WHITE PAPER

GLOBAL SALES TARGETS FOR ZERO-EMISSION MEDIUM- AND HEAVY-DUTY VEHICLES—METHODS AND APPLICATION

Baha M. Al-Alawi PhD., CALSTART
Owen MacDonnell, CALSTART
Cristiano Façanha PhD., CALSTART

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LIST OF ACRONYMS

ACT	Advanced Clean Truck (regulation)
CARB	California Air Resources Board
COP 26	26th 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
NGO	Non-governmental Organization
OEM	Original equipment manufacturer
PF	Preference factor
PTO	Power take-off unit
U.S.	United States
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 global zero-emission medium- and heavy-duty vehicle (ZE-MHDV) sales targets through 2050 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.

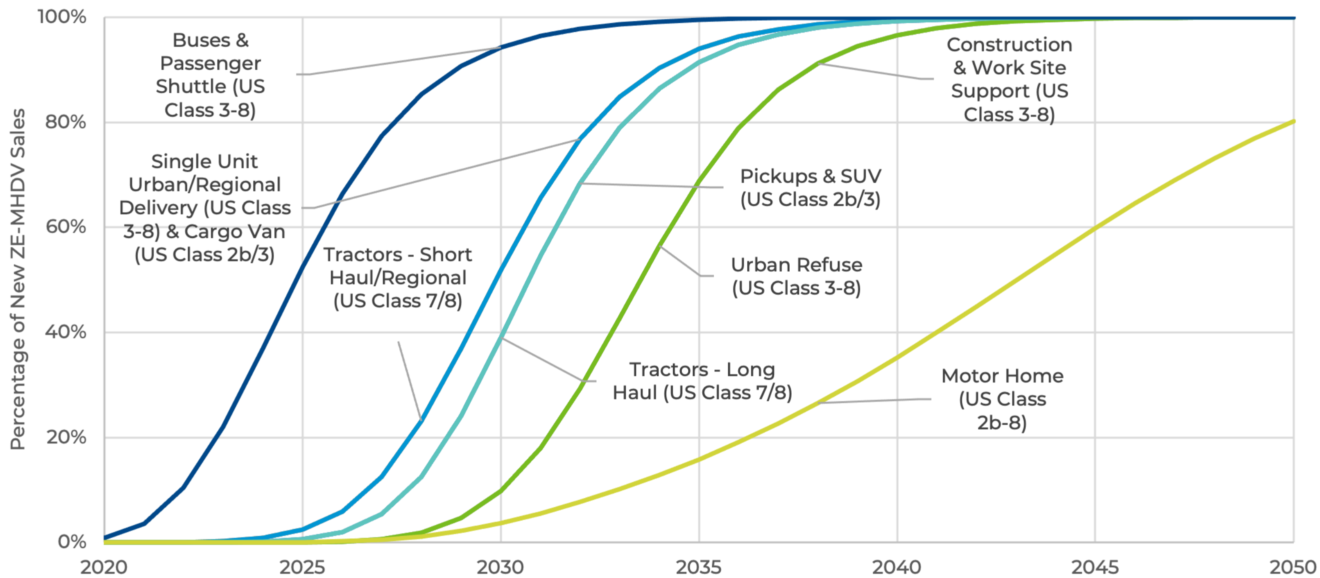
The projections outlined in this paper have been developed to meet the ambitions of a Global MOU for ZE-MHDVs, launched at COP26 in Glasgow in 2021. Led by the Dutch government and CALSTART, and signed by 15 countries, the MOU seeks to achieve 100% ZE sales of all MHDV segments by 2040, and an interim 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 across countries. The tool is an interactive and user-friendly input-output model that incorporates the beachhead strategy to forecast ZE-MHDVs in different regional markets by vehicle segments. The model uses five input parameters, namely: technology readiness, fleet bias, supply scalability, infrastructure availability, and fleet innovation profile.

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. The curves are modeled using the parameters 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 buses and passenger shuttles/vans, followed by single-unit trucks for urban and regional delivery and short/regional haul tractors, tailed closely by pickups/SUVs (Figure ES-1). These results reflect the timing for technology readiness of ZE technologies for different vehicle vocations, types and weights, and recognize that ZE technologies can be transferred across vehicle types as technologies evolve and costs decrease. Further along in the adoption timeline are more specialized vehicles like refuse and construction trucks, as well as mobile homes, all of which represent a relatively small, specialized share of MHDVs.

Figure ES-1. ZE-MHDV Sales Targets by Segment



These results illustrate global adoption pathways by vehicle segment, but do not differentiate by country. Acknowledging geographic 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. These projections are then applied to the United States (U.S.) as an example of how adopting the targets of the proposed Global MOU would impact ZE-MHDV volumes through 2050. Subsequent analyses could apply the projections to other countries beyond the U.S. if accurate and reliable data are 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. Implementing the ambition of the Global MOU and based on the ZE-MHDV sales targets in this analysis, 6.6 billion barrels of crude oil (~18 million barrels per day) and 812 million tons of GHGs would be avoided from the operation of new MHDVs sold in 2050.

The targets established by the Global MOU represent a critical first step in decarbonizing the global MHDV fleet, and its impact will be augment as new nations join the MOU and countries start turning the ambition into concrete policies. All nations must now accelerate efforts to decarbonize the heaviest polluters on the road. Implementing an ecosystem of conducive policies comprised of regulations that gradually increase in stringency, targeted and timebound incentives and infrastructure investments to enable the early introduction of regulations, and a suite of innovative policies like restriction zones or congestion pricing is vital at this stage and the only way to effectively drive progress across the world.

CHAPTER 1

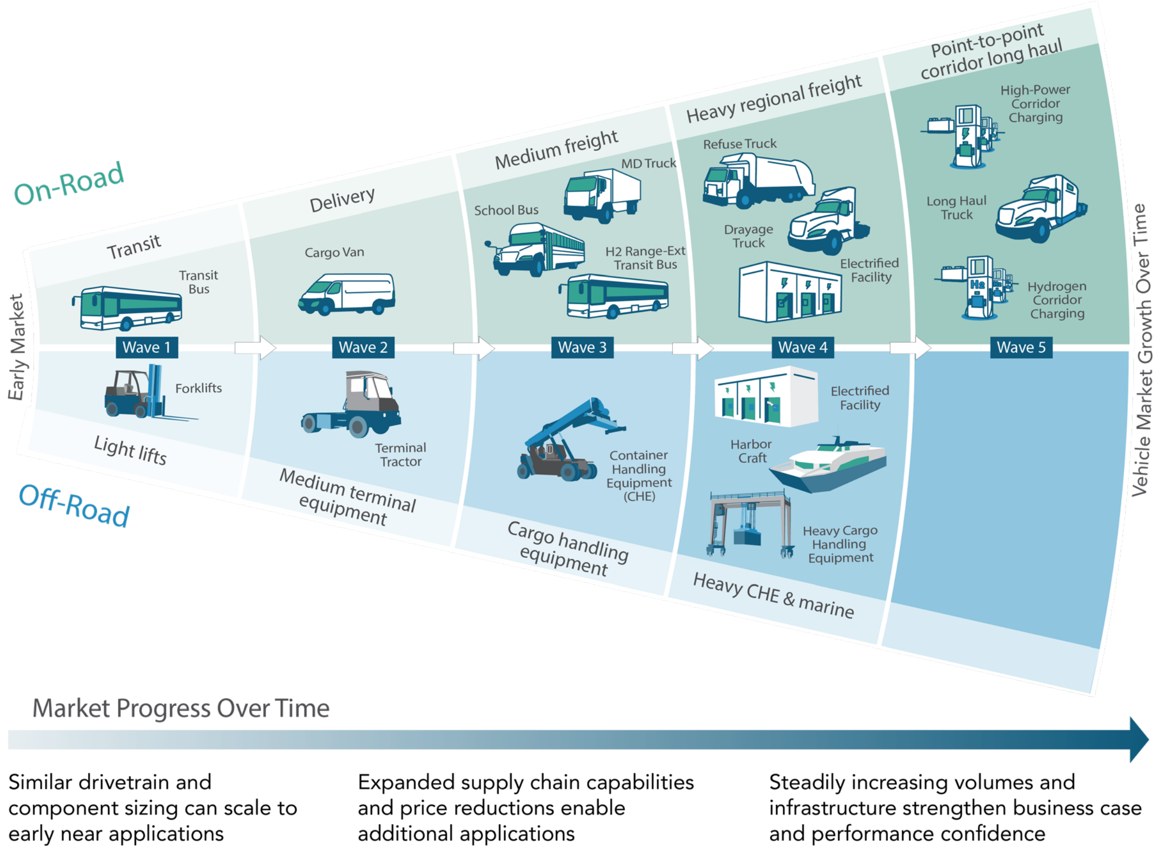
BACKGROUND AND MOTIVATION

Constituting only 4% of the global on-road vehicle fleet, MHDVs are responsible for roughly 36% of on-road fuel consumption, and upwards of 73% of NOx (CALSTART, 2020). 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. 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 the heavier vehicle segments. Awareness of ZE-MHDV technological capability and model availability lags what is being offered on the market today. 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, 2020b). Most cost analyses already predict that all ZE-MHDV applications will achieve cost parity before 2030.

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 1) (CALSTART, 2021a).

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 important GHG 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 MOU that establishes sales targets 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).

The announcement of California's ACT rule in 2020 was followed swiftly by an MOU between 15 other states in addition to the District of Columbia in the U.S., sending strong signals to manufacturers, fleets, and other regions that decarbonizing MHDVs is a top priority and one that is critical to mitigating impact on the climate and public health especially in disadvantaged communities (NESCAUM, 2020). At the time of writing, 5 out of the 15 states including New York, New Jersey, Massachusetts, Oregon, and Washington—together representing 20% of U.S. MHDV sales—have joined California and adopted the ACT rule at the state level (CALSTART, 2021c).

Government leadership toward ZE-MHDVs is also strengthened by industry ambition. 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. This alignment is necessary to accelerate the ZE-MHDV deployments globally. Table 1 below highlights the commitments made thus far by MHDV manufacturers, which align with the ambition of the Global MOU.

Table 1. Manufacturer Commitments to ZEV Sales and Carbon Neutrality (CALSTART, 2021)

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
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 segment-specific adoption curves for ZE-MHDV sales 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

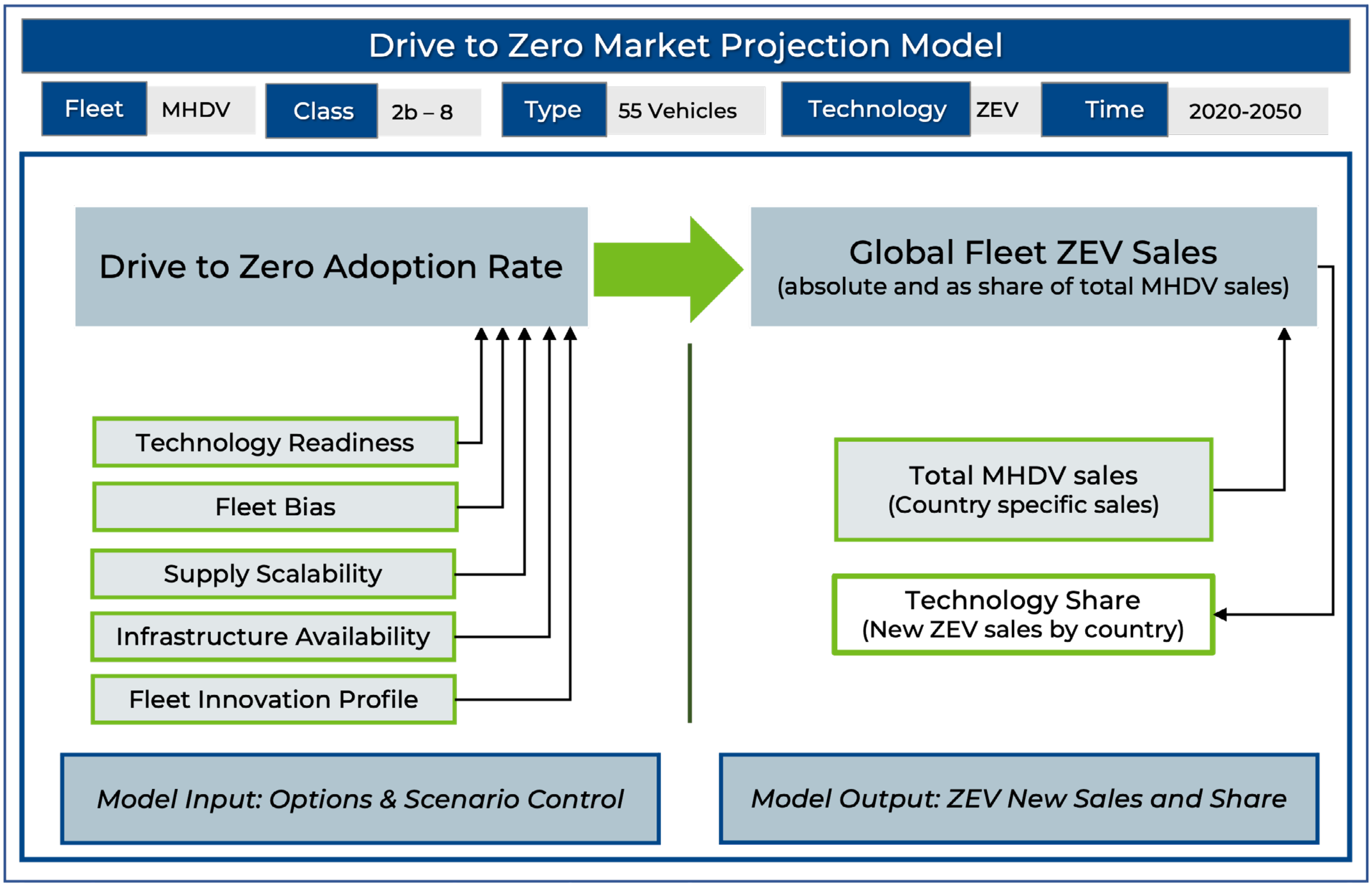
METHODOLOGY FOR ZE-MHDV SALES TARGET DEVELOPMENT

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 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 ZE technologies mature. For example, ZE 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 routes and return to depots for charging overnight. As ZE 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 model simulates decision makers' (fleet owners, manufacturers, and policy makers) technology adoption quantitatively and, where required, qualitatively.

Figure 2 illustrates the comprehensive analytical model components and interactions. The model estimates absolute ZE-MHDV sales and ZE share of total MHDV sales (outputs) between 2020 and 2050 by vehicle application (see Section 3: Results).

Figure 2. Drive to Zero Market Projection Model



The goal of these projections is to develop ambitious yet feasible targets for ZE-MHDVs, in terms of total sales and 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, fleet bias towards new technologies, and supply scalability for different vehicle segments.

Fleet decisions to acquire ZE-MHDVs are approximated quantitatively and qualitatively. Beginning with the projected total market size, the demand response is 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); and (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 due to lack of available data.

Table 2. Analytical Model Parameters

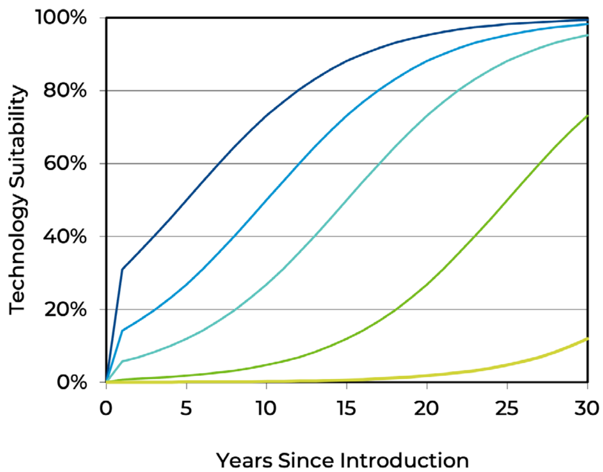
PARAMETER	DESCRIPTION
Technology readiness	Availability and suitability of the technology to an application, depending on technology, location, vehicle type, application, and timing.
Fleet bias	Individual fleet preference toward a new technology, considering its risk and reliability, and the time it 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 2 and described in greater detail in the following sections.

2.1. TECHNOLOGY READINESS

Technology readiness refers to the availability and suitability of the new technology to an application, dependent on technology, location, vehicle type, vocation, and timing. Each curve represents the share of the selected vehicle sales that are suitable for ZE technologies (Figure 3), based on the year when the technology is operationally suitable for 50% of the market in that segment.

Figure 3. Technology Readiness Curves and Parameter Options



OPTION	DESCRIPTION
Very high market	Technology is suitable for over 50% of the market after 5 years
High market	Technology is suitable for over 50% of the market after 10 years
Medium market	Technology is suitable for over 50% of the market after 15 years
Low market	Technology is suitable for over 50% of the market after 25 years
Very low market	Technology is suitable for over 50% of the market after 40 years

2.2. FLEET BIAS (LOGISTIC CURVE)

The logistic curve for fleet bias, or evolution of experience/risk/preference over time, represents the attitude of individual fleet owners toward new technologies. Fleets' attitude toward a new technology is critical in this assessment. It identifies the fraction of the market that a technology option could attain over time when its costs attributes (capital and operational costs) are equal to the baseline technology. To include this adjustment, a preference factor (PF) is integrated. This decimal value (between 0 – 1.0) captures positive or negative non-cost attributes and individual fleet owners' biases. This parameter specifies how attracted or averse a fleet owner is toward a new technology, resulting in a share of the market that the technology option would achieve if its cost attributes were identical to the baseline (Table 3). For example, a value of 0.5 is technology neutral, meaning 50% of the buyers would choose the alternative technology if it cost the same to buy and operate as the baseline vehicle. By contrast, a value of 0.3 is technology averse, meaning 70% of the buyers would choose the baseline technology if the cost were the same to buy and operate as the baseline vehicle.

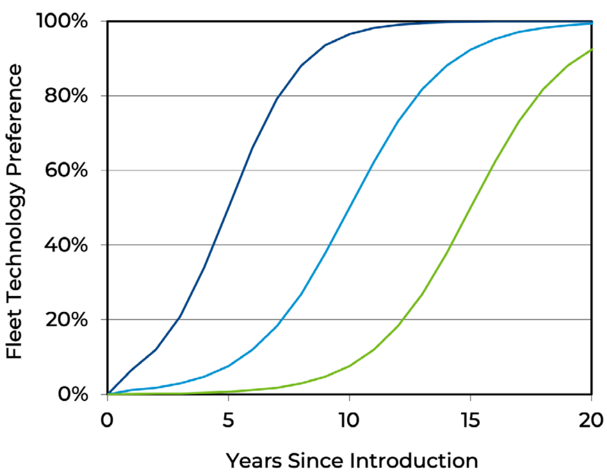
Table 3. Fleet Bias Preference Factor

SENTIMENT	PREFERENCE FACTOR (PF)
Technology neutrality	PF = 0.5
Bias against a technology	0 < PF < 0.5
Bias toward a technology	0.5 < PF < 1

The initial year and starting value for PF is specified by a fleet as well as the expected PF specified at a future point in time representing a fleet's willingness to acquire ZEVs as their familiarity and confidence grows with the new technology (Figure 4). In short, when a new technology is introduced to a market, in this case ZE-MHDVs, it takes a significant amount of time for fleet owners to build confidence in the new technology and its operational capacity. Therefore, irrespective of cost, individual fleets will adopt new technology faster or slower based on their experience, preference, and knowledge of benefits or risks associated with the operating and using ZEV technology.

Figure 4 includes three curves that indicate the time it takes for fleet owners to reach 50% purchase preference. As time progresses and fleets become more aware of the benefits of the technology, the PF will continue to increase and result in fleets' preference toward the new technology over the baseline technology. For example, following the accelerated scenario it will take fleet owners five years to reach 0.5 PF (50% fleet technology preference).

Figure 4. Fleet Bias Curves and Parameter Options

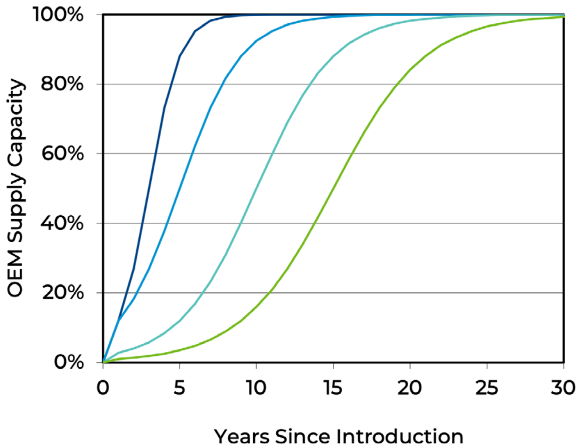


OPTION	DESCRIPTION
Accelerated	Option where technology attracts 50% of fleet owners after 5 years
Average	Option where technology attracts 50% of fleet owners after 10 years
Slow	Option where technology attracts 50% of fleet owners after 15 years

2.3. SUPPLY SCALABILITY

Original equipment manufacturers (OEMs) play a critical role in realizing the ambitions of the Global MOU and are positioned to benefit greatly from the shift to innovative ZEV technology. Supply scalability refers to how fast OEMs can scale up production of ZE technology, depending on their size, purchasing power, and manufacturing capacity. The model associates different levels of supply scalability with OEM types, which account for vehicle technology supply limitation under each vehicle segment. The OEM supply capacity and limitation is due to brand, size, market share, and financial position. Figure 5 below describes the input options for this parameter and the corresponding supply curve options.

Figure 5. Supply Scalability Curves and Parameter Options

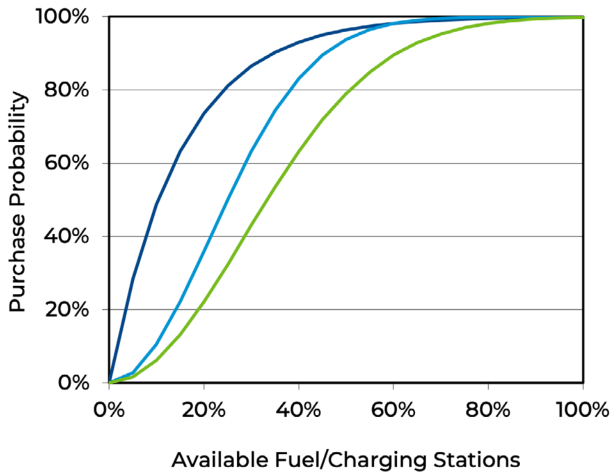


OPTION	DESCRIPTION
Very High	**Global OEM** (10,001-100,000 capacity), where OEM can supply 50% of new segment sales after 3 years
High	**National OEM** (1,001-10,000 capacity), where OEM can supply 50% of new segment sales after 5 years
Medium	**Emerging OEM** (101 -1,000 capacity), where OEM can supply 50% of new segment sales after 10 years
Low	**Startup OEM** (1 -100 capacity), where OEM can supply 50% of new segment sales after 15 years

2.4. INFRASTRUCTURE AVAILABILITY

Whether fleet owners rely on private or public charging/fueling, access to infrastructure is a significant factor in ZE-MHDV purchase decisions. This parameter is reflected in the model as three possible adjustment curves reflecting different levels of infrastructure availability (accelerated, average, slow). The curves in Figure 6 represent fleets' probability of purchasing a ZE-MHDV against the relative availability of refueling/charging stations. Refueling/charging station availability is a factor in fleets' decision to acquire ZEVs, but fleets are willing to invest in those technologies even with limited available refueling infrastructure. In short, the relationship between refueling/recharging availability and vehicle purchase decision is not one-to-one and fleets will acquire ZEVs even with limited infrastructure availability compared to the base case. For example, fleets are willing to purchase a technology at 70% availability even when refueling availability is 30-40% as compared to diesel fueling station availability. For the purposes of developing this analysis of strong ZE-MHDV targets, this analysis assumes that infrastructure is readily available and does not pose a constraint in fleet purchase decisions.

Figure 6. Infrastructure Availability Curves and Parameter Options

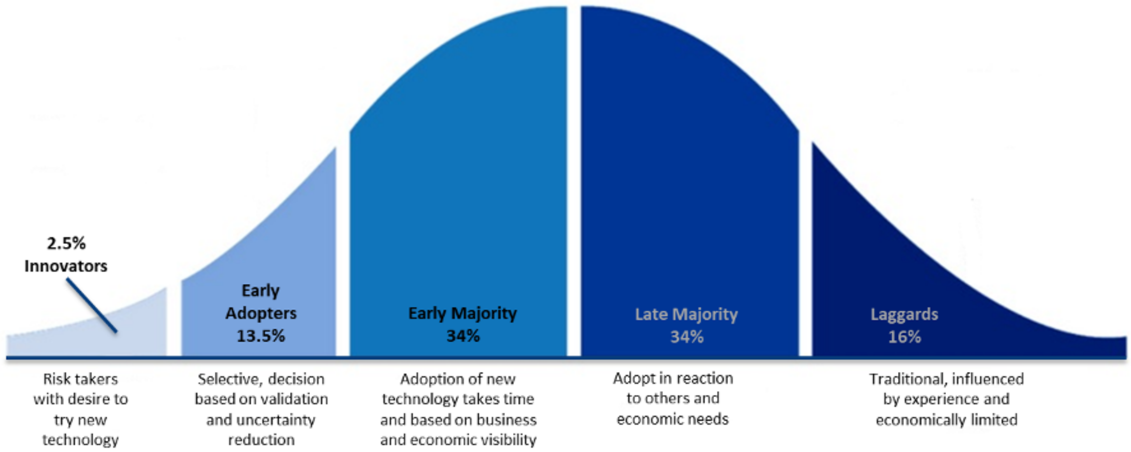


OPTION	DESCRIPTION
Accelerated	Fuel/energy is available at 50% after 3 years and 100% after 10 years.
Average	Fuel/energy is available at 50% after 9 years and 100% after 15 years
Slow	Fuel/energy is available at 50% after 15 years and 100% after 20 years

2.5. FLEET INNOVATION PROFILE

Fleet innovation profile refers to how quickly fleets, as a whole, will adopt a new technology, borrowing heavily from consumer behavior theory. Vehicle purchase decisions are not the same across fleets. While parameters described above have options that represent the behavior and decision-making of a spectrum of individual stakeholders, this parameter groups fleet owners into different profiles based on whether they are financially driven, technology driven, environmentally driven, and/or socially driven. This is distinct from the fleet bias parameter, which examines individual fleet decisions over time through the lens of experience and knowledge of the new technology and appetite for uncertainty/risk. This parameter allows for simulating different types of fleet behavior based on Rogers' innovation curve, which stratifies fleets/consumers in five groups: innovators, early adopters, early majority, late majority, and laggards (Figure 7) (Rogers, 1995). For example, the first buyers of a new technology that costs more than the baseline vehicle are grouped as innovators. Late majority and laggards represent those who buy when the technology is well established, similar, or provides more benefits as compared to the baseline vehicle. Although the model allows stratification of different innovation profiles based on a fleet's driving factor (where the result would ultimately be the combined penetration of each fleet based on its size) the assumption is that fleets will follow the target analysis at 100%, grounded in the ambitions of the Global MOU of 100% sales of ZE-MHDVs by 2040.

Figure 7. Fleet Innovation Profile (Rogers, 1995)



2.6. MHDV CLASSIFICATION

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

MHDV classification varies by country, typically based on vehicle type (e.g., automobile, bus, van, truck) and gross vehicle weight rating (GVWR). Examples of MHDV classification systems are presented in Appendix A. Because vehicle classification systems do not typically include vocation (i.e., how a vehicle is operated) and more detailed vehicle types, both of which heavily influence ZE technology applicability and suitability and thus ZE-MHDV adoption rates, this analysis also differentiates vocation.

This analysis and underlying model include different tiers of vehicle segmentation (Table 4). In the most aggregate classification system, vehicles can be categorized in three categories as light-, medium-, and heavy HDVs (Tier 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). The most common vehicle classification systems used worldwide resemble tier 3 and 4 which are not sufficient to identify specific vehicle vocations to accurately project global ZE-MHDV 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.

For this analysis, further segmentation is needed to assess the suitability of ZE 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) approach and the Beachhead theory of change (CALSTART, 2013) (CALSTART, 2020a). The most disaggregated tier (Tier 1) is only applicable where vehicle data are available on a model-by-model basis. Appendix A includes the definitions for all vehicle segments in Tier 1.

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 8 describes each vehicle category in tier 2 based on vehicle type, weight class, vocation, and technology applicability, and provides indicative models for each.

Figure 8. Vehicle Segmentation and Examples (Tier 2)

2.7. ZERO-EMISSION TECHNOLOGY PATHWAYS

This analysis considers ZEVs 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 section presents the projections for ambitious yet feasible ZE-MHDV sales targets, outlines the assumptions used for each parameter, and compares global projections with the first and only regulations for ZE-MHDVs, namely California's ACT and Innovative Clean Transit (ICT) rules. This section also provides a case study for how ZE-MHDV sales targets apply in the case of U.S., since there is sound, reliable available data. Finally, this section estimates the GHG and oil savings derived from the faster adoption of ZE-MHDVs (CALSTART 2020a).

3.1. ZE-MHDV SALES TARGETS BY VEHICLE SEGMENT

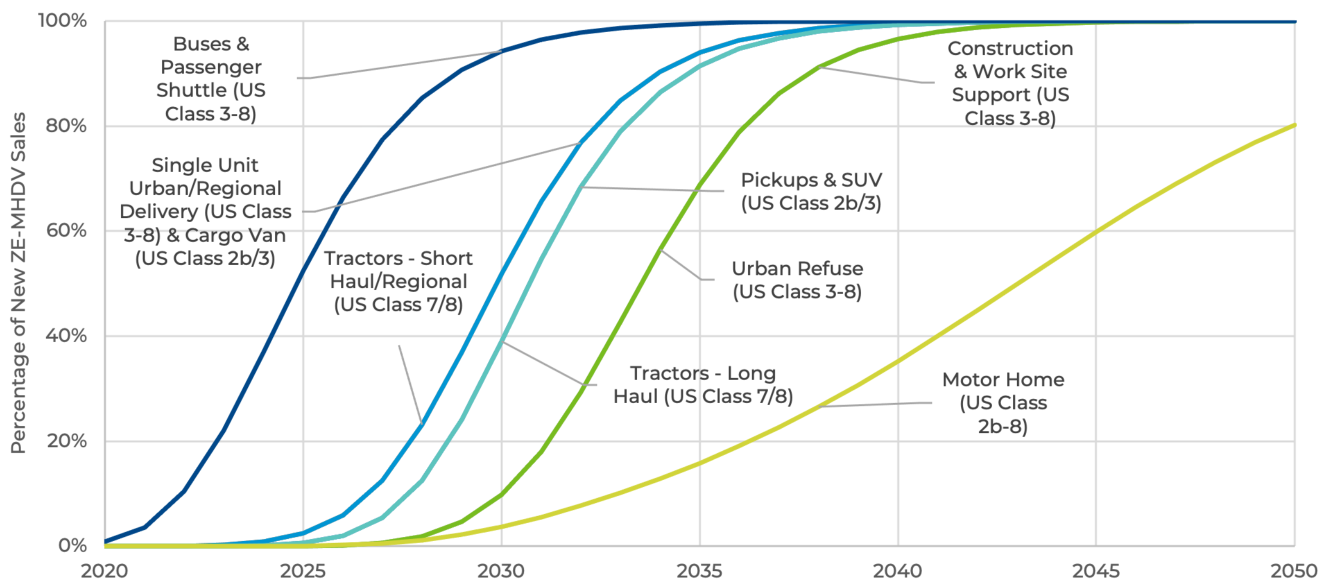
This analysis is grounded in the Beachhead theory of change as a framework for technological market acceleration and future trends on technology availability, fleet behavior, and supply growth options. This analysis applies parameter options for technology readiness, fleet bias, and supply scalability for each of the eight vehicle segments, based on current knowledge of technology readiness and model availability. 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. Target Scenario: High Adoption

VEHICLE SEGMENT	TECHNOLOGY READINESS	FLEET BIAS	SUPPLY SCALABILITY
Tractors - Long Haul (U.S. Class 7/8)	High Market	Average	High
Tractors - Short Haul/Regional (U.S. Class 7/8)	High Market	Average	High
Urban Refuse (U.S. Class 3-8)	Medium Market	Average	High
Single Unit Urban/Regional Delivery (U.S. Class 3-8) & Cargo Van (U.S. Class 2b/3)	Very High Market	Average	High
Construction & Work Site Support (U.S. Class 3-8)	Medium Market	Average	Medium
Buses and Passenger Shuttle (U.S. Class 3-8)	Very High Market	Accelerated	Very High
Pickups & SUV (U.S. Class 2b/3)	High Market	Accelerated	Medium
Motor Home (U.S. Class 2b-8)	Low Market	Average	Medium

ZE-MHDV sales targets over the eight vehicle segments (Figure 9) are derived based on the above control options. Results show early adoption for ZE buses and passenger shuttles and vans, reflecting how battery-electric buses have become commercially available from global and national OEMs with high acceptance by transit fleets in leading markets worldwide as the technology has matured and continues to prove its reliability.

Figure 9. ZE-MHDV Sales Targets by Segment



The gold curve in Figure 9 above shows the path for urban/regional delivery, short/regional haul trucks, and cargo vans all of which benefit from traveling along relatively shorter distances in urbanized environments and usually charge overnight at depots (like transit buses). In alignment with the Beachhead strategy these kinds of vehicles are the next best suited for deployment after buses due to their operational characteristics and duty cycle attributes. For regional delivery tractors, models are commercially available from national OEMs, but are just starting deployments in more specific applications where technology is operationally viable.

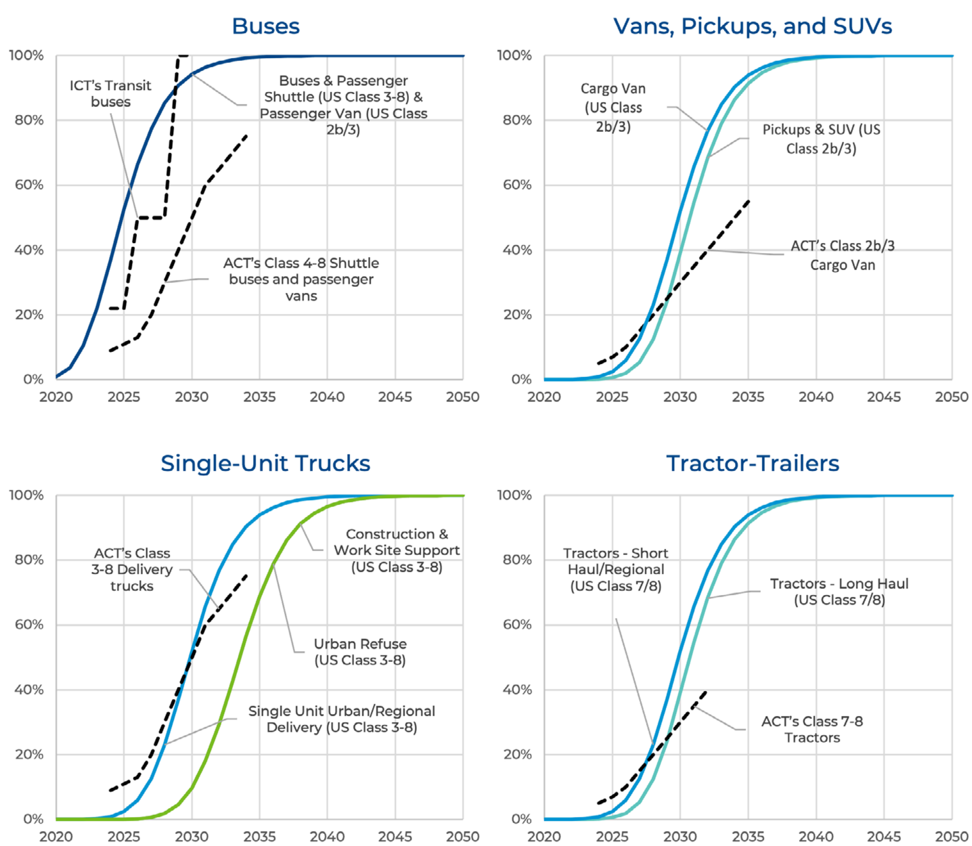
ZE long-haul tractor uptake follows slightly later, in line with pickups and SUVs. Available battery technology today is most suitable for regional haul and drayage applications due to available weight, range, and public infrastructure availability. In addition, fuel cell electric tractors, which offer ranges sufficient to meet long-haul applications, are not yet widely commercially available. Even so, optimism from OEMs globally is driving innovation in ZE long-haul trucks and there is indication that commercialization of this segment will happen more rapidly than expected.

Pickups are larger and heavier than the average light-duty vehicle, requiring more torque and energy relative to their size, adding greater cost due to the required battery capacity. ZE specialty vehicles (e.g., construction, refuse, fire, and emergency trucks) and motor homes have a relatively late start and slow adoption curves due to their lower production volumes and vocationally specific duty cycle to be designed around. Specialty vehicles span a wide range of drive cycles and applications, complicating technology readiness and fleets' perceptions of available models. These vehicles often haul very heavy loads and may have additional power requirements of a power take-off (PTO) unit. Motor homes (i.e., recreational vehicles) represent a small share of vehicles (4% of U.S. on-road Class 2b-8) but are very popular recreational and luxury vehicles in the U.S. and the United Kingdom. Due to their high base purchase cost, energy needs, and drive cycle, electrification will take longer to become suitable for electrification.

3.2. COMPARISON OF GLOBAL SALES TARGETS TO CALIFORNIA'S ACT AND ICT REGULATIONS

This section compares the projected ZE-MHDV global adoption rates with California's ACT and ICT regulations to compare the level of global ambition with a U.S. state that has already adopted the regulations and incentives to accelerate the ZE-MHDV market. Although the ZE-MHDV projections outlined by Figure 9 are ambitious, they are generally aligned with the stringency of California's ACT and ICT regulations (Figure 10). In the case of buses, the global curves are more ambitious and rely on the latest information regarding ZEB model availability and operational performance. For single-unit trucks, the global curve is consistent with ACT, with the exception of specialty vehicles (e.g., construction, refuse, fire, and emergency trucks), since they represent a relatively small share of vehicle sales of class 4-8. For cargo vans, pickups, SUVs, and tractor-trailers, the global curves enable a slightly later start but faster adoption rates compared to the ACT.

Figure 10. Comparison of Global ZE-MHDV Sales Targets with California's ACT and ICT Regulations

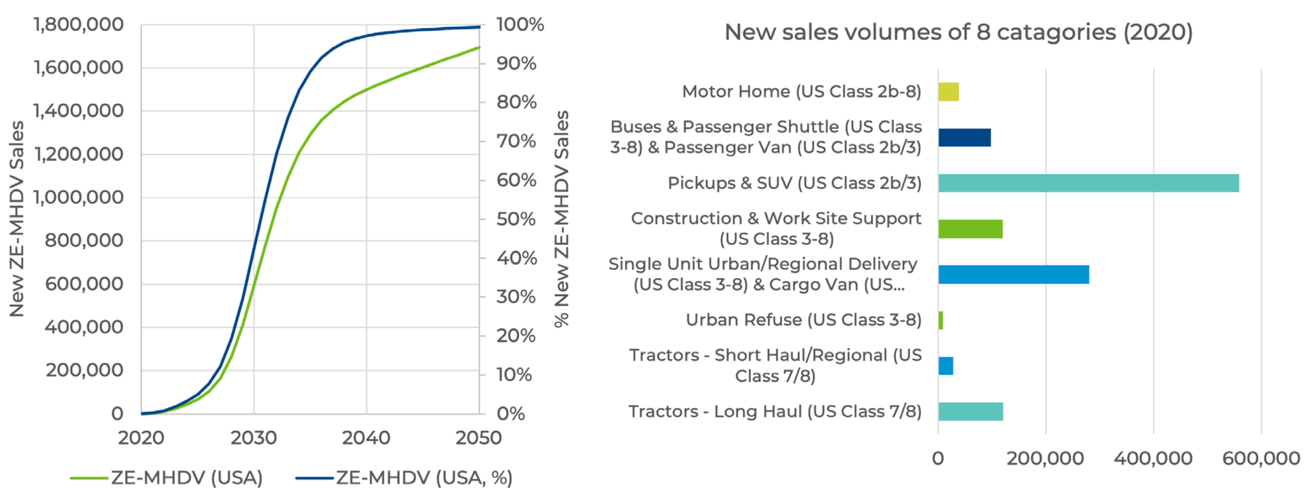


3.3. REGIONAL APPLICATION – U.S. CASE

As different regions evaluate sales targets for ZE-MHDVs, it is necessary to consider current and future vehicle sales by segment, so that the segment-specific curves in the previous section can be combined in more aggregated categories. This section applies the target curves by segment to the U.S. market and estimates future ZE-MHDV sales through 2050. The projections in this analysis assume a rapid but feasible transition to ZE-MHDVs, driven by massive investments in battery-electric charging and hydrogen fueling infrastructure, reductions in the incremental costs of ZEVs, and the rapid scaling of ZE-MHDV production by manufacturers.

Considering current MHDV sales data in the U.S. in 2020 (Figure 11, right panel) and assuming the same growth factor for all segments though 2050, a single adoption curve can be derived (Figure 11, left panel). In the left panel the blue curve illustrates the progression of the annual sales of new ZE-MHDVs, with the orange curve highlighting the corresponding percentage of the total U.S. MHDV fleet those new sales represent.

Figure 11. Aggregated ZE-MHDV Target Sales and Sales Shares in the U.S. (left) and New Sales of MHDVs in 2020 (right)



By understanding the current market breakdown of MHDVs by the 8 categories this analysis deploys, and using the projections derived from this analysis (Figure 9), the absolute volumes of ZE-MHDVs sold in the U.S. through 2050 can be attained (Table 6).

Table 6. ZE-MHDV Target Sales by Segment

	2020	2025	2030	2035	2040	2045	2050
Tractors - Long Haul (U.S. Class 7/8)	0	778	52,690	129,632	147,858	156,461	164,533
Tractors - Short Haul/ Regional (U.S. Class 7/8)	1	723	16,206	30,858	34,325	36,245	38,106
Urban Refuse (U.S. Class 3-8)	0	5	980	7,279	10,724	11,634	12,258
Single Unit Urban/Regional Delivery (U.S. Class 3-8) & Cargo Van (U.S. Class 2b/3)	16	7,242	162,315	309,074	343,830	363,080	381,746
Construction & Work Site Support (U.S. Class 3-8)	0	76	13,018	96,667	142,461	154,565	162,879
Buses & Passenger Shuttle (U.S. Class 3-8) & Passenger Van (U.S. Class 2b/3)	887	54,676	103,153	114,504	120,890	127,102	133,587
Pickups & SUV (U.S. Class 2b/3)	3	3,597	243,351	598,717	682,909	722,651	759,937
Motor Home (U.S. Class 2b-8)	0	36	1,590	7,161	16,766	29,906	42,129
	907	67,133	593,303	1,293,892	1,499,763	1,601,644	1,695,175

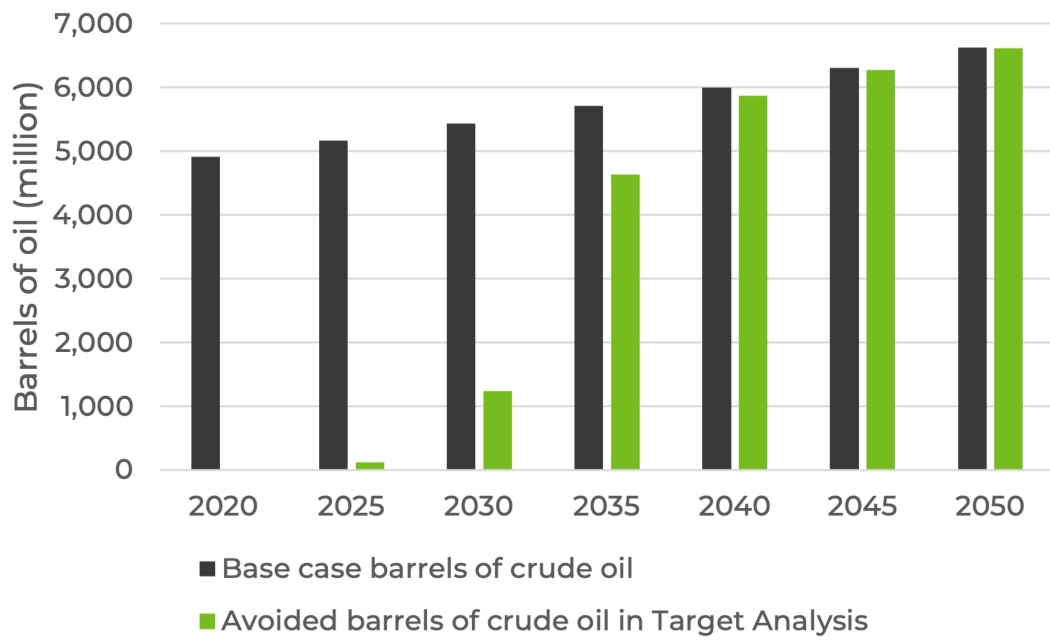
This table highlights the annual ZE-MHDV sales through 2050 by segment, indicating the highest sales for class 2b and 3 (ZE pickups/SUVs and delivery trucks), due to their high sales volumes compared to other MHDV segments (Figure 11, right panel). The result in Table 6 will look different depending on the country examined and that country's MHDV fleet composition and sales volumes.

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

This section estimates expected annual oil consumption and GHG emissions 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 each country/region to calculate total avoided oil consumption. The analysis also assumes tailpipe CO2 and GHG[1] emission factors per unit of diesel fuel consumed, namely 0.010228 tons of CO2 and 0.01035 GHG produced per gallon of diesel (Argonne National Laboratory, 2020).

Based on the global ZE-MHDV sales targets in this analysis, 6.6 billion barrels of crude oil (~18 million barrels per day) and 813 million tons of GHGs would be avoided from the operation of new ZE-MHDVs in 2050. The black bars (base case) in Figure 12 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 12. Global Annual Avoided Barrels of Crude Oil from Operation New ZE-MHDV Sales



1 GHG emissions include: (CO2) carbon dioxide, (CH4) methane, (NOx) oxides of nitrogen, (VOC) volatile organic compounds, (CO) carbon monoxide, (BC) black carbon, (OC) organic carbon

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.

Region-specific analyses should be developed to allow for more informed planning and targeted policy action. 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. While the scenario modeled in this analysis is global by design, the applicability of the model to a specific region is demonstrated in Section 3.3. By adapting the global curves to specific regions, 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).

Tracking progress towards ZE-MHDV policies and adoption is a vital part of the transition. A way of documenting and centralizing country-specific vehicle model availability, policy targets, regulations, incentives, and other innovative policy is needed to highlight successes and difficulties certain countries are facing. By highlighting the policies that work, and understanding how certain regions have navigated barriers, the industry has the capacity to move much faster. There are numerous available resources currently published that assist in tracking the criteria described above, however, the recently launched Progress Dashboard tool provides a centralized interface for policy overview by country related to ZE-MHDV adoption (CALSTART, 2021d). The Zero-Emission Technology Inventory (ZETI) is another tool that has been developed to help fleets, manufacturers, and governments understand what vehicles are available globally (CALSTART, 2022). The tool takes inventory of all ZE-MHDV models across countries and collects key specs for each vehicle. In turn, this allows for summary data to be compiled on figures like average estimated range, payload, and counts of vehicles specific to a certain segment. While these tools indicate the progress made so far, they must continue to be developed and expanded upon.

APPENDIX

Table 7. Global MHDV classification, weight in 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 13. More disaggregated vehicle segmentation (Tier 1)

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 8. Vehicle Type Definitions (Tier 1)

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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