WHITE PAPER

TECHNOLOGY AND COMMERCIALIZATION PATHWAYS FOR ZERO-EMISSION MEDIUM- AND HEAVY-DUTY VEHICLES IN CHINA

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LIST OF ACRONYMS

ACT	Advanced Clean Truck (regulation)
CARB	California Air Resources Board
COP 26	26^{th} Conference of Parties
GHG	Greenhouse gas
GVWR	Gross vehicle weight rating
HVIP	Hybrid and Zero-Emission Truck and Bus voucher Incentive Program
ICT	Innovative Clean Transit (rule)
MHDV	Medium- and heavy-duty vehicle
MOU	Memorandum of Understanding
NEV	New Energy Vehicle
NGO	Non-governmental Organization
OEM	Original equipment manufacturer
PF	Preference factor
PTO	Power take-off unit
VMT	Vehicle miles traveled
ZE	Zero-emission
ZEB	Zero-emission bus
ZE-MHDV	Zero-emission medium- and heavy-duty vehicle
ZEV	Zero-emission vehicle

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EXECUTIVE SUMMARY

This analysis establishes projections of zero-emission medium- and heavy-duty vehicle (ZE-MHDV) sales targets through 2050 for the People's Republic of China in alignment with the recently launched Global Memorandum of Understanding (MOU) for trucks and buses. Recognizing that medium- and heavy-duty vehicles (MHDVs) are responsible for a disproportionate share of on-road fuel consumption, greenhouse gas (GHG) emissions, and a vast majority of health-threatening pollutants, accelerated efforts must be made to shift away from diesel-powered to cleaner, zero-emission vehicle (ZEV) alternatives. The adverse impact of MHDVs will only be exacerbated with the progression of time and inaction, as these vehicles are projected to continue to increase in volumes across global markets, defining the way freight and people are transported.

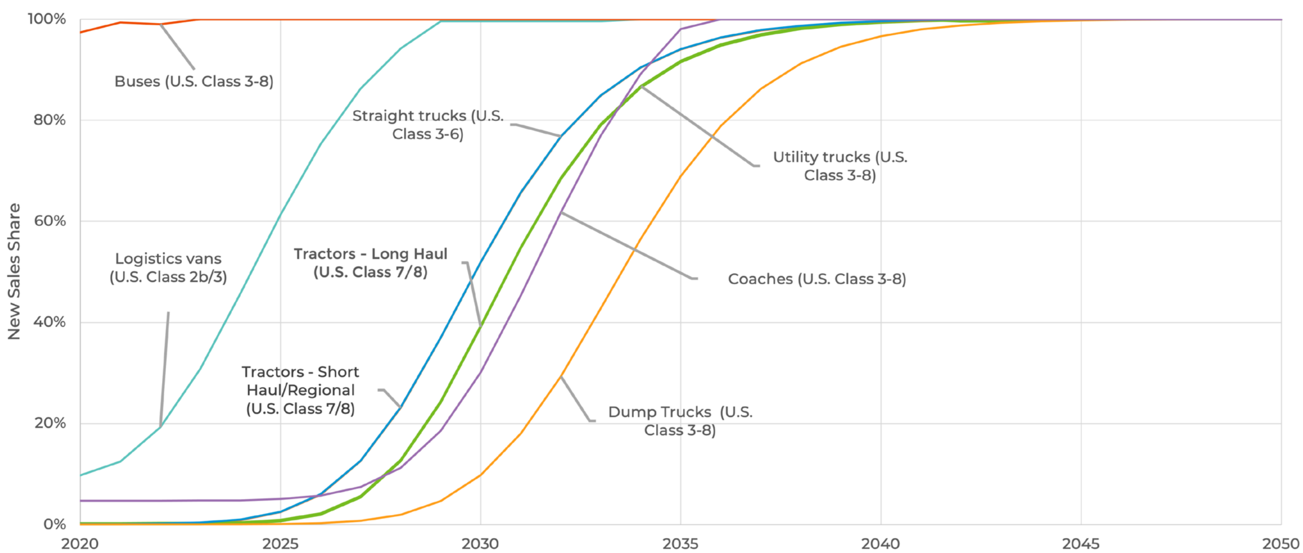
In September 2020 China's President Xi Jinping announced and outlined the broad steps towards peaking CO2 emissions by 2030 and achieving carbon neutrality by 2060. While China has been successful to drive passenger vehicle and bus electrification, the same level of success has not been true with heavy-duty trucks. And yet, diesel-powered heavy-duty vehicles are a major contributor to greenhouse gas (GHG) emissions and air pollution. In China, trucks make up 10.9% of the on-road vehicle fleet, but are responsible for 46.9% of on-road GHG emissions, 83.5% of nitrogen oxides (NOX) and 90.1% of particulate matter (PM) pollution from all road vehicles (ICCT 2021).

The projections outlined in this paper have been developed to meet the ambitions of a Global MOU for ZE-MHDVs, launched at COP26 in Glasgow in 2021. Led by the Dutch government and CALSTART, and signed by 15 countries, the MOU seeks to achieve 100% ZE sales of all MHDV segments by 2040, and an interim target of 30% by 2030. Drawing heavily from the ambition and tangible targets established by California's first-of-its-kind Advanced Clean Truck Regulation (ACT), this Global MOU seeks to coordinate and unify global action toward ZE-MHDVs.

This analysis uses CALSTART's Drive to Zero Market Projection Model to estimate the adoption rate of on-road ZE-MHDVs in China. The model uses five input parameters, namely: technology readiness, fleet bias, supply scalability, infrastructure availability, and fleet innovation profile. This analysis applies the framework established for the global MHDV market, to China, using best available data on Chinese vehicles volumes. Sales target projections are broken into eight segments based on vehicle vocation, type, and weight. Although this analysis is technology neutral, the assumptions used in the modeling are based on battery-electric technology due to its wider commercial availability in every MHDV segment considered and the proliferation of this technology throughout the Chinese market. The curves are modeled using the five parameters mentioned above, and the input for each parameter is modified to reflect the fastest adoption pathway based on best available intelligence.

Results show early adoption for zero-emission buses which have practically achieved full penetration in terms of new vehicle sales, reflecting the operational realities of the technology and the power of impactful incentives to spur uptake in the early market. Though nowhere near as advanced as buses from a sale perspective, logistics vans have also made significant headway on the path to be decarbonized and sales are expected to rapidly expand over the coming years based on very favorable conditions like urban operations, lighter duty-cycle requirements, and rapidly accelerating cost parity. The following curve (dark blue) shows the projected path for straight trucks and regional haul tractors, both of which benefit from traveling along relatively shorter distances in urbanized environments and usually charge overnight at depots—like transit buses—simplifying the infrastructure development.

Figure ES-1. ZE-MHDV Sales Targets by Vehicle Segment – China



Long-haul tractor electrification (green) follows slightly later, in very close alignment with utility trucks. Available battery technology today is most suitable for regional haul and drayage applications due to available weight, range, and infrastructure availability (mostly private at depots). However, optimism from global OEMs is driving innovation in zero-emission long-haul trucks and there is indication that commercialization of this segment will happen more rapidly than expected especially in China. Coaches are expected to progress slightly later than utility trucks and tractors and will likely reach full sales saturation by 2035. This segment benefits greatly from existing development in zero-emission bus powertrain and battery technology, offering a sound example of technology transfer from the Beachhead theory of change. The final modeled curve represents the future path for dump trucks. This is a unique segment that is widespread in China and ranges from smaller class 3 models all the way up to very heavy class 8 models. Because there is high variability in the operation and power/energy requirement this segment will progress more slowly, but with room for targeted deployments where the technology is ready now.

These results illustrate adoption pathways by vehicle segment specific to China and acknowledges differences in terms of vehicle volumes, duty cycles, and vocations among other characteristics. The model prepared for this study allows for a high level of detail and precision where data is available.

This analysis also quantifies GHG emission and fuel savings from the operation of new ZE-MHDVs in alignment with the targets laid out in this model. Based on the Chinese ZE-MHDV sales targets in this analysis, 1.62 billion barrels of crude oil (~2.74 million barrels per day) and 201 million tons of GHGs would be avoided from the operation of new MHDVs sold in 2050.

The ZE-MHDV sales targets projections in this analysis present a vision for the future of transportation technology in the Chinese market. The current ambitions established by the Chinese government do not accurately reflect the realities of the technology, economics and operational feasibility of these vehicles in a region that is leading the charge from the perspective of sales and deployments. In modeling adoption curves for each vehicle segment there are inherent limitations to the Drive to Zero Market Projection Model's ability to accurately capture the implicit variations and unique attributes of a specific country's MHDV market and landscape. This is to say that the major limitation of going beyond the eight categories employed by this paper is a more robust dataset detailing the Chinese market. This is a high priority in the next steps of this research and analysis and by understanding the market—with an emphasis on elements like vehicle segmentation, and sales data including model-specific details—progress toward the goals of the global MOU can be accelerated and expedited.

CHAPTER 1

BACKGROUND AND MOTIVATION

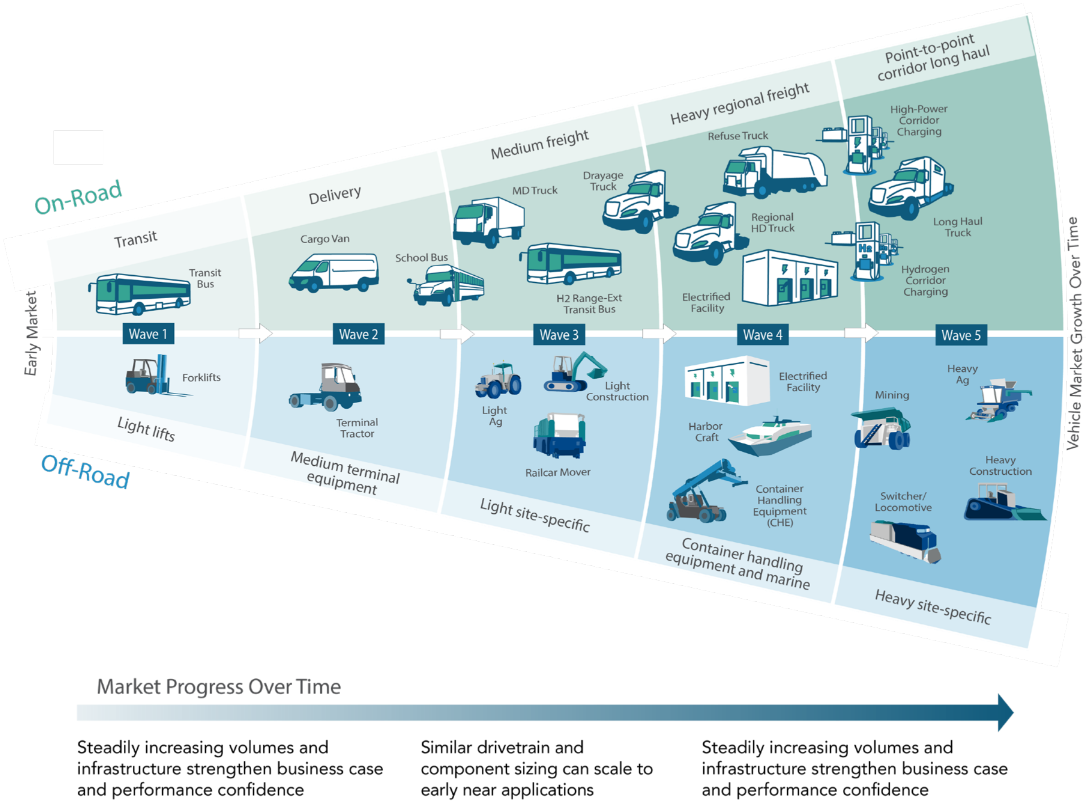
In September 2020 China's President Xi Jinping announced and outlined the broad steps towards peaking CO2 emissions by 2030 and achieving carbon neutrality by 2060. While China has been successful to drive passenger vehicle and bus electrification, the same level of success has not been true with heavy-duty trucks. And yet, diesel-powered heavy-duty vehicles are a major contributor to greenhouse gas (GHG) emissions and air pollution. In China, trucks make up 10.9% of the on-road vehicle fleet but are responsible for 46.9% of on-road GHG emissions, 83.5% of nitrogen oxides (NOX) and 90.1% of particulate matter (PM) pollution from all road vehicles (ICCT 2021).

The disproportionate impact that these vehicles have on GHG emissions and other harmful pollutants makes them a threat to both air quality and the climate, and therefore a major target for decarbonization. Emissions from commercial vehicles, in particular freight vehicles, are also forecast to increase significantly over the next decades. From 2020 to 2050, GHG emissions from freight are expected to double and harmful particulate matter (PM2.5) associated with combusting diesel is predicted to increase by more than 40% in this time frame (CALSTART, 2020). If meaningful action is to be taken against climate change, there must be a coordinated global undertaking to reduce the impact of MHDVs on the road and ensure the future of trucking and goods movement does not have an adverse impact on the environment and public health.

In approaching the decarbonization of the transportation sector, passenger vehicles and the light-duty segment have been a top priority for policy, incentives, and technology development. However, considering the disproportionate emissions impact that such a relatively small share of the on-road fleet is responsible for, policy attention must also focus on these heavier vehicle segments. Awareness of ZE-MHDV technological capability and model availability lags what is being offered on the market today and thus limits decisionmakers' abilities to make informed policy choices based on the realities of the technology. Major barriers such as range and operational feasibility have largely been overcome for select segments such as transit buses, urban delivery, and regional haul with all segments boasting models that can meet or exceed the characteristic drive cycle for these operations (CALSTART, 2021). Most cost analyses already predict that all ZE-MHDV applications will achieve cost parity before 2030. However, a number of total-cost of ownership analyses have revealed that based on the more advanced state of the Chinese market, that almost all major heavy vehicle segments in China could reach cost parity well before 2030, especially in combination with policy intervention (ICCT 2021b).

By focusing on the vehicle segments where ZE models can be deployed in today, production can be scaled up more quickly and technology can be transferred across platforms. This approach reflects the Beachhead theory of change, a framework developed collaboratively by California's Air Resource Board and CALSTART to accelerate ZE-MHDV deployments strategically (Figure 2) (CALSTART, 2020a).

Figure 1. The Beachhead Strategy



With climate urgency building and nations aiming higher to meet the goals of the Paris Climate Agreement, ZE-MHDVs can lead to critical climate-warming emissions reductions and help nations achieve their climate commitments. Although ZE technologies are increasingly more commercially viable and cost competitive for many MHDV applications, much stronger signals from national governments are needed to trigger faster vehicle deployment.

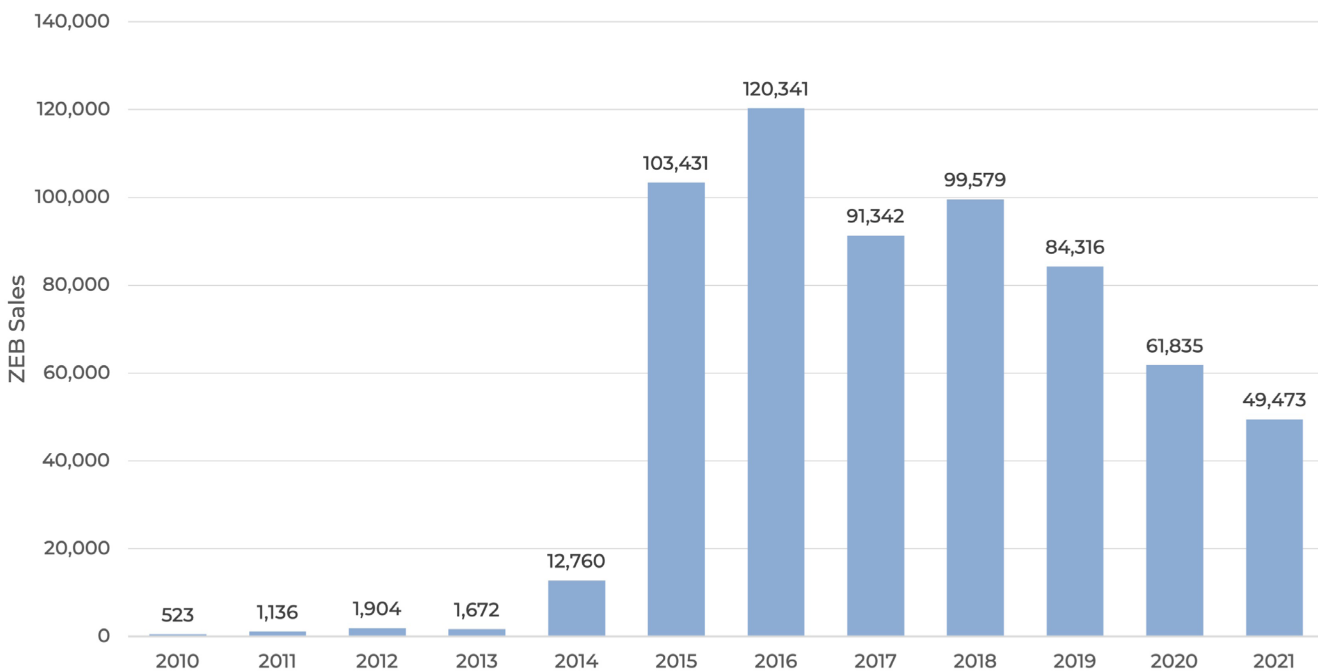
In a historic announcement at the 26th Conference of Parties (COP26), 15 leading nations pledged their support to a Global Memorandum of Understanding (MOU) that establishes targets for countries of 100% ZE-MHDV sales by 2040 that will enable net-zero carbon emissions by 2050. The signatories of the MOU include a diverse array of national governments as well as partners from the private sector and NGOs. Austria, Canada, Chile, Denmark, Finland, Luxembourg, Netherlands, New Zealand, Norway, Scotland, Switzerland, Turkey, United Kingdom, Uruguay, and Wales have all pledged their support to the MOU and agreed to enabling 30% ZE-MHDV sales by 2030, and 100% ZE-MHDV sales by 2040. This landmark agreement draws significant inspiration from California's first-of-its-kind Advanced Clean

Truck Regulation (ACT) that similarly requires an increasing share of MHDV that are sold to be zero emission through 2035 (CARB, 2021).

1.1. THE CHINESE ZERO-EMISSION MHDV MARKET

Undoubtedly a trailblazer in new energy vehicle (NEV) technology, China has made tremendous progress instigating a major transition to ZE-MHDVs. Currently the Chinese market accounts for close to 99% of the global stock of ZE-MHDVs, focused primarily on the urban bus segment which is a priority to achieve cleaner air and cities (ICCT, 2021c). China instituted a system of monetary incentives to spur growth of zero-emission buses (ZEBs) seeing major uptake from 2013 to 2016, after which annual sales steadily decrease, but still remain orders of magnitude higher than any other country or region (Figure 3).

Figure 3. ZEB Sales in China[1]



Shenzhen, Guangzhou, and Dalian, major Chinese cities, have already completed total electrification of their bus fleets with close coordination between local, provincial and national governments, and assisted by national subsidies. During the peak of these pilots, a ZEB purchased could be eligible for a total of up to $150,000 USD, a major driver behind deployments over this time (WRI, 2018). Beginning

1 Source: EV Volumes data

in 2018 subsidies for buses were tightened and reduced based on kWh capacity up to 3,000RMB/kWh. Without hard regulations like California's ACT rule, China is missing a major opportunity to solidify the trajectory of the market with provisions that require automakers to sell an increasing share of NEVs over time. Though China's New Energy Vehicle Technology Roadmap 2.0 does propose HD-NEV targets over time, they peak at 20% share by 2035 which is significantly less ambitious than regions that are less developed than China's market, and do not apply adequate pressure on the private sector to accelerate development and deployment of NEVs.

1.2. OEM LEADERSHIP

Government leadership toward ZE-MHDVs is also strengthened by industry ambition. For example, the European Automobile Manufacturers Association, the umbrella organization which includes vehicle manufacturers such as Scania, Daimler, Ford, MAN, DAF, Iveco, and others, announced that by 2040 all new commercial vehicles sold must be fossil-free to ensure carbon neutrality by 2050. Table 1 highlights the commitments made thus far by MHDV manufacturers, which align well with the ambition of the Global MOU.

Table 1. OEM Commitments to ZEV Sales and Carbon Neutrality (CALSTART 2021a)

OEM	COMMITMENT	DATE
GM Group	100% carbon neutral in global products and operations	2040
Stellantis	70% low-emission vehicle sales in Europe, and 40% in the US	2030
Ford Group	100% fossil free new vehicle sales	2040
Daimler Group	100% carbon neutral in driving operation in Europe, North America, and Japan	2039
Toyota Group	100% CO2 neutral in life cycle by 2050	2050
Changan Automobile Group	100% electric vehicle sales	2025
Great Wall Motor Company Ltd. (GWM)	100% CO2 neutral, with interim target of 80% new energy vehicle sales by 2025	2045
Mahindra & Mahindra	100% carbon neutral in operations	2040
VW Group	100% CO2 neutral balance sheet	2050
Renault	100% CO2 neutral worldwide, with interim target of 100% CO2 neutral in Europe by 2040	2050
Nissan	100% carbon neutral across operations and product life cycle	2050
Mitsubishi	100% carbon neutral, with 50% EV sales by 2030	2050

OEM	COMMITMENT	DATE
Isuzu	100% CO2 neutral in vehicle operation and plants sheet	2050
Paccar	100% fossil free new vehicle sales	2040
Suzuki	90% reduction in CO2 emissions in driving operation	2050
Volvo Trucks Group	100% fossil free new vehicle sales	2040
CNH Industrial	100% fossil free new vehicle sales	2040
Honda	100% battery-electric and fuel cell electric vehicle sales in North America, with interim targets of 40% by 2030 and 80% by 2035	2040
Mazda	90% reduction in CO2 emissions in driving operation and energy production	2050
Hyundai Kia Automotive Group	100% CO2 neutral in all operations	2050

Research included all OEMs with >100,000 sales in 2020 and publicly available commitments to 70%-100% ZEV sales or carbon neutrality. Based on publicly available information as of July 15th, 2021.

The following sections of this report examine the inputs, assumptions, and methodology used to determine the targets and vehicle-specific adoption curves for ZE-MHDVs outlined in the Global MOU. The path to 100% ZE-MHDV sales by 2040 has been segmented according to a vehicle's weight classification and vocation in order to most appropriately represent broad groups of vehicles across regions as accurately as possible with available data. The projections are modeled in this study using global vehicle data and five quantitative and qualitative parameters on technology readiness, fleet demand, supply scalability, infrastructure availability, and fleet innovation.

CHAPTER 2

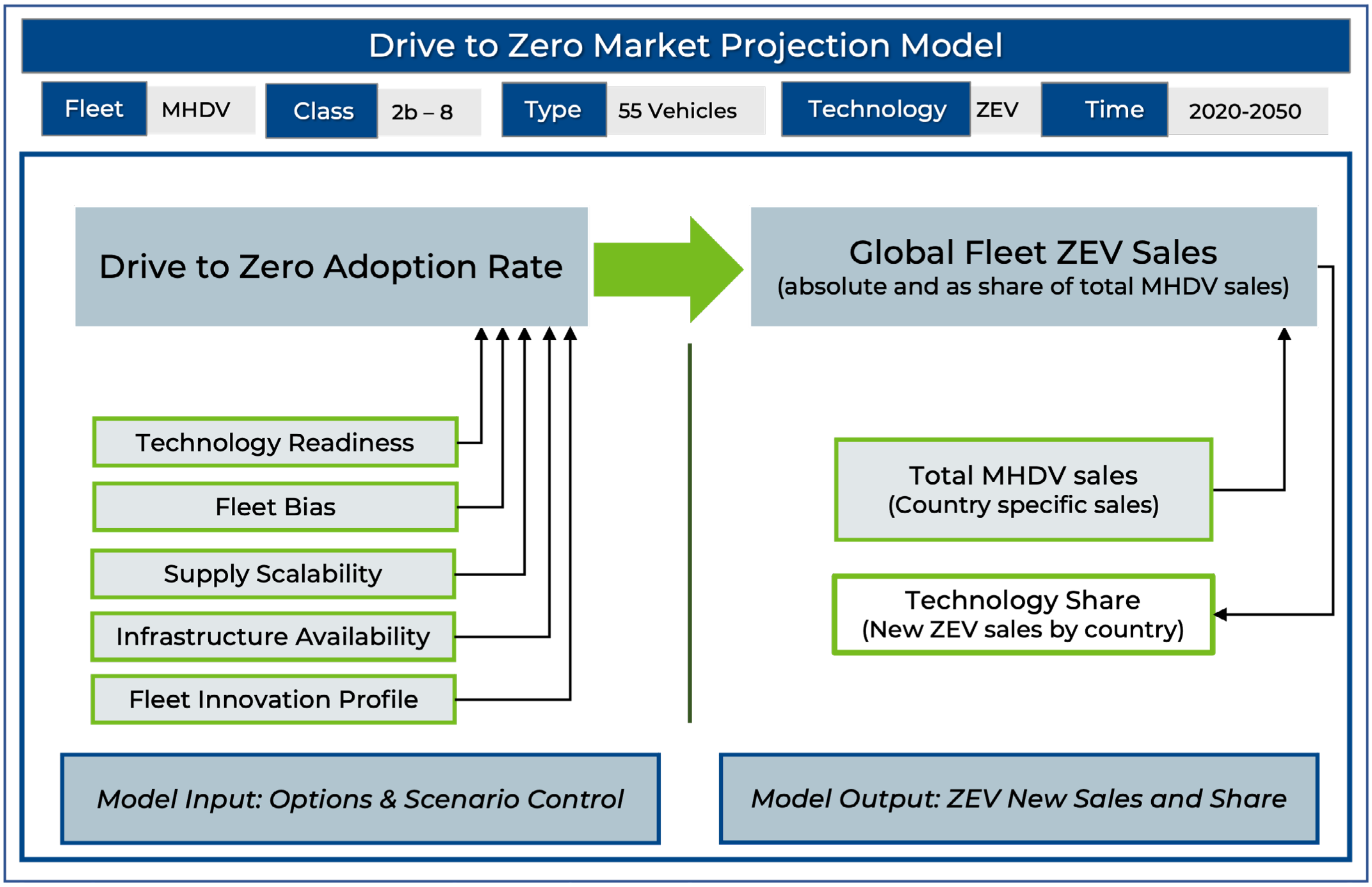
METHODOLOGY FOR TARGET DEVELOPMENT

Developing forecasts for the future adoption of ZE-MHDVs is crucial for policy planning and vehicle market evaluation, as well as fleet and infrastructure strategic planning and deployment. Projections of future market behavior depend on many assumptions that are informed by today's conditions and expectations about how quickly the market may adopt ZE technologies. In addition, this is also a dynamic, emerging market, so the results presented in this analysis will be revised frequently as technology evolves.

This analysis uses CALSTART's Drive to Zero Market Projection Model to estimate the adoption rate of on-road ZE-MHDVs across countries (Al-Alawi, 2021). The model is an interactive and user-friendly input-output (I/O) model that incorporates CALSTART's Beachhead theory of change to forecast ZE-MHDVs in different regional markets (CALSTART, 2020a). This means that the model considers the potential for technology transfer across vehicle segments as zero-emission technologies mature. For example, zero-emission technologies have been more readily available and applicable for transit buses because their vocational use allows them to navigate challenges to electrification. Buses almost always travel along known and relatively shorter urban routes and return to depots for charging overnight. As zero-emission technologies mature over time, they are transferred to other vehicle segments such as urban delivery vehicles, medium-duty trucks, and eventually to heavier vehicles traveling along longer routes. The model supports infrastructure planning, policy planning, and technology/fuel evaluation. The projection model simulates decision makers' (fleet owners, OEM, and policy makers) technology adoption quantitatively and, where required, qualitatively. A more detailed description of this model and associated methodology, parameters, and results was published as a framework for applying global projections to a specific region or country (CALSTART, 2022).

Figure 4 illustrates the comprehensive analytical model components and interactions. The model estimates ZE-MHDV share of total MHDV sales (output) between 2020 and 2050 by vehicle application (See Results chapter).

Figure 4. Drive to Zero Market Projection Model (CALSTART, 2022)



The goal of these projections is to develop ambitious yet feasible targets for ZE-MHDVs, in terms share of new vehicle sales by application and region through 2050. Projections are meant to be ambitious and align with targets announced by world governments and global manufacturers, ensuring that 100% of new MHDV sales are zero emissions by 2040, with an interim target of 30% by 2030. Projections are also feasible in that they consider technology readiness, supply scalability, fleet bias towards new technologies for different vehicle segments.

Fleet decisions to acquire ZE-MHDVs were approximated quantitatively and qualitatively. Beginning with the projected total market size, the demand response was modeled to include three of the five parameters listed in Table 2, namely: (1) technology readiness (i.e. availability and suitability of the technology to an application); (2) fleet bias (i.e. preference towards technology risk and reliability, and time it takes for fleets to have confidence in a new technology); (3) supply scalability (i.e., how fast manufacturers can scale up production). The model can also consider infrastructure availability and fleet innovation profile, both of which are not explicitly used in this analysis for simplification purposes and due to lack of data availability.

Table 2. Analytical Model Parameters (CALSTART, 2022)

PARAMETER	DESCRIPTION
Technology readiness	Availability and suitability of the technology to an application, depending on technology, location, vehicle type, application, and timing.
Fleet bias	Individual fleet preference toward a new technology, considering its risk and reliability, and the time it takes for fleet owners to gain confidence in a new technology.
Supply scalability	How fast manufacturers can scale up production, depending on size, purchase power, and operational capacity.
Infrastructure availability	Fleet owners' behavioral response to charging/fueling infrastructure availability, depending on the use of private and public infrastructure.
Fleet innovation profile	How quickly fleets will adopt a new technology, based on consumer behavior theory that stratifies fleets based on their technology adoption profile (e.g., innovators, early adopters).

These parameters are represented by probability curves based on market and fleet behavior knowledge to reflect different ZE-MHDV adoption rates. Although each parameter can consider a range of adoption scenarios, this analysis considers only the most aggressive global scenario for each parameter for each of the different vehicle segments through 2050. ZE-MHDV adoption rates are based on five parameters listed in Table 1 and described in greater detail in the following sections.

2.1. MHDV CLASSIFICATION

This analysis establishes sales targets for ZE-MHDVs by vehicle segment, recognizing that zero-emission technologies are adopted at different rates and time frames depending on the application. For example, zero-emission technology has been more readily available for urban transit buses than for long-distance truck applications early on.

MHDV classification varies by country, typically based on vehicle type (e.g., automobile, bus, van, truck) and gross vehicle weight rating (GVWR). Table 3 compares the US MHDV classification system with China's equivalent classification to add clarity to the discussion of various vehicle types in this paper.

Table 3. Truck Classification Comparison between U.S. and China

<table>
<tr><th colspan="2">US</th><th colspan="2">China</th></tr>
<tr><th></th><th></th><th>Trucks</th><th>Tractors</th></tr>
<tr><th>Class</th><th>Weight</th><th>Weight</th><th>Weight</th></tr>
<tr><td>2b</td><td>3.86 - 4.54</td><td>3.5 - 4.5</td><td rowspan="7">3.5 - 18</td></tr>
<tr><td>3</td><td>4.54 - 6.35</td><td>4.5 - 5.5</td></tr>
<tr><td>4</td><td>6.35 - 7.26</td><td>5.5 - 7</td></tr>
<tr><td>5</td><td>7.26 - 8.85</td><td>7 - 8.5</td></tr>
<tr><td>6</td><td>8.85 - 11.79</td><td>8.5 - 10.5</td></tr>
<tr><td>7</td><td>11.79 - 14.97</td><td>10.5 - 12.5</td></tr>
<tr><td rowspan="3">8a</td><td rowspan="3">14.97 - 27.22</td><td>12.5 - 16</td></tr>
<tr><td>16 - 20</td><td rowspan="2">18 - 27</td></tr>
<tr><td>20 - 25</td></tr>
<tr><td rowspan="6">8b</td><td rowspan="6">> 27.7</td><td>25 - 31</td><td>27 - 35</td></tr>
<tr><td rowspan="5">> 31</td><td>35 - 40</td></tr>
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<tr><td>43 - 46</td></tr>
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</table>

However, because vehicle classification systems do not typically include vocation (i.e., how a vehicle is operated) or more detailed vehicle types, this analysis and underlying model include different tiers of vehicle segmentation. In the most aggregate classification system, vehicles can be categorized in three categories as light-, medium-, and heavy-duty vehicles (tier 4 in Table 4). In the U.S., on-road commercial motor vehicles are divided into seven classes, with LHDVs represented by class 2b, MHDVs by class 3-6, and HHDVs by class 7-8 (tier 3 Table 4). The most common vehicle classification system used resembles tier 3 and 4 (Table 4) which is not sufficient to identify specific vehicle vocations to accurately project global sales. For example, trucks and buses can be grouped under the same classes, and delivery and construction trucks can also be grouped together in tier 3 under the same classes despite having significantly different operational characteristics. This is not sufficient to accurate project the sales penetration by segment, as the vocational use will greatly impact a vehicle's potential for decarbonization For more details on the segmentation of global commercial vehicle classification systems, please see Appendix A. For this analysis, further segmentation is needed to assess the suitability of zero-emission technologies by accounting for the use of the vehicle and not only the weight class. Tier 2 categorizes vehicles into eight categories based on vehicle type and vocation, following an update to the California Hybrid and Efficient Advanced Truck Research Center (CalHEAT)[2] approach and the Beachhead theory of change (CALSTART, 2013) (CALSTART, 2020a). The most disaggregated tier 1 is only applicable where vehicle data are available on a model-by-model basis (See Appendix A).

Table 4. Vehicle Classification and Segmentation Tiers

TIER	DESCRIPTION	GROUPS
4	Most aggregated: groups vehicles into three different categories: light HDVs (class 2b-3), medium HDV (class 4-6), and heavy HDVs (class 7/8)	3 Categories
3	Less aggregated: defines vehicles by class (class 2b-8)	7 Classes
2	Less disaggregated: CalHeat approach assigns vehicles into 8 categories based on vehicle type and vocation	8 Categories
1	Most disaggregated: Only applicable to the US where HDV registration data allows for the stratification of further information like make, model, vocation, operator business type, and class.	77 Segments

Because vehicle data for most countries are only available by make but not by model, tier 2 allows for the most comprehensive approach, and is the segmentation applied in this analysis. Figure 5 describes each vehicle category in tier 2 based on vehicle type, weight class, vocation, and technology applicability, and provides indicative models for each. Because this methodology was initially developed for the US market, some of the original categories in tier 2 had to be adapted for the Chinese market based on the dominating MHDV segments in China. 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 a number of vocations. Figure 5 illustrates indicative models for each of the 8 segments modeled for the Chinese market and their attributes.

2 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

Figure 5. Tier 2 MHDV Segmentation in China

2.2. ZERO-EMISSION TECHNOLOGY PATHWAYS

This analysis considers zero-emission vehicles as those with zero tailpipe emissions, while recognizing that upstream emissions from energy production and distribution can be sizeable and need to be decarbonized in parallel with vehicle tailpipe emissions. Although this analysis is technology neutral, the assumptions used in the modeling are based on battery-electric technology due to its wider commercial availability in every MHDV segment considered. However, the targets for ZE-MHDVs in this analysis include not only battery-electric technology but other zero tailpipe emission pathways such as hydrogen fuel cell powered vehicles.

CHAPTER 3

RESULTS

This chapter establishes the results of the Drive to Zero Market Projection Model and projections for ambitious yet feasible ZE-MHDV sales targets, outlines the assumptions used for each parameter, and compares the projections with the first and only binding regulations for ZE-MHDVs, namely California's Advanced Clean Truck Regulation (ACT) and Innovative Clean Transit rule (ICT). This chapter also provides a case study for how ZE-MHDV sales targets apply to the specific attributes of the Chinese market, using current available data. Finally, this chapter estimates the GHG and fossil fuel savings derived from the faster adoption of ZE-MHDVs.

3.1. ZE-MHDV SALES TARGETS BY VEHICLE SEGMENT

This analysis is grounded in the Beachhead theory of change as a framework for technological market acceleration and future trends on technology availability, fleet behavior, and supply growth options. This analysis applies parameter options for technology readiness, fleet bias, and supply scalability for each of the eight vehicle categories, based on current knowledge of technology readiness and model availability (CALSTART, 2022). Infrastructure availability and fleet innovation profile parameters are not explicitly included in this table, as an assumption has been made across all vehicle categories for their applicability. The assumptions are that infrastructure will be available for fleets purchasing ZEVs, and that fleets, regardless of innovation status, will meet the provisions of the global MOU of 100% ZE-MHDV sales by 2040 (Table 5).

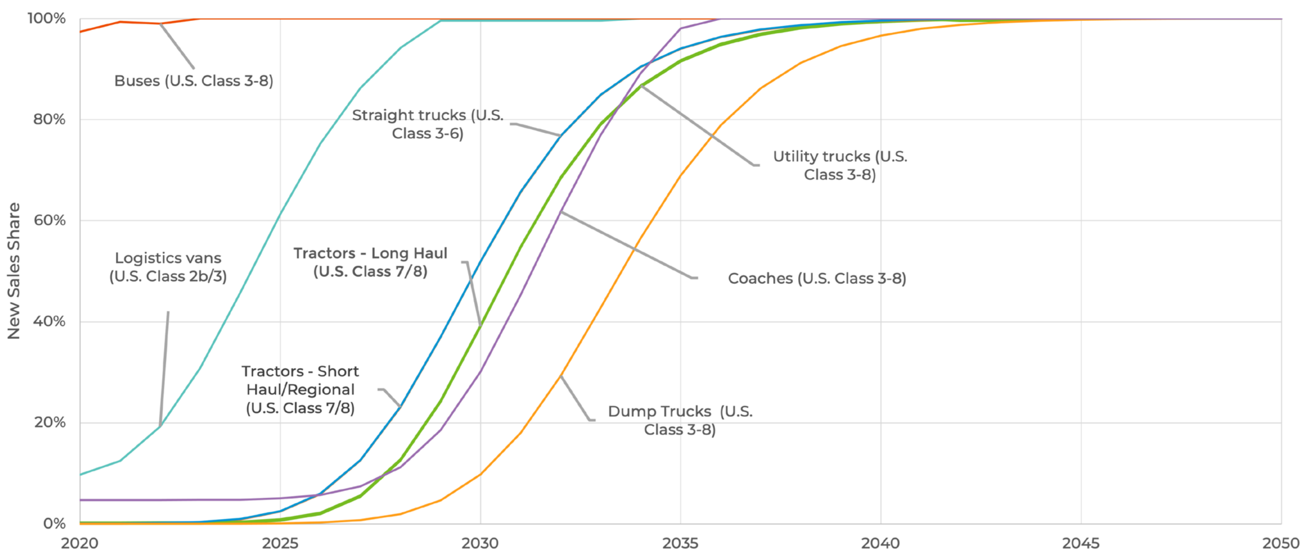
Table 5. Model Control Options by Parameter

VEHICLE SEGMENT	TECHNOLOGY READINESS	FLEET BIAS	SUPPLY SCALABILITY
Tractors - Long Haul (U.S. Class 7/8)	High Market	Average	Medium
Tractors - Short Haul/Regional (U.S. Class 7/8)	High Market	Accelerated	Medium
Utility trucks (U.S. Class 3-8)	High Market	Average	Medium
Straight trucks (U.S. Class 3-6)	High Market	Accelerated	Medium
Dump Trucks (U.S. Class 3-8)	Medium Market	Average	Medium
Logistics vans (U.S. Class 2b/3)	Very High Market	Accelerated	Very High
Buses (U.S. Class 3-8)	Very High Market	Accelerated	Very High
Coaches* (U.S. Class 3-8)	High Market	Average	Medium

**Due to current volumes of ZE coaches, and the operational feasibility of the technology, the uptake of coaches will be delayed in the market. This is reflected in figure 8.*

ZE-MHDV sales targets over the eight vehicle segments (Figure 6) are derived based on the above control options (Table 5). Results show early adoption for zero-emission buses which have practically achieved full penetration in terms of new vehicle sales, reflecting the operational realities of the technology and the power of impactful incentives to spur uptake in the early market. Though nowhere near as advanced as buses from a sale perspective, logistics vans have also made significant headway on the path to be decarbonized and sales are expected to rapidly expand over the coming years based on very favorable conditions like urban operations, lighter duty-cycle requirements, and rapidly accelerating cost parity. Zero-emission logistics vans' ability to meet the needs of fleets and reduce costs of a rapidly growing e-commerce sector should make them a high priority for decarbonization.

Figure 6. ZE-MHDV Sales Targets by Vehicle Segment – China



The following curve (dark blue) shows the projected path for straight trucks and regional haul tractors, both of which benefit from traveling along relatively shorter distances in urbanized environments and usually charge overnight at depots—like transit buses—simplifying the infrastructure development. For regional delivery tractors, models are commercially available from national OEMs, but have only recently started deployments in more specific applications where technology is operationally viable. It is important to highlight to robust availability of truck models in the Chinese market that can fulfill the duty cycle requirement of a traditional truck and save fleets operational expenses over the life of the vehicle. These realities are only beginning to be realized by fleet owners, and greater measures must be taken to facilitate their uptake through targeted policy and incentives.

Long-haul tractor electrification (green) follows slightly later, in very close alignment with utility trucks. Available battery technology today is most suitable for regional haul and drayage applications due to available weight, range, and infrastructure availability (mostly private at depots). However, optimism from global OEMs is driving innovation in zero-emission long-haul trucks and there is indication that commercialization of this segment will happen more rapidly than expected (Scania, 2021). Building out corridor charging will help enable and accelerate long-haul trucking as confidence in refueling opportunity charging grows. In addition, fuel cell tractors, which offer ranges sufficient to meet long-haul applications, are not yet widely commercially available, but are successfully being deployed in parts of China to pave the way for widespread adoption specifically long-haul and heavy heavy-duty segments.

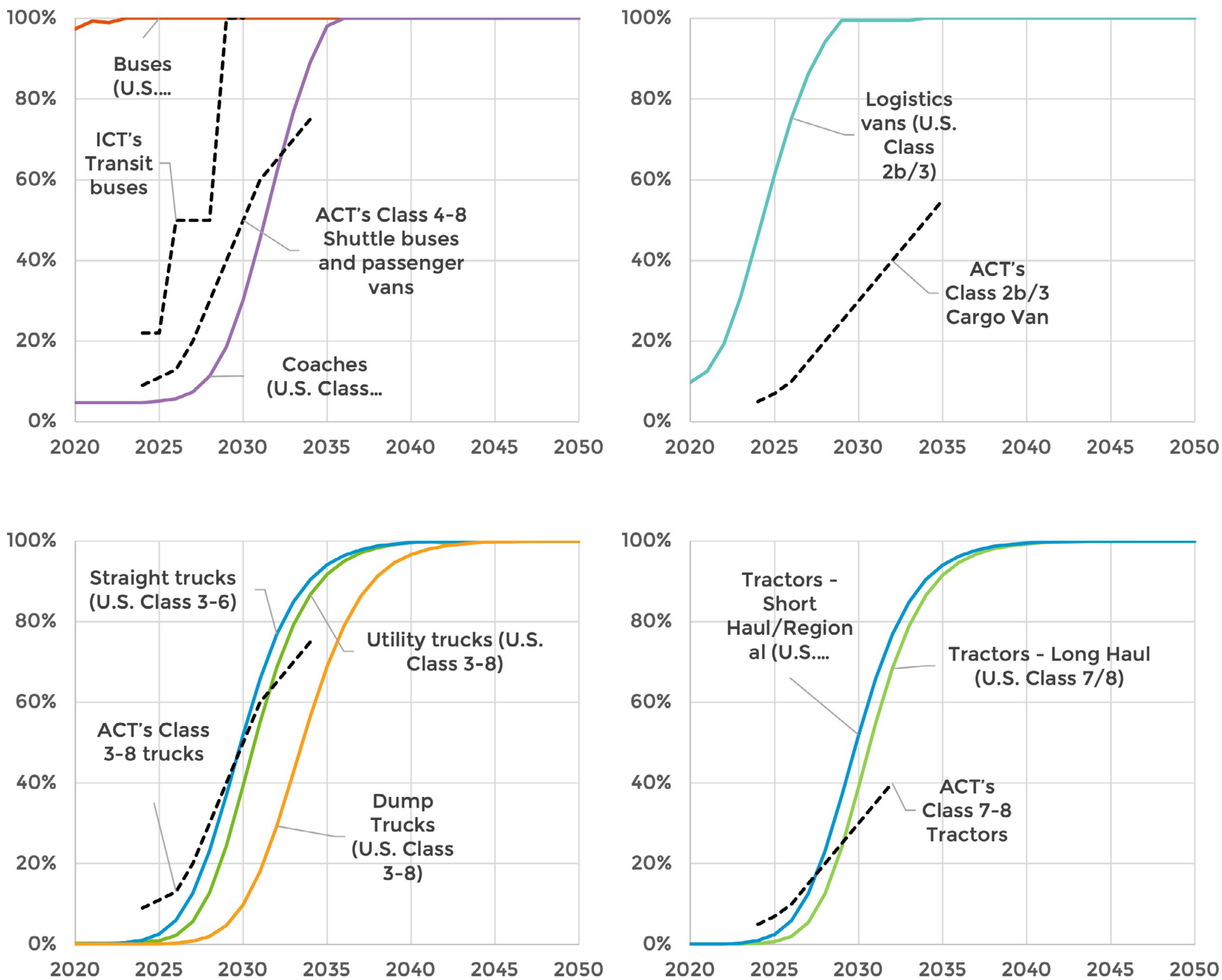
Coaches are expected to progress slightly later than utility trucks and tractors and will likely reach full sales saturation by 2035. This segment benefits greatly from existing development in zero-emission bus powertrain and battery technology, offering a sound example of technology transfer from the Beachhead theory of change. The regional travel and longer distances for these kinds of buses compared to city buses slow penetration, with ongoing development of charging corridors and urban infrastructure development, coaches will see uptake increase especially for some of the shorter inter-city routes.

The final modeled curve represents the future path for dump trucks. This is a unique segment that is widespread in China and ranges from smaller class 3 models all the way up to very heavy class 8 models. Because there is high variability in the operation and power/energy requirement this segment will progress more slowly, but with room for targeted deployments where the technology is ready now. These vehicles often haul very heavy loads and may have additional power requirements of a PTO unit.

3.2. COMPARISON OF CHINA SALES TARGETS TO CALIFORNIA ACT AND ICT REGULATIONS

This section compares the projected ZE-MHDV adoption rates in China with California's ACT and ICT regulations to compare this level of global ambition with a U.S. state that has led in adopting the regulations and incentives necessary to accelerate the ZE-MHDV market. Although the ZE-MHDV projections outlined in the previous section (Figure 6) are ambitious, they are generally aligned with the stringency of California's ACT and ICT regulations. In the case of buses, China's adoption has been more ambitious and has achieved full market penetration of new vehicles sold. The ACT rule in California is more ambitious than the projected curve for coaches in a market that is less saturated with zero emission alternatives. For straight trucks and utility trucks, the modeled curve is consistent with ACT, except for dump trucks which will lag behind due to more intensive operational requirements and technology readiness. For logistics vans, China is ahead of California and is expected to outpace the ACT requirement. For tractors, the ACT initiates more ambitious targets at first but is soon outpaced by the rate China has the potential to move at (Figure 7).

Figure 7. Comparison of Global ZE-MHDV Sales Targets with California's ACT and ICT Regulations



3.3. BENEFITS AND AVOIDED GHG UNDER ZE-MHDV TARGETS TO 2050 AND BEYOND

This section estimates expected annual oil consumption and GHG emissions[3] related to MHDV sales targets from 2020 to 2050. The analysis assumes average vehicle activity (in vehicle kilometers traveled) and fuel economy for each vehicle segment in China to calculate total avoided oil consumption. The

3 GHG emissions include: (CO_2) carbon dioxide, (CH_4) methane, (NO_x) oxides of nitrogen, (VOC) volatile organic compounds, (CO) carbon monoxide, (BC) black carbon, (OC) organic carbon

analysis also assumes tailpipe CO_2 and GHG emission factors per unit of diesel fuel consumed, namely 0.010228 tons of CO_2 and 0.01035 GHG produced per gallon of diesel (ANL, 2020).

Based on the Chinese ZE-MHDV sales targets in this analysis, 1.62 billion barrels of crude oil (~4.44 million barrels per day) and 201 million tons of GHGs would be avoided from the operation of new MHDVs sold in 2050. The black bars (base case) in Figure 8 represent MHDV oil consumption assuming no penetration of ZE technologies, while the green bars represent oil savings from introducing ZE-MHDVs compared to the base case per the projections of this analysis.

Figure 8. Annual Avoided Barrels of Oil in China from New ZE-MHDV Operation

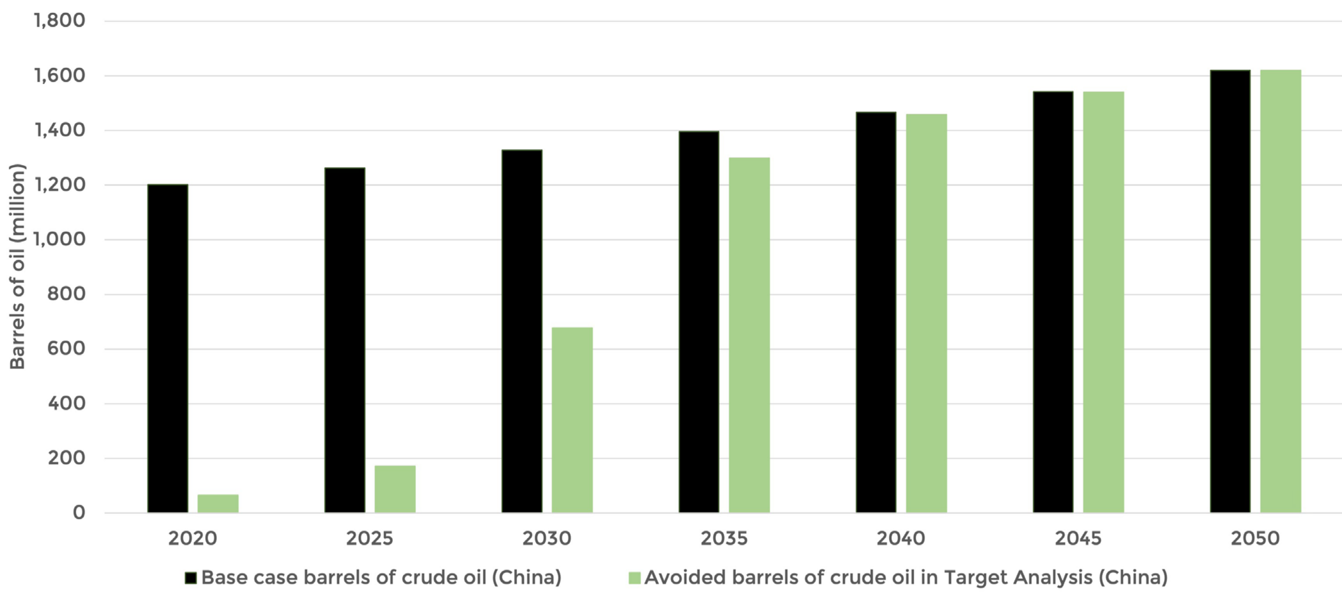
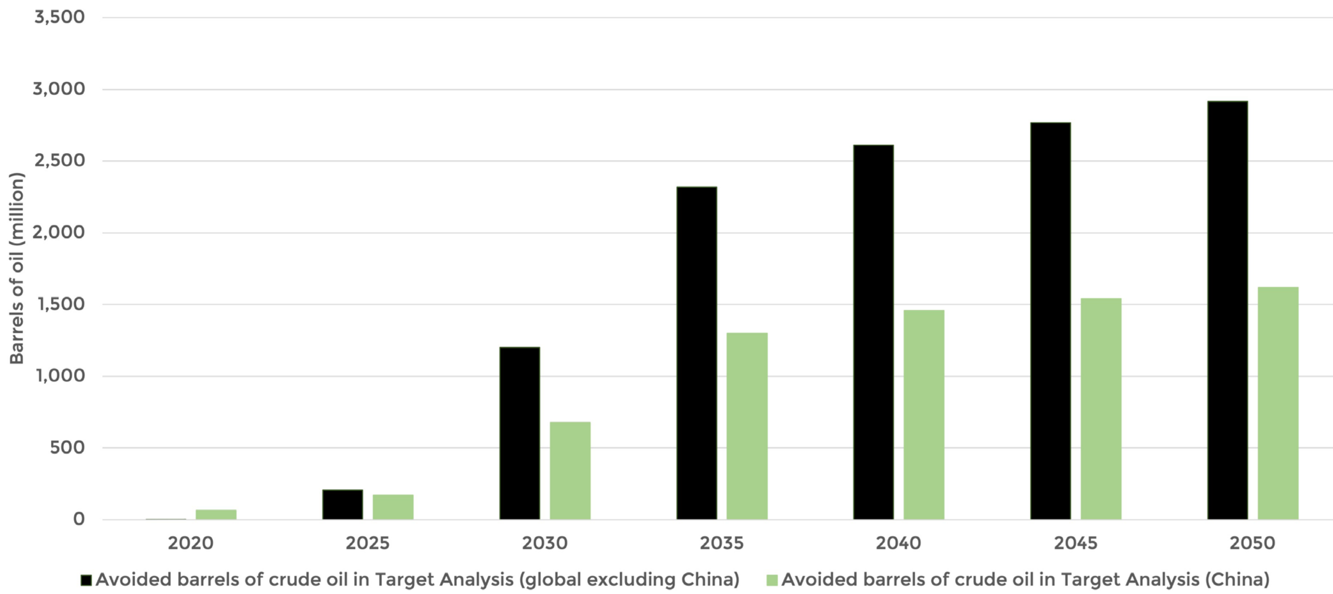


Figure 9 compares the global scenario of avoided oil use (Figure 8) to the Chinese market scenario of avoided oil use under the target analysis. This means the combined oil use in China outpaces that of the rest of the world combined, thus making the electrification of MHDVs in China imperative.

Figure 9. Comparison of Avoided Barrels of Oil Globally and in China from New ZE-MHDV Operation



CHAPTER 4

CONCLUSIONS AND OUTLOOK FOR FUTURE RESEARCH

The targets established by the Global MOU at COP26 are a key milestone in the efforts to curb harmful global MHDV emissions, and momentum to accelerate ZE-MHDVs will only increase as new nations join the Global MOU and current nations turn the MOU ambition into concrete policies. The methodology introduced in this analysis provides the framework for continued market development and acceleration through targeted deployment of technology that ensures the greatest success of vehicles where they work now. The sequenced approach of the Beachhead strategy has shown that as the industry and market grow, key components like batteries and motors will become more efficient and less costly, allowing more difficult-to-electrify segments of the market, like long-haul trucks, to be decarbonized.

The ZE-MHDV sales targets projections in this analysis present a vision for the future of transportation technology in the Chinese market. In modeling adoption curves for each vehicle segment there are inherent limitations to the Drive to Zero Market Projection Model's ability to accurately capture the implicit variations and unique attributes of China's MHDV market and landscape. Currently available data limits the number of segments that can be accurately modeled (see section 2) and may ultimately impact the actual trajectories of ZE-MHDV adoption. With more detailed data the methodology of this model can be revised.

The result of this analysis outlines the pathways for ZE-MHDV adoption across the eight vehicle segments used to represent the market, ensuring that vehicle weight, class, and vocation are properly accounted for. By adapting the framework of this analysis to other leading countries/regions beyond China, policy ecosystems can be developed with greater efficacy in achieving accelerated ZE-MHDV uptake. As demonstrated by California, it will only be through setting ambitious targets, establishing binding regulations, and introducing timebound incentives that progress will accelerate to a pace appropriately in line with global climate agreements (CALSTART, 2022a).

APPENDIX A

VEHICLE CLASSIFICATION

Table 6. Global MHDV classification (metric ton)

<table>
<tr><th colspan="2">US</th><th colspan="4">EU</th><th colspan="4">China</th><th colspan="4">Japan</th></tr>
<tr><th></th><th></th><th></th><th></th><th colspan="2">Trailers & Semitrailers</th><th colspan="2">Trucks</th><th colspan="2">Tractors</th><th colspan="2">Trucks</th><th colspan="2">Tractors</th></tr>
<tr><th>Class</th><th>Weight</th><th>Class</th><th>Weight</th><th>Class</th><th>Weight</th><th>Class</th><th>Weight</th><th>Class</th><th>Weight</th><th>Class</th><th>Weight</th><th>Class</th><th>Weight</th></tr>
<tr><td colspan="2"></td><td>N1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2b</td><td>3.86 - 4.54</td><td rowspan="6">N2</td><td rowspan="6">3.5 - 10</td><td rowspan="2">O1</td><td rowspan="2">< 0.75</td><td></td><td>3.5 - 4.5</td><td rowspan="7"></td><td rowspan="7">3.5 - 18</td><td rowspan="3">1 - 4</td><td rowspan="3">3.5 - 7.5</td><td rowspan="8">1</td><td rowspan="8">< 20.0</td></tr>
<tr><td>3</td><td>4.54 - 6.35</td><td></td><td>4.5 - 5.5</td></tr>
<tr><td>4</td><td>6.35 - 7.26</td><td rowspan="3">O2</td><td rowspan="3">0.75 - 3.5</td><td></td><td>5.5 - 7</td></tr>
<tr><td>5</td><td>7.26 - 8.85</td><td></td><td>7 - 8.5</td><td>5</td><td>7.5 - 8</td></tr>
<tr><td>6</td><td>8.85 - 11.79</td><td></td><td>8.5 - 10.5</td><td>6</td><td>8 - 10</td></tr>
<tr><td>7</td><td>11.79 - 14.97</td><td rowspan="5">O3</td><td rowspan="5">3.5 - 10</td><td></td><td>10.5 - 12.5</td><td>7</td><td>10 - 12</td></tr>
<tr><td rowspan="4">8a</td><td rowspan="4">14.97 - 27.22</td><td rowspan="10">N3</td><td rowspan="10">> 12.0</td><td></td><td>12.5 - 16</td><td>8</td><td>12 - 14</td></tr>
<tr><td rowspan="2"></td><td rowspan="2">16 - 20</td><td rowspan="3"></td><td rowspan="3">18 - 27</td><td>9</td><td>14 - 16</td></tr>
<tr><td rowspan="2">10</td><td rowspan="2">16 - 20</td><td rowspan="8">2</td><td rowspan="8">> 20.0</td></tr>
<tr><td></td><td>20 - 25</td></tr>
<tr><td rowspan="6">8b</td><td rowspan="6">> 27.7</td><td rowspan="6">O4</td><td rowspan="6">> 10</td><td></td><td>25 - 31</td><td></td><td>27 - 35</td><td>11</td><td>> 20</td></tr>
<tr><td rowspan="5"></td><td rowspan="5">> 31</td><td></td><td>35 - 40</td><td rowspan="5"></td><td rowspan="5"></td></tr>
<tr><td rowspan="4"></td><td>40 - 43</td></tr>
<tr><td>43 - 46</td></tr>
<tr><td>46 - 49</td></tr>
<tr><td>> 49</td></tr>
</table>

Figure 10. Tier 1 Vehicle Segmentation

Model 1	2b – 8 (77 Segments)	Technology	Battery Electric	Market	2020-2040

Class 3	Class 4	Class 5	Class 6	Class 7	Class 8
Bus	Bus	Bus	Bus	Bus	Bus
City Bus	City Bus	City Bus	City Bus	City Bus	City Bus
Construction Truck	Construction Truck	Construction Truck	Construction Truck	Construction Truck	Construction Truck
Emergency Truck	Emergency Truck	Emergency Truck	Emergency Truck	Drayage	Fire Truck
Motor Home	Motor Home	Motor Home	Motor Home	Fire Truck	Heavy Haul Truck
PickUp	PickUp	PickUp	PickUp	Long Haul Truck	Long Haul Truck
Refuse	Refuse	Refuse	Refuse	Motor Home	Motor Home
Regional Truck	Regional Truck	Regional Truck	Regional Truck	Refuse	Refuse
School Bus	School Bus	School Bus	School Bus	Regional Truck	Regional Truck
Shuttle Bus	Shuttle Bus	Shuttle Bus	Shuttle Bus	School Bus	School Bus
Step Van	Step Van	Step Van	Step Van	Shuttle Bus	Terminal Tractor
SUV				Step Van	Coach
Van Cargo				Terminal Tractor	

Table 7. Vehicle Type Definitions

SEGMENT	
Bus	Any other Bus that is used to transport people
Cargo Van	One-piece vehicle: Cargo area can be conveniently accessed from inside the vehicle for loading and unloading of cargo.
City Bus	City bus that operates within the city (also big bus, commuter bus, transit bus, town bus, urban bus, stage bus, public bus, or simply bus) is a type of bus used on shorter-distance public transport bus services.
Coach	Bus used for longer-distance service
Construction Truck	Heavy-duty vehicles used for heavy equipment or heavy machinery operations including utility work, specially designed for executing construction/ maintenance tasks, e.g., Dump/Cement Truck
Drayage	Drayage is the transport of goods over a short distance in the shipping and logistics industries. Drayage is often part of a longer overall move, such as from a ship to a warehouse.
Emergency Truck	Aa vehicle that is used by emergency services to respond to an incident. (e.g., ambulance)
Fire Truck	Trucks used to transport firefighters and their equipment — ladders, rescue gear, and power
Heavy haul Truck	Long distance heavy equipment transport tractor
Long haul Truck	Tractor Freight for long distance transport (transports materials and goods through the country)
Motor Home	A motorhome (or motor coach) is a type of self-propelled recreational vehicle (RV) which offers living accommodation combined with a vehicle engine.
Passenger Van	One-piece vehicle like Cargo van but with seats to transport people
Pickup	A pickup truck or pickup is a light truck having an enclosed cab and an open cargo area with low sides and tailgate.
Refuse	A garbage truck specially designed to collect municipal solid waste and transport it to a solid waste treatment facility, such as a landfill
Regional Truck	Delivery Truck, Box Truck, Furniture Truck, Delivery Truck, or Beverage Truck that runs in a specific area.
School Bus	Bus to transport Students to/from school
Shuttle Bus	A bus that travels regularly between two places (shuttles people from one main location such as (airport, hotels, convention center, or sports stadium) to one or more satellite locations).
Step Van	Walk-In Delivery Van
SUV	All use a car-based unibody design, typically an off-roading capable car, an SUV (Sports Utility Vehicle).

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