WHITE PAPER

ZERO-EMISSION TRUCK REAL-WORLD PERFORMANCE IN US AND EUROPE AND IMPLICATIONS FOR CHINA

Yin Qiu
Shuhan Song
Ross McLane
CALSTART

April 2022

ACKNOWLEDGMENTS

This report was funded by the Energy Foundation China, ClimateWorks Foundation and the William & Flora Hewlett Foundation. The authors would like to thank FIER Automotive staff, including Rob Kroon, for their contribution to this work. The authors would like to thank key CALSTART staff for their critical review of and additions to this report, including Dr. Cristiano Facanha, Owen MacDonnell, Baha Al-Alawi, Kevin Leong, Chase LeCroy, and John Zhang. This document is based on information gathered as of February 2022. Any errors are the authors' own.

Global Commercial Vehicle Drive to Zero

www.globaldrivetozero.org
@TeamDriveToZero

CALSTART

www.calstart.org
@calstart

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF ACRONYMS

BET	Battery Electric Truck
CARB	California Air Resources Board
Cargo Van	Cargo Van (Class 3)
FCET	Fuel Cell Electric Truck
GVWR	Gross Vehicle Weight Rating
HD Truck	Heavy Duty Truck (Class 7/8)
HVIP	Hybrid and Zero-Emission Truck and Bus voucher Incentive Program
ICCT	International Council on Clean Transportation
ICE vehicles	Internal Combustion Engine vehicles
LHDV	Light Heavy-Duty Vehicles (Class 2b)
MHD ZEV	Medium- and Heavy-duty Zero-Emission Vehicles
MHD ZET	Medium- and Heavy-duty Zero-Emission Trucks
MD step van	Medium-duty step van (Class 3-6)
MD truck	Medium-duty truck (Class 3-6)
MOU	Memorandum of Understanding
MSRP	Manufacturer's Suggested Retail Price
OEM	Original Equipment Manufacturer
TCO	Total Cost of Ownership
US	United States of America
Yard tractor	Yard/Terminal tractor
ZET	Zero-Emission Truck
ZETI	Zero-Emission Truck Inventory

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Medium- and heavy-duty (MHD) trucks disproportionately emit greenhouse gases (GHGs) and other air pollutants including nitrous oxides (NOx) and particulate matter (PM) due to their longer driving mileages, diesel-fueled engines, higher weights, more intense duty cycles and generally lower fuel efficiencies. Zero-emission alternatives can alleviate these issues by eliminating tailpipe emissions and significantly reducing lifecycle GHG emissions compared to conventionally fueled MHD trucks.

Adoption of zero-emission trucks (ZETs) has been uneven across the globe and largely dependent on national and state government policies. In the United States and Europe, ZETs, mostly medium-duty trucks, are being produced and purchased by fleets in increasing numbers. The United States has deployed over 1,200 ZETs since 2010 and US ZET original-equipment manufacturers (OEMs) have non-binding orders for over 140,000 ZETs to be delivered over the next 10 years. In addition, most US OEMs have commitments to electrification, which if summed, equate to roughly 35% of annual MHD truck sales being zero-emission by 2035. Europe has deployed over 2,300 ZETs since 2017 and the European Automobile Manufacturers Association estimates that 40,000 MHD ZETs will be deployed across Europe by 2025 and 270,000 by 2030 (ACEA, 2021).

Driving these US and European trends is a combination of strong state and national government targets, incentives, and regulations. The State of California in the United States of America exemplifies these driving factors - the state has an executive order which targets 100% ZE MHDVs by 2045, a voucher incentive program (HVIP) which has provided over $400 million for ZETs and zero-emission buses to date, and a regulation which will require manufacturers to selling increasing proportions of ZETs each year, reaching 45-75% by 2035.

While the US and Europe have high growth rates of ZET sales, China currently leads in terms of ZET deployments with 232,000 MHD trucks in the country. Despite its leadership, China's current ambition is not aligned with its capability. The China Society of Automotive Engineers (China-SAE) recently proposed sales targets regarding new energy trucks[1] (NETs) with gross vehicle weights over 3.5 tonnes: 12% by 2025, 17% by 2030 and 20% by 2035 (China SAE, 2021). In comparison, a coalition of 15 countries has signed onto a global memorandum of understanding (Global MOU)[2] wwhich sets targets for 100% zero-emission truck and bus sales by 2040 with an interim target of 30% by 2030. This report is meant to encourage Chinese decision-makers to align China's capability with its ambition and commit to more aggressive ZET targets. To support this goal, this study evaluates the technical and economic feasibility of ZETs.

---

[1] New Energy Vehicles are defined in China as partially or fully powered by electricity, such as battery electric vehicles (BEVs), plug-in hybrids (PHEVs), and hydrogen fuel cell vehicles (FCEVs)

[2] Austria, Canada, Chile, Denmark, Finland, Luxembourg, Netherlands, New Zealand, Norway, Scotland, Switzerland, Turkey, United Kingdom, Uruguay, and Wales.

TECHNICAL FEASIBILITY

Much of the hesitation in decision making around the world has been due to a lack of confidence in the technical capability of ZETs to replace conventionally fueled trucks, however, increasingly this difference is dwindling. This report evaluates several different sources of technical data – not only manufacturer quoted but also real-world performance data under the test of various combinations of differences in climate, terrain, driving speed, congestion, and frequency of stops. Although the impacts of each factor above were yet to be well attributed, the resulting performance can reveal the status quo of ZE-MHDVs' technical capabilities in multiple aspects.

Nominal ranges and battery capacities as claimed by OEMs currently are sufficient for urban use and quickly approaching ranges comparable to ICEs. Compared to vehicle models in China (where data were available), existing ZET models in the US and Europe can achieve similar nominal range in MD trucks and cargo vans but offer superior nominal range in HD trucks. Larger size of batteries can extend battery range but can possibly increase the curb weight and limit the payload capacity if GVWR remains constant. Payload capacities are currently comparable to their ICE counterparts. Although battery-electric trucks (BETs) performed relatively well in the above technical capabilities, some of the high-end models announced are not necessarily production-ready soon due to the complicated dynamics of supply chain nowadays.

When performing regular duty cycles, BE yard tractor, MD truck, MD step van and cargo van have comparable capabilities compared to conventionally fueled trucks. The BE models tested in the HD truck segment can well perform the jobs in regional duty cycles that normally require one shift and less than 200 miles (322 km) a day, however, challenges are found if there is dynamic (unpredictable) routing, longer routes, longer wait time or when drivers do not return to base each day for recharging.

Better energy efficiency is known as an advantage of electric drive vehicles, around 2 to 4 times of the diesel truck efficiency. US BE yard tractors and HD box trucks have median energy efficiencies at 2.62 kWh/mi (14.5 MPGe) and 2.17 kWh/mi (17.6 MPGe), performing worse than nominal efficiency most of the time, but these electric models are still about twice of the efficiency of diesel counterparts (6.5 – 8 MPG). HD day cab tractors and MD step vans performed relatively well, with the median efficiency at 1.95 kWh/mi (19.5 MPGe) and 1.12 kWh/mi (34 MPGe) respectively, which are 3 to 4 times of the efficiency of the diesel trucks (6.5 MPG and 9 MPG). In addition, using yard tractors as example, worse energy efficiencies were found to be associated with colder ambient temperatures. The impact of temperature was more pronounced in Northeast and Midwest than West Coast in the US, presumably due to the fact that these two regions have greater seasonable variations and lower temperatures in winter.

ECONOMIC FEASIBILITY

Economic feasibility of BETs is assessed based on literature review on total cost of ownership (TCO). Several cost factors are analyzed across references accounting for the variation in assumptions and methodologies. Manufacturer's suggested retail prices (MSRP) are currently more expensive than those for diesel trucks, but the cost differential is projected to reduce over time as battery technology matures and production volumes increase. BETs in general have cheaper fuel cost than diesel trucks in both current and future scenarios where fuel efficiency is the determinant factor influencing their fuel cost. Because BETs have no needs for oil changes and aftertreatment system maintenance, maintenance cost of BETs is estimated to be lower than that for diesel counterparts despite disparities among cost estimates. Putting everything together, BETs could achieve TCO parity with supportive policies as of today and be economically viable without economic incentives by 2030.

RECOMMENDATIONS

China leads the world in zero-emission vehicle (ZEV) deployments, ZEV and battery manufacturing capacity, and ZEV incentives. Despite this leadership, the zero-emission truck (ZET) market in China has not experienced the same success as its zero-emission light-duty passenger vehicle and bus segments. Slow deployment can be attributed to a multitude of technical and economic challenges in MHD truck electrification, while the unique characteristics of the Chinese truck market have made these challenges particularly outstanding. Over 70% of truck drivers in China are independent owner-operators and earn low wages, making the upfront cost of MHD ZETs (almost double the cost of diesel trucks) unbearable by these independent owner-operators, which have limited financing options compared to larger scale logistics companies.

However, these barriers are not insurmountable. An integrated program of strong national ZET targets, regulations, and incentives can provide systematic guidance for the industry and provincial governments to take action to accelerate ZET commercialization and improve the financial feasibility of ZETs until their total costs of ownership reach parity with conventional trucks. Below is a list of recommendations for China::

- **Announce Strong Targets to Maintain Chinese Leadership**
  Targets can guide the development of ambitious regulations and send clear market signals to local governments, MHD truck manufacturers and fleets. If China intends to maintain its lead in zero-emission transportation, announcing strong ZET targets at least in line with those announced by other countries and US states is a critical first step.
- **Implement Strong Regulations to Provide Market Certainty**
  Regulations can provide market players long-term certainty and encourages investment. To solidify a transition to ZETs, China should back up any ambitious ZET targets with regulatory policy in the form of sales or stock quota from manufacturers and/or adoption requirements for fleets.
- **Extend Targeted and Timebound Incentives**
  To maintain and accelerate ZET adoption, purchase incentives should be extended and increased to fill the TCO gap between ZETs and conventional diesel trucks, and additional operational incentives for ZETs should be designed. Reintroduced incentives should be both targeted and timebound, developing a comprehensive package aligned with regulations would provide market certainty for investment and clarity on when incentives will be phased down.
- **Continue Investment in Battery Electric Technologies**
  All BET segments are expected to achieve TCO parity without incentives in 2025-2035 timeframe.

Given the urgency to tackle climate change and the ability to leverage Chinese investment in battery manufacturing, a prudent ZET roadmap would maximize the deployment of BETs in every truck segment possible, before turning to more expensive and less technologically mature fuel-cell technologies. A combination of investment in BETs while continuing to invest in the development and early-deployment of FCETs would enable the fastest and most cost-effective transition to ZETs in China.

- **Prioritize Zero-Emission Tailpipe Technologies**
  China should prioritize "zero-emission" tailpipe technologies over "near-zero" or "low-emission" technologies for the MHD truck segment in any future targets, regulations, or incentives. These other technologies are still producing harmful pollutants and not reducing enough GHG to meet international climate goals (ICCT, 2021c). In addition, since many MHD truck sectors are electrifiable, the truly sustainable biofuels and expensive electro-fuels might be reserved for the harder-to-abate sectors of marine shipping and aviation, where battery technology is not yet compatible.
- **Leverage Zero-Emission Bus Investments to Accelerate Zero-Emission Trucks**
  China is the global leader in electrifying the bus segment, with over 98% of global ZEBs (IEA, 2021). As outlined in the internationally recognized "Beachhead Strategy," ZEBs are a "first-success" zero-emission technology (or "Beachhead") which can expedite the development of harder-to-electrify vehicle segments. China can and should leverage this experience in manufacturing and promoting ZEBs to accelerate the commercialization of the ZETs. A few of the Chinese medium- and heavy-duty manufacturers are already poised to take advantage of this strategy. With targeted policy, similar investments can be expanded into the heavy-duty truck segment.

CHAPTER 1

INTRODUCTION

Medium- and heavy-duty (MHD) trucks disproportionately emit greenhouse gases and air pollutants (Figure 1). In 2020, heavy-duty trucks made up just over 3% of global vehicle stock but were responsible for 30% of CO_2 emissions, 62% of NOx emissions, and about 50% of PM2.5 emissions from on-road vehicles (ICCT, 2019a; ICCT, 2019b). Under a business-as-usual scenario, CO_2 emissions are expected to more than double by 2050, while NOx and PM2.5 emissions are expected to grow by more than 20% and 40%, respectively, during the same time frame, largely driven by a significant increase in global domestic and international freight demand (ITF, 2019). The problem is exacerbated by the fact that these emissions disproportionately impact low-income communities and communities of color, which tend to be located closer to highways and rely more heavily on public transportation.

Figure 1. Business-As-Usual Projections of Global Truck Stock, Energy Consumption and Tailpipe Emissions (Source: ICCT)

In China MHD trucks (those with gross vehicle weights above 4.5 tons) make up 4% of the on-road vehicle fleet but are responsible for 40% of total GHG emissions, 84% of nitrogen oxides (NO_x), and 90% of particulate matter (PM) pollution from all on-road vehicles (ICCT, 2021; Xue, 2021).

The deployment of zero-emission trucks (ZETs) can mitigate these disproportionate emissions by eliminating tailpipe pollutants as well as drastically reducing lifecycle GHG emissions, even when ZETs are refueled by relatively coal-heavy electrical grids. A 2021 study by the International Council on Clean Transportation (ICCT) found that lifecycle emissions of battery-electric light-duty passenger vehicles in China during the period of 2021 to 2035 would be roughly 40% lower than the emissions of a light-duty passenger vehicle powered by a blend of gasoline and biofuels (ICCT, 2021). A similar study for zero-emission MHD trucks would very likely yield similar GHG emissions reductions over diesel vehicles.

Currently China leads the ZET market with over 232,000 ZETs over 3.5 tons sold as of 2021 (EV Volumes, 2021). In addition, China also leads the zero-emission passenger vehicle and bus segments with 41% and 98% of the global market, respectively. Despite China's dominance, the country's ambition underestimates its capability. Despite strong financial incentives for zero-emission trucks and buses, as of 2021, no national zero-emission truck or bus targets or regulations have been announced (IEA, 2021). In comparison, a coalition of 15 countries led by the Netherlands and CALSTART has signed onto a global memorandum of understanding (Global MOU)[3] which sets targets for 100% zero-emission truck and bus sales by 2040 with an interim target of 30% by 2030. Similarly, a group of 18 US states [4], comprising 34% of the total MHD truck market in the US, has signed an MOU committing them to 100% zero-emission truck and bus sales by 2050. A subset of those states has adopted regulations which require an increasing share of MHD truck and bus sales to be zero emission starting in 2024 and eventually reaching 40-75% by 2035.

This report seeks to encourage and inform Chinese decision-making with respect to ZET technical capability and economic feasibility to accelerate their commercialization. By providing US and European ZET market context and analyzing ZET operational vehicle data, this report intends to provide a fuller picture of ZET deployments and policies in other leading advanced vehicle markets around the world. The report is divided into three broad sections: US and European Market Context, US and European Vehicle Data Analysis, and Recommendations for China. The first provides a snapshot of the ZET markets in the US and Europe and provides context on any unique developments in those markets. The second section provides in-depth analysis of ZET operational data from the latest and most advanced ZET pilots underway or that have recently concluded in both regions. The final section provides further guidance to China about policies and pathways to accelerate ZET deployment, informed by market context and data analysis.

---

3 Austria, Canada, Chile, Denmark, Finland, Luxembourg, Netherlands, New Zealand, Norway, Scotland, Switzerland, Turkey, United Kingdom, Uruguay, and Wales.

4 California, Colorado, Connecticut, Hawaii, Maine, Maryland, Massachusetts, Nevada, New Jersey, New York, North Carolina, Oregon, Pennsylvania, Rhode Island, Vermont, Virginia, Washington, and Washington D.C.

CHAPTER 2

VEHICLE SEGMENTATION

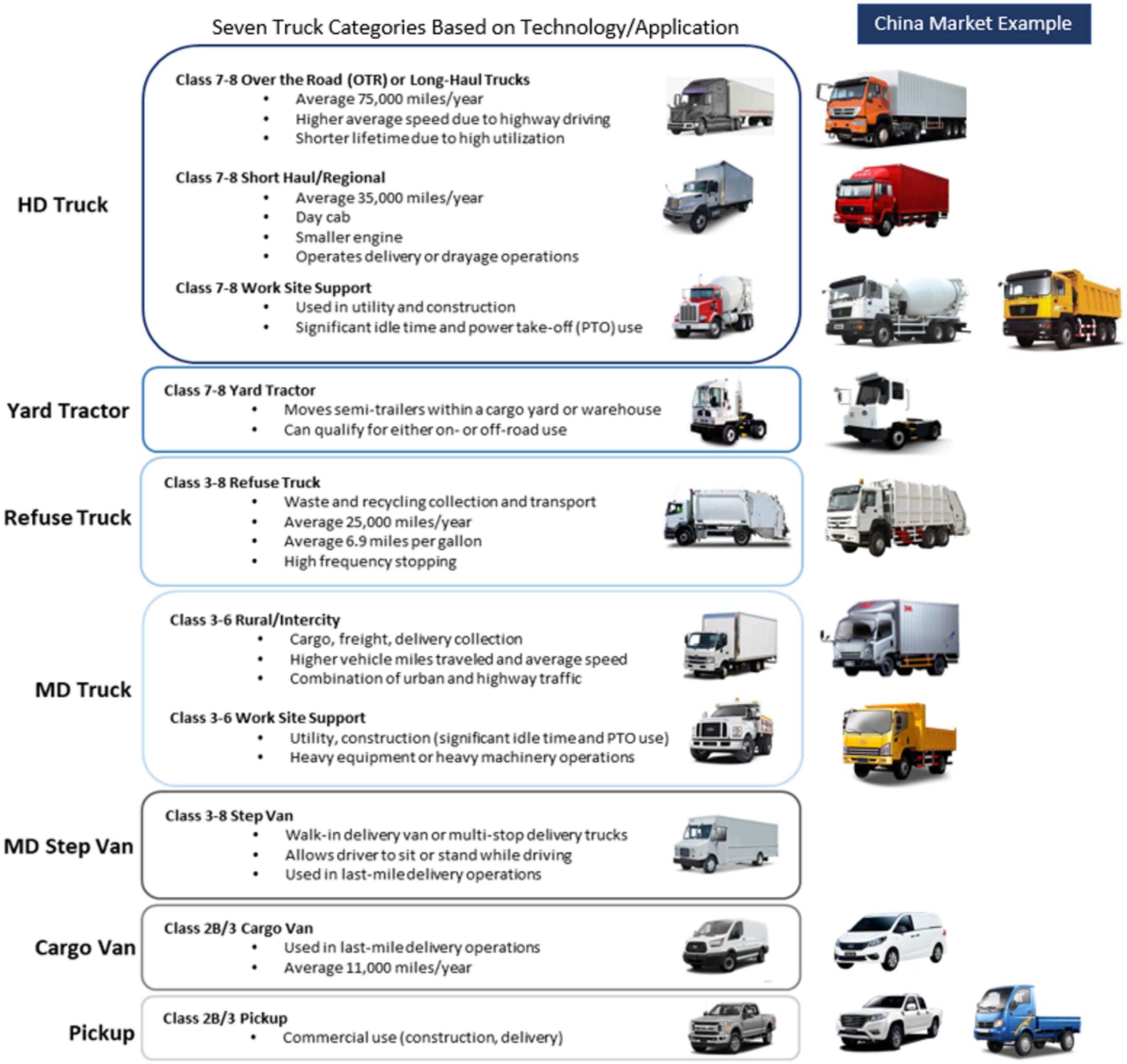
Vehicle classification is important in determining the status of vehicles segments, and the readiness of technology across global markets. While there are numerous ways to approach vehicle segmentation with varying degrees of specificity, the majority of this report refers to MHDVs in the U.S. and Europe using segmentation defined by eight categories based on vehicle type, which are used to characterize the MHDV market globally: **heavy-duty trucks** (U.S. Class 7/8), **medium-duty trucks** (U.S. Class 4-6), **medium-duty step vans** (U.S. Class 3-6), **transit buses** (U.S. Class 3-8), **yard tractors** (U.S. Class 7/8), **cargo vans** (U.S. Class 2b/3), **pickup trucks** (U.S. Class 2b/3) and **refuse trucks** (U.S. Class 3-8). These categories represent vehicle types that can span a range of weight classes and vocational uses. To adapt to the scope of trucks in this report, we removed the transit bus segment and kept the seven categories for trucks with their vocational uses and illustrative examples on the Chinese market (Figure 2). This segmentation approach was developed following an update to the California Hybrid and Efficient Advanced Truck Research Center (CalHEAT)[5] approach and the CALSTART's Beachhead Theory of Change.[6]

---

[5] CalHEAT was established by the California Energy Commission in 2010 as a project operated by CALSTART to research, plan, support commercialization and demonstrate truck technologies that will help California meet environmental policies mandated through 2050. https://calstart.org/wp-content/uploads/2018/10/CalHEAT-Roadmap.pdf

[6] https://globaldrivetozero.org/public/The_Beachhead_Model.pdf

Figure 2. Truck Vehicle Segmentation Based on Technology and Application



Seven Truck Categories Based on Technology/Application

China Market Example

HD Truck

Class 7-8 Over the Road (OTR) or Long-Haul Trucks
- Average 75,000 miles/year
- Higher average speed due to highway driving
- Shorter lifetime due to high utilization

Class 7-8 Short Haul/Regional
- Average 35,000 miles/year
- Day cab
- Smaller engine
- Operates delivery or drayage operations

Class 7-8 Work Site Support
- Used in utility and construction
- Significant idle time and power take-off (PTO) use

Yard Tractor

Class 7-8 Yard Tractor
- Moves semi-trailers within a cargo yard or warehouse
- Can qualify for either on- or off-road use

Refuse Truck

Class 3-8 Refuse Truck
- Waste and recycling collection and transport
- Average 25,000 miles/year
- Average 6.9 miles per gallon
- High frequency stopping

MD Truck

Class 3-6 Rural/Intercity
- Cargo, freight, delivery collection
- Higher vehicle miles traveled and average speed
- Combination of urban and highway traffic

Class 3-6 Work Site Support
- Utility, construction (significant idle time and PTO use)
- Heavy equipment or heavy machinery operations

MD Step Van

Class 3-8 Step Van
- Walk-in delivery van or multi-stop delivery trucks
- Allows driver to sit or stand while driving
- Used in last-mile delivery operations

Cargo Van

Class 2B/3 Cargo Van
- Used in last-mile delivery operations
- Average 11,000 miles/year

Pickup

Class 2B/3 Pickup
- Commercial use (construction, delivery)

Table 1 below acts as a reference and guide to understanding the similarities and differences between the U.S. and Chinese markets from a weight-class perspective.

Table 1. US & China Equivalent Weight Class Comparison

	US			China			
				Trucks			Tractors
	Weight (lb)	Class	Weight (ton-kg)	Class	Weight (ton-kg)	Class	Weight (ton-kg)
LHDVs	8,501 - 10,000	2b	3.86 - 4.54		3.5 - 4.5		3.5 - 18
MHDVs	10,001 - 14,000	3	4.54 - 6.35		4.5 - 5.5		
	14,001 - 16,000	4	6.35 - 7.26		5.5 - 7		
	16,001 - 19,500	5	7.26 - 8.85		7 - 8.5		
	19,501 - 26,000	6	8.85 - 11.79		8.5 - 10.5		
HHDVs	26,001 - 33,000	7	11.79 - 14.97		10.5 - 12.5		
	33,001 - 60,000	8a	14.97 - 27.22		12.5 - 16		
					16 - 20		18 - 27
					20 - 25		
	60,001 and over	8b	> 27.7		25 - 31		27 - 35
					> 31		35 - 40
							40 - 43
							43 - 46
							46 - 49
							> 49

Since vehicle data for most countries are only available by make but not by model, the seven vehicle categories for trucks described above allow for a more comprehensive analysis across regions. As a reference, the accompanying analysis to this report “Technology and Commercialization Pathways for Zero-Emission Medium- and Heavy-Duty Vehicles in China” contextualized the vehicle segmentation for the Chinese market that adds greater insight to the vocational use of certain vehicle types, seen in Figure 3. While mainly a matter of nomenclature, notable segments in the Chinese market that are not as prominent in the US are dump trucks and utility trucks. In the US these vehicles are aggregated into categories spanning several vocations. Figure 3 below illustrates indicative models for each of the 8 segments modeled for the Chinese market and their attributes.

Figure 3. MHDVs Segmentations Contextualized for the Chinese Market

Eight Truck/Bus Categories Based on Technology Applicability

China Market Example

Class 7/8 Tractors

Tractors – Long Haul (U.S. Class 7/8)
- Younger trucks & high annual VMT
- Mostly higher average speed and highway driving

Tractors – Short Haul/Regional (U.S. Class 7/8)
- Between cities, delivery, drayage and day cabs
- New and second use trucks
- Trucks with smaller engines

Class 2b-8 Vocational Work Trucks

Utility trucks (U.S. Class 3-8)
- Engineering trucks, maintenance, and utility
- Lots of idle time and lots of PTO use
- Lower VMT and lower average speed

Straight trucks (U.S. Class 3-6)
- Cargo, freight, and delivery collection
- Higher VMT and higher average speed
- Combination of urban and highway traffic

Dump Trucks (U.S. Class 3-8)
- Construction and worksite use
- Lots of idle time and lots of PTO use

Class 3-8 Buses

Buses (U.S. Class 3-8)
- Passenger transportation
- Stop-start operation
- City bus
- Transit, airports, hotels, and schools

Coaches (U.S. Class 3-8)
- Passenger transportation
- Regional travel

Class 2b/3

Logistics vans (U.S. Class 2b/3)
- Private and commercial use
- Goods transport
- Urban delivery

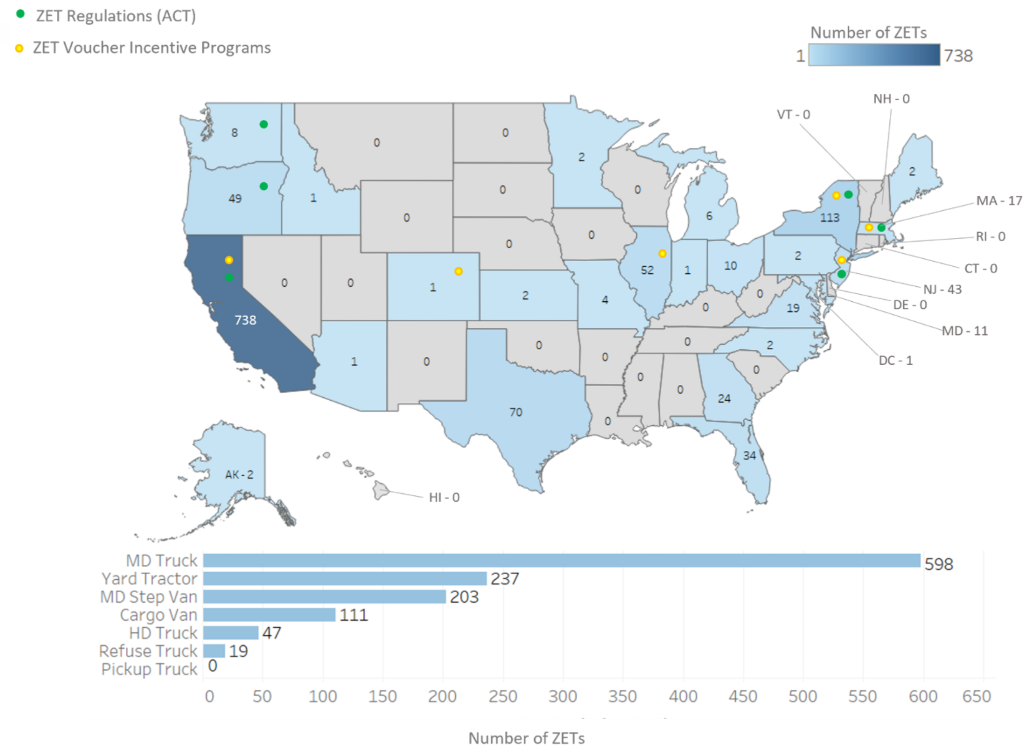
CHAPTER 3

US AND EUROPEAN ZET MARKET CONTEXT

3.1. US ZET MARKET CONTEXT

As of 2021, 1,215 ZETs have been deployed in the United States, the majority of which being battery-electric (99.5%) deployed in California (60.7%) (CALSTART, 2022). Figure 4 shows the breakdown of where these ZETs are deployed throughout the country and a breakdown by vehicle segment.

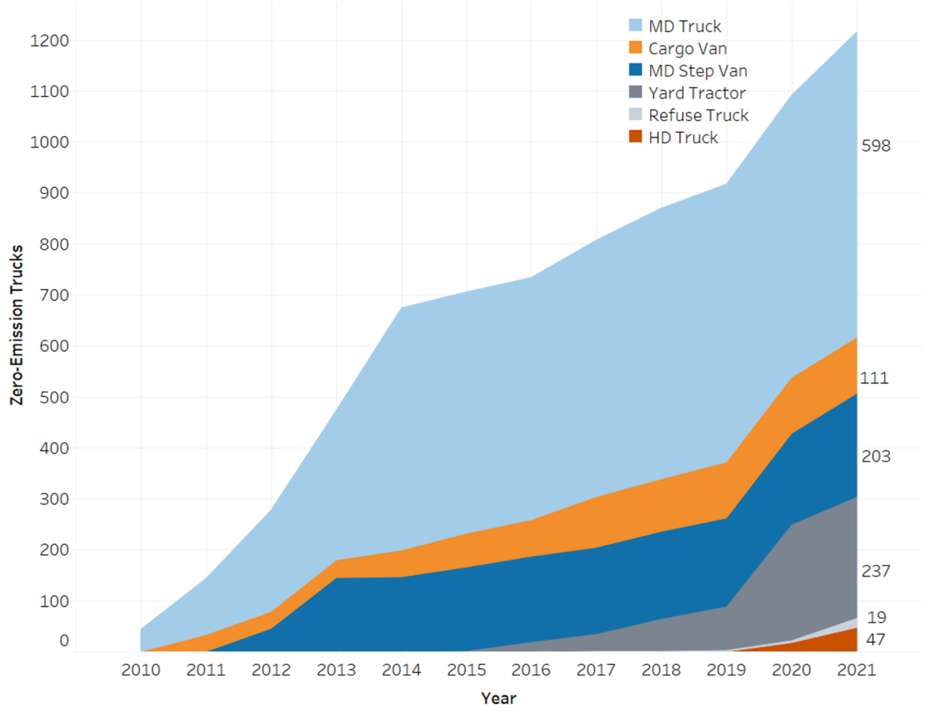
Figure 4. United States ZET Deployments by State (2011-2021)



Because all segments of ZETs have not yet reached total cost of ownership (TCO) parity with diesel trucks in the US, ZET deployment is concentrated in states that offer significant monetary incentives to reduce the upfront purchase price of a ZET. The states of California, Illinois, New York, New Jersey and Massachusetts have the most significant ZET voucher incentive programs and therefore some of the highest concentrations of ZETs. California runs the Hybrid- and Zero-Emission Voucher Incentive Program (HVIP) and Clean Off-Road Equipment (CORE) voucher program which together were funded for $873 million in 2021, about equal to the previous cumulative allocated sum of $881 million that has been allocated to heavy-duty on- and off-road vehicle programs from 2013-2020 (CARB, 2021c; CARB, 2020a). Of all incentive programs, California's HVIP program has deployed the most vehicles of any incentive program in the nation, responsible for 61% of all California ZET deployments and 37% of all US ZET deployments.

The ZET deployments in the US to date are largely consistent with the Beachhead Theory of Change (also known as Beachhead Strategy), a strategy pioneered by CALSTART and CARB, which predicts how zero-emission technology will propagate throughout various MHD vehicle segments (CALSTART, 2020). In the Beachhead Strategy, now widely recognized across the clean transportation industry, vehicle segments with applications and duty cycles more suited to zero-emission technology transition first, influencing the development of subsequent harder-to-electrify segments because of the potential for technology transfer across applications. The Beachhead Strategy can be seen materializing in Figure 5, where MD trucks, cargo vans, and MD step vans—all vehicle types well-suited for electric drivetrain and battery technology—were the first to electrify between 2010 and 2015 and have influenced the later development of harder-to-electrify segments like HD trucks and refuse trucks starting in 2019.

Figure 5. United States ZET Deployments Across Time



As more states adopt regulation and incentive programs, the distribution of ZETs is expected to even out across the US and rise drastically. In the near term, HVIP has 1,200 ZET orders which are expected to be fulfilled over the next 18 months, doubling the number of ZETs deployed in the US.[7] In total there are non-binding orders for over 140,000 ZETs which are expected to be fulfilled in the next 1-10 years depending on manufacturer capacity and order size. Additionally, if all states that have signed the Multi-State MOU reach their goals, there would be roughly 756,000 ZET deployments between 2024 and 2035 (about 3% of total registered in-use MHD trucks in the US). Most major OEMs that serve the US market have commitments to produce zero-emission vehicles – if all commitments were met, 35% of annual truck sales would be zero-emission by 2035.

The US ZET market is predominately composed of battery-electric trucks (BETs) that rely exclusively on static conductive cable charging. As of 2022, no manufacturers have made available BET models with battery swapping, wireless charging, or pantograph charging capabilities. In 2018, Siemens in partnership with a local California air quality agency piloted three electric and hybrid-electric heavy-duty trucks retrofitted with active pantograph charging on a one-mile stretch of road in California equipped with overhead catenary cables. However, no other "eHighways" have been piloted or developed for commercial purposes in the US since.

Most charging solutions for BETs in the United States revolve around either depot charging (capable of refueling a BET anywhere between 1 and 10 hours) and/or en-route high-powered "megawatt" charging, a technology that is currently still under development. In 2022, a project was initiated in California, funded by the California Energy Commission, which aims to pilot two of the first megawatt charging stations for drayage trucks and to pave the way for a high-powered charging corridor in California. Daimler Truck North America, NextEra Energy Resources and BlackRock Renewable Power have announced an MOU to establish a joint venture and invest $650 million into a high-performance charging network for medium- and heavy-duty battery electric and hydrogen fuel cell vehicles in the US (Daimler Truck, 2022).

Battery-swapping in the United States has been tested by some private organizations focused on the light-duty vehicle sector, however, there have been no pilots or demonstrations that apply battery-swapping for ZETs. The benefits of battery-swapping include faster refueling times, the possibility of operationalizing battery costs (therefore reducing upfront ZET prices), and the possibility of providing storage services to the grid. The disadvantages of a battery-swapping model include the fact that battery-swapping stations require sophisticated robotic systems, complex logistics to match battery supply and demand, a multiplication of expensive battery costs, and unprecedented coordination between US OEMs to produce standardized battery-swapping systems. As battery technology for BETs improves and high-powered charging stations become more prevalent, the need for battery-swapping is less likely to become a dominant charging strategy in the US.

Technological and economic conditions that make battery swapping unlikely in the US do not necessarily exist in China, where most major electric truck OEMs have announced battery swapping zero-emission truck models (Liu & Danilovic, 2021). Cheaper labor, significant electronics manufacturing capacity, and

---

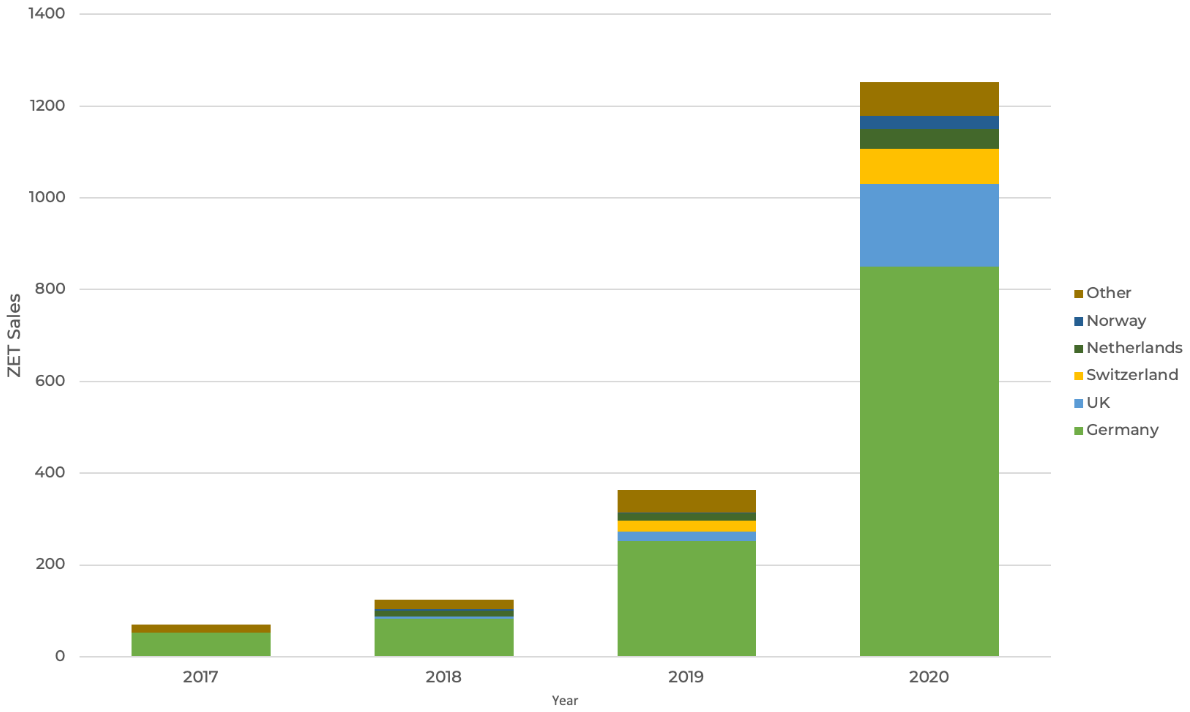
[7] Orders are non-binding and subject to cancellation by the purchaser or manufacturer.

a larger coordination between OEMs could mean that battery-swapping is a larger part of the zero-emission solution for heavy-duty trucks in China.

3.2. EUROPEAN ZET MARKET CONTEXT

Across Europe[8], over 2,300 MHD ZETs have been deployed since 2017. The leading countries in terms of ZET deployments are Germany (56%), the United Kingdom (9%), Switzerland (7%), Netherlands (4%) and Norway (3%) as seen in Figure 6.

Figure 6. European ZET Sales by Country (2017-2020)



Of ZETs deployed in Europe, 56% were medium-duty trucks (US Class 2b-6), while 44% were heavy-duty trucks (US Class 7-8). Germany, the United Kingdom and Netherlands were all dominated by medium-duty Fuso eCanter trucks in urban logistics applications (Figure 7). Switzerland has a large proportion of Hyundai XCIENT fuel cell electric trucks (FCETs) deployed in regional distribution, while Norway has a high percentage of Volvo FE & FL Electric heavy-duty trucks (US Class 7) operating in logistics and construction.

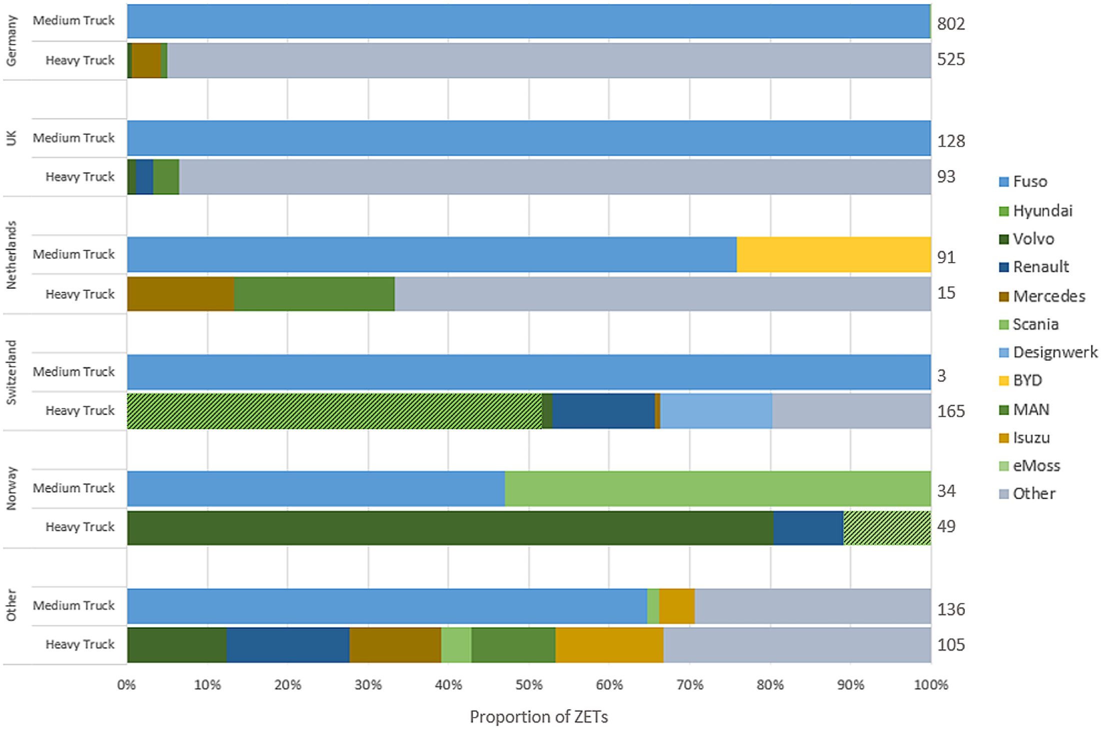
---

[8] Including the European Union, European Free Trade Association, and United Kingdom

Figure 7. Fuso eCanter trucks employed by logistics firm DB Shenker, Hyundai XCIENT heavy-duty truck in Switzerland, and Volvo FE heavy-duty truck in Oslo (Left to Right)

Deployment in these countries has been driven by purchases from large logistics companies and supported by zero-emission truck incentives and innovative financing models. German logistics company DB Shenker, for instance, has purchased 36 electric FUSO eCanter trucks that it has deployed in 11 European cities and has plans to order close to 1,500 ZETs from Swedish OEM Volta Trucks, while Norwegian food wholesaler ASKO has deployed 16 Scania P-Series heavy-duty trucks and plans to receive 59 more. Some of these purchases have been supported by financial incentives for ZETs offered in the UK, Germany, and the Netherlands (OZEV, 2021; FMDT, 2021; City of Amsterdam, 2021). Switzerland, on the other hand, has deployed 81 heavy-duty FCETs to over 25 Swiss companies operating in logistics, distribution and supermarket fulfillment, through a joint venture between Hyundai and Swiss H2 Energy, which leases these vehicles to operators on a pay-per-use basis and includes hydrogen supply.

Figure 8. Top European Country ZET Sales by Weight Class and Brand



Nine countries in Europe have signed onto the Global MOU committing to 100% ZET sales by 2040. If all these commitments were fulfilled, this would mean that these countries would be selling between 65,000 - 195,000 ZETs per year by 2050, based on 2021 truck sales and depending on freight demand growth. The European Automobile Manufacturers Association estimates that 40,000 MHD BETs will be deployed across Europe by 2025 and 270,000 by 2030 (ACEA, 2021).

Due to the diversity in national policies and strategies across Europe, ZET charging technology is less homogenous in Europe than it is in the US. Charging strategies being considered for BETs mostly revolve around static conductive cables, but also include some in-road and over-head conductive and inductive charging highways. Volvo, Daimler, and Traton plan to install 1,700 high-powered charging stations for BETs Europe by 2022 at a cost of approximately 500 million euros. Meanwhile, Germany has piloted seven pantograph equipped Scania heavy-duty ZETs in an overhead catenary cable pilot project near Frankfurt. Similarly, Sweden has piloted two electric highway projects based on conductive rails embedded in the road, one based on conductive overhead catenary cables, and one which employs inductive charging technology embedded below the road surface. Battery-swapping has not garnered much attention in Europe for reasons similar to those in the US.

CHAPTER 4

US AND EUROPEAN TECHNICAL AND ECONOMIC FEASIBILITY ANALYSIS

Economic feasibility of ZETs compared with conventionally fueled trucks and technical capability of ZETs to accomplish the same tasks as conventionally fueled trucks are two of the most important indicators for measuring ZETs' path towards full adoption in the US and Europe.

Under current conditions, BETs (the vast majority of all deployed ZETs in the US and Europe) are only economically feasible with financial incentives but are expected to achieve TCO parity without incentives in 2025-2035 timeframe across all truck segments. Although lower operational and maintenance costs create significant cost advantages of BETs over diesel trucks, high initial investment still hinder large scale BET expansion. This justifies the role of regulations to provide market clarity, and incentives to enable to early introduction of regulations. With strong regulations and targeted incentives, barriers due to high upfront capital costs will decrease gradually as technologies mature and battery costs decrease. Fuel economy of trucks, as well as duty cycles and charging management, also significantly influence TCO of BETs due to their influence on operational costs. All considered, BETs are projected to be as competitive as traditional fuel trucks in the market before 2030 for all truck segments.

Technical capabilities of BETs are overall satisfactory. We evaluated several different sources of technical data – not only manufacturer quoted but also real-world performance data under the test of various combinations of differences in climate, terrain, driving speed, congestion, and frequency of stops. Although the impacts of each factor above were yet to be well attributed, the resulting performance can reveal the status quo of ZE-MHDVs' technical capabilities in multiple aspects.

Nominal ranges and battery capacities as claimed by OEMs currently are sufficient for urban use and quickly approaching ranges comparable to ICEs. Compared to vehicle models in China (where data were available), existing ZET models in the US and Europe can achieve similar nominal range in MD trucks and cargo vans but offer superior nominal range in HD trucks. Larger size of batteries can extend battery range but can possibly increase the curb weight and limit the payload capacity if GVWR remains constant. Payload capacities are currently comparable to their ICE counterparts. Although BETs performed relatively well in the above technical capabilities, we should be aware that some of the high-end models announced are not necessarily production-ready soon due to the complicated dynamics of supply chain nowadays.

When performing regular duty cycles, BE yard tractor, MD truck, MD step van and cargo van have comparable capabilities compared to conventionally fueled trucks. The BE models tested in the HD truck segment can well perform the jobs in regional duty cycles that normally require one shift and less than 200 miles (322 km) a day, however, challenges are found if there is dynamic (unpredictable) routing, longer routes, longer wait time or when drivers do not return to base each day for recharging.

Better energy efficiency is known as an advantage of electric drive vehicles, around 2 to 4 times of the diesel truck efficiency. US BE yard tractors and HD box trucks have median energy efficiencies at 2.62 kWh/mi (14.5 MPGe) and 2.17 kWh/mi (17.6 MPGe), performing worse than nominal efficiency most of the time, but these electric models are still about twice of the efficiency of diesel counterparts (6.5 – 8 MPG). HD day cab tractors and MD step vans performed relatively well, with the median efficiency at 1.95 kWh/mi (19.5 MPGe) and 1.12 kWh/mi (34 MPGe) respectively, which are 3 to 4 times of the efficiency of the diesel trucks (6.5 MPG and 9 MPG). In addition, using yard tractors as example, worse energy efficiencies were found to be associated with colder ambient temperatures. The impact of temperature was more pronounced in Northeast and Midwest than West Coast in the US, presumably due to the fact that these two regions have greater seasonable variations and lower temperatures in winter.

4.1. DATA SOURCES

Data for the technical and economic feasibility analysis are largely derived from real-world ZET demonstrations and pilots across the US. While currently limited, real-world data provides an advantage over nameplate, or manufacturer-quoted, data because it is closer to the truth of how MHD ZETs will perform technically and economically when deployed.

Data sources from the US market are derived from data collection and demonstration projects executed by CALSTART, such as real-world vehicle performance data collection funded by the US Department of Energy (DOE), and ZET performance data from the Volvo Low Impact Green Heavy Transport Solutions (LIGHTS) project funded by California Air Resources Board (CARB). Vehicle technical configuration data for the US, Europe and China were collected by Zero-Emission Technology Inventory (ZETI) developed by CALSTART. Given the outstandingly global coverage of models in ZETI, we would caveat that the validation and update of model configurations outside North America have been more challenging. Thus, some observations may not accurately reflect ZETs in China or Europe.

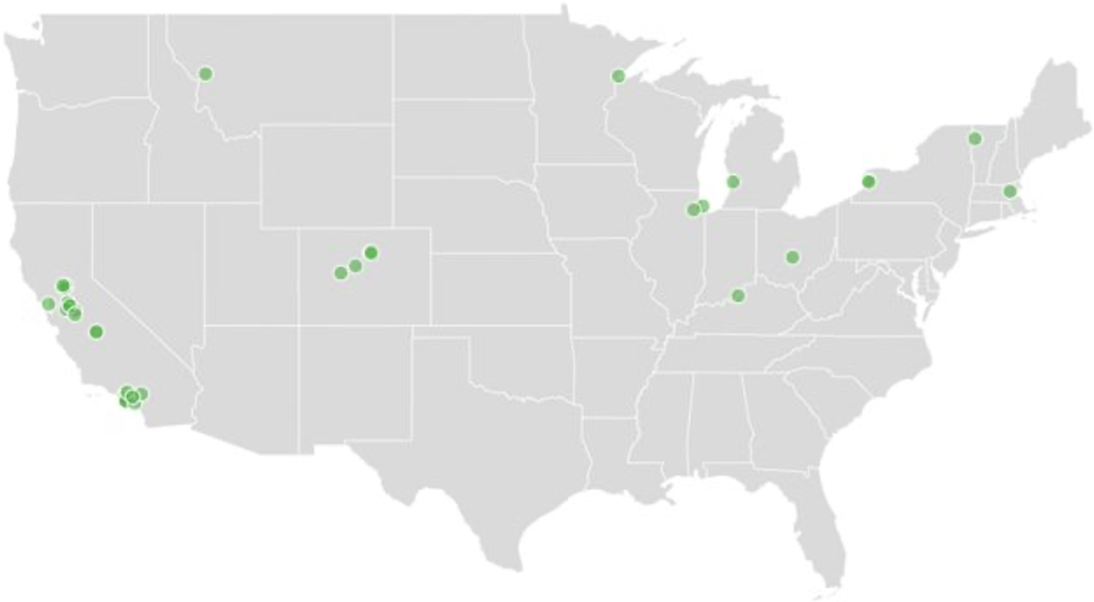
Table 2 summarized the main data sources in this report. Other data sources from past projects or studies, if not listed below, will be cited respectively throughout the report.

Table 2. Summary Table of Real-World ZET Data Sources

VEHICLE SEGMENT	WEIGHT CLASS	COUNT OF VEHICLES	PROJECTS	TIME	MARKET
HD Yard Tractor	US Class 7/8	7	ZETI	2019 - 2024	Global
HD Truck	US Class 8	73	ZETI	2019 - 2024	Global
MD Truck	US Class 3-6	112	ZETI	2019 - 2024	Global
MD Cargo Van	US Class 2b-6	42	ZETI	2019 - 2024	Global
MD Step Van	US Class 2b-6	27	ZETI	2019 - 2024	Global
HD Yard Tractor	US Class 7/8	25	DOE MD/HD EV Data Collection	2020 - 2021	US
HD Truck	US Class 8	19	DOE MD/HD EV Data Collection	2018, 2019, 2021	US
MD Step Van	US Class 2b-6	5	DOE MD/HD EV Data Collection	2019	US

Both battery electric and fuel cell electric are important technologies to meet different use cases of ZETs. However, due to the lack of in-use operations and data collection for fuel cell electric vehicles at this stage, this study focuses on battery electric truck (BET) segments. Ongoing data collection activities funded by the US DOE have confirmed 324 MHD participating vehicles across the US (Figure 9), which will establish the first and largest database capturing performance, charging and maintenance data of ZETs and their facilities. Although the COVID pandemics have slowed down the operational data collection, once more data become available, we expect to substantially extend our database for higher coverage of vehicle segments and better understanding of their real-world performance under various circumstances.

Figure 9. Map of MHD EV Deployments for US DOE Data Collection Project



4.2. TECHNICAL CAPABILITY

Whether MHD ZETs on the market have the capability to meet existing duty cycle requirements is a key consideration when fleets decide to switch from internal combustion engine (ICE) trucks. It is vital that evidence of technical capability rely not only on manufacturer-quoted vehicle configurations, but also capture real-world performance data with various factors such as climate, terrain, driving speed, congestion, and frequency of stops.

Technical capabilities are analyzed along five dimensions: nominal range, battery capacity, payload capacity, duty cycle, and energy efficiency. The models analyzed are battery-electric truck (BET) models. Overall technical capabilities of BETs along each of these dimensions are very promising in the vehicle segments analyzed:

- *Nominal Range* – Most HD electric trucks currently offered in the US and Europe quote nominal ranges between 200 km and 500 km, while Tesla boasts range up to 800 km. For reference, most diesel class 8 semi-trucks have ranges between 1,600 to 3,200 km but are often limited not by driving range but by allowable driving hours, which require drivers to stop after 9-11 hours of continuous driving (950km – 1100km at average driving speeds) (FMCSA, 2015; EU, 2006). Compared to vehicle models in China (where data were available), existing ZET models in the US and Europe can achieve similar nominal range in MD trucks and cargo vans but offer superior nominal range in HD trucks.

- *Battery Capacity* – Battery capacities of medium-duty BETs in the US and Europe were similar and averaged around 150-200 kWh, reflecting their smaller required ranges and urban use. HD trucks in the US and Europe were mostly between 300-400 kWh, but announced models have battery capacities as high as 1000 kWh. BET models in the US and Europe have larger range of battery capacity options than the models in China and a few OEMs offer the more advanced configurations than are available in Chinese market.
- *Payload Capacity* – US BET models in the four vehicle segments studied (HD truck, MD truck, MD step van and MD cargo van) have comparable estimated payload capacity to meet operational requirements of their ICE counterparts through the pilots under real-world duty cycles and driving conditions.
- *Duty Cycle* - When performing regular duty cycles, BE yard tractor, MD truck, MD step van and cargo van have comparable capabilities. The BE models tested in the HD truck segment can well perform the jobs in regional duty cycles that normally require one shift and less than 200 miles (322 km) a day, but challenges are found if there is dynamic (unpredictable) routing, longer routes, longer wait time or when drivers do not return to base each day for recharging.
- *Real-world Energy Efficiency* – US BE yard tractors and HD box trucks have median energy efficiencies at 2.62 kWh/mi and 2.17 kWh/mi, performing less efficient than nominal efficiency most of the time. HD day cab tractors and MD step vans were performing relatively well, with the median efficiencies at 1.95 kWh/mi and 1.12 kWh/mi respectively. In the preliminary regression analysis, worse energy efficiencies were found to be associated with colder ambient temperatures for yard tractors. The impact of temperature was more pronounced in Northeast and Midwest than West Coast in the US, presumably due to the fact that these two regions have greater seasonable variations and lower temperatures in winter.

Ongoing real-world data collection will further strengthen the understanding of the technical capabilities of the BET model offerings.

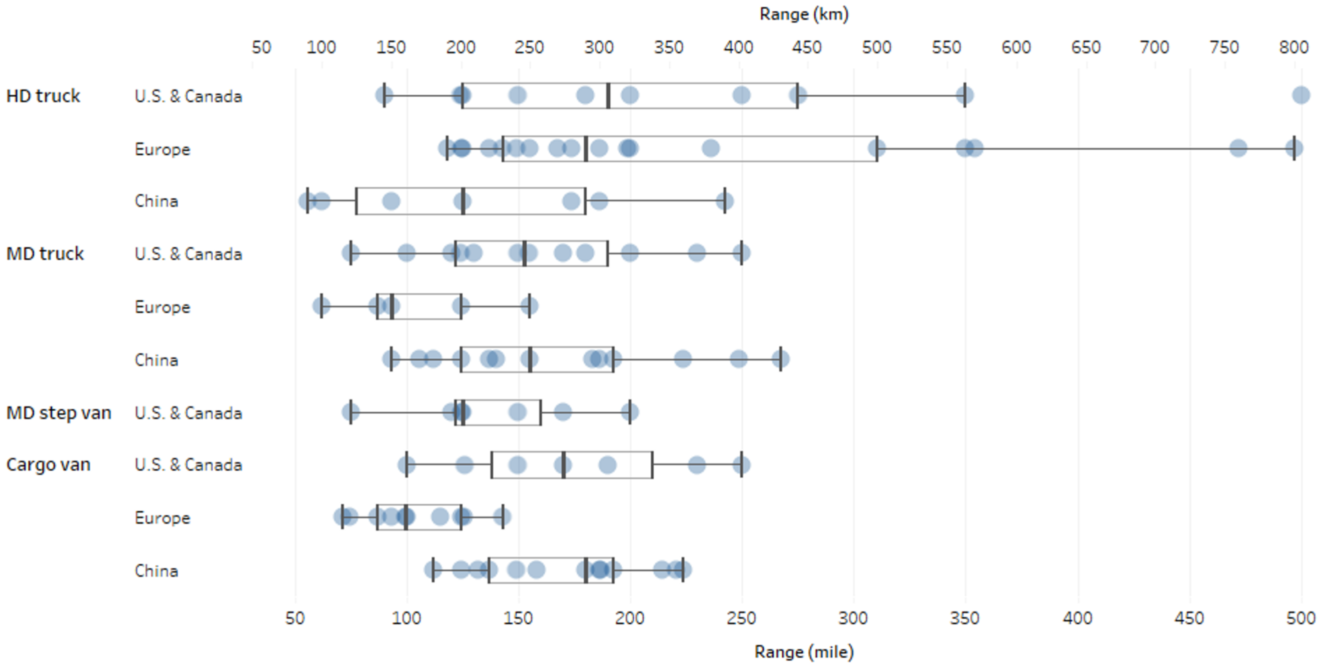
4.2.1. NOMINAL RANGE

The nominal ranges analyzed in this section are battery range configurations of models collected from manufacturers and other reliable sources. BET models are periodically added and reviewed in the ZETI database, currently including availability through 2024. Figure 10 below displayed truck ranges by vehicle type available by 2022 in the US, Europe, and China. It can be used to examine these models' technical competitiveness in the Chinese BET market. While MD truck ranges are largely similar in the US, Europe and China, HD truck ranges are on average superior in the US and Europe compared to China.

HD trucks in the US have a broader dispersion of battery range, including models capable of traveling on a single charge for 275 miles (443 km) from Volvo, 350 miles (563 km) from Nikola, and 500 miles (805 km) from Tesla. Besides those available in the US market, Futuricum is expected to offer in Europe for range up to 472 miles (760 km) by 2022. However, in the MD truck and cargo van segments, China has similar or slightly better nominal ranges than the US models, and they seem to both outperform models offered in Europe.

In summary, we can safely conclude that the nominal range of MD BET in the US and Europe can achieve similar nominal range as models available in China, while HD BET in the US and Europe have more options with extended nominal range over 310 miles (500 km). When these higher range models become available in the market, fleets can be more confident to replace the ICE trucks for short-haul and long-haul duty cycles.

Figure 10. Truck Range by Vehicle Type in the US & Canada, Europe, and China (2019-2022)



Notes on how to read a boxplot: The vertical ticks in the boxplot, from left to right, represent the minimum, 25% quartile, median, 75% quartile and maximum value of truck range. Each truck model is shown as a blue dot in the chart, where the opacity of dots is used to indicate the overlap of multiple models at certain level of truck range. The dots beyond the maximum or minimum tick are identified as outliers using the 1.5 interquartile (IQR) method.*

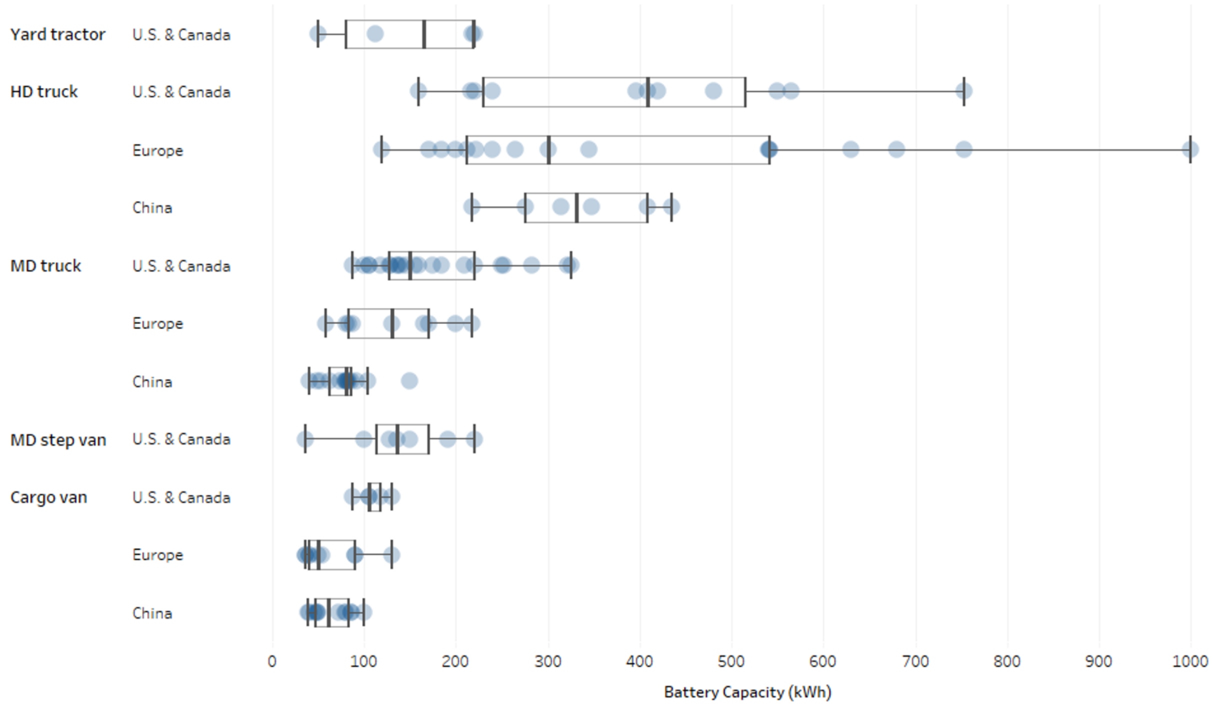
4.2.2. BATTERY CAPACITY

Battery capacity is a key configuration of energy reserved, measured in kWh, when examining technical capabilities of BETs. The energy reserved in the battery pack directly affects truck range especially when charging opportunities are rare in longer-distance operations. Larger size of batteries can extend battery range but can possibly increase the curb weight and limit the payload capacity if GVWR remains constant. This requires improvement of battery technologies to increase energy density over time.

In Figure 11, we compared BET battery capacities across the US, Europe, and China. For yard tractors, the models available have a lower range of battery capacity than other vehicle segments, between 50 and 220 kWh, but since these off-road tractors are operating within or between facilities, they can easily take advantage of charging opportunities during shift turnovers. For HD trucks, the US and European models have a widespread distribution of battery capacity compared to models in China where data are available. OEMs have announced a number of outstandingly high battery capacity in the US and Europe, including Tesla (1000 kWh), Nikola (753 kWh), and Futuricum (680 kWh). Looking at the MD truck segment, the US and Europe both offer more varieties and overall higher volumes in battery capacities. Freightliner, International, Peterbilt and Kenworth are the leaders with battery size in the range of 282 kWh to 325 kWh. For cargo van, battery capacities available in the US are generally higher than the battery capacities in China where there are two clusters of models around 45 kWh and 80 kWh. Europe also has several models offering 45 kWh battery capacity, but also have higher configuration up to 130 kWh.

To conclude, the cross-region comparison of the same vehicle types indicates that the models offered in the US and Europe have more varieties of battery capacity, with some OEMs offering the most advanced configurations in HD truck and MD truck segments that do not seem available in China based on current ZETI data.

Figure 11. Truck Battery Capacity by Vehicle Type in the US & Canada, Europe and China (2019-2022)



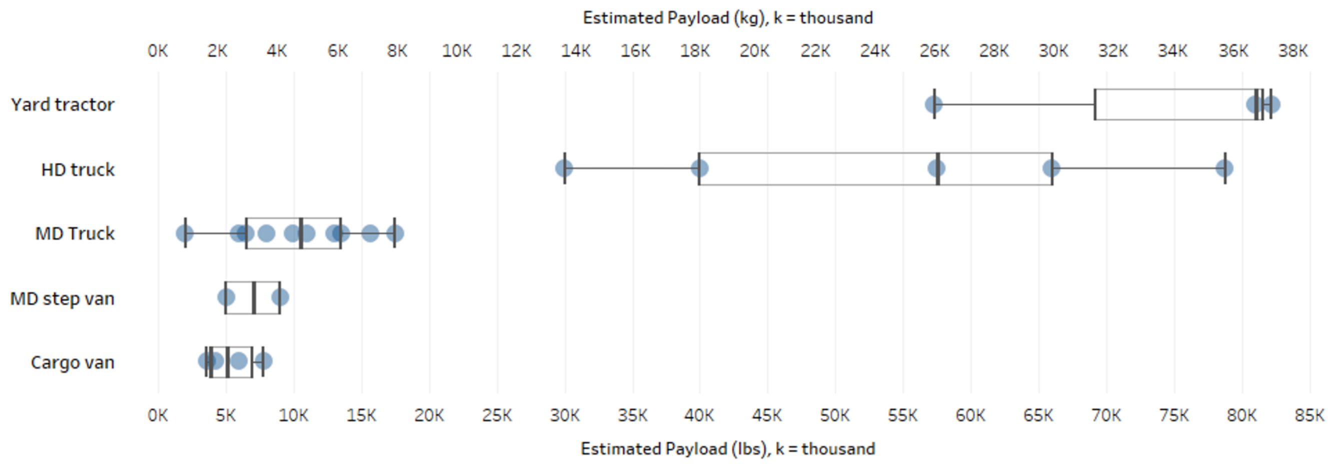
Notes on how to read a boxplot: The vertical ticks in the boxplot, from left to right, represent the minimum, 25% quartile, median, 75% quartile and maximum value of battery capacity. Each truck model is shown as a blue dot in the chart, where the opacity of dots is used to indicate the overlap of multiple models at certain level of battery capacity. The dots beyond the maximum or minimum tick are identified as outliers using the 1.5 interquartile (IQR) method.*

4.2.3. PAYLOAD CAPACITY

Payload capacity is an important parameter since it directly impacts total cost of ownership (TCO). In Figure 12, we present the truck payload of BETs in the US.[9] Since MD/HD ZEVs market is still nascent and technologies are evolving quickly, we understand the estimated payload capacities in the ZETI database are not necessarily most up to date or comprehensive. However, the boxplot can provide a sense of estimated payload that are already offered in the US BET market.

As for operational requirements of benchmark ICE trucks in the US, the estimated payload is about 40,000 lbs (18,144 kg) for HD truck, up to 15,000 lbs (6,804 kg) for MD truck, 10,080 lbs (4,572 kg) for MD step vans and 4,200 lbs (1,905 kg) for MD cargo vans (NACFE, 2022a). The majority of BET models in the ZETI database showed sufficient payload capacity to meet the requirements of their ICE counterparts in these four segments. In other words, from the payload perspective, the segments of HD truck, MD truck, MD step van and cargo van appear to be electrifiable. However, we should be aware that some of the high-end models, although announced by the OEMs, are not necessarily production-ready in the coming year or two due to the complicated dynamics of supply chain nowadays.

Figure 12. Truck Estimated Payload in the US (2019-2022)



---

[9] While most countries use metric system for their units of measure (e.g. kg, m, km), the US use imperial system (e.g. pounds/lbs, feet, inches). We use the conversion of 1kg = 2.2046 lbs to make the payloads in metric system comparable to the payloads reported in the US market.

Notes on how to read a boxplot: The vertical ticks in the boxplot, from left to right, represent the minimum, 25% quartile, median, 75% quartile and maximum value of truck estimated payload (lbs). Each truck model is shown as a blue dot in the chart, where the opacity of dots is used to indicate the overlap of multiple models at certain level of payload. The dots beyond the maximum or minimum tick are identified as outliers using the 1.5 interquartile (IQR) method.*

4.2.4. DUTY CYCLE

Duty cycle analysis is mainly based on DOE MD/HD EV database, collecting performance data from real-world deployments and demonstrations of BETs across the US. We also summarized findings from projects including Volvo LIGHTS (2022), NACFE Run-on-Less Electric (2022b), USPS Zero-Emission Delivery Truck Pilot (2020) and NREL MD Plug-in Electric Delivery Trucks (2014, 2016). We find that when performing regular duty cycles, battery electric trucks (BETs) have comparable capabilities in the segments of HD yard tractor, MD truck, MD step van and MD cargo van. The BET models tested in the HD truck segment can well perform the jobs in duty cycles that normally require one shift and less than 200 miles (322 km) a day, but challenges are found if there is dynamic (unpredictable) routing, longer routes, longer wait time or when drivers do not return to base each day for recharging.

The DOE MD/HD EV database incorporated real-world vehicle performance data of 19 HD trucks (14 Class 8 tractors and 5 Class 7 box trucks) and 5 MD step vans from over 10 fleets operating in Southern California. There are also 25 Yard Tractors operating in multiple states (California, Illinois, Ohio and New York) that can provide lessons learned about off-road HD BETs. Table 3 shows the duty cycle of the MHD BETs in the DOE database. Since there are some extreme high values in the dataset that could potentially skew our analysis, we use median rather than mean to represent the central tendency of the distributions. The daily run time is considered as key-on time, which includes idle time. The average driving speed is computed as daily distance divided by daily driving time (not including idle time) for every vehicle-day, also represented by median in the table. The HD day cab tractors and HD box trucks in the database are in the regional or drayage duty cycle, which means the trucks drive up to 150 - 200 miles a day and return to base each day.

Table 3. Duty Cycle of HD/MD BETs in DOE database

VEHICLE SEGMENT	VEHICLE TYPE	MEDIAN DAILY DISTANCE (MI)	MEDIAN DAILY KEY-ON TIME (HR)	MEDIAN DAILY AVERAGE DRIVING SPEED (MPH)	DUTY CYCLE AND USE CASE
Yard Tractor	Yard Tractor	32	10	3	Single to multiple shifts, fixed routes
HD Truck	HD Day Cab Tractor	58	4	20	Return to base, port drayage or regional duty cycle, fixed routes
	HD Box Truck	48	4	16	Return to base, regional duty cycle, fixed routes
MD Step Van	MD Step Van	44	14	23	Return to base, urban delivery of mail or packages, variable routes

Yard Tractor: The yard tractors are mostly running about 6 -13 hours for a day and can run up to 21 hours in the data log. Since yard tractors are off-road HD vehicles moving freight between or within facilities, their driving distance and speed are relatively low. Daily driving distance is about 19 – 48 miles and daily average speed is about 2 – 7 mph. For a typical day of an electric yard tractor, it spent about the same time idling and driving (about 4 hours each), and about 2.5 hours charging occurred during shift turnovers.[10] The fleet managers expressed positive feedbacks about the BE yard tractors being tested. Despite initial concerns about how often the equipment would have to charge, operations were not disrupted by the new practice of keeping the vehicle plugged in. The BE yard tractors were quieter, cleaner, and cooler than the diesel counterparts.[11]

HD Day Cab Tractor: The HD day cab tractors are driving mainly 35 - 91 miles a day for 2 – 6 hours; the maximum distance is logged at 200 miles a day and maximum run time is close to 14 hours. The average speed is mainly about 14 - 25 mph and can reach 60 - 70 mph on average in some days. The electric tractor models in the Volvo LIGHTS project, with a battery range of 120 miles, performed well on the regional routes (less than 150 miles), the shorted routes of the fleet. However, they would not be able to operate on short-haul duty cycles (150-250 miles) until deploying the next generation of BET that have a range above 300 miles. These electric tractors must use overnight depot charging, which limited them to one shift per day while ICE tractors can perform two shifts. The tractor model being tested has a small battery range among all available or soon to be available models in the HD truck

---

[10] Statistics from the Volvo LIGHTS Data Collection project.

[11] Feedbacks from the Volvo LIGHTS Data Collection project.

segment when referring to Figure 10, and we noted that they were not necessarily using up the full range when operating on the shortest routes, so the daily run time and distance appeared to be low. In order to apply electric tractors to short-haul and long-haul duty cycles, possible solutions include use faster charging, batteries with higher energy density, and opportunity charging when available.[12]

HD Box Truck: The HD box trucks are driving mainly 35 to 80 miles a day for 3 – 7 hours; the maximum driving distance is logged around 133 miles a day and maximum run time is close to 11 hours. The average speed is around 11 – 25 mph and can reach 60-70 mph. These electric box trucks can use both opportunity charging and overnight depot charging, which help extend their daily range. According to the Volvo LIGHTS project report, there was only once a box truck ran out of energy enroute during the first week of deployment. After Volvo increased the usable battery capacity from 70% to 80% of the full battery capacity, the fleet gained confidence in the electric truck operations.[13]

MD Step Van: The MD step vans are driving mainly 22 – 48 miles a day for 13 – 15 hours; the maximum distance is logged at 88 miles while maximum run time is over 22 hours in a day. The average speed is about 20 – 25 mph and can reach up to 55 mph. According to the USPS Zero-emission Delivery Truck Pilot (CALSTART, 2020), the 5 step vans are powered by an 84.8 kWh battery and can be charged with Level 2 EV charger. The MD step vans have a range up to 75 miles and take about 10.5 hours to fully recharge. The main takeaways from the project are, first, MD truck charging infrastructure can be challenging and expensive to deploy in large scale and requires significant upfront planning, and second, electric parcel delivery trucks can successfully replace ICE counterparts for the required duty cycle.

In January 2022, the Run-on-Less Electric (RoL-E) project also published the results of the demonstration of 13 commercial BETs operating under real-world vocational conditions in eight states in the US (Table 4). The project compared 13 BET models with benchmark diesel models in the same vehicle segments to analyze whether BETs can satisfy the regular real-world duty cycle requirements. The vehicle segments are about the same as the DOE database, including Class 8 yard tractors, Class 8 regional haul tractors, Class 6 MD box trucks and Class 3-5 MD cargo vans and Class 3-5 MD step vans. The report concluded that these tested electric trucking technologies are mature enough to perform the duty cycles and jobs of their diesel counterparts in all vehicle segments, except for HD trucks in long-haul or certain regional-haul duty cycles that are still challenging when there are dynamic (unpredictable) routing, longer routes, more wait time and drivers not returning to base each day(NACFE, 2022a). Whether the longer-haul segment is electrifiable depends, at minimum, on regional charging infrastructure. Besides, current estimates indicate the curb weight of HD BETs are going to be 3,000 – 5,000 lbs (1,361 – 2,268 kg) heavier than ICE tractors, meaning that, unless BETs are allowed heavier GVWR limits due to additional battery weights, fleets carrying heavy loads may have to reduce the payload to ensure they do not exceed the GVWR limit.

---

[12] CALSTART, 2022. Volvo LIGHTS Data Collection Project.

[13] CALSTART, 2022. Volvo LIGHTS Data Collection Project (DRAFT).

Table 4. Duty Cycle of MD/HD BETs in Run-on-Less Electric Project

VEHICLE SEGMENT	VEHICLE TYPE	DAILY DISTANCE OR RUN TIME	DRIVING SPEED	DUTY CYCLE AND USE CASE
Yard Tractor	Yard Tractor	10-22 hours/day	Mostly under 20 mph	Single to multiple shifts, fixed routes
HD Truck	HD Regional Haul Tractor	Less than 300 miles/day	Mostly under 40 mph	Single shift, return to base, regional haul, fix routes
MD Truck	MD Box Truck	Less than 120 miles/day	Mostly under 40 mph	Return to base, local pickup and delivery, variable routes
MD Step Van	MD Step Van	Less than 50 miles/day	Mostly under 40 mph	Return to base, urban delivery or last mile, fixed routes
MD Cargo Van	Cargo Van	Less than 100 miles/day	Mostly under 40 mph	Return to base, urban delivery or last mile, fixed routes

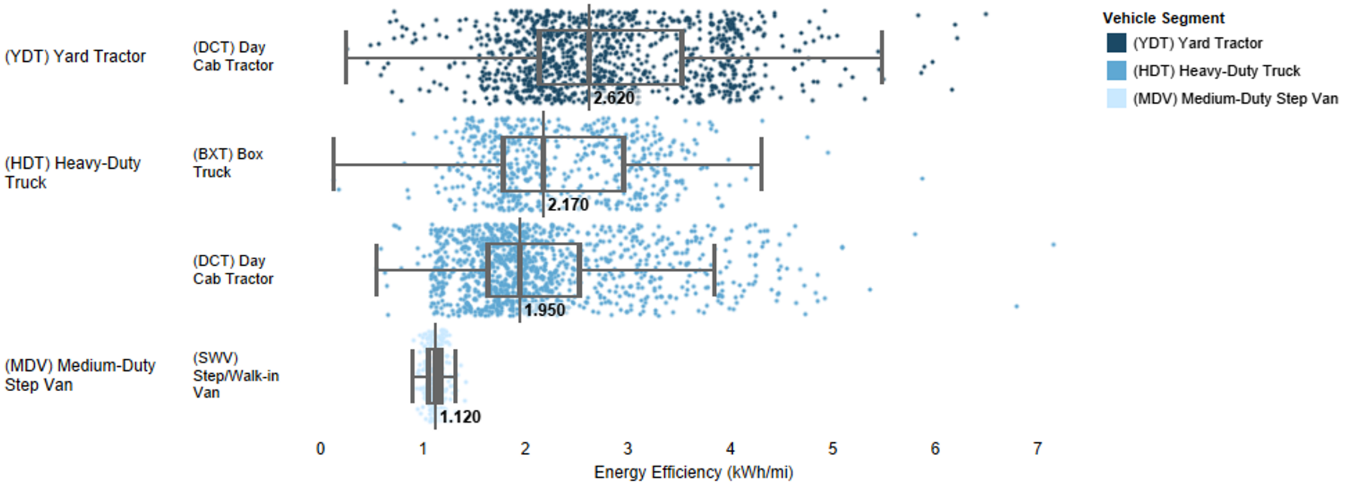
In an earlier pilot study in 2016, a field evaluation of Class 6 MD battery-electric delivery trucks found that 10 electric trucks equipped with 90 kWh batteries could meet the operational requirements serving the greater Tacoma, Washington area, the same as the 9 baseline diesel delivery trucks (NREL, 2016). Truck performance data were logged for 17 days, equivalent to 123 vehicle-days. On average, trucks were driven for 1.5 hours and less than 40 miles per day (8,488 miles annually). They operated at an average speed of 22 mph, equivalent to 35 km/hour. They left the facility around 2-4am and returned between 10am-1pm, having about 44 stops on the route every day. The fleet evaluation shows the success of advanced vehicle technologies highly dependent on the drive cycle characteristics and general operation of the vehicles, such as considerations of peak demand charges, charging infrastructure requirements as well as time required for charging between shifts.

4.2.5. REAL-WORLD ENERGY EFFICIENCY

Energy efficiency analysis is also based on the MD/HD EV data in DOE database. Their duty cycles are described in the previous section and summarized in Table 3. In this section, we compared the real-world energy efficiency with nominal efficiency provided by OEMs by vehicle segments, conducted a visual exploration of the seasonable pattern of energy efficiency and lastly a preliminary regression analysis to understand the correlation between energy efficiency and ambient temperature across three regions. We observed that yard tractors and HD box trucks have the median energy efficiencies at 2.62 kWh/mi (14.5 MPGe) and 2.17 kWh/mi (17.6 MPGe), performing worse than nominal efficiency most of the time, but these electric models are still about twice of efficiency of diesel counterparts (6.5 – 8 MPG). HD day cab tractors and MD step vans have the median efficiency at 1.95 kWh/mi (19.5 MPGe) and 1.12 kWh/mi (34 MPGe) respectively, which are over 3 times of those of the diesel counterparts (6.5 MPG and 9 MPG). In the preliminary regression analysis, worse energy efficiencies were found to be associated with colder ambient temperatures for yard tractors. The impact of temperature was more pronounced in Northeast and Midwest than West Coast in the US, presumably due to the fact that these two regions have greater seasonable variations and lower temperatures in winter.

When assessing real-world energy efficiency of MD/HD EVs, multiple factors can influence performance, including the weight of cargo they haul, driving speed, idling time, climate, terrain, congestion and number of stops. Figure 13 displayed the distributions of energy efficiency of BETs by vehicle segments, and the vehicle segments are further broken down into vehicle body styles (e.g. box truck and day cab tractor under HD truck). Each datapoint in the figure represents a vehicle-day efficiency performance. The median of the distribution is labeled in each boxplot to represent the center of energy efficiency of the specific vehicle category. In the following paragraphs, nominal efficiency of vehicle models provided by manufacturers, also known as OEMs, are used to compare with performance data captured in DOE database. Real-world performance is often different from nominal efficiency given various combinations of operational conditions.

Figure 13. Energy Efficiency of MD/HD BETs in DOE Database



Notes on how to read a boxplot with jitter marks: The vertical ticks in the boxplot, from left to right, represent the minimum, 25% quartile, median, 75% quartile and maximum value of truck energy efficiency (kWh/mi). Each vehicle-day data is shown as a blue dot in the chart. The dots are randomly laid out in the vertical direction when multiple datapoints share the same energy efficiency value. The dots beyond the maximum or minimum tick are identified as outliers using the 1.5 interquartile (IQR) method.*

For HD yard tractors, he nominal efficiency provided by OEMs are about 2.3 – 2.5 kWh/mi, located between the 25% quartile and median of the real-world efficiency performance distribution. Based on the sample of 25 HD yard tractors operating over 1.5 years in four states across the US, **over half of the real-world operations are less efficient than the nominal efficiency.** The median efficiency at 2.62 kWh/mi (14.5 MPGe) is still much more advanced than fossil fueled vehicles, over twice of the efficiency of diesel counterparts (6.5 MPG).

For HD day cab tractors, nominal efficiency is around 2.0-2.2 kWh/mi, located between the median and 75% quartile of the real-world sampling distribution. The median efficiency at 1.95 kWh/mi (19.5 MPGe) is 3 times of that of the diesel counterparts (6.5 MPG). Based on the operations of 14 HD day cab tractors for about 8 months, **over half of the real-world operations are more efficient than the nominal efficiency.** One possible explanation is the current data coverage are not evenly covering a whole year but mostly in warmer seasons (between April to December). **Vehicle efficiency in warmer months is found to be better than in colder seasons according to our data observations.** Another factor to consider is geographic location. All the HD day cab tractors in the database operated in California, where average ambient temperatures are in the higher range compared to most other states. **Due to the myriad of external factors that influence efficiency, these results are not prescriptive to all MD/HD EV platforms.** As mentioned, other duty cycle factors and driving conditions can also affect efficiency performance and they are worth further investigation when more data become available.

For HD box trucks, nominal efficiency is claimed at 1.76 kWh/mi, located slightly lower than the 25% quartile level at 1.79 kWh/mi. Based on the operations of 5 HD box trucks, **over 75% of real-world operations are less efficient than the nominal efficiency.** The median efficiency at 2.17 kWh/mi (17.6 MPGe) is over twice of that of diesel counterparts (8 MPG).

For MD step vans, 5 vehicles, with a battery capacity of 85 kWh, were tested for about 9 months from May 2019 to January 2020. The **real-world energy efficiency was about 1.12 kWh/mi as the median.** Nominal efficiency was not provided for these vehicles, so we were not able to do a comparison like other segments. To add on more energy efficiency data from previous studies, the NREL MD Plug-in Electric Delivery Trucks pilot study (NREL, 2016) showed the fuel economy of Class 6 electric delivery trucks was averaged at 24.09 MPG diesel equivalent[14] (**about 1.58 kWh/mi**[15]), which was 3.15 times improvement of the diesel counterpart at 7.63 MPG (about 5 kWh/mi). Another NREL field study (NREL, 2014) tracked the operation of 259 Class 6 delivery trucks of the same model with the same battery capacity of 80 kWh found similar results. The study lasted about three years, covered 81 operating cities, with 4.4 million kilometers of total distance traveled. Fuel efficiency of these step vans was found to be 24.9 MPG diesel equivalent (**about 1.53 kWh/mi**), which was 3.26 times higher than the diesel fuel consumption in the field study in 2016.

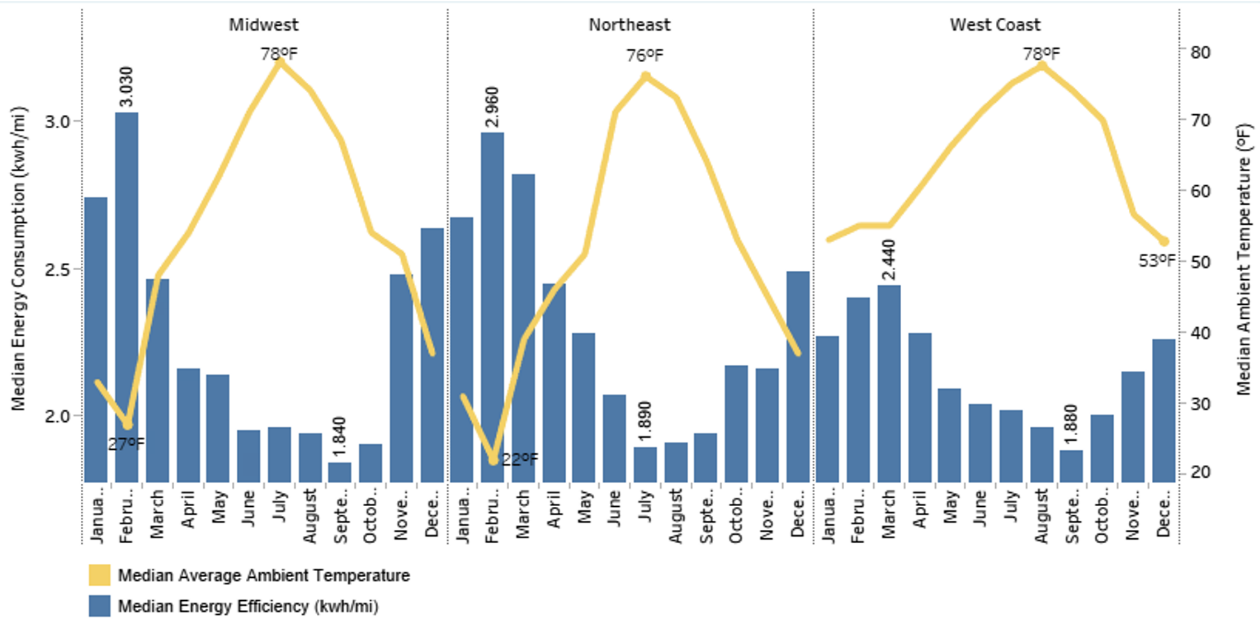
In addition to the findings by vehicle segments, we conducted a **descriptive analysis between energy efficiency and ambient temperature** to observe the seasonal pattern of HD yard tractor data from the DOE database. As an example, yard tractors currently have more comprehensive data coverage across the country over the two years (January 2020 - September 2021). Figure 14 described the seasonal pattern of energy efficiency for yard tractors, consuming more energy per mile in colder months and less in warmer months. Colder months are referred to as months with lower ambient temperatures in winter and early spring, depending on specific locations, which are usually between November and March. This may be due to the extra energy draw from heating system to maintain vehicle operations at lower temperatures.

---

[14] Miles per gallon equivalent assumes 90% charger efficiency.

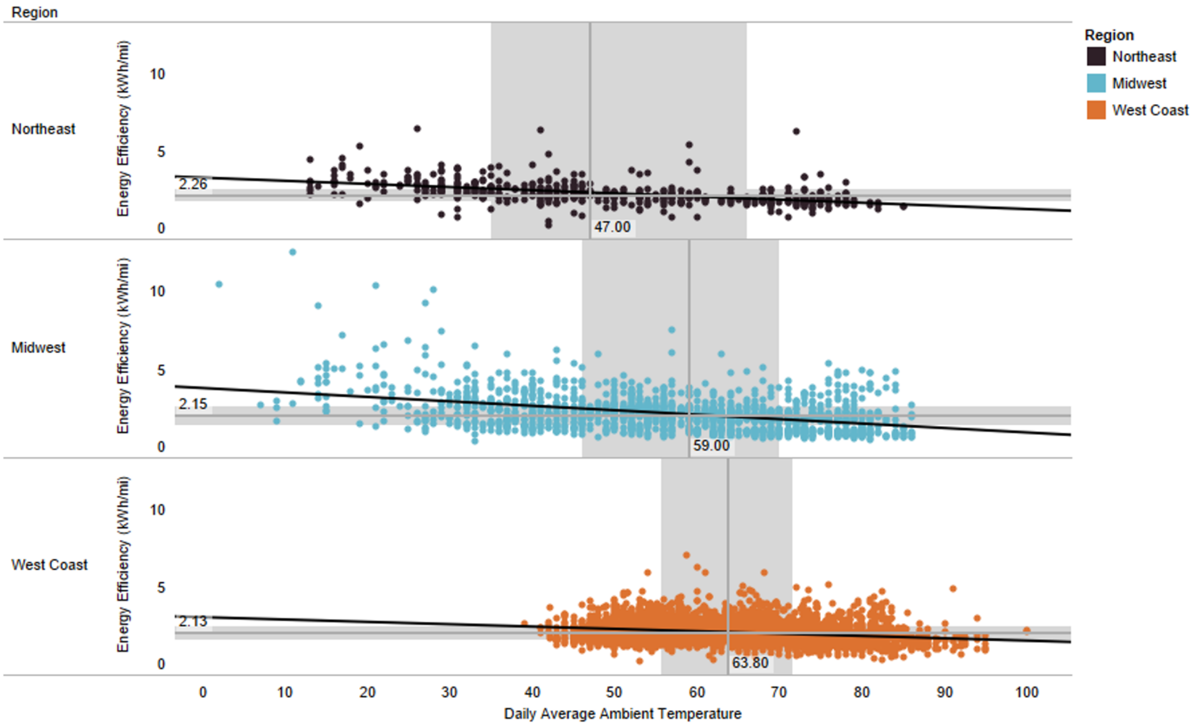
[15] 38.1 kWh of electricity is equivalent to the energy powered by 1 gallon of diesel fuel.

Figure 14. Seasonal Patterns of Yard Tractor Energy Efficiency vs Ambient Temperature in Multiple Regions



A preliminary regression analysis is further conducted to analyze the correlation between energy efficiency and ambient temperature for yard tractors. The coefficient is found to be negative with 95% statistical significance, where in colder climates EVs would be less energy efficient, and such correlation is observed to be more pronounced in geographic regions that have greater seasonal variations. In Northeast and Midwest, ambient temperatures mainly vary between 10 and 85 Fahrenheit degrees, while in West Coast, temperatures are mainly between 40 and 95 Fahrenheit degrees. In Figure 15, the 25% to 75% quartiles of temperatures and energy efficiency are shaded in grey, while medians of temperature and energy efficiency are labeled. According to the ordinary least squares (OLS) regression analysis, **energy efficiency performance is observed to be worse in colder climates compared to warmer climates since the coefficient of ambient temperature is negative. In addition, the coefficients of ambient temperature in Northeast and Midwest are about 30% and 87% larger in magnitude than that of West Coast.** However, this preliminary OLS regression analysis can be improved to accurately measure the impact of temperature by adding control variables such as driving speed, idling time and other variables that are known to affect energy efficiency. It can also be improved by changing the model specification to fit the non-linear correlation between energy efficiency and ambient temperature. As more data become available for other segments, we can further analyze whether and to what extend this seasonal pattern still exists, and what underlying factors can be attributed to for such patterns.

Figure 15. Scatter Plot of Yard Tractors Energy Efficiency vs Ambient Temperatures in Multiple Regions



4.3. ECONOMIC FEASIBILITY

Analysis of economic feasibility was based on literature review on total cost of ownership (TCO). Fixed costs included manufacturer's suggested retail price (MSRP) and residual value after first-user life, which were discounted to current scenario based on discount rates. Variable costs included fuel/energy costs, maintenance costs and charging station infrastructure costs. Other costs included costs of lost payload, driver wages and benefits, insurance, permits, road-use charge and tolls, registration and ownership taxes, and dwell time when trucks were not performing actual work but charging/refueling or loading/unloading equipment during on-duty hours. Three main cost factors were investigated, which were MSRP, fuel costs, and maintenance costs, for all sources by vehicle segment and fuel types to understand their magnitude and variations. The impact of policies and incentives for BET adoption were also briefly discussed (Table 5). Appendix I included costs and results of TCO from literature. Table I-1 listed detailed information on all the costs used in each source. The results of TCO analysis were presented in Table I-2 as cost per mile, projected years to reach cost parity, or breakeven prices between diesel fuel and electricity. Incentives were found to be important in the short-term but would not a must for BETs to be economically competitive with diesel counterparts by 2030.

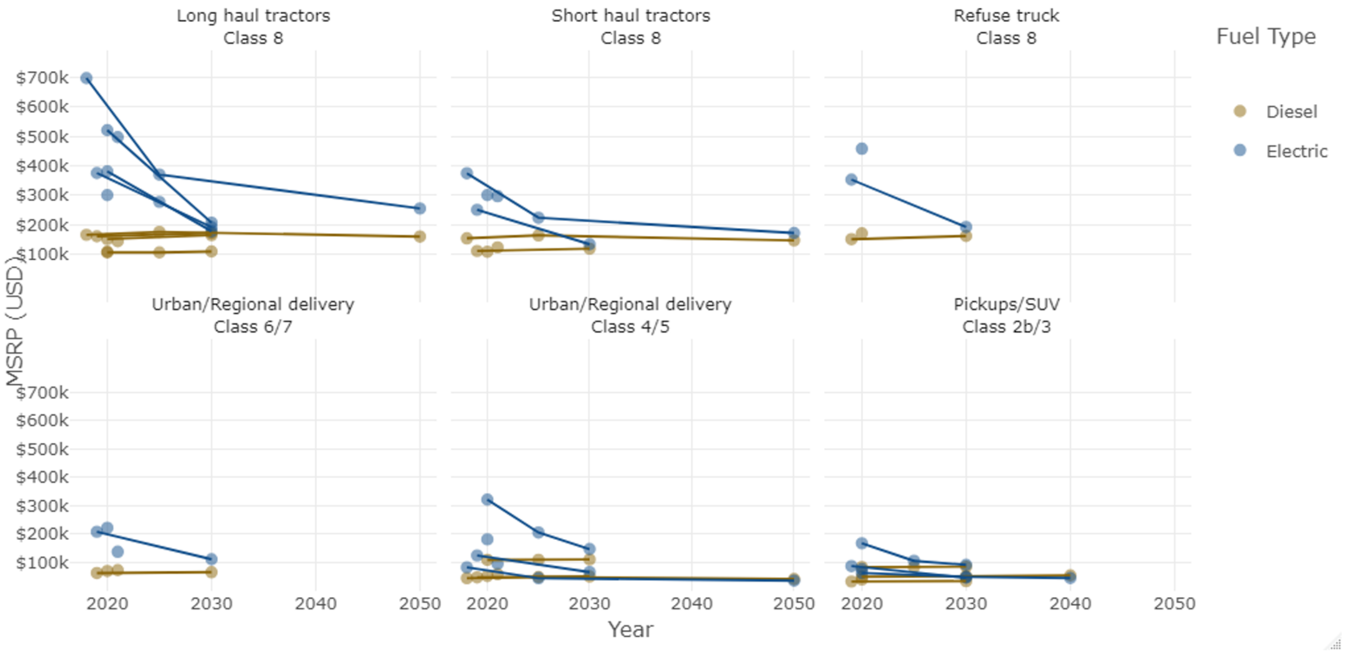
Table 5. Region and analysis usage for each data sources

REFERENCE	REGION	COST PARAMETERS USED IN ANALYSIS BELOW
Basma, Saboori, & Rodríguez 2021	Europe	MSRP, fuel cost, maintenance cost, incentives
ICF, 2019	California, US	MSRP, fuel cost, maintenance cost, incentives
Hunter, et al., 2021	US	MSRP, fuel cost, maintenance cost
HVIP TCO Calculator, 2021	California, US	MSRP, fuel cost, maintenance cost
Mulholland, 2022	US	MSRP, fuel cost, maintenance cost
Vijayagopal & Rousseau, 2021	US	MSRP, fuel cost
Welch, et al., 2020	Global	MSRP, incentives
Prohaska, et al., 2016	Washington, US	Fuel cost

4.3.1. MSRP

Manufacturer's suggested retail price (MSRP) is the original purchase price of a vehicle. Although the MSRP of BETs are more expensive than the equivalent for diesel trucks, especially for HD trucks, the cost differential will reduce over time as battery technology matures and production volumes increase (Welch, et al., 2020). In Figure 16, estimated MSRPs from the same literature in different timestamp were connected in a line (see Figure I-1 for more details). BETs for all segmentations had higher MSRP than diesel or gasoline trucks under current scenarios. HD trucks such as long-haul or short-haul tractors and refuse trucks have greater MSRP disparity than MD trucks and LHDV used for urban or regional delivery. Projected into the future, MSRPs for BETs would significantly decrease over time (Figure 16), which might result from lower battery costs as the technology and market matures. Most literatures agreed that diesel trucks' MSRP would increase in the future due to more stringent regulations and higher taxations, while other research estimated lower MSRPs for baseline trucks in the future (Hunter, et al., 2021). Despite the variation in the direction of changes, future MSRP for diesel trucks would not change significantly from their value of today (Figure 16). A significantly lower BET's MSRP and a relatively constant MSRP for diesel/gasoline truck would lead to a significant decrease in MSRP disparity. However, it might be hard for trucks in all vehicle segmentations to achieve MSRP parity (Vijayagopal & Rousseau, 2021), especially for trucks in classes above Class 4/5. In this way, TCO parity between BETs and diesel/gasoline baseline trucks would depend heavily on differences in fuel and maintenance costs.

Figure 16. Projected current and future MSRP for BETs and diesel baseline trucks in TCO analysis



4.3.2. FUEL COST

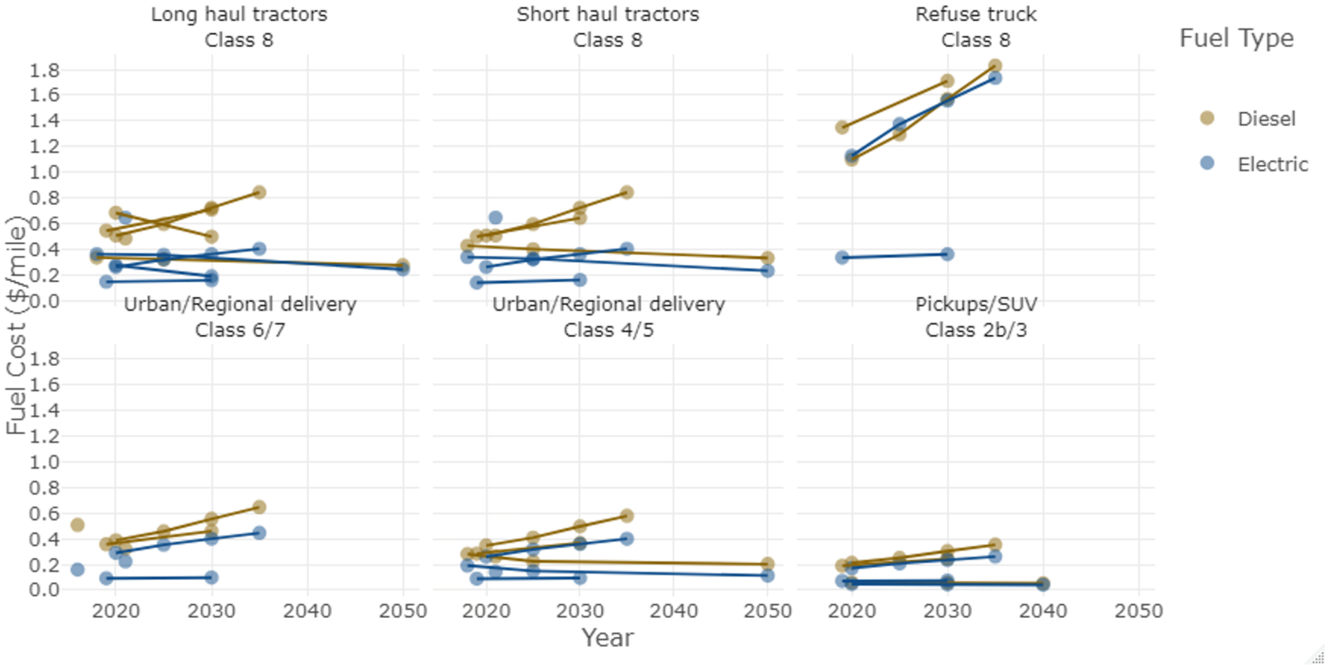
Fuel cost is defined as the cost of fuel consumption per mile driven by a truck, which depends on both future fuel price and fuel efficiency. BETs in general are estimated to have cheaper fuel cost than diesel trucks in both current and future scenarios. Fuel efficiency is the determinant factor influencing fuel cost of a BET.

Fuel efficiency was mainly expected to improve over time (Basma, Saboori, & Rodríguez 2021, Hunter et al. 2021, Mulholland 2022) despite three sources did not give explicit assumptions on how fuel efficiency would change (HVIP TCO Calculator 2021, ICF 2019, Vijayagopal & Rousseau 2021). It was modeled using inputs of use-case specific drive cycles and vehicle specifications (Hunter et al. 2021, ICF 2019, Vijayagopal & Rousseau 2021).

Fuel price was challenging to project into the future. Sources at state-level, specifically ICF (2019) and HVIP TCO Calculator (2021) analyzing truck TCO in California, estimated that both diesel and electricity prices would increase in the future. For analysis in the US or Europe, direction and magnitude of changes were hard to project. Diesel prices were highly uncertain mainly driven by the variations in crude oil (Basma, Saboori, & Rodríguez 2021). Electricity prices were uncertain due to evolving electricity rate structures (Bloch-Rubin, Gallo, & Tomić, 2014) and variation among regions in a country (Hunter, et al., 2021). In this way, sensitivity analysis or scenario modeling was used to analyze a range of fuel prices to account for the uncertainty in reports above.

Fuel cost of BETs would be generally lower than that of diesel trucks for both current and future projections. A real-world field evaluation conducted in Federal Way, Washington, USA concluded a fuel cost of $0.507/mile for Class 6 diesel delivery trucks and $0.159/mile for electric counterparts (Prohaska, et al., 2016). Figure 17 plotted estimated fuel costs from literature and connected data points from the same sources with different timestamp (see Figure I-2 for more details). Where fuel cost was analyzed under different scenario, averages were calculated and illustrated in the plot to give a general trend based on results across different research.

Figure 17. Projected current and future fuel cost ($/mile) for BETs and baseline trucks in TCO analysis



In current scenario, BETs have cheaper fuel costs than diesel counterparts except for Vijayagopal and Rousseau (2021) on Class 8 tractors and HVIP TCO Calculator's data on Class 8 refuse truck. Both sources concluded a relatively higher fuel costs for BETs because their estimated fuel efficiencies were lower than other sources in their vehicle segmentations, which implied that fuel efficiency would have a significant impact on fuel costs. For example, Vijayagopal and Rousseau (2021) used 11.5 miles per diesel gallon equivalence (mile/dge) for Class 8 electric long haul tractors while other reports used fuel efficiency from 14.9 to 29.5 mile/dge, implying electric ones could have better fuel efficiency than Vijayagopal and Rousseau's estimation. For Class 8 electric long haul tractors, ICF (2019) assumed they were four times more efficient in energy consumptions than diesel counterparts while Vijayagopal and Rousseau (2021) assumed electric ones were less than double the fuel efficiency of diesels. Besides, Hunter et al. estimated the upper bound for diesel long haul tractors to be 12.9 mile/dge, which were higher than Vijayagopal and Rousseau's (2021) estimates on electric one.

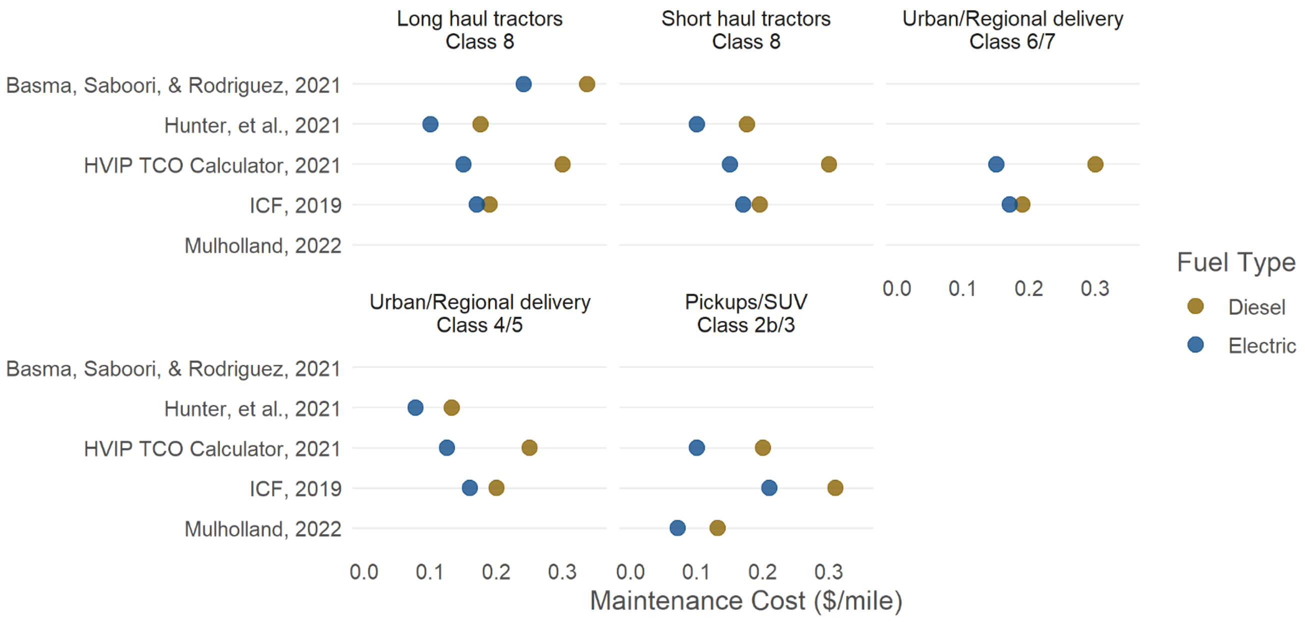
In addition, for trucks with lower fuel economy, the change in fuel prices would more heavily impact their fuel costs. Using refuse truck as an example, data behind HVIP TCO Calculator (2021) estimated the fuel cost of electric refuse trucks would be about the same price as diesel counterparts with fuel efficiency of 8.81 kWh/mile. While fuel efficiency was assumed to be the same through time, fuel costs of refuse trucks increase steeply through time, even just with a slight increase in fuel prices (ICF 2019, HVIP TCO Calculator 2021). In summary, fuel efficiency of BETs would significantly influence their economic feasibility.

4.3.3. MAINTENANCE COST

In this report, maintenance costs include costs on general maintenance and repair. General maintenance can be classified into scheduled and unscheduled maintenance based on whether the service is preventive replacement at regular intervals or based on inspection and diagnostic tests (Burnham, et al., 2021). Examples of general maintenance are oil changes, fluid replacement, aftertreatment system maintenance, and engine maintenance. Because BETs have no needs for oil changes and aftertreatment system maintenance, their maintenance costs were estimated to be lower than those for diesel counterparts by 30%-50% (Basma, Saboori, & Rodríguez 2021, HVIP TCO Calculator 2021, Mulholland 2022). Looking into the future, maintenance cost per mileage travelled was not assumed to decline over time except ICF (2019) which assumed it would reduce by half for BETs in 2030.

While all literatures agree on BETs having lower maintenance costs than diesel trucks, there is disparity among the specific cost estimates (Figure 18). Estimated maintenance costs for electric long-haul Class 8 tractors in Europe (Basma, Saboori, & Rodríguez, 2021) were higher than those in the US. Among estimations in the US, those based on analysis in California (ICF, 2019) were more expensive than the others using averages across the country (Hunter et al., 2021, Mulholland 2022). In addition to data shown in the plot, data of Class 8 refuse trucks were excluded due to high uncertainty because of lack of data. ICF (2019) estimated that refuse trucks had much higher estimated maintenance costs than the rest of vehicle segmentations ($2.89/mile for diesel and $2.83/mile for electric), while HVIP TCO Calculator assumed refuse trucks costed the same as other Class 8 trucks ($0.3/mile for diesel and $0.15/mile for electric).

Figure 18. Current maintenance cost ($/mile) for BETs and baseline trucks in TCO analysis



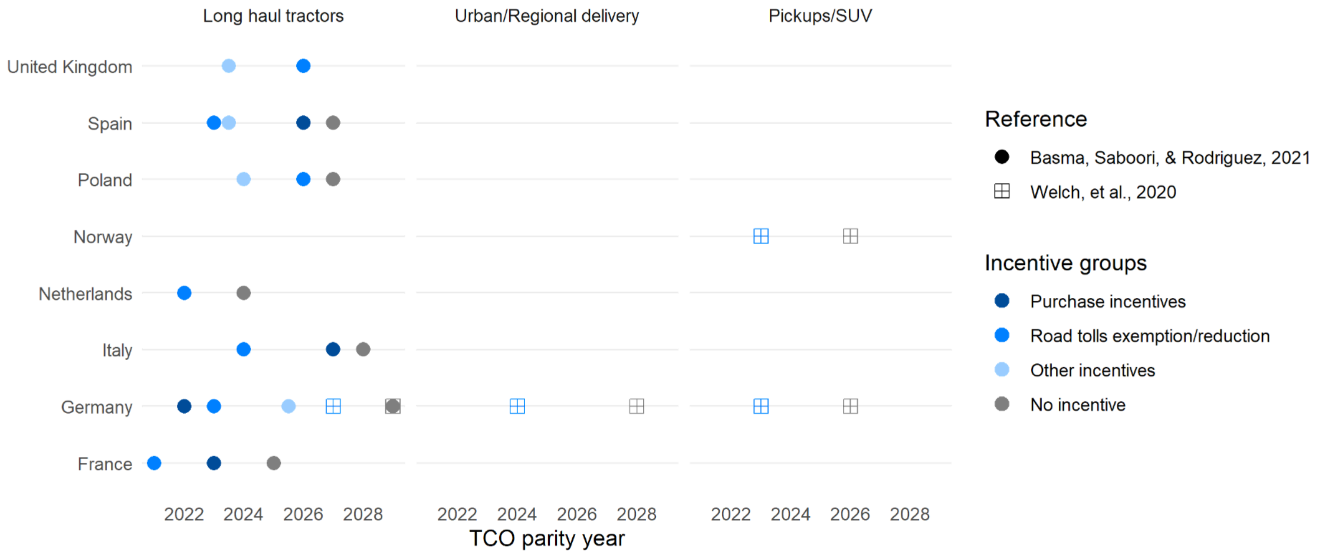
4.3.4. POLICIES AND INCENTIVES

BETs could achieve TCO parity with supportive policies such as incentives and credit programs (see 8.1.3) as of today and be economically viable without economic incentives by 2030, according to analysis in California and Europe (Basma, Saboori, & Rodríguez 2021, ICF 2019). With incremental cost as the main barrier of major adoption, policies that reduce upfront costs and improve residual values of BETs can be extremely effective (Welch, et al., 2020). Contrarily, taxes, levies, and surcharges on electricity production and transmission can create barriers for BETs adoptions by increasing electricity cost and lowering the fuel cost advantage of BETs (Basma, Saboori, & Rodríguez, 2021).

Current lifetime incentives included in TCO analysis by ICF (2019) ranged from $222,000-$250,500 for Class 8 tractors and refuse trucks, $112,000-$131,400 for Class 4-7 urban/regional delivery trucks, and $44,800-$68,800 for Class 2b/3 pickups and SUV. The amount was expected to reduce by 70-80% in 2030 across all vehicle segmentations when all BETs were estimated to be able to achieve TCO parity without incentives (ICF 2019). In addition, case studies on road toll exemptions in Europe found annual exemptions could reach $8,200-$60,000 for BETs in different segmentations and countries (Welch, et al., 2020).

Supportive policies could advance the year of TCO parity between BETs and diesel trucks by up to 8 years (Figure 19). Case studies in Europe showed that exemptions of road tolls and road-use taxes of BETs might advance TCO parity years by 2-4 years for trucks ranging from Class 2b/3 cargo vans to Class 8 long haul tractors (Welch, et al., 2020). In addition, Class 8 electric long-haul tractors in all seven countries modeled in Basma, Saboori, & Rodríguez (2021) could achieve TCO parity by 2030 with the earliest in 2024 without any incentives. If CO2-based user charges were in place in 2021, all seven countries could reach TCO parity in or before 2023. Purchase incentives will significantly advance TCO parity in Germany from 2029 to 2022. Combining the impacts of purchase incentives, Emission Trading Systems for transport, addition of CO2 external costs to road tolls, and road tolls reductions/exemptions to ZETs, all seven countries in Europe could have achieved TCO parity today.

Figure 19. Advancement of TCO parity years from supportive policies



4.3.5. TCO RESULT

For all vehicle segmentations, BETs can achieve TCO parity with diesels between 2020-2030 timeframe as agreed by majority of the literature (Figure 20, Table 6). Operational and maintenance cost of BETs outcompetes that of diesel trucks, but incremental cost is a significant adoption barrier. Besides, BETs with high fuel efficiency require a cheaper smaller-sized battery and lower fuel costs to more feasibly achieve TCO parity with diesel trucks. Use conditions can also increase operational costs of BETs if the trucks are not operating during on-duty time because of charging or loading equipment, which is also known as dwell time cost (Hunter, et al., 2021). Dwell time cost is more challenging to manage for BETs operating multiple shifts where charging cannot be fully done during off-duty hours. Incentives are critical for BETs to be competitive in the near term. By 2030 when retail prices go down with lower battery cost and fuel efficiency improves, BETs can compete with diesel counterparts given their low operational and maintenance costs even without incentives. Table I-2 in Appendix listed TCO, year of reaching TCO parity, and breakeven price with diesels from literature by vehicle segmentation.

Figure 20. Earliest TCO parity years between BETs and diesel trucks

In addition to fixed costs and operational costs discussed above, infrastructure cost was an important cost factor that was not fully discussed. It can be broken down into cost of chargers procurement, installation, and annual maintenance. It will increase the TCO of BETs especially in the initial stage where fleets need to install in depot overnight charging stations. However, data on infrastructure costs were limited and excluded in majority of the literature reviewed. A real-world field study in Washington found the average cost of installing a charging station with 3.8-19.2 kW output power rating was about $22,000, which was dominated by construction fees of trenching, conduit installation, and concrete mounting (Prohaska, et al., 2016). It was estimated that infrastructure costs would decrease over time in the future with lower capital cost and maintenance cost as the market matures (Basma, Saboori, & Rodríguez 2021, ICF 2019).

Table 6. Summary result of BETs reaching TCO parity with diesel trucks

VEHICLE CLASSIFICATION	EARLIEST PURCHASE YEAR WHEN BETS CAN ACHIEVE TCO PARITY WITH DIESEL TRUCKS OVER LIFETIME	REGION	REFERENCE
Long haul tractors			
Class 8	Between 2024-2029 under fixed fuel cost and no incentives scenario; 2021 with all incentives combined	Europe	Basma, Saboori, & Rodríguez, 2021
	Single shift use case: 2018 with $4/gal diesel price and 2025 with any diesel prices. Multi-shifts use case: 2025 with $4/gal diesel prices. (did not consider infrastructure costs or incentives)	US	Hunter, et al., 2021
	2030 without incentives	California, US	ICF, 2019
	when battery costs less than $100/kWh with $3+/gal diesel or $200/kWh with $4+/gal diesel (did not consider infrastructure costs or incentives)	US	Vijayagopal & Rousseau, 2021
	2029 without incentives (did not consider infrastructure costs)	Global	Welch, et al., 2020
Short haul tractors and drayage			
Class 8	Single shift use case: 2018 with any diesel prices. Multi-shifts use case: 2018 with $4/gal diesel price and 2025 with any diesel prices. (did not consider infrastructure costs or incentives)	US	Hunter, et al., 2021
	2030 without incentives	California, US	ICF, 2019
	when battery costs less than $100/kWh with $3+/gal diesel or $150/kWh with $4+/gal diesel (did not consider infrastructure costs or incentives)	US	Vijayagopal & Rousseau, 2021
Refuse truck			
Class 8	2030 without incentives	California, US	ICF, 2019

VEHICLE CLASSIFICATION	EARLIEST PURCHASE YEAR WHEN BETS CAN ACHIEVE TCO PARITY WITH DIESEL TRUCKS OVER LIFETIME	REGION	REFERENCE
Urban/Regional delivery			
Class 8	when battery costs less than $100/kWh with $2.5+/gal diesel or $180/kWh with $4+/gal diesel (did not consider infrastructure costs or incentives)	US	Vijayagopal & Rousseau, 2021
Class 6/7	2030 without incentives	California, US	ICF, 2019
Class 4/5	Single shift use case: 2018 with any diesel prices. Multi-shifts use case: unable to reach TCO parity due to high dwell time cost (did not consider infrastructure costs or incentives)	US	Hunter, et al., 2021
	when battery costs less than $150/kWh with $3+/gal diesel (did not consider infrastructure costs or incentives)	US	Vijayagopal & Rousseau, 2021
	2028 without incentives (did not consider infrastructure costs)	Global	Welch, et al., 2020
	2030 without incentives	California, US	ICF, 2019
Pickups/SUV			
Class 2b/3	2020 for BETs with 100-mile range; 2035 for BETs with ranges up to 400 miles (did not consider infrastructure costs or incentives)	US	Mulholland, 2022
	2026 without incentives (did not consider infrastructure costs)	Global	Welch, et al., 2020
	2020 with incentives; 2030 without incentives	California, US	ICF, 2019

Electric Class 2b/3 pickups and SUVs are most promising to achieve TCO parity and can be the first vehicle segmentation for BET transition. With incentives, BETs in this segment already have cheaper TCO than diesel counterparts in 2020 (ICF 2019). Besides, BETs with different ranges due to differences in battery capacity will reach TCO parity in different years. Those with 100-mile range can already outcompete diesel pickup trucks and vans in current scenario (Mulholland, 2022). BETs with 200-mile and 300-mile range will be competitive by 2030 while those with 400-mile range will be able to outcompete the baselines by 2040 (Mulholland, 2022; ICF, 2019). In addition, BETs in this segmentation will achieve payback period less than 3 years relative to by purchase year of 2030 (Mulholland, 2022).

Class 4 BETs have higher TCO than diesel trucks as of 2018 but will become competitive starting in 2025

(Hunter, et al., 2021, Vijayagopal & Rousseau, 2021). Sensitivity analysis found that single shift Class 4 parcel delivery trucks are significantly promising to reach TCO parity while those used for multi-shifts can't achieve TCO parity regardless of diesel prices and electricity prices (Hunter, et al., 2021). This is because trucks used for multi-shifts are more challenging to manage dwell costs so that will have higher operational costs. Class 5-6 and HD urban/regional delivery trucks face a tougher challenge due to the need for larger battery packs (Vijayagopal & Rousseau, 2021). Larger battery packs are more expensive so that increase incremental costs for BET adoptions. New York State's EV voucher incentive program offers a $60,000 voucher but the incremental cost of an 80-kWh Smith Newton at $86,791 over the cost of a comparable conventional vehicle (Prohaska, et al., 2016).

Class 8 refuse trucks, short- and long-haul tractors could also reach TCO parity around 2030. Their economic feasibility is sensitive to battery cost, diesel cost, and incentives. Class 8 refuse trucks have limited data and studies. Their fuel cost might not be lower than diesel trucks due to low fuel efficiency which weakens BET's advantages in operational cost. There are countries like Netherlands and France where BETs can achieve TCO parity under any combination of electricity and diesel fuel prices variation (Basma, Saboori, & Rodríguez, 2021). However, for the majority, low diesel prices, nonrecoverable levies and surcharges on electricity will delay the year BETs reach TCO parity with diesel counterparts. Therefore, imposing high taxes on diesel fuel prices and implementing fiscal incentives for use of renewable electricity encourage BETs achieving TCO parity.

CHAPTER 5

RECOMMENDATIONS FOR CHINA

China leads the world in zero-emission vehicle (ZEV) deployments, ZEV and battery manufacturing capacity, and ZEV incentives. Despite this leadership, the zero-emission truck (ZET) market in China has not experienced the same success as its zero-emission light-duty passenger vehicle and bus segments.

Slower deployment of ZETs can be attributed to a multitude of challenging technical and economic factors related to MHD truck electrification. MHD trucks travel relatively long distances and demand more power compared to other vehicle segments and therefore require large battery capacities to accomplish their daily routes. With truck battery pack costs ranging from $300-$1,000/kWh and BET battery capacities ranging from 200-500 kWh, these batteries are the largest cost component of the ZET and contribute to a higher incremental capital cost compared to conventionally fueled vehicles (CALSTART, 2021). At current battery energy densities, these large battery capacities also translate to heavier battery weights, reducing the loading capacity of trucks by 10-20% (Liu & Danilovic, 2021). In addition, a sufficient high-powered truck charging network is needed to support ZETs, something that has not yet emerged in China or any other country.

In addition to the technical and economic challenges of ZETs, China has a unique set of truck market conditions that make ZET deployments particularly challenging. Over 71% of heavy-duty truck drivers in China are independent owner-operators and earn low wages, while heavy-duty diesel trucks typically cost between 400,000 and 500,000 RMB and heavy-duty ZETs cost between 800,000 and 1,000,000 RMB (Khanna, 2021; Liu & Danilovic, 2021). This low profit-to-cost ratio means that many truck drivers must rely on low or zero down payment bank loans and have much less robust financing options compared to larger trucking logistics organizations.

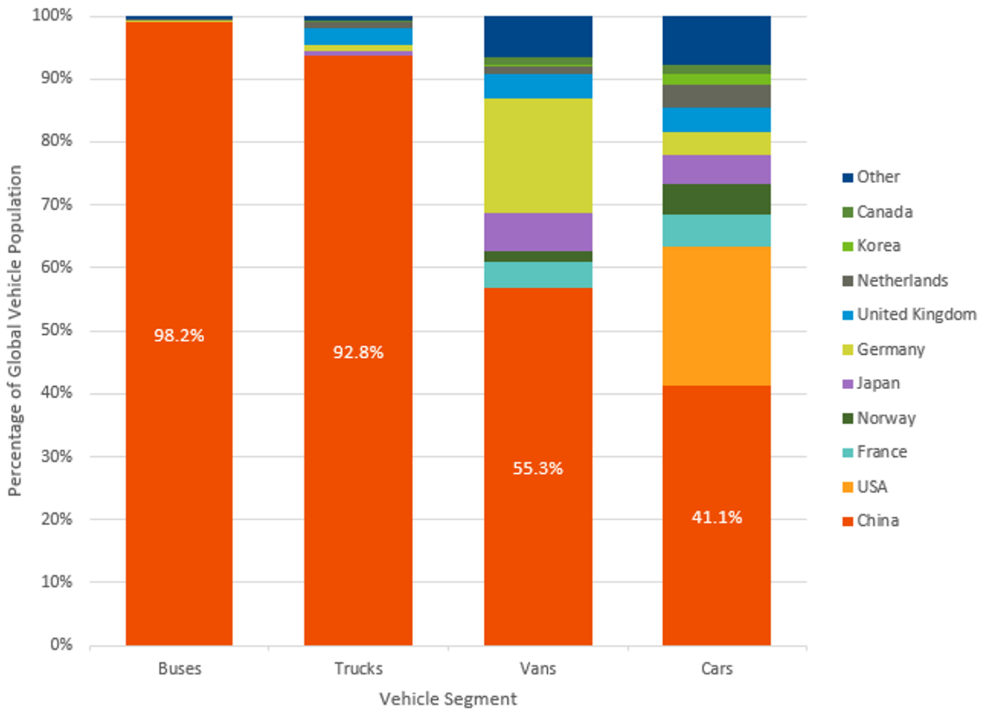
These barriers are not, however, insurmountable. An integrated program of strong national ZET sales/stock targets, regulations, and targeted and timebound ZET incentives can provide systematic guidance for manufacturers and provincial governments to take action to accelerate ZET commercialization and improve the financial feasibility of ZETs until their total costs reach parity with conventional trucks. An example of the success of this strategy has been demonstrated in California, where a combination of targets, regulations, and incentives has spurred rapid growth in the ZET segment, encouraged manufacturer commitments, and influenced similar targets and regulations in other populous American states.

This section provides a non-exhaustive list of recommendations for China to accelerate ZET commercialization based on the results of this report's market research and technical and economic data analysis.

5.1. ANNOUNCE STRONG TARGETS TO MAINTAIN CHINESE LEADERSHIP

There is a major gap between Chinese current ZET market share and future ambitions. China is responsible for 98.2% of global zero-emission bus market share, 92.8% of global zero-emission truck market share, 55.3% of global zero-emission van market share, and 41.1% of global zero-emission light-duty car market share (Figure 21). Despite Chinese dominance in zero-emission vehicles, China currently has no national targets for zero-emission trucks (IEA, 2021). Having national targets for ZETs is especially important in China, because unlike in the US and Europe, where subnational governments set independent policies that are more aggressive than national policies, in China, much decision making on the provincial level is heavily influenced by policies and decisions made at the national level.

Figure 21. Global Car, Van, Bus and Truck Market Share (Source: IEA Global EV Outlook 2021)[16]

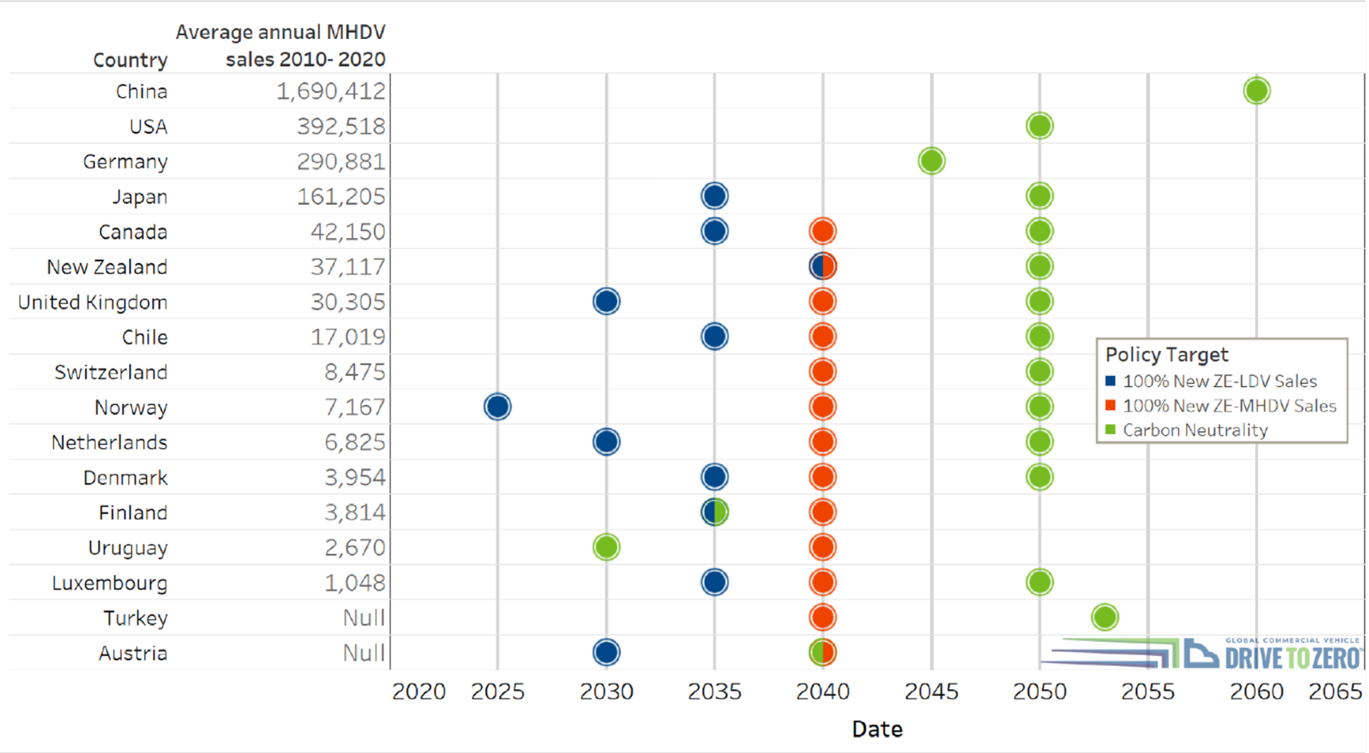


---

16 Vans are defined as vehicles with GVWR less than 3.5 tonnes, trucks have GVWR greater than 3.5 tonnes

The China Society of Automotive Engineers (China-SAE) recently proposed sales targets regarding new energy trucks[17] (NETs) with gross vehicle weights over 3.5 tonnes: 12% by 2025, 17% by 2030 and 20% by 2035 (China SAE, 2021). In contrast, other countries and states around the world, with lower current market shares in ZETs than China, are committing to more aggressive targets. A coalition of national governments[18] led by the Netherlands and CALSTART has set a target to achieve 30% medium- and heavy-duty vehicle (MHDV) sales being zero emissions by 2030 and 100% by 2040 (Figure 22). Similarly, a group of 18 US states states (including Washington DC)[19], cumulatively responsible for roughly 34% of MHD truck sales in the US, have set the same target for 2030 and a target of 100% MHDV sales being zero emissions by 2050.

Figure 22. Global LDV and MHDV Targets (Source: CALSTART)[20]



Targets are a vital component of comprehensive clean transportation policy because they guide the development of ambitious regulations and send clear market signals to local governments, MHD

---

17 New Energy Vehicles are defined in China as partially or fully powered by electricity, such as battery electric vehicles (BEVs), plug-in hybrids (PHEVs), and hydrogen fuel cell vehicles (FCEVs)

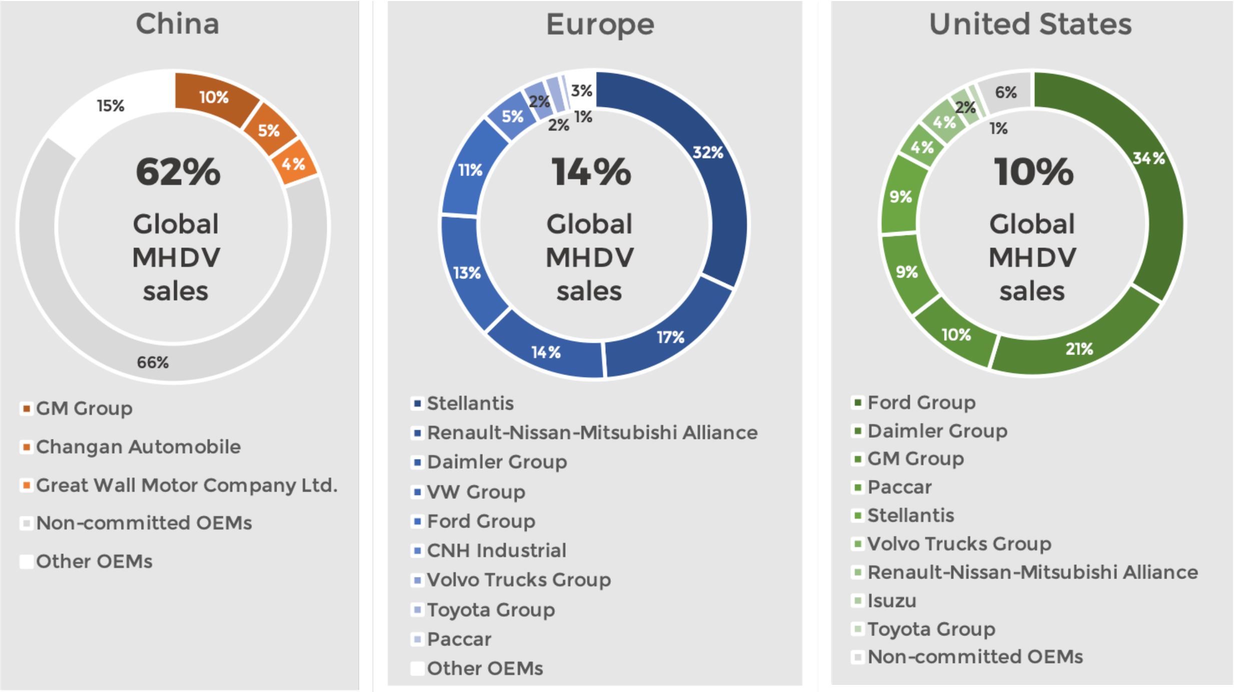
18 Austria, Canada, Chile, Denmark, Finland, Luxembourg, Netherlands, New Zealand, Norway, Scotland, Switzerland, Turkey, United Kingdom, Uruguay, and Wales.

19 California, Colorado, Connecticut, Hawaii, Maine, Maryland, Massachusetts, Nevada, New Jersey, New York, North Carolina, Oregon, Pennsylvania, Rhode Island, Vermont, Virginia, Washington, and Washington D.C.

20 https://globaldrivetozero.org/publication/country-policy-targets-briefing

truck manufacturers and fleets. Without clear targets, domestic manufacturers are less likely to set ambitious targets for themselves or to make early investments in zero-emission technologies. In the US and Europe, where aggressive ZET targets are spreading throughout national and subnational actors, OEMs responsible for 94% and 97% of the MHD market have committed to a complete transition to zero-emission transport respectively, while in China, where targets have yet to be codified, OEMs responsible for only 33% of the MHD market have done so (Figure 23). If China intends to maintain its lead in zero-emission transportation, announcing strong ZET targets at least in line with those announced by other countries and US states is a critical first step.

Figure 23. Regional Market Share of ZEV-Committed OEMs, 2020

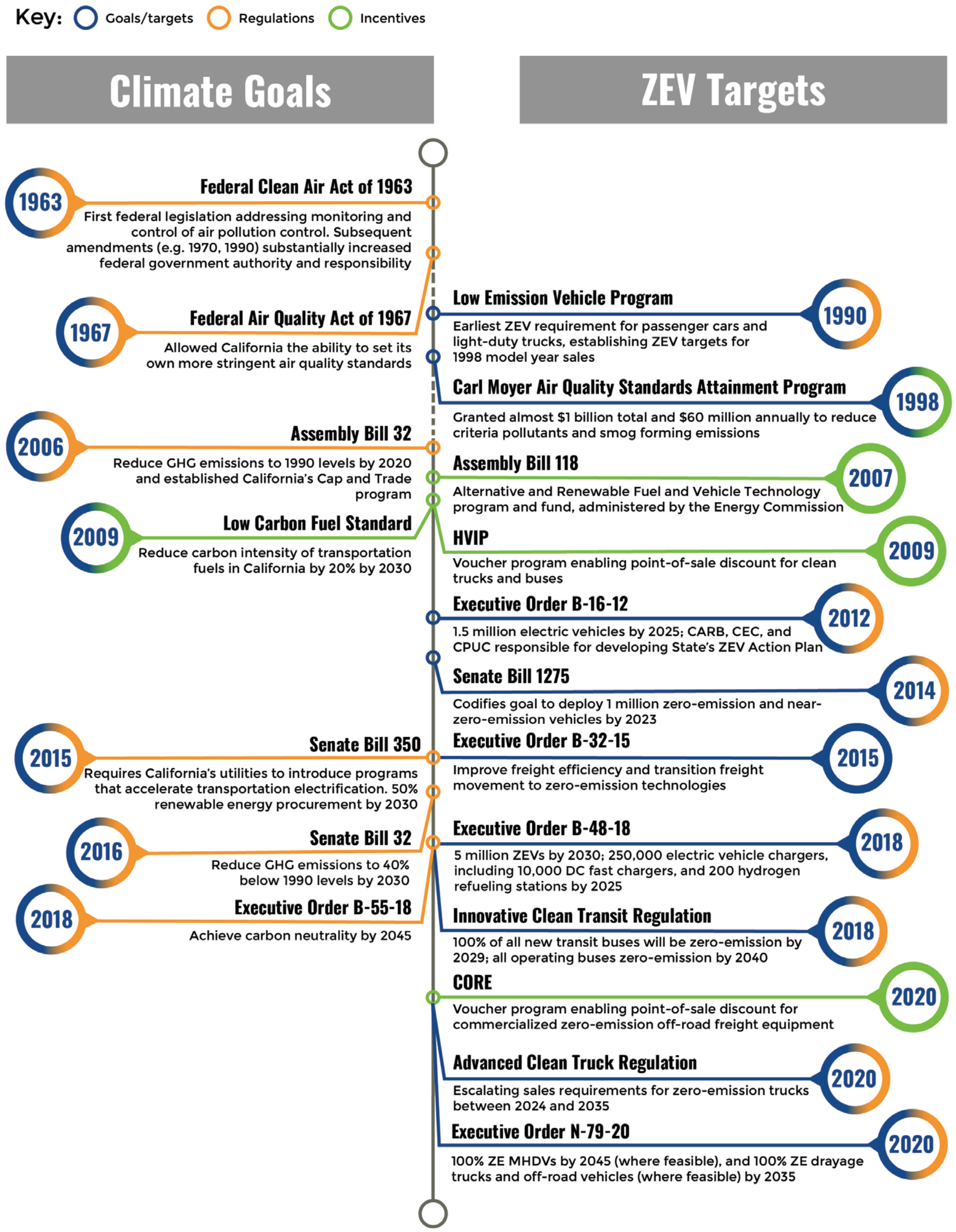


5.2. IMPLEMENT STRONG REGULATIONS TO PROVIDE MARKET CERTAINTY

Regulation is a necessary aspect of coordinated clean transportation policy because it provides market players long-term certainty and encourages investment. To solidify a transition to ZETs, China should back up any ambitious ZET targets with regulatory policy in the form of sales or stock quota from manufacturers and/or adoption requirements for fleets.

This is the approach taken in California, where targets passed by the legislature or through executive order by the Governor are backed up by regulations introduced and approved by the California Air Resources Board (CARB), the primary regulatory body tasked with controlling air pollution and climate change in California. Figure 24 shows the progression of California truck and bus targets and regulations from 1963 to 2020.

Figure 24. California Automobile Targets and Regulations (1963-2020) Source: CALSTART



1963 **Federal Clean Air Act of 1963**
First federal legislation addressing monitoring and control of air pollution control. Subsequent amendments (e.g. 1970, 1990) substantially increased federal government authority and responsibility

1967 **Federal Air Quality Act of 1967**
Allowed California the ability to set its own more stringent air quality standards

1990 **Low Emission Vehicle Program**
Earliest ZEV requirement for passenger cars and light-duty trucks, establishing ZEV targets for 1998 model year sales

1998 **Carl Moyer Air Quality Standards Attainment Program**
Granted almost $1 billion total and $60 million annually to reduce criteria pollutants and smog forming emissions

2006 **Assembly Bill 32**
Reduce GHG emissions to 1990 levels by 2020 and established California's Cap and Trade program

2007 **Assembly Bill 118**
Alternative and Renewable Fuel and Vehicle Technology program and fund, administered by the Energy Commission

2009 **Low Carbon Fuel Standard**
Reduce carbon intensity of transportation fuels in California by 20% by 2030

2009 **HVIP**
Voucher program enabling point-of-sale discount for clean trucks and buses

2012 **Executive Order B-16-12**
1.5 million electric vehicles by 2025; CARB, CEC, and CPUC responsible for developing State's ZEV Action Plan

2014 **Senate Bill 1275**
Codifies goal to deploy 1 million zero-emission and near-zero-emission vehicles by 2023

2015 **Senate Bill 350**
Requires California's utilities to introduce programs that accelerate transportation electrification. 50% renewable energy procurement by 2030

2015 **Executive Order B-32-15**
Improve freight efficiency and transition freight movement to zero-emission technologies

2016 **Senate Bill 32**
Reduce GHG emissions to 40% below 1990 levels by 2030

2018 **Executive Order B-48-18**
5 million ZEVs by 2030; 250,000 electric vehicle chargers, including 10,000 DC fast chargers, and 200 hydrogen refueling stations by 2025

2018 **Executive Order B-55-18**
Achieve carbon neutrality by 2045

2018 **Innovative Clean Transit Regulation**
100% of all new transit buses will be zero-emission by 2029; all operating buses zero-emission by 2040

2020 **CORE**
Voucher program enabling point-of-sale discount for commercialized zero-emission off-road freight equipment

2020 **Advanced Clean Truck Regulation**
Escalating sales requirements for zero-emission trucks between 2024 and 2035

2020 **Executive Order N-79-20**
100% ZE MHDVs by 2045 (where feasible), and 100% ZE drayage trucks and off-road vehicles (where feasible) by 2035

In 2020, California Governor Gavin Newsom signed an executive order which set a target for 100% of passenger vehicle, light-duty truck, drayage truck and off-road vehicle sales to be zero-emission by 2035 and 100% of MHDV sales to be zero-emission by 2045, where applicable. The same year, CARB finalized a regulation (Advanced Clean Truck Rule) which requires ZETs to be increasing percentages of OEM sales starting in 2024 and eventually reaching 40-75% of all MHDT sales by 2035. This regulation is structured as a credit and deficit accounting system, where each year manufacturers generate deficits based on their total on-road HDT sales and can earn credits to offset those deficits through the sale of zero-emission or near zero-emission vehicles. Despite not being in force yet, the regulation is already encouraging investment in ZETs because credits generated from 2021 through 2023 can be “banked” and used to comply with the requirements when they begin in 2024.

CARB is currently developing a counterpart regulation to the Advanced Clean Truck (ACT) rule, called the Advanced Clean Fleet (ACF) rule which will provide demand certainty to OEMs by requiring the purchase of ZETs by California fleets. Rulemaking is expected to be finalized in 2022 with the rule coming into effect in 2023.

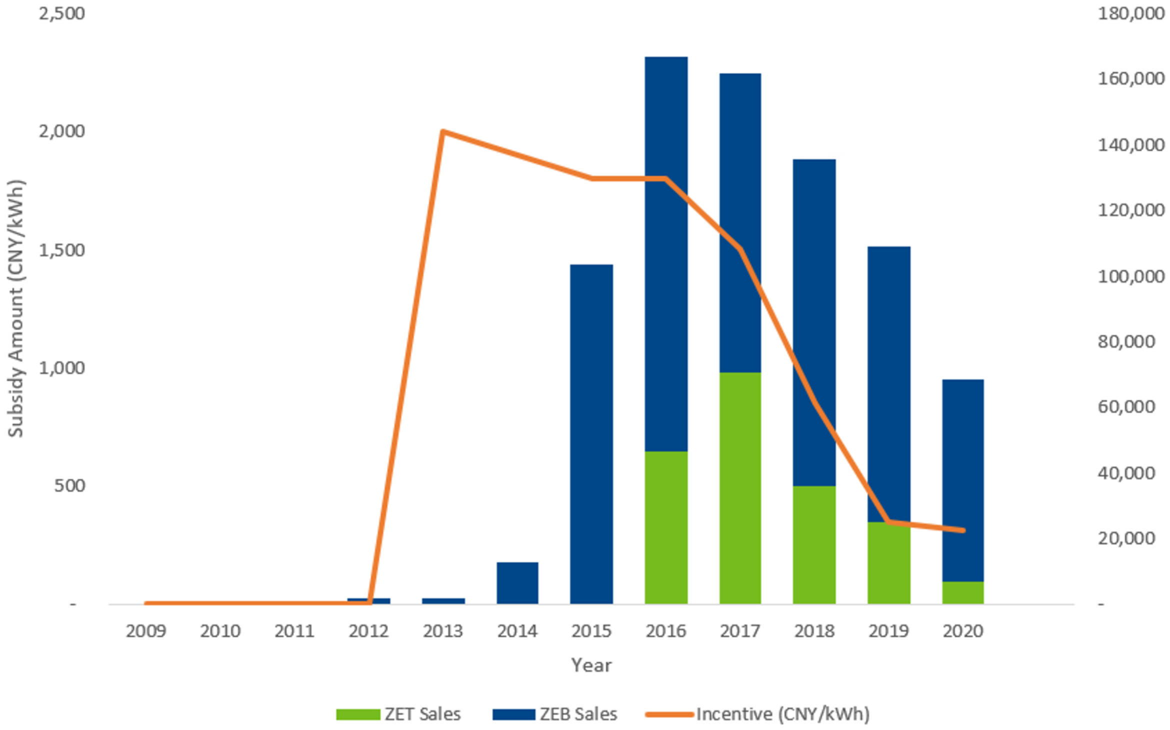
A similar combination of supply- and demand-side regulations in China would build manufacturing capacity for ZETs and provide confidence to OEMs that there will be fleet demand for the ZETs they produce.

5.3. EXTEND TARGETED TIMEBOUND INCENTIVES

As of 2021, no zero-emission truck segment in China has reached total cost of ownership (TCO) parity with diesel vehicles (ICCT, 2021c). Without additional incentives all battery electric truck segments will reach TCO parity with diesel vehicles by the end of the decade, while fuel cell electric vehicles are not projected to reach TCO parity until after 2030.

The effect of this continual TCO gap is that sales of ZETs are still tied to the availability of incentives for ZET purchases. This can be seen in the Chinese market where, as incentives have been phased out, sales of ZETs have diminished drastically. Between 2017 and 2020, battery-electric truck incentives fell by 83%. Over the same time-period battery-electric truck sales fell 92% (Figure 25).

Figure 25. Chinese ZET and ZEB Incentives and Sales (Source: ICCT, 2021c; ICCT, 2021b)



To maintain and accelerate ZET adoption, purchase incentives for ZETs should be extended and increased to fill the TCO gap between ZETs and conventional diesel trucks, and additional operational incentives for ZETs should be designed. Reintroduced incentives should be both *targeted and timebound.*

- *Targeted* – Incentives should direct money to different vehicle segments based on need. Heavier-duty segments with larger TCO gaps should be given proportionally more incentive money to accelerate their timelines. Table 7 shows how California's HVIP program devotes larger amounts of money to different weight class/fuel type combinations based on their cost compared to diesel vehicles. Additionally, incentives should target vehicle applications based on the Beachhead Model of Change. Vehicle applications like buses might need less incentive funding as the market progresses and becomes self-sustaining, whereas the truck market might need proportionally more incentive funding because it is not as far along its path to commercialization. The process of deciding how to allocate funds to different vehicle segments is determined in California by the Air Resources Board and informed by an annual report – The Three-Year Heavy-Duty Investment Strategy (CARB, 2021).
- *Timebound* – Incentives should be set to phase out at a certain date when the market becomes self-sustainable. This will allow market players to transition away from a reliance on public funds and develop an economically viable business model without incentives.

Table 7. California HVIP Funding Amounts by Class and Fuel Type

WEIGHT CLASS	NON-DISADVANTAGED COMMUNITY			DISADVANTAGED COMMUNITY		
	Battery Electric	Fuel Cell Electric	Plug-In Hybrid	Battery Electric	Fuel Cell Electric	Plug-In Hybrid
Class 2b (85,001-10,000 lbs)	TBD	TBD	TBD	TBD	TBD	TBD
Class 3 (10,001-14,000 lbs)	$45,000	$90,000	$22,500	$49,500	$99,000	$24,750
Class 4-5 (14,001-19,500 lbs)	$60,000	$120,000	$30,000	$66,000	$132,000	$33,000
Class 6-7 (19,501-33,000 lbs)	$85,000	$170,000	$42,500	$93,500	$187,000	$46,750
Class 8 (33,000+ lbs)	$120,000	$240,000	$60,000	$132,000	$264,000	$66,000
Class 8 Drayage (33,000+ lbs)	$150,000	$300,000	$75,000	$165,000	$330,000	$82,500[21]

Chinese ZET incentives in the past have also been both targeted and timebound but lacked complementary regulations to provide market certainty and compel manufacturers to invest in production capacity. Moving forward, a comprehensive package of aligned regulations and incentives would provide market certainty for investment, and clarity with respect to when incentives will be phased down.

5.4. CONTINUE INVESTMENT IN BATTERY ELECTRIC TECHNOLOGIES

Fuel-cell electric trucks (FCETs) are a promising long-term option for long-haul and heavy-duty vehicle segments that are more difficult to satisfy with battery-electric technology. However, the total cost of owning a FCET continues to be more expensive than that of diesel counterparts and is not expected to reach total cost parity until after 2030. On the other hand, all BET segments are expected to achieve TCO parity without incentives in 2025-2035 timeframe. Because of the urgency to tackle climate change and the ability to leverage Chinese investment in battery manufacturing, a prudent ZET roadmap would maximize the deployment of battery-electric technologies in every truck segment possible, before turning to more expensive and less technologically mature fuel-cell technologies. A combination of investment in BETs while continuing to invest in the development and early-deployment of FCETs

---

[21] These incentive amounts represent the amount of money provided to manufacturers of the full ZET including the drive-train and chassis. For "upfitter" manufacturers that fit conventional chassis with zero-emission drive trains, these incentive amounts are reduced by 50%.

would enable the fastest and most cost-effective transition to ZETs in China.

FCETs in the US, Europe, and China will continue to be more expensive than their diesel counterparts until after 2030 on a total cost of ownership (TCO) basis, largely due to technological immaturity, a lack of hydrogen filling stations, and the high cost of clean hydrogen solutions across the whole value chain (ICF, 2019; ICCT, 2021c). A 2020 study in the US found that Class 8 fuel cell electric tactors in California would remain 23% more expensive on a TCO basis than diesel vehicles by 2030, while battery-electric tractors would be 48% less expensive than their diesel counterparts the same year. A similar study of Chinese ZETs found that fuel cell tractors would remain ¥500,000 ($78,600 in 2022 dollars) more expensive than diesel tractors on a TCO basis, while BETs are expected to be at TCO parity with diesel vehicles by 2030 in all truck segments (ICCT, 2021c).

Additionally, BETs in pilots and demonstration projects in the US are proving themselves capable of performing in heavier-duty truck applications. Class 2b-8 BETs performing urban, short- and regional-haul delivery applications have been used successfully in pilots and demonstration projects and future pilots seek to increase the scale at which heavy-duty BETs are tested.

As battery and charging technologies continue to improve, the range capabilities of BETs will continue to increase, allowing them to satisfy longer duty-cycles with less charging required. Drive to Zero's Zero-Emission Technology Inventory (ZETI) shows that in the US and Europe by 2023, there will be 56 battery-electric HD truck models available, 25% of which will have ranges over 250 miles (400 km). Many of these HD truck models can recharge 80% of their battery capacity between 1 and 3 hours, allowing them to charge at their depots easily. As megawatt charging systems (MCS) are developed, standardized, and deployed across the US (a timeline that the US Department of Energy expects to take until 2025 in the United States), BETs will be increasingly capable of performing the long-haul truck applications that are now reserved for diesel trucks. An alternative to MCS, pantograph charging, is being piloted in Europe where Siemens and Scania have collaborated on deploying 15 pantograph-equipped heavy-duty BETs on German roadways.

The early success of BETs is seen in the US and Europe, where 99.5% and 99.4% of currently deployed ZETs were BETs, respectively, and consisted of all truck segments from medium-duty cargo vans to heavy-duty class 8 trucks (IEA, 2021). The remaining ZETs were heavy-duty (class 7-8) FCETs built by manufacturers Hyundai, Scania, and Paccar and are deployed in demonstration drayage or regional logistics and distribution operations.[22]

---

[22] Scania has chosen to temporarily shut down its fuel cell truck operations to focus on battery-electric technology, quoting the increasing market readiness of battery technology and the currently poor economics of hydrogen fuel cell technology. More can be found here: https://www.scania.com/group/en/home/newsroom/news/2021/Scanias-commitment-to-battery-electric-vehicles.html

5.5. PRIORITIZE ZERO-EMISSION TAILPIPE TECHNOLOGIES

China should prioritize "zero-emission" tailpipe technologies over "near-zero" or "low-emission" technologies for the MHD truck segment in any future targets, regulations, or incentives. Near-zero and low-emission technologies like natural gas, hybrid-diesel, biofuel and electro-fuel engines still rely on combustion as an energy source and therefore still produce harmful pollutants like nitrogen oxides (NO_x), sulfur dioxide (SO_x), volatile organic compounds (VOCs) and particulate matter (PM) which impact local air quality conditions. In addition, these technologies do not reduce greenhouse gases (GHGs) enough to be consistent with deep decarbonization strategies needed to meet international climate goals (ICCT, 2021c).

While natural gas and hybrid technologies can deliver modest environmental gains in the near-term, they cannot align the transportation sector with the Paris climate targets in the long-term. Similarly, at best some biofuels (those produced from waste sources that do not generate indirect land use change emissions, compete for land and food production, or use large amounts of freshwater resources) can offer modest GHG reductions. At worst, many biofuels emit more GHGs over their lifetime than conventional transportation fuels. The supply of the truly sustainable biofuels is limited and unlikely to be able to meet significant transportation energy demand.

Electro-fuels, drop-in liquid or gaseous fuels that can be used directly in current ICEs and that are made by combining hydrogen (produced from electrolysis) and carbon dioxide, can be a low-carbon solution, but are also very limited supply and carry a large price premium over diesel fuels. Electro-fuels in Europe are expected to be no lower than 3-4 euros per liter by 2030 (130-208% higher than average diesel prices in the European Union from 2010-2018) and are only expected to reach cost parity with fossil fuels by 2050 in a best-case scenario (ICCT, 2021b).

Because many MHD truck sectors can be satisfied by battery electric and fuel cell electric technologies, the truly sustainable biofuels and expensive electro-fuels might be reserved for the harder-to-abate sectors of marine shipping and aviation, where battery technology is not yet compatible with battery weight, energy, and power requirements.

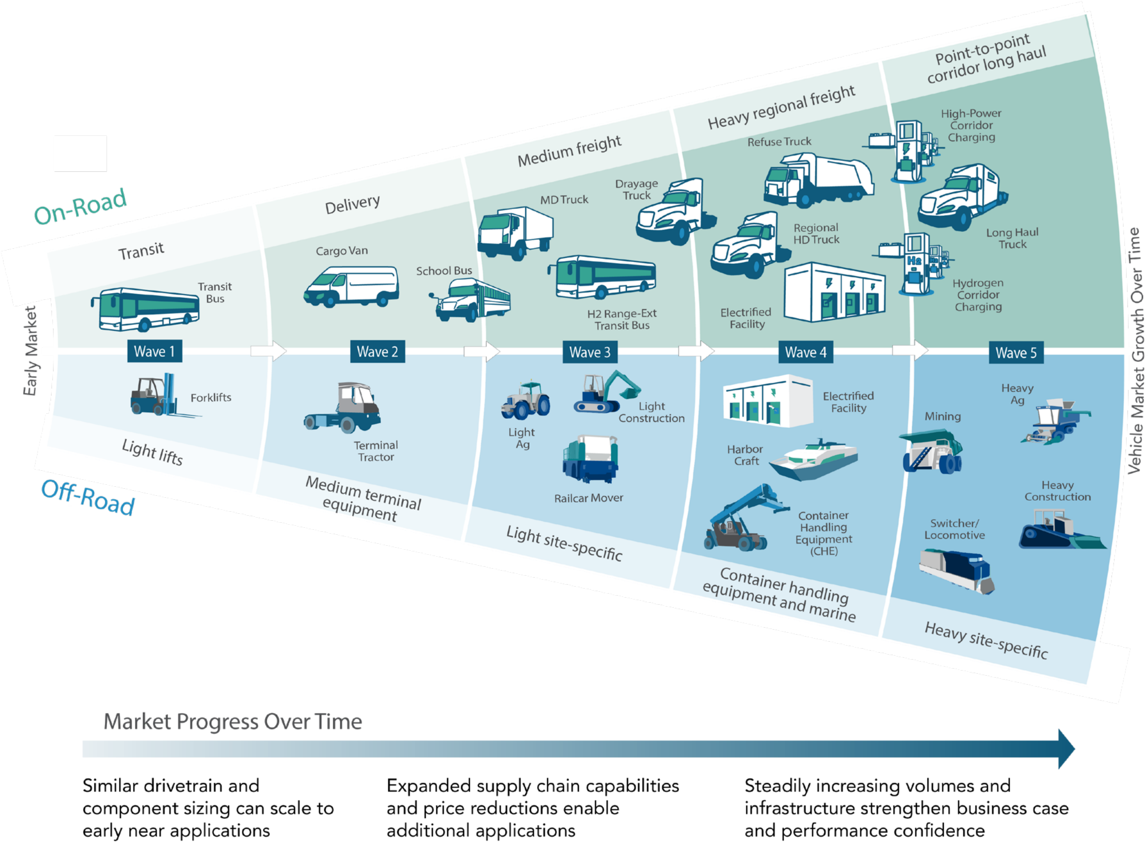
5.6. LEVERAGE ZEB INVESTMENTS TO ACCELERATE ZETS

China is the global leader in Zero-Emission Buses (ZEBs) with 558,336 on the road as of 2020 - over 98% of global zero-emission bus stock (IEA, 2021). In 2021, there were over 30 separate bus manufacturers producing over 150 models of transit and shuttle buses. China can and should leverage this experience in manufacturing and promoting ZEBs to accelerate the commercialization of the zero-emission trucks (ZETs).

As outlined in the internationally recognized "Beachhead Model," ZEBs are a "first-success" zero-emission technology (or "Beachhead") which can expedite the development of harder-to-electrify vehicle segments. ZEBs can attribute their early success to the suitability of electric-drive technology for typical bus operations. Municipal transit buses tend to run along relatively short and established routes where vehicles return to base and can charge overnight. This allows ZEBs to have smaller battery sizes and to charge with relatively cheap electricity, both factors which improve the total cost of ownership of a ZEB relative to its diesel counterpart.

From the technological standpoint[23], buses share common components (batteries, electric motors, power electronics controls, etc.) with other medium- and heavy-duty (MHD) vehicle segments, including trucks, their development and commercialization help pave the way for the development and commercialization of the MHD truck segment. Figure 26 shows the succession of zero-emission transportation technology established by The Beachhead Model. Each successive wave represents a MHD vehicle segment with longer and less predictable routes, making them harder to electrify. The first vehicles to electrify are "wave 1" vehicles, with predictable and short routes which subsequently influence the development of other waves of commercial vehicles through technology and knowledge transference, eventually reaching "wave 5" vehicles like long-haul trucks.

Figure 26. The Beachhead Strategy



---

[23] We understand the business model, government subsidies and stakeholder dynamics for bus electrification in China is very different from the ones for truck electrification, but the lessons learned from the technological standpoint are still transferrable.

The Beachhead Model is especially applicable in China, where transit-buses have already been proven as a first success in the zero-emission market. While Chinese ZEBs were over 55% of all buses in 2019, ZETs lagged at just 0.15% of total trucks in the country during the same year (GIZ, 2020; National Bureau of Statistics of China, 2020). By shifting regulatory and fiscal policy focus to ZETs, China can leverage its investments in buses to create similar growth in the ZET market. This is the same approach taken in California, where regulation of commercial vehicles began with the Innovative Clean Transit (ICT) regulation, which requires 100% of California transit agency buses purchases to be zero-emission by 2029 but has shifted to regulation focused on ZETs with the passage of the Advanced Clean Truck (ACT) rule in 2020 which will require between 45% and 75% of truck sales in the state to be zero-emission by 2035.

BYD, Foton, and Dongfeng Motors are just a few of the Chinese medium- and heavy-duty manufacturers which are already poised to take advantage of this strategy. These companies have gained experience and significant market share in the bus market and have recently begun to sell light- and medium-duty zero-emission trucks and heavy-duty trucks with the swappable battery technologies. With targeted policy, similar investments can be expanded into the heavy-duty truck segment.

CHAPTER 6

OUTLOOK FOR FUTURE RESEARCH

Despite a full discussion on the ZET market, technical and economic feasibility, and recommended strategies, there remains several research and analysis gaps that can be covered in future studies as technology and market mature. Driven by both policies and market preferences, an increasing number of ZET projects are expected to be deployed and generate more and more real-world operational and economic data for further and better understanding on how to achieve a net-zero future. It is especially important to expand data collection to cover more vehicle segments, such as refuse trucks, long-haul trucks, and drayage trucks, when technologies and data become available. The data will continue to help us understand operational performance of BETs in later waves in the Beachhead Strategy and provide valuable insights for applications in China. Additionally, future research should investigate the impacts of infrastructure costs on TCO including costs associated with installation, operation, and maintenance. Where applicable, solar and energy storage systems may also contribute to economic feasibility of ZET in China that needs closer attention when data become available. Finally, ZET have significant environmental and socio-economic benefits in US and Europe that are not conveyed in this report. Future studies can look into how ZET may benefit public health and social resilience in China by reducing emissions, transforming industry, creating new job opportunities, and improving sustainability.

REFERENCES

ACEA. (2021). Truck charging points needed in Europe by 2025 and 2030, per country. Retrieved from https://www.acea.auto/figure/interactive-map-truck-charging-points-needed-in-europe-by-2025-and-2030-per-country

Basma, H., Saboori, A., & Rodríguez, F. (2021). Total Cost of Ownership for Tractor-Trailers in Europe: Battery Electric Versus Diesel. Europe: ICCT.

Bloch-Rubin, T., Gallo, J.-B., & Tomić, J. (2014). Peak Demand Charges and Electric Transit Buses. U.S. Department of Transportation Federal Transportation Agency.

Burnham, A., Gohlke, D., Rush, L., Stephens, T., Zhou, Y., Delucchi, M. A., . . . Boloor, M. (2021). Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains. Chicago: Argonne National Laboratory. Retrieved from https://publications.anl.gov/anlpubs/2021/05/167399.pdf

CALSTART. (2021). Commercial Vehicle Battery Cost Assessment. Retrieved from https://calstart.org/wp-content/uploads/2021/12/Commercial-Vehicle-Battery-Costs-Industry-Report-Final_12.22.21.pdf

CALSTART. (2021). How Zero-Emission Heavy-Duty Trucks Can Be Part of The Climate Solution. Retrieved from https://globaldrivetozero.org/site/wp-content/uploads/2021/05/How-Zero-Emission-Heavy-Duty-Trucks-Can-Be-Part-of-the-Climate-Solution.pdf

CALSTART. (2022). Zeroing in on ZETs.

CARB. (2021). Retrieved from https://calstartcompany.sharepoint.com/sites/D2ZChina-eTruckpilotsandTCO/Shared%20Documents/General/Task%202/3YP

City of Amsterdam. (2021). Retrieved from https://www.amsterdam.nl/en

Daimler Truck. (2022). Retrieved from https://media.daimlertruck.com/marsMediaSite/en/instance/ko/Daimler-Truck-North-America-NextEra-Energy-Resources-and-BlackRock-Renewable-Power-Announce-Plans-To-Accelerate-Public-Charging-Infrastructure-For-Commercial-Vehicles-Across-The-US.xhtml?oid=5187

FMDT. (2021). The future of mobility is electric. Retrieved from https://www.bmvi.de/SharedDocs/EN/Dossier/Electric-Mobility-Sector/electric-mobility-sector.html

GIZ. (2020). New Energy Buses in China. Retrieved from https://www.changing-transport.org/wp-content/uploads/2020_GIZ_New-Energy-Buses-in-China.pdf

Green Car Congress. (2021). Retrieved from https://www.greencarcongress.com/2022/01/20220120-rhetta.html

Hunter, C., Penev, M., Reznicek, E., Lustbader, J., Birky, A., & Zhang, C. (2021). Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks. NREL.

HVIP. (2021). Total Cost of Ownership Estimator. Retrieved from California HVIP: https://californiahvip.org/tco

ICCT. (2019a). Retrieved from https://www.globalfueleconomy.org/media/708302/gfei-working-paper-20.pdf

ICCT. (2019b). Retrieved from https://theicct.org/publication/global-progress-toward-soot-free-diesel-vehicles-in-2019

ICCT. (2021a). A Global Comparison of the Life Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars. Retrieved from https://theicct.org/publication/a-global-comparison-of-the-life-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars

ICCT. (2021b). Race to Zero: How Manufacturers are positioned for zero-emission commercial turcks and buses in China. Retrieved from https://theicct.org/sites/default/files/publications/china-race-to-zero-aug2021.pdf

ICCT. (2021c). Total Cost of Ownership for Heavy Trucks in China: Battery-Electric, Fuel Cell Electric, and Diesel Trucks. Retrieved from https://theicct.org/publication/total-cost-of-ownership-for-heavy-trucks-in-china-battery-electric-fuel-cell-and-diesel-trucks

ICCT. (2021d). Zero-emission integration in heavy-duty vehicle regulations: A global review and lesson for China. Retrieved from https://theicct.org/wp-content/uploads/2021/12/china-hdv-reg-zev-review-sep21.pdf

ICF. (2019). Comparison of Medium and Heavy Duty Technologies in California. Retrieved from https://caletc.aodesignsolutions.com/assets/files/Summary-for-Policymakers_FINAL.pdf

IEA. (2021a). EV Outlook 2021. Retrieved from https://www.iea.org/reports/global-ev-outlook-2021

IEA. (2021b). Global EV Outlook 2020. Retrieved from https://www.iea.org/reports/global-ev-outlook-2020

IEA. (2021c). IEA EV Policy Explorer. Retrieved from https://www.iea.org/articles/global-ev-policy-explorer

ITF. (2019). Retrieved from https://www.oecd-ilibrary.org/transport/itf-transport-outlook-2019_transp_outlook-en-2019-en

Khanna, N. L. (2021). Near and long-term perspectives on strategies to decarbonize China's heavy-duty trucks through 2050.

Liu, J. L., & Danilovic, M. (2021). EXPLORING BATTERY SWAPPING FOR HEAVY TRUCKS IN CHINA 1.0. Retrieved from https://hh.se/download/18.7b11fe917c2ac07303bf9d3/1632994342544/Sweden-China%20Bridge%20-%20Exploring%20Battery%20Swapping%20for%20Heavy%20Trucks%20in%20China%201.0%5B68%5D.pdf

Mulholland, E. (2022). Cost of Electric Commercial Vans and Pickup Trucks in the United States through 2040. ICCT.

National Bureau of Statistics of China. (2020). China Statistical Yearbook 2020. Retrieved from https://www.statista.com/statistics/278424/amount-of-trucks-in-china

OZEV. (2021). Plug-In Vehicle Grant. Retrieved from https://www.gov.uk/plug-in-car-van-grants

Prohaska, R., Simpson, M., Ragatz, A., Kelly, K., Smith, K., & Walkowicz, K. (2016). Field Evaluation of Medium-Duty Plug-in Electric Delivery Trucks. NREL.

Traton. (2021). The TRATON GROUP, Daimler Truck, and Volvo Group sign joint venture agreement for European high-performance charging network. Retrieved from https://traton.com/en/newsroom/press_releases/press-release-16122021.html

Vijayagopal, R., & Rousseau, A. (2021). Electric Truck Economic Feasibility Analysis. World Electric Vehicle Journal.

Welch, D., Façanha, C., Kroon, R., Bruil, D., Jousma, F., & Weken, H. (2020). Moving Zero-Emission Freight toward Commercialization.

Xue, L. (2021). Technology Pathways to Decarbonize China’s Heavy-Duty Trucks. Retrieved from https://thecityfix.com/blog/technology-pathways-to-decarbonize-chinas-heavy-duty-trucks

APPENDIX

TCO COSTS AND RESULTS

Table I-1. Selected costs used in TCO analysis from literature

VEHICLE CLASSIFICATION	FUEL TYPE	MSRP	FUEL COST	MAINTENANCE COST	DISCOUNT RATE	OTHER COSTS	REGION	REFERENCE
Long haul tractors								
Class 8	Diesel	$150,440 (2020) $164,000 (2030	$3.23-$4.83/gal	$0.337/mile	9.5%	Residual value, charging infrastructure costs, registration and ownership taxes, fixed annual road-use charge, distance-based road tolls	Europe	Basma, Saboori, & Rodríguez, 2021
	Electric	$520,300 (2020) $186,630-$226,220 (2030)	$0.11-$0.16/kWh	$0.241/mile				
	Diesel	$165,000 (2018) $175,000 (2025) $159,000 (2050)	$1.5-$4/gal (2018) $1.6-$4.5/gal (2025) $1.8-$4.6/gal (2050)	$0.06-$0.143/mile	3% and 7%	Residual value, lost payload cost, taxation, driver wages and benefits, insurance, permits, tolls, dwell time (time where trucks are on-duty but not in transit moving the products, i.e. refueling/recharging time, loading/unloading equipment time)	US	Hunter, et al., 2021
	Electric	$579,000-$816,000 (2018) $316,000-$423,000 (2025) $228,000-$281,000 (2050	$0.07-$0.4/kWh (2018) $0.07-$0.5/kWh (2025) $0.07-$0.45/kWh (2050)	$0.06-$0.143/mile				

VEHICLE CLASSIFICATION	FUEL TYPE	MSRP	FUEL COST	MAINTENANCE COST	DISCOUNT RATE	OTHER COSTS	REGION	REFERENCE
Class 8	Diesel	$160,000 (2019) $171,000 (2030)	$232,180 (2019) $301,800 (2030)	$69,920	5%	Residual value, fueling/charging infrastructure cost, incentives of BETs	California, US	ICF, 2019
	Electric	$375,000 (2019) $191,153 (2030)	$63,226 (2019) $68,475 (2030)	$63,665 (2019) $31,830 (2030)				
	Diesel	$143,500	$2.5-$4/gal	-	7%	-	US	Vijayagopal & Rousseau, 2021
	Electric	$496,800	$0.1-$0.3/kWh	-				
Short haul tractors								
Class 8	Diesel	$153,000 (2018) $163,000 (2025) $146,000 (2050)	$1.5-$4/gal (2018) $1.6-$4.5/gal (2025) $1.8-$4.6/gal (2050)	$0.075-$0.301/mile	3% and 7%	Residual value, lost payload cost, taxation, driver wages and benefits, insurance, permits, tolls, dwell time (time where trucks are on-duty but not in transit moving the products, i.e. refueling/recharging time, loading/unloading equipment time)	US	Hunter, et al., 2021
	Electric	$374,000 (2018) $223,000 (2025) $171,000 (2050)	$0.07-$0.4/kWh (2018) $0.07-$0.5/kWh (2025) $0.07-$0.45/kWh (2050)	$0.06-$0.143/mile				
	Diesel	$110,000 (2019) $118,000 (2030)	$165,600-$166,500 (2019) $213,350-$214,500 (2030)	$51,817-$54,971 (2018) $49,473-$54,971 (2030)	5%	Residual value, fueling/charging infrastructure cost, incentives of BETs	California, US	ICF, 2019
	Electric	$250,000 (2019) $133,100 (2030)	$43,300-$50,800 (2019) $46,970-$62,100 (2030)	$45,047-$50,052 (2019) $22,523-$25,026 (2030)				

VEHICLE CLASSIFICATION	FUEL TYPE	MSRP	FUEL COST	MAINTENANCE COST	DISCOUNT RATE	OTHER COSTS	REGION	REFERENCE
Class 8	Diesel	$122,300	$2.5-$4/ gal	-	7%	-	US	Vijayagopal & Rousseau, 2021
	Electric	$296,200	$0.1-$0.3/ kWh	-				
Refuse truck								
Class 8	Diesel	$150,000 (2019) $160,970 (2030)	$210,370 (2019) $267,000 (2030)	$332,990	5%	Residual value, fueling/ charging infrastructure cost, incentives of BETs	California, US	ICF, 2019
	Electric	$352,500 (2019) $191,520 (2030)	$52,550 (2019) $56,560 (2030)	$326,080 (2019) $163,040 (2030)				
Urban/Regional delivery								
Class 8	Diesel	$96,800	$2.5-$4/ gal	-	7%	-	US	Vijayagopal & Rousseau, 2021
	Electric	$221,800	$0.1-$0.3/ kWh	-				
Class 6/7	Diesel	$63,000 (2019) $66,000 (2030)	$75,280-$86,840 (2019) $96,977-$111,869 (2030)	$32,982-$38,479 (2019) $32,982-$38,479 (2030)	5%	Residual value, fueling/ charging infrastructure cost, incentives of BETs	California, US	ICF, 2019
	Electric	$167,000-$250,000 (2019) $89,920 - $133,100 (2030)	$19,868-$21,918 (2019) $21,225-$23,202 (2030)	current: $30,031 - $35,036 2030: $15,016 - $17,518				
	Diesel	$73,400	$2.5-$4/ gal	-	7%	-	US	Vijayagopal & Rousseau, 2021
	Electric	$138,000	$0.1-$0.3/ kWh	-				
	Diesel	-	$0.507/ mile	-	-	-	Washington, US	Prohaska, et al., 2016
	Electric	-	$0.159/ mile	-	-	-	Washington, US	Prohaska, et al., 2016

VEHICLE CLASSIFICATION	FUEL TYPE	MSRP	FUEL COST	MAINTENANCE COST	DISCOUNT RATE	OTHER COSTS	REGION	REFERENCE
Class 4/5	Diesel	$48,000 (2019) $51,000 (2030)	$69,630 (2019) $89,700 (2030)	$41,315	5%	Residual value, fueling/ charging infrastructure cost, incentives of BETs	California, US	ICF, 2019
	Electric	$100,000-$150,000 (2019) $53,000-$79,920 (2030)	$21,830 (2019) $23,310 (2030)	$ 32,810 (2019) $16,400 (2030)				
	Diesel	$45,000 (2018) $49,000 (2025) $42,000 (2050)	$1.5-$4/ gal (2018) $1.6-$4.5/ gal (2025) $1.8-$4.6/ gal (2050)	$0.057-$0.233/mile	3% and 7%	Residual value, lost payload cost, taxation, driver wages and benefits, insurance, permits, tolls, dwell time (time where trucks are on-duty but not in transit moving the products, i.e. refueling/ recharging time, loading/ unloading equipment time)	US	Hunter, et al., 2021
	Electric	$83,000 (2018) $45,000 (2025) $36,000 (2050)	$0.07-$0.4/kWh (2018) $0.07-$0.5/kWh (2025)	$0.046-$0.111/mile				
	Diesel	$59,100	$2.5-$4/ gal	-	7%	-	US	Vijayagopal & Rousseau, 2021
	Electric	$95,900	$0.1-$0.3/ kWh	-				

VEHICLE CLASSIFICATION	FUEL TYPE	MSRP	FUEL COST	MAINTENANCE COST	DISCOUNT RATE	OTHER COSTS	REGION	REFERENCE
Pickups/SUV								
Class 2b/3	Diesel	$48,600-$51,300 (2020) $50,000-$53,000 (2030) $53,000-$56,000 (2040)	$12,800-$15,900	$11,700-$12,300	5%	Residual value, fueling/charging infrastructure costs, insurance, other indirect vehicle costs	US	Mulholland, 2022
	Electric	$47,000-$80,000 (2020) $39,000-$60,000 (2030) $38,000-$53,000 (2040)	$3,500-$5,200	$6,100-$6,900	5%			
	Diesel	$27,500-$39,000 (2019) $28,700-$40,700 (2030)	$36,800-$42,300 (2019) $47,400-$54,000 (2030)	$52,500	5%	Residual value, fueling/charging infrastructure cost, incentives of BETs	California, US	ICF, 2019
	Electric	$75,000-$100,000 (2019) $40,000-$53,160 (2030)	$13,880-$15,890 (2019) $14,200-$16,850 (2030)	$36,000 (2019) $18,000 (2030)	5%			

Table I-2. TCO results from literature review by vehicle segmentations and US classifications

VEHICLE CLASSIFICATION	TCO RESULTS	REGION	REFERENCE
Long haul tractors			
Class 8	BET TCO: $600,000-$850,000 (2020); $350,000-$500,000 (2030) Diesel TCO: $400,000-$600,000 (2020); $400,000-$550,000 (2030) BETs reach TCO parity between 2024-2029 under fixed fuel cost and no incentives scenario.	Europe	Basma, Saboori, & Rodríguez, 2021
	BET TCO: $1.55-$2.8/mile (2018); $1.25-$2.1/mile (2025); $1.15-$1.7/mile (2050) Diesel TCO: $1.18-$1.38/mile (2018); $1.17-$1.4/mile (2025); $1.14-$1.39/mile (2050) Single shift breakeven price: $0.6/gge when diesel is $4/gal (2018); $1.4-$4.9/gge (2025); $3-$6.7/gge (2050) Multiple shifts breakeven price: can't break even in 2018; $0.2/gge when diesel is $4/gal (2025); $0.7-$2.6/gge when diesel is $3/gal or higher (2050)	US	Hunter, et al., 2021
	BET TCO: $195,200 (2019); $174,500 (2030) Diesel TCO: $414,600 (2019); $491,800 (2030)	California, US	ICF, 2019
	Class 8 trucks will be cost-effective only if battery pack cost drops under $100/kWh when diesel costs $3/gal or if diesel prices rise to more than $4/gallon and batteries cost less than $200/kWh.	US	Vijayagopal & Rousseau, 2021
Short haul tractors and drayage			
Class 8	BET TCO: $1.16-$1.7/mile (2018); $1-$1.47/mile (2025); $0.91-$1.33/mile (2050) Diesel TCO: $1.03-$1.27/mile (2018); $1.02-$1.29/mile (2025); $0.98-$1.25/mile (2050) Single shift breakeven price: $0.6-$5.1/gge (2018); $3.8-$8.4/gge (2025); $5.1-$9.8/gge (2050). Multiple shifts breakeven price: $2.2/gge when diesel is $4/gal (2018); $0.2-$4.8/gge (2025); $0.5-$5.3/gge (2050)	US	Hunter, et al., 2021
	BET TCO: $122,700-$115,500 (2019); $141,800-$159,100 (2030) Diesel TCO: $298,700 - $302,800 (2019); $349,800 - $356,500 (2030)	California, US	ICF, 2019
	Class 8 trucks will be cost-effective only if battery pack cost drops under $100/kWh when diesel costs $3/gal or if diesel prices rise to more than $4/gallon and batteries cost less than $150/kWh.	US	Vijayagopal & Rousseau, 2021

VEHICLE CLASSIFICATION	TCO RESULTS	REGION	REFERENCE
Refuse truck			
Class 8	BET TCO: $528,600 (2019); $373,800 (2030) Diesel TCO: $696,900 (2019); $764,500 (2030)	California, US	ICF, 2019
Urban/Regional delivery			
Class 8	Class 8 trucks will be cost-effective only if battery pack cost drops under $100/kWh when diesel costs $2.5/gal or if diesel prices rise to more than $4/gallon and batteries cost less than $180/kWh.	US	Vijayagopal & Rousseau, 2021
Class 6/7	BET TCO: $78,200-$170,000 (2019); $77,000-$137,100 (2030) Diesel TCO: $155,300-$172,400 (2019); $179,100-$199,600 (2030)	California, US	ICF, 2019
Class 4/5	BET TCO: $1.1-$1.8/mile (2018); $0.95-$1.6/mile (2025); $0.9-$1.55/mile (2050) Diesel TCO: $1.05-$1.25/mile (2018); $1.03-$1.26/mile (2025); $1-$1.23/mile (2050) Single shift breakeven price: $2.4-$7.9/gge (2018); $7.9-$13.6/gge (2025); $9.3-$15.3/gge (2050). Multiple shifts breakeven price: unable to break even	US	Hunter, et al., 2021
	At diesel cost of $3/gallon, TCO parity for a Class 4 delivery truck can be achieved if the battery pack costs less than $125/kWh when annual mileage is 4,800 miles or $150/kWh when annual mileage is 9,000 miles. At 770 Wh/mile, Class4 delivery truck will save $0.16/mile. At 18,000 miles per year, savings for the operator are $2900/year.	US	Vijayagopal & Rousseau, 2021
	BET TCO: $71,600 (2019); $87,000 (2030) Diesel TCO: $147,200 (2019); $169,400 (2030)	California, US	ICF, 2019
Pickups/SUV			
Class 2b/3	BETs TCO: $69,000-$107,000 Diesel truck TCO: $82,000-$88,000 BETs with 100-400 miles' ranges can achieve TCO parity by 2035. BETs will achieve payback period less than 3 years for diesel trucks by 2030.	US	Mulholland, 2022
	BETs have cheaper TCO in 2020 with incentives. In 2030, without large incentives, BETs will have TCO of $64,000 while that for diesel counterparts will be $130,000.	California, US	ICF, 2019

Figure I-1. Projected current and future MSRP ($) for BETs and baseline trucks with sources

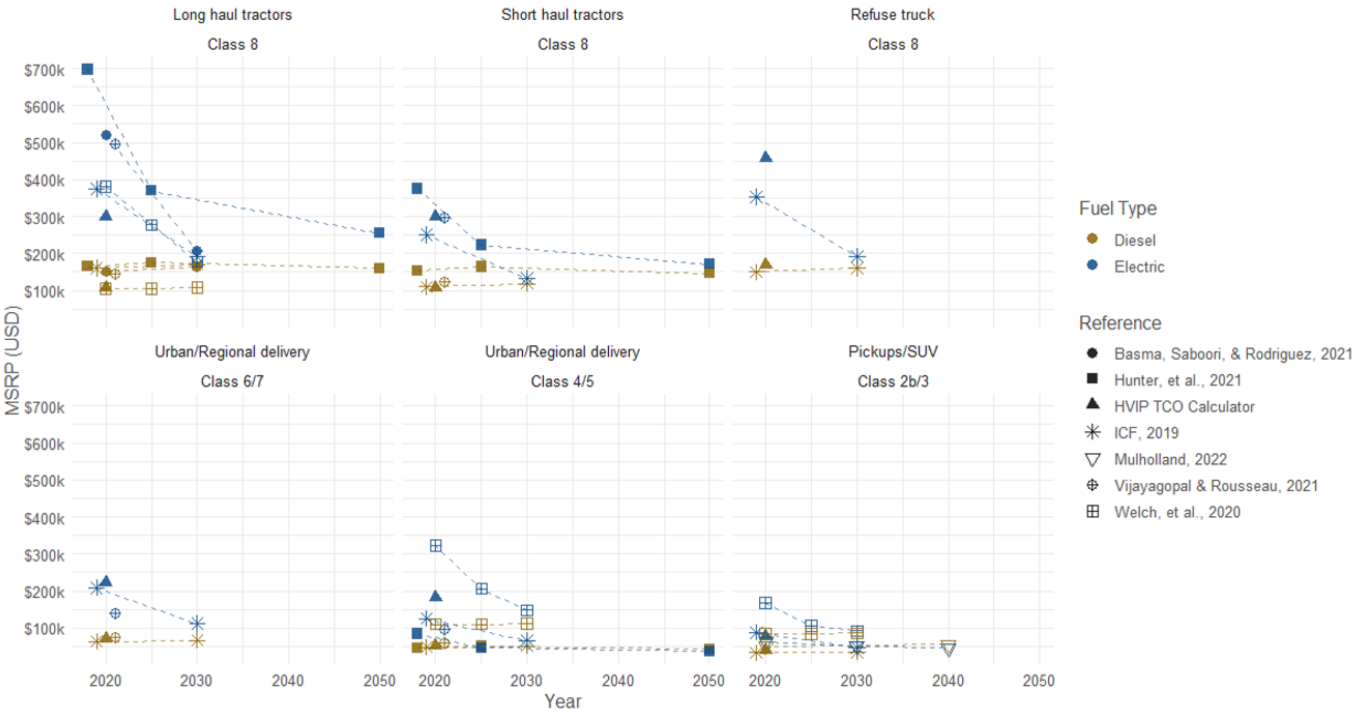


Figure I-2. Projected current and future fuel cost ($/mile) for BETs and baseline trucks with sources