49,750	-$4,500
Box Truck (freight)	Class 3-5	100	70	86	$50,000	$26,100	$21,900
Box Truck (freight)	Class 6-7	150	80	97	$187,000	$106,939	$56,427
Box Truck (freight)	Class 8	250	115	140	$215,000	$83,500	$1,250
Stake Truck (construction)	Class 3-5	100	64	78	$50,000	$26,100	$21,900
Stake Truck (construction)	Class 6-7	150	74	91	$187,000	$106,939	$56,427
Dump Truck	Class 8	250	105	129	$215,000	$83,500	$1,250

Note that the estimated incremental EV purchase cost values shown in Figure A6 may still be conservative (high) as there is significant uncertainty as to future EV costs in a very dynamic market. For example, if the current 5-year lag in M/HDV battery costs (relative to LDV battery costs) disappears by 2030 as the M/HD EV market develops, incremental EV purchase costs for most market segments could be $4,000 - $6,000 lower than shown in Figure A6, and up to $12,000 lower for long-haul tractors and transit buses (the vehicles with the largest batteries). The estimated EV incremental purchase costs in Figure A6 also do not account for potential future compliance costs for new diesel and gasoline engines to meet more

[31] The F150 lighting base model is <8,500 lb GVWR so is not a Class 2B vehicle. While similar, Class 2B and Class 3 heavy-duty pickups and vans would have higher energy needs than the base F150 lighting and would therefore be expected to have higher incremental EV cost than this vehicle, as reflected in Figure A6.

stringent NOx emission standards currently under consideration by EPA. More stringent NOx standards will likely increase the cost of future diesel and gasoline vehicles, thus reducing incremental EV costs.

In addition, the 2025 and 2030 incremental cost estimates for School and Transit buses are not included in Figure A6 due to significant concerns about the original ICF cost estimates for these vehicle types. The original ICF estimates show significantly greater cost reductions for Class 8 single-unit and combination trucks than for Transit and School buses between 2020 and 2030, despite similar electric drive train and battery requirements among all these vehicle types. The reason for the difference is not clear. If relative cost reductions for electric transit and school buses match projected reductions for other Class 8 electric trucks, 2025 and 2030 incremental EV Transit and School bus costs will be significantly lower than ICF's estimates.

Annual fuel use for diesel trucks in each market segment (gallons/year), was calculated using the data in Figure A2. Average EV energy use for trucks in each market segment (kWh/yr) was calculated using data in Figure A2 (mi/yr) and Figure A4 (kWh/mi). To calculate annual fuel cost savings for EVs compared to diesel vehicles, MJB&A used these estimates combined with U.S. average projected future energy costs ($/gallon, $/kWh) from the Energy Information Administration [19]. Estimated annual fuel cost savings over the vehicle life was discounted using a 5% real discount rate (7% nominal discount rate) to calculate the Lifetime Discounted Fuel Cost Savings for EVs compared to diesel vehicles in each market segment. For this calculation, vehicle lifetime was assumed to be 10 years for Class 2b – 5 trucks, 14 years for Class 6 – 7 trucks, and 18 years for Class 8 trucks.

Given the uncertainties as to future EV incremental purchase costs (discussed above), the projections presented here of when M/HD EVs in each market segment might achieve life-cycle cost parity with ICE vehicles are a first order estimate; additional work to refine future EV cost estimates based on recent and on-going market developments is warranted to refine this preliminary understanding of how the M/HD EV business case will evolve in the short- and medium-term.

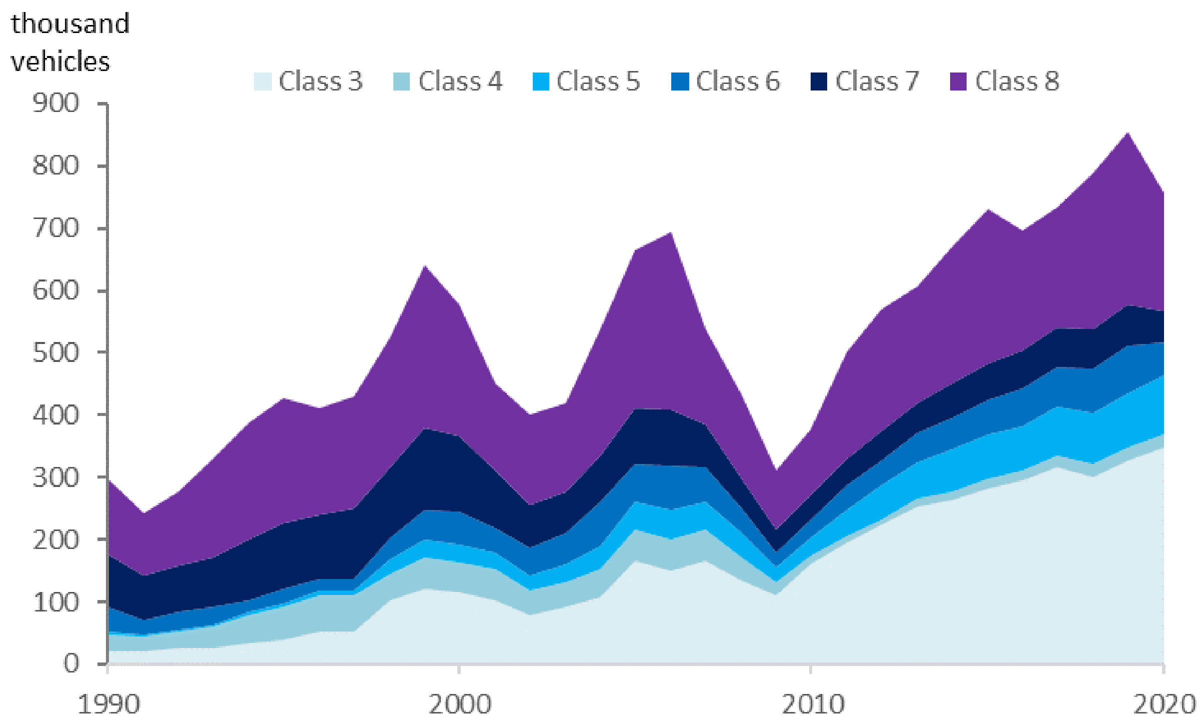
MJB&A used previous project experience, and data from the ARB ACT Spreadsheet to determine EV charging location (Private, Public) for vehicles in each market segment, and calculated "low" and "high" average charging demand (kW/vehicle) by dividing EV daily energy use (kWh/day) by the number of hours available for charging each day. For Public charging vehicles were assumed to charge for only 1 hour per day, with one charger for every 12 vehicles. For Private (depot-based) charging, available charge time varies by market segment, based on the number of hours per day that vehicles are typically used. For most market segments vehicles are assumed to be used for 8 – 10 hours per day; exceptions include School Bus (4 – 7 hours), Transit Bus (8 – 15 hours), Refuse Hauler (4 – 8 hours), and Class 8 Box Truck (10 – 12 hours). See Figure A7 for a summary of estimated annual energy use, discounted EV lifetime fuel savings, and charging requirements for vehicles in each market segment.

Figure A7 Energy Use, EV Discounted Fuel Cost Savings, and EV Charging Requirements

MARKET SEGMENT	Weight Class	Annual Fuel		Life-time EV Discounted Fuel Cost Savings	EV CHARGING		
		Diesel gal	*EV* kWh		Location	Avg Demand (kW/veh) *low*	*high*
Heavy Duty Pickup & Van	Class 2B Class 3	957	11,973	$11,265	PRIVATE	2.7	16.3
Regional Haul Tractor	Class 7 - 8	6,040	75,602	$120,794	MIXED	35.7	78.5
Long Haul Tractor	Class 8	12,864	161,031	$257,289	PUBLIC	35.8	107.4
Transit Bus	Class 8	5,000	62,581	$99,990	PRIVATE	16.9	121.3
School Bus	Class 7	1,252	15,676	$20,281	PRIVATE	2.9	14.8
Shuttle Bus	Class 3-5	4,806	60,162	$56,601	PRIVATE	10.3	38.7
Delivery Van	Class 3-5	1,143	14,306	$13,459	PRIVATE	3.0	17.9
Delivery Truck	Class 6-7	3,704	46,361	$59,978	PRIVATE	10.3	23.2
Service Van	Class 3-5	1,143	14,306	$13,459	PRIVATE	3.0	8.9
Service Truck	Class 6-7	1,481	18,544	$23,991	PRIVATE	3.9	11.6
Refuse Hauler	Class 8	3,120	39,056	$62,403	PRIVATE	5.5	14.6
Box Truck (freight)	Class 3-5	1,043	13,062	$12,289	PRIVATE	2.7	16.3
Box Truck (freight)	Class 6-7	1,724	21,582	$27,921	MIXED	9.6	46.2
Box Truck (freight)	Class 8	6,667	83,450	$133,333	MIXED	45.9	173.9
Stake Truck (construction)	Class 3-5	1,048	13,114	$12,337	PRIVATE	3.0	11.9
Stake Truck (construction)	Class 6-7	1,358	16,999	$21,992	PRIVATE	3.9	15.5
Dump Truck	Class 8	5,797	72,565	$115,942	PRIVATE	15.1	45.4

Appendix B – Supplemental Information

Figure B1 Historical M/HD Vehicle Sales by Weight Class



Source: Oakridge National Laboratory, Transportation Energy data Book

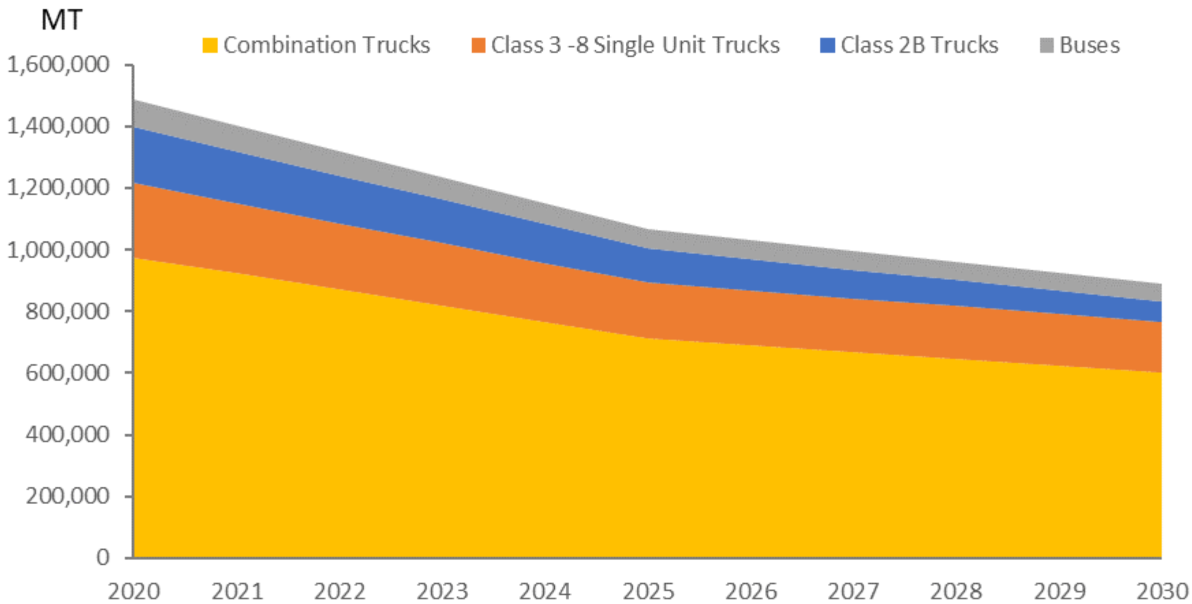
Figure B2 Example Fleet Electrification Commitments

Sector	Company	Electric Fleet Plans
Retail	Ikea Group*	2020: Electrify deliveries in Amsterdam, Los Angeles, New York, Paris, and Shanghai (25% global of deliveries) 2025: 100% EV or other zero-emissions solutions for deliveries and services through suppliers
	Amazon	2022: 10,000 electric delivery vans (short-term goal) 2030: 100,000 electric delivery vans total (long-term goal)
	Clif Bar & Company*	2030: 100% fleet electrification
	Unilever	2030: 100% fleet electrification (11,000 vehicles)
	Walmart	2040: Zero emission vehicle fleet, including long-haul (6,000 trucks)
Power	Schneider Electric*	2030: 100% electric fleet (14,000 vehicles)
	Edison Electric Institute (EEI) Member Companies (investor-owned utilities)	2030: More than 70 percent of EEI member companies will collectively electrify more than one-third of their total fleet vehicles, including two-thirds of passenger vehicles in fleets. Examples include: • Xcel Energy: 2023: 100% electric sedan portion of fleet; 2030: 100% electric light-duty fleet; 30% M/HD vehicles • Consumers Energy: 2025: Buy or lease 100% of EVs for fleet • Southern California Edison: 2030: 100% electric passenger car and small-to-midsize SUV, 30% medium-duty vehicles and pickup trucks, 8% heavy-duty trucks, 60% forklifts
Transportation	Lyft**	2026: 100% new vehicles for Express Drive (driver rental program) are electric 2030: 100% EVs on platform
	King County Metro (WA)	2030: 100% zero-emissions fleet
	Lime*	2030: 100% conversion of operations fleet
	Uber**	2030: 100% of rides take place in EVs in U.S., Canadian, and European cities 2040: 100% of rides take place in ZEVs, on public transit or with micromobility
Delivery	DHL	2025: 70% of first- and last-mile delivery services with clean transport modes 2050: Reduce logistics-related emissions to zero
	FedEx	2025: 50% of Express global parcel pickup and delivery (PUD) fleet purchases electric 2030: 100% PUD fleet purchases electric 2040: 100% ZEV PUD fleet
Biotech	Genentech	2030: 100% electrification of sales fleet (1,300 vehicles) and commuter buses
Municipal	New York City, New York	2017: Only purchase PHEVs for non-emergency sedans going forward 2025: Add 2,000 EVs to NYC sedan fleet 2040: 100% electric MTA bus fleet
	New Jersey	2024: At least 10% of new bus purchases will be zero emission buses 2026: At least 50% of new bus purchases will be zero emissions buses 2032: 100% of new bus purchases will be zero emissions buses
	Los Angeles, California	2028: 100% ZEV vehicle conversions "where technically feasible" (2028: taxi fleet, school buses; 2035: urban delivery vehicles) 2035: 100% electrification of sanitation fleet through LA Department of Sanitation Commitment
	Houston, Texas	2030: 100% EV non-emergency, light-duty municipal fleet
	Chicago, Illinois	2040: 100% electric Chicago Transit Authority (CTA) bus fleet (1,850 buses)
	Montgomery County, Maryland	2033 (approximately 12-year process): Electrify entire school bus fleet for Montgomery County Public School district (1,400 school buses serving over 200 schools)

*Member companies of EV100, through which 102 committed member companies will electrify over 4.8 million vehicles globally
**Drivers for Lyft and Uber are contractors rather than employees, so it may be difficult to convince drivers to switch to EVs. Lyft does not intend to remove drivers from platform who do not drive electric or provide financial incentives to drivers for the transition. Instead, much of the plan revolves around exerting pressure on competitors, lawmakers, and automakers. Uber will pay BEV and hybrid drivers an incentive of $1.50 and $0.50 per trip, respectively, and GM and Renault-Nissan will offer discounts to EVs. While Uber has not explicitly stated they will not remove non-electric drivers, they may be in a similar position as Lyft. Uber recently announce it will roll out "Uber Green" in 1,400 North American cities and launch partnerships to expand EV access for its drivers.

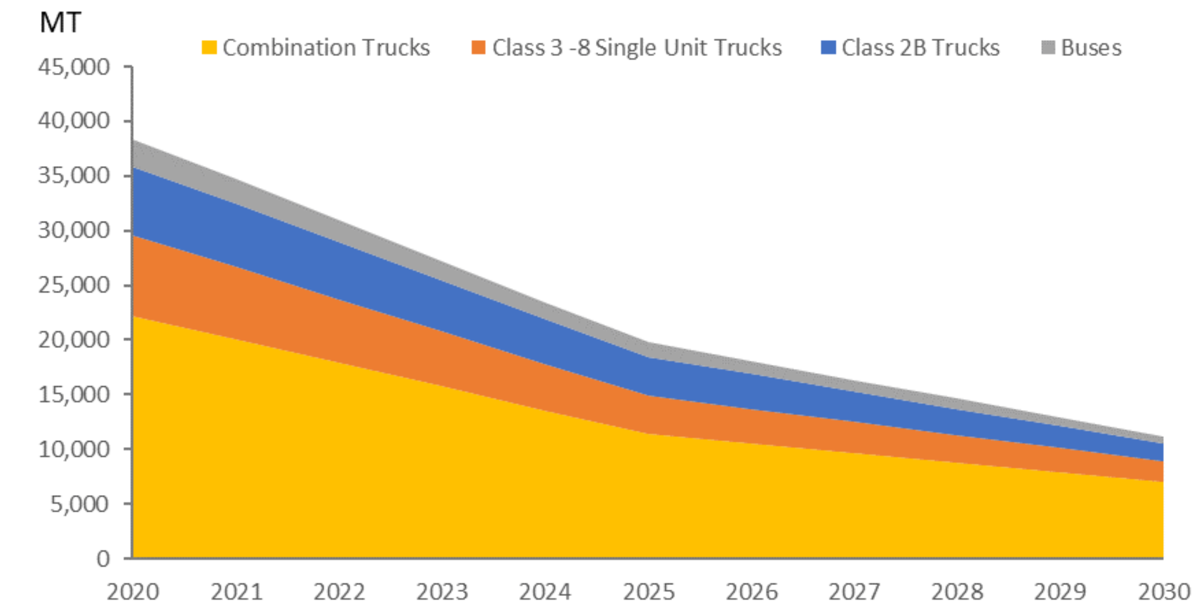
Source: M.J. Bradley & Associates

Figure B3 EPA Estimated Annual M/HDV Fleet NOx Emissions, 2020 - 2030



Source: EPA MOVES3

Figure B4 EPA Estimated Annual M/HDV Fleet PM Emissions, 2020 - 2030



Source: EPA MOVES3

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