White Paper

Methods for Assessing Technology and Market Readiness for Clean Commercial Transportation

October 2023

Acknowledgments

This report will be updated on a periodic basis in support of the publication of the California Air Resources Board's Appendix D: Long-Term Heavy-Duty Investment Strategy. A previous version of this report was published in October 2022.

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List of Acronyms

Acronym	Definition
ACF	Advanced Clean Fleets regulation
ACT	Advanced Clean Trucks regulation
CARB	California Air Resources Board
CORE	Clean Off-Road Equipment Voucher Incentive Project
EnergIIZE	Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles Project
HDIS	Appendix D: Long-Term Heavy-Duty Investment Strategy
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
ICT	Innovative Clean Transit regulation
IRA	Inflation Reduction Act
MHD	Medium- and heavy-duty
MRI	Market readiness indicator
MSRP	Manufacturer's suggested retail price
MY	Model year
LCFS	Low Carbon Fuel Standard
OEM	Original equipment manufacturer
TCO	Total cost of ownership
TRL	Technology readiness level
ZE	Zero-emission
ZETI	Zero-Emission Technology Inventory

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Executive Summary

CALSTART and the California Air Resources Board (CARB) conduct yearly assessments to analyze the technology status and market progress of zero-emission medium- and heavy-duty (MHD) vehicle and equipment technologies. This document aims to build an understanding of the methods and process used to create and update these assessments, known as technology status and market readiness snapshots. These snapshots are key to the development and direction of successful incentive policy and regulation. CARB utilizes the insights derived from these snapshot updates each year to calibrate and inform MHD vehicle and equipment funding recommendations. The approaches detailed in this report are enacted, reviewed, and modified (if necessary) by CALSTART and CARB every year prior to the publication of CARB's Appendix D: Long-Term Heavy-Duty Investment Strategy (HDIS).

In combination, the technology status and market readiness snapshots depict a comprehensive view of clean commercial vehicle and equipment platform performance and readiness for the marketplace:

- Technology status snapshots assess the maturity level of a particular technology, determining viability primarily from technological performance. CALSTART and CARB use technology readiness levels (TRLs) to score four categories that currently include applications for both on- and off-road platforms for battery-electric and fuel cell electric vehicles and equipment. Within these four categories, platforms receive individual TRL scores measured on a scale from "1" to "9," with 9 being a commercially mature application. TRL scores are then visualized as graphics that are published in CARB's HDIS each year.
- Market readiness snapshots help describe a platform's viability for success with respect to market or economic factors that could impede development or adoption. Technology platforms that have reached a TRL greater than 8 are evaluated against the following seven market readiness indicators (MRIs): production capacity, workforce/service network, cost parity (with and without incentives), duty cycle capability, supply chain, and infrastructure. The supply chain indicator is currently used only for on-road platforms. Platforms receive an MRI score of 0, 25, 50, 75, or 100 percent, which are then visualized as graphics in CARB's HDIS.

The ultimate purpose of these technology and market snapshots is to provide valuable context for agencies that can influence vehicle and equipment markets through incentives or regulations. Incentive programs have used technical and market assessments to support funding and clean vehicle and equipment deployment goals. This approach helps to ensure that the requirements for production and/or adoption mandates align with both technologically mature and market-ready vehicle and equipment applications, setting up manufacturers and fleets for success. Example assessments are included in this paper to illustrate the methods and process but are not intended as a full summary of all sectors, applications, and technologies.

I. Introduction

To help track the status and progress of the emerging market for clean medium- and heavy-duty (MHD) vehicle and equipment technologies, CALSTART and the California Air Resources Board (CARB) conduct technology and market readiness assessments on a yearly basis. This document aims to build an understanding of the methods and process used to create and update these assessments, which are included each year in CARB's Appendix D: Long-Term Heavy-Duty Investment Strategy (HDIS).[1] The State of California's goals to improve air quality are directly tied to fostering and supporting a self-sustained market for zero-emission (ZE) and ZE-enabling vehicles and equipment. Several technology and market-based hurdles currently hinder this development. To help accelerate the viability of clean MHD vehicles and equipment, CARB has implemented ambitious market and regulatory actions that are guided by rigorous analysis and exploration of market and technology factors. Such analyses and exploration of the market progress and technology status of MHD vehicles and equipment are vital to the development and direction of incentive policy and regulation. These yearly assessments, known as technology status and market readiness updates, or "snapshots," help ensure that vehicle and equipment technology platforms receive appropriate CARB funding.

These assessments each describe distinct maturity levels in the commercialization process for clean vehicle and equipment applications. Technology status snapshots track the reliability and progress of separate vehicle and equipment applications from the early-market testing and demonstration phase through the market readiness stage. This process sets a specific numerical score, known as a technology readiness level (TRL), to each application in order to track technology commercialization progress. Market readiness snapshots provide a more complete picture of an application's commercialization status within a complex market. This status can be assessed by considering seven major market readiness indicators (MRIs): production capacity, workforce/service network, cost parity (with and without incentives), duty cycle capability, supply chain, and infrastructure.

[1] For more information on CARB's "Appendix D: Long-Term Heavy-Duty Investment Strategy," visit https://ww2.arb.ca.gov/sites/default/files/2023-10/fy2023-24lctfundingplan_appd.pdf.

Creating standardized, numerical assessments for technology and market readiness provides consistent viability scorecards to enable effective incentive programs and regulatory action. This report aims to break down CARB and CALSTART's methodologies for determining TRL scores and visualizing the results in snapshots (Section II); describe the seven market readiness categories and how each indicates a platform's viability for success (Section III); and highlight examples of both incentive programs and regulations that have been supported by these assessments (Section IV). Appendix A: TRL Scoring Rubric provides a copy of the rubric utilized by CALSTART and CARB's internal team of subject matter experts during the TRL scoring process. Appendix B: Market Readiness Scoring Rubric On-Road provides tables detailing the scoring criteria for each MRI for on-road platforms. Finally, Appendix C: Market Readiness Scoring Rubric Off-Road provides tables detailing the scoring criteria for each MRI for off-road platforms.

II. Technology Status

A clean commercial technology's path to commercialization can be understood first and foremost by a technology status snapshot. The goal of these technical assessments for MHD vehicle and equipment applications is to determine a platform's viability primarily from its technological performance. As such, technology status snapshots provide directional guidance, but not precise measurements, on a technology's readiness for commercialization. Status updates for MHD vehicles and equipment illustrate overall technology progress, lending insight to the type of additional development or funding that could further support and accelerate the market for each application. They assist in determining appropriate research, development, or deployment investments to further encourage vehicle and equipment adoption or to help certain technologies or platforms that face more difficult adoption barriers by providing point-in-time evaluations. CARB therefore utilizes these assessments to ensure the continued effectiveness of its policies and investments as described in its HDIS.

To quantitatively assess a vehicle or equipment's technology status, CALSTART and CARB use TRLs, a type of measurement system NASA devised to determine the maturity level of a particular technology it had pioneered. CALSTART and CARB have adapted NASA's general methodology by applying this scoring process to an entire MHD vehicle or equipment platform, rather than a single component or technology system. CALSTART and CARB use TRLs to score four categories, though these categories have changed over time. These categories currently include vehicle and equipment applications for both on- and off-road:

- On-road battery-electric
- On-road fuel cell electric
- Off-road battery-electric
- Off-road fuel cell electric

Within these four categories are vehicles and equipment that receive individual TRL scores. For example, the on-road battery-electric category currently includes the following platforms:[2]

- Heavy-duty long haul
- Heavy-duty urban/regional/drayage
- Medium-duty truck
- Step van
- Shuttle bus
- School bus
- Transit bus
- Coach bus
- Cargo van
- Refuse truck
- Work truck

TRLs are measured on a scale from "1" to "9," with 1 defined as platforms with scientific evidence for potential innovation and 9 defined as a fully commercially available application. The definitions and general technology level of each TRL score are detailed in Appendix A: TRL Scoring Rubric. This scoring rubric is provided to industry experts to conduct the yearly TRL scoring assessments, which include review of additional or updated data and information from literature, public information sources, conversations with technology providers, and field data where available. Once a platform has received a TRL score of 8 or higher in consecutive years, it is deemed technologically mature and will receive only the market readiness assessment going forward. The approach detailed below is enacted, reviewed, and modified (if necessary) by CALSTART and CARB every year prior to HDIS publication. These scores do not influence market readiness scores.

Technology Readiness Scoring Methodology

1. Determining a TRL score begins with the internal CALSTART and CARB team, which consists of subject matter experts with expertise in at least one vehicle or equipment segment. This team develops a comprehensive list of vehicles and equipment for consideration that fall within a particular TRL platform.
2. Members of the internal CALSTART and CARB team assess and record each vehicle or equipment's capabilities and development progress. Factors such as economic or market challenges are not included in TRL scoring, as these characteristics contribute instead to market readiness.

[2] Definitions for these platforms can be found in the Vehicle and Equipment Classification Descriptions of the Fiscal Year 2023-24 HDIS; see https://ww2.arb.ca.gov/sites/default/files/2023-10/fy2023-24lctfundingplan_appd.pdf

3. Once the individual vehicle and equipment assessments are compiled, internal industry experts score the technologies according to the scoring rubric (Appendix A). Each industry expert scores all technologies as applicable to individual expertise. A discussion is then held to calibrate results and rectify any significant discrepancies in the scoring.
4. Once each score has been vetted by industry experts, the impact each vehicle and/or equipment model has on the entire TRL platform is weighted based on a manufacturer multiplier, which gives a higher weighting to platforms from companies that have larger market penetration and demonstrated ability to ramp up production, as well as a model longevity multiplier, which gives higher weighting to models that have been on the market longer. These weighted factors are preferable to a simple average: early-stage vehicles and equipment do not define the entire status of a platform. Further, vehicles and equipment that have not made as much commercialization progress still impact the overall status of a platform. For instance, a model from a vertically integrated global original equipment manufacturer (OEM) receives more weight than a model from a start-up manufacturer. A model that has been available since 2020 receives more weight than a model that is new to market in 2023. This approach enables a more realistic assessment of a platform's overall technical and commercial readiness. TRLs are therefore displayed as the general aggregated score of assessed and weighted scores within a platform. In doing so, this approach may result in a platform receiving a score of 7 or 8 (i.e., entering the pilot stage) while some models from certain manufacturers in the platform may already be in commercial production.
5. Once the TRL score for each platform is determined, the results are visualized in snapshot graphics, which are described in the next section.

Technology Status Snapshots

Graphics depicting TRL scores are developed and published in CARB's HDIS for each of the four vehicle and equipment categories listed above.[3] Each graphic contains the following elements, which may have changed over time from previous iterations of CARB's HDIS.

- The x-axis follows the TRL scores from 5 to 9. Platforms in the early demonstration stages are shown on the left, and those closer to commercial readiness are shown on the right. There is a blue gradient from 8 to 9 to represent the stage of early market entry, as any technology that falls within that range will be assessed for market readiness.
    - It should be noted that the x-axis begins at 5, rather than 1, as any platform receiving a TRL score of 1 through 5 would not be ready for demonstration projects. For the purposes of CARB's HDIS, applications are characterized in terms of three general stages on the path to commercialization: demonstration, pilot, and commercial.
- The current weighted status of each platform is shown by a triangle shape, while its status in the previous year—if rated the previous year—is represented by a circle.

Current examples from the Fiscal Year 2023–24 HDIS are shown on the following page (Figure 1 and Figure 2).

The Readiness Gradient

When a platform reaches a TRL of 8 or above, it enters the "Readiness Gradient Area." This area is denoted as a gradient shaded area on the technology status snapshot graphic and signifies that the technology is beginning to reach a level of maturity where market factors—not just technology factors—will play a major role in its overall viability. When a technology's current year TRL enters this gradient, the platform is ready to be assessed for market readiness and will most likely require more nuanced or tailored incentive strategies to further deepen adoption in the industry.

[3] For matters of formatting and legibility, the off-road battery-electric technology snapshot was split into three separate graphics in the Fiscal Year 2023–24 HDIS, grouped by application type.

Figure 1. Technology Status Snapshot Example: Off-Road Fuel Cell Electric (CARB, 2023)

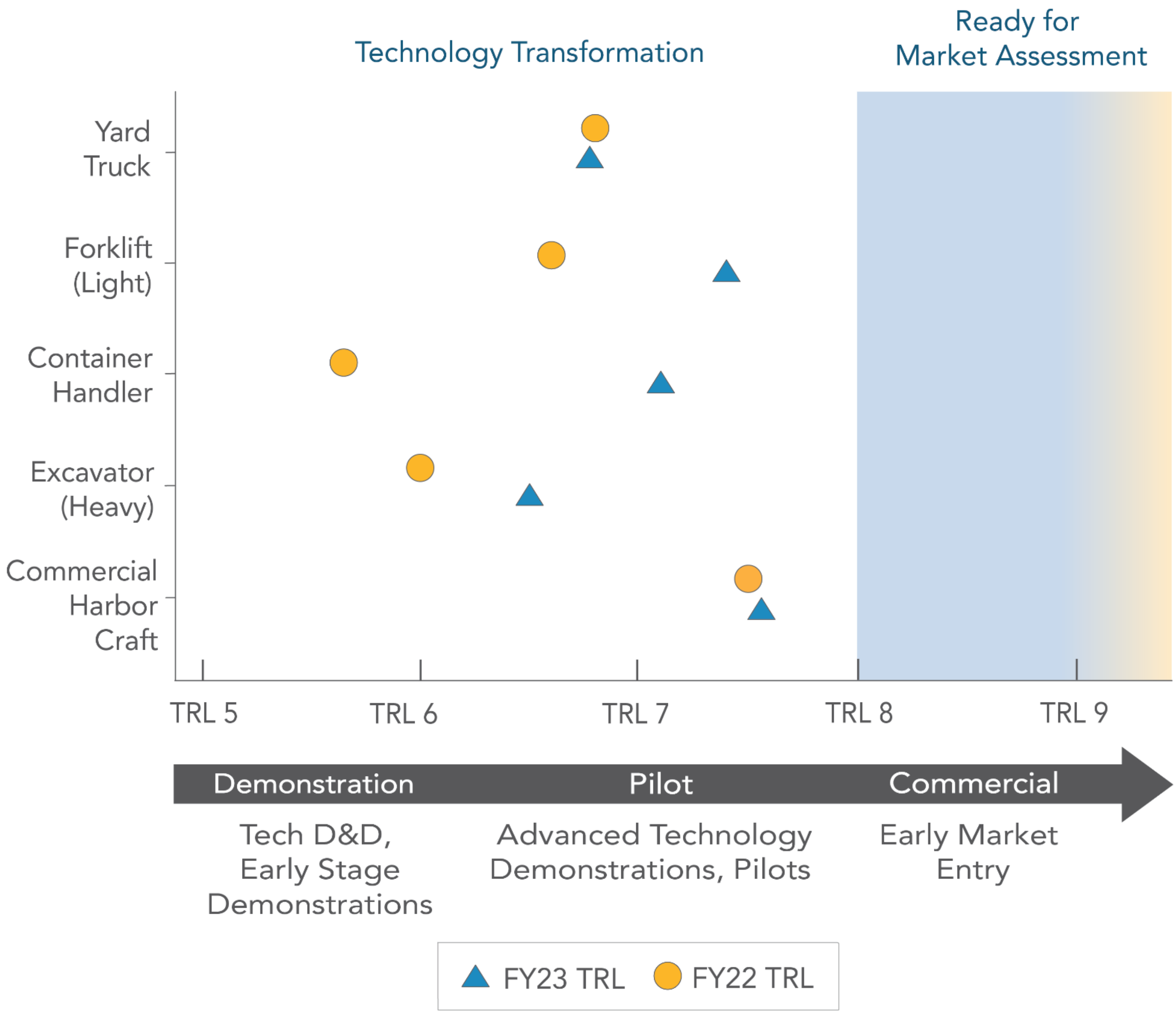
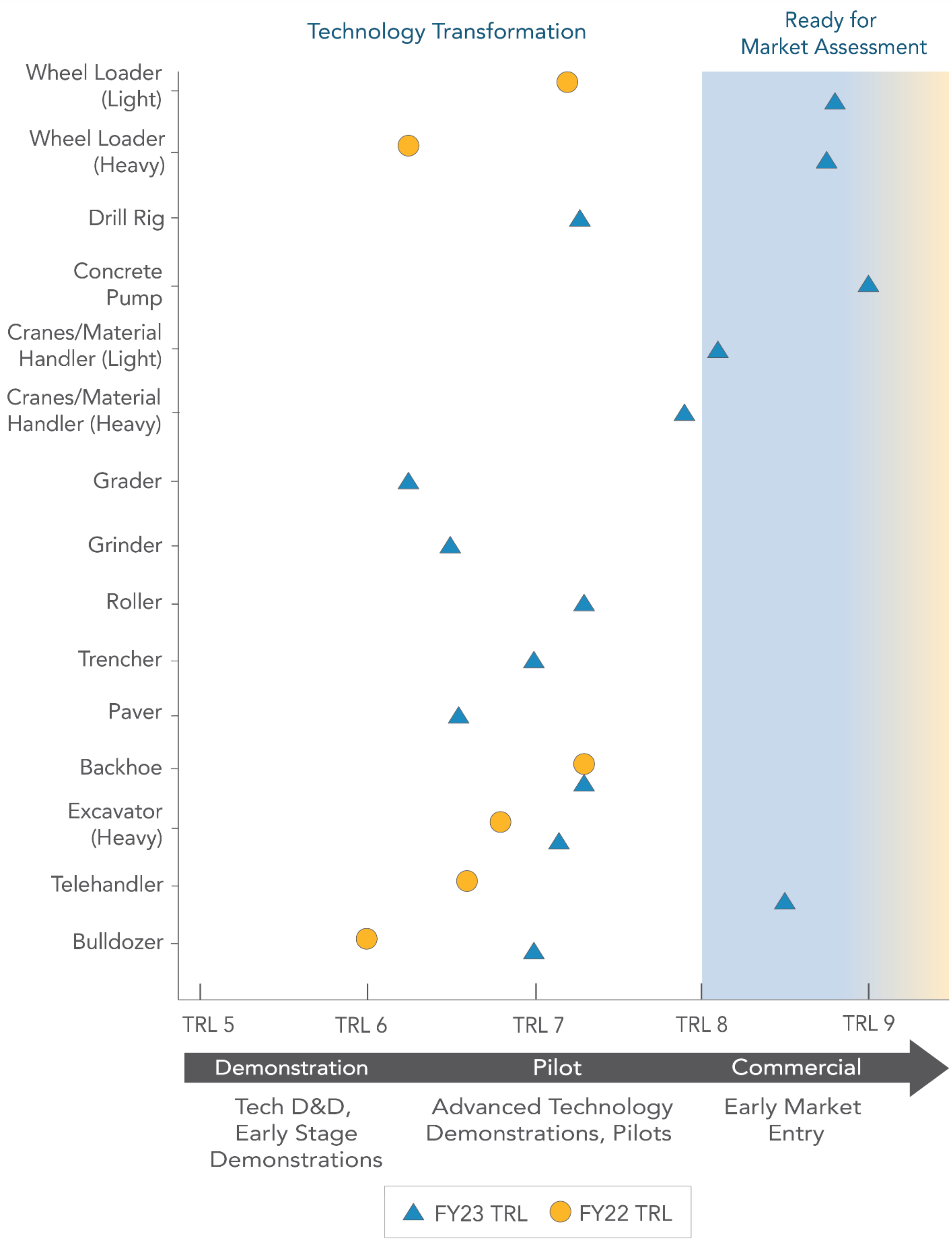


Figure 2. Technology Status Snapshot Example: Off-Road Battery-Electric: Construction (CARB, 2023)



III. Market Readiness

Market readiness describes the viability of a platform to succeed when addressing production or economic factors that could impede the development or adoption of a platform. Similar to technology status snapshots, which constitute a comprehensive TRL numerical score, market readiness snapshots provide a score for a vehicle or equipment's attainment of certain market attributes. A technology likely has strong market viability when it attains a high score in all seven overarching market readiness categories (production capacity, workforce/service network, cost parity (with and without incentives), duty cycle capability, supply chain, and infrastructure) as determined by internal subject matter experts at CARB and CALSTART. If a technology has yet to attain high scores in all seven categories, then the technology may still require assistance from incentives or other market development mechanisms to succeed. CARB utilizes the insights derived from market readiness snapshots completed by the internal team to calibrate and inform MHD vehicle and equipment funding recommendations.

Market Readiness Scoring Methodology

Similar to the TRL methodology, the market readiness scores begin with refining scoring rubrics annually (if necessary) that create relative thresholds for each of the seven indicators. The rubrics are determined by internal CALSTART and CARB subject matter experts. The thresholds are scaled from 0–100 percent in increments of 25 for each indicator. Each technology platform that received a score greater than 8 in the TRL assessments is scored along each indicator. The indicators are scored independently of each other. For example, an OEM may have the ability to manufacture 20,000 vehicles a year but due to supply chain constraints is unable to produce that volume. In such a case, the production capacity score would be evaluated independently of any supply chain issues.

Members of the internal CALSTART and CARB team gather relevant data, assess, and record the scores for each vehicle or equipment segment's market readiness according to the scoring rubrics, which are found in Appendix B: Market Readiness Scoring Rubric On-Road and Appendix C: Market Readiness Scoring Rubric Off-Road. The scoring of the indicators for each vehicle or equipment type is not an exact measurement, and these scores can fluctuate year to year based on how the market progresses. The process of scoring each indicator is outlined below.

Production Capacity

This category estimates the current and future manufacturing capacity of an on- or off-road technology segment, where zero represents production limited to pilot/demonstration vehicles, while 100 percent represents the case where multiple OEMs have begun serial production at relatively high volumes and are positioned to meet the entirety of current internal combustion market demand in the next one to five years. This metric also weighs absolute production capacity against the total market size of a technology platform. For instance, although the total industry production capacity for ZE rubber-tired gantry (RTG) cranes is extremely low compared to on-road vehicles, it is much larger compared to the total annual market size for RTG cranes. Data used for this indicator is acquired through OEM surveys about current and future annual production by vehicle type. For OEMs that do not respond to the survey, publicly available information about production capacities and estimations based on current delivery numbers are used. Information for on-road vehicles is compared to the expected California demand based upon the Advanced Clean Fleets (ACF) regulation[4] and the current registrations of all MHD vehicles in the state. Information about off-road is compared against current market size determined by publicly available data and industry experts weighing in to fill in the gaps.

Workforce/Service Network

Workforce/service network measures the existence and accessibility of a workforce for maintenance and repair of ZE vehicles and equipment. A score of zero corresponds to the case where no service network is available through an OEM, dealer, or independently in California. A score of 100 percent corresponds to the case where a developed service network exists that is geographically distributed to serve demand; there are no wait times significant enough to inhibit uptime of the vehicles and equipment. Data used for this indicator includes OEM survey responses about maintenance training program offerings (often exclusive to customers) and certified dealerships in California, internal research about workforce development programs for ZE maintenance and repair, and data from the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) about vehicle

[4] For more information on CARB's "Advanced Clean Fleets Regulation Summary," visit https://ww2.arb.ca.gov/sites/default/files/2021-08/210909costdoc_ADA.pdf. .

downtime. For OEMs that do not respond to the survey, publicly available information about their training programs is used.

Cost Parity (With and Without Incentives)

Cost parity is a measure of the difference between ZE total cost of ownership (TCO) and internal combustion TCO for vehicles and equipment. The TCO analysis used for HDIS purposes is based on CARB's draft ACF TCO analysis and makes all the same assumptions.[5] Two MRIs are constructed from this analysis. The first, Cost Parity, is the case in which Low Carbon Fuel Standard (LCFS) credits are the only form of incentive included in the platform's TCO (i.e., without incentives). The second, Cost Parity with Incentives, includes both LCFS credits and current HVIP/Clean Off-Road Equipment Voucher Incentive Project (CORE) base incentives, coupled with the Commercial Clean Vehicle Credit. LCFS credit assumptions are based on CARB's draft ACF TCO analysis and use the LCFS Credit Price Calculator[6] to determine the amount of revenue generated. All TCO calculations are projected for ZE technology platforms purchased in 2025.

For both cost parity MRIs, a score of zero corresponds to the case where ZE TCO is greater than 30 percent of internal combustion TCO. A score of 100 percent corresponds to the case where ZE TCO is at or below cost parity with combustion. HVIP and CORE modifiers that could increase or decrease voucher amounts (e.g., fleet size adjustments, bulk purchase requirements, disadvantaged community status, etc.) are not included in the Cost Parity with Incentives analysis, nor are any additional funding sources that could be stacked. This analysis is meant to represent an average case scenario for each segment, as many factors are dynamic and have a wide range of values, such as manufacturers' suggested retail prices (MSRPs), infrastructure costs, annual miles driven, electricity costs, and more. This analysis assumes a one-for-one replacement of a vehicle or piece of equipment for each segment. Because of the many variables associated with TCO, this analysis is not representative of every use case within a particular technology platform. Rather, it provides a high-level estimate of how TCO for ZE technologies compares to that of their internal combustion engine counterparts.

Duty Cycle Capability

Duty cycle capability estimates how well a given technology platform can meet the range of duty cycles required of it. For on-road vehicles, a score of zero represents the

[5] For more information on CARB's "Draft Advanced Clean Fleets Total Cost of Ownership Discussion Document," visit https://ww2.arb.ca.gov/sites/default/files/2021-08/210909costdoc_ADA.pdf.

[6] For more information on CARB's "LCFS Credit Price Calculator," visit https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/dashboard/creditvaluecalculator.xlsx.

case where range, payload capacity, and power of ZE models are not sufficient to meet the majority of duty cycle requirements, while a score of 100 percent means that ZE models can meet all known requirements for that segment. For off-road technologies, a score of 100 percent corresponds to the case where power, lift capacity, and operating time of ZE models are sufficient to meet duty cycle requirements. Data used to score this indicator comes from the Zero-Emission Technology Inventory (ZETI) tool.[7] The duty cycle demands are aggregated by vehicle segment and compared against the Environmental Defense Fund's Medium- & Heavy-Duty Vehicles Market Structure, Environmental Impact, and EV Readiness[8] report where applicable and internal staff expertise where not applicable.

Infrastructure

This category measures the extent to which charging or refueling infrastructure is available and easy to install for a given on- or off-road vehicle platform. A score of zero represents the case where the appropriate charging or refueling infrastructure is completely unavailable commercially or in pilot/demonstration projects. A score of 100 percent, on the other hand, represents the case where charging or refueling equipment is completely available to customers who want it with no significant barriers (e.g., high cost, difficult and long permitting process, difficult utility connection/coordination, or high utility rates). This indicator is scored based on internal staff expertise relative to each platform's unique charging needs. For example, heavy-duty long-haul trucks will need to rely primarily on high-powered, public-facing charging infrastructure that is still developing, while school buses are often able to utilize lower-power depot charging that is sufficient for their duty cycles.

Once industry experts have scored each segment against the seven categories above, a discussion is then held to calibrate results and rectify any significant discrepancies in the scoring. Upon determination of the final market readiness scores for each segment, the results are visualized in market readiness snapshots, which are described below.

Supply Chain

Supply chain evaluates on-road technology platforms for their vulnerability to ongoing supply chain disruptions and constraints. A score of zero represents the case where

[7] For more information on CALSTART's "Zero-Emission Technology Inventory" tool, visit https://globaldrivetozero.org/tools/zeti/.

[8] For more information on EDF's "Medium- & Heavy-Duty Vehicles Market Structure, Environmental Impact, and EV Readiness" report, visit https://www.edf.org/sites/default/files/documents/EDFMHDVEVFeasibilityReport22jul21.pdf.

delivery timelines are around two years and the delivery rate of vehicles is low. A score of 100 percent represents the case where delivery timelines are under a year and have a high percentage of vehicles delivered. Data used to score this indicator are vehicle delivery timelines and the percentage of vehicles delivered through HVIP. An OEM survey about vehicle delivery timelines by segment was also used in conjunction with the HVIP data. HVIP data does not account for delivery times that have been impacted by infrastructure delays.

Market Readiness Snapshots

These snapshots are provided for all technologies that have achieved a TRL of 8 or greater. Each chart on the following pages (Figure 3 and Figure 4) contains the elements below:

- Technology segments are listed along the left side with MRI categories across the top.
- Technology segments and MRIs that are new to the market readiness assessments in Fiscal Year 2023–24 are marked with an asterisk.
- The score for each MRI is shown as a circle, or pie shape, that is shaded to represent 0, 25, 50, 75, or 100 percent.
- The crosshatch in the pie charts represents an increase in score from Fiscal Year 2022–23. If there is no crosshatch in the pie chart, the score stayed the same from the previous year.

Figure 3. Market Readiness Snapshot Example: On-Road Battery-Electric (CARB, 2023)

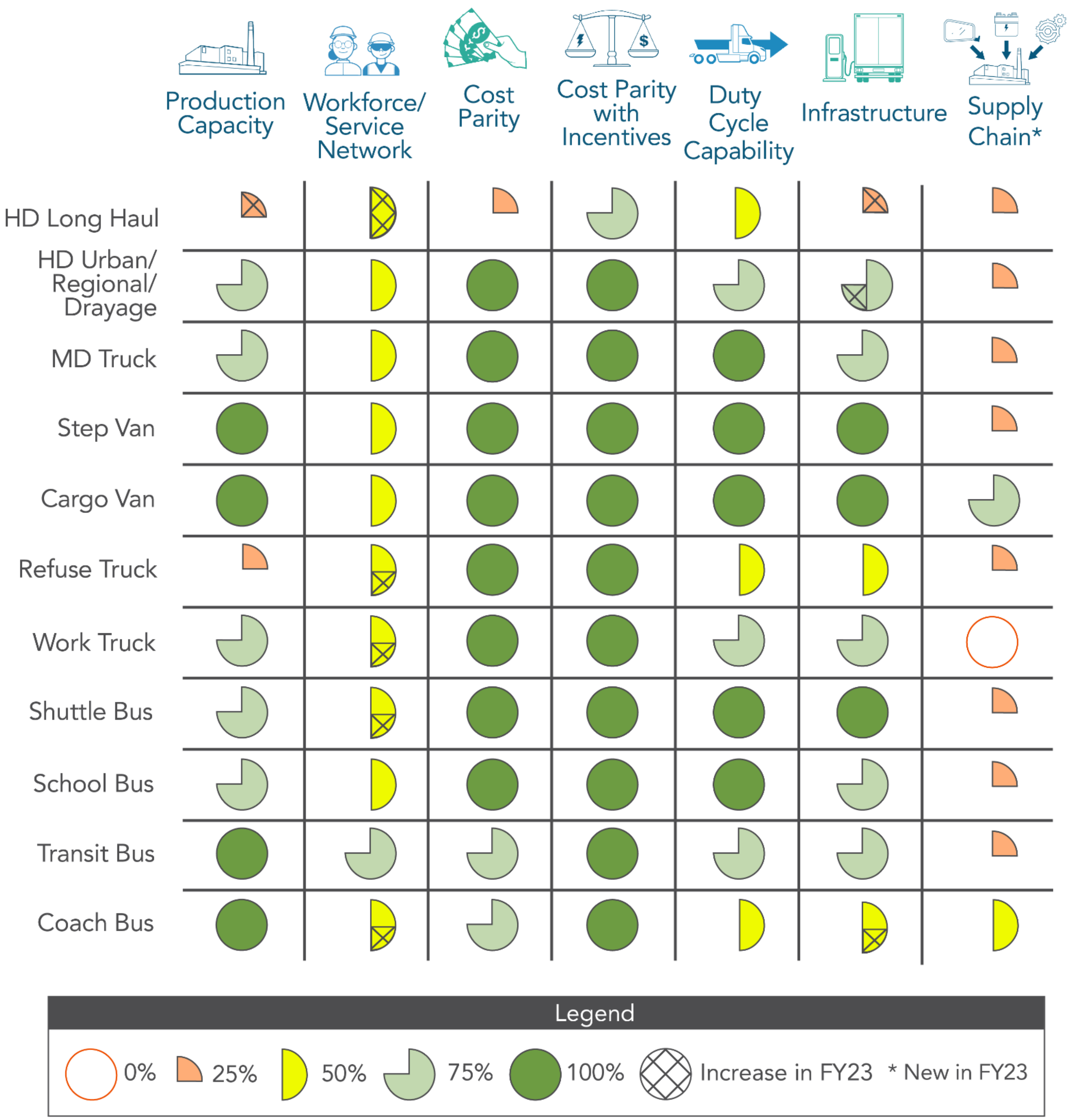
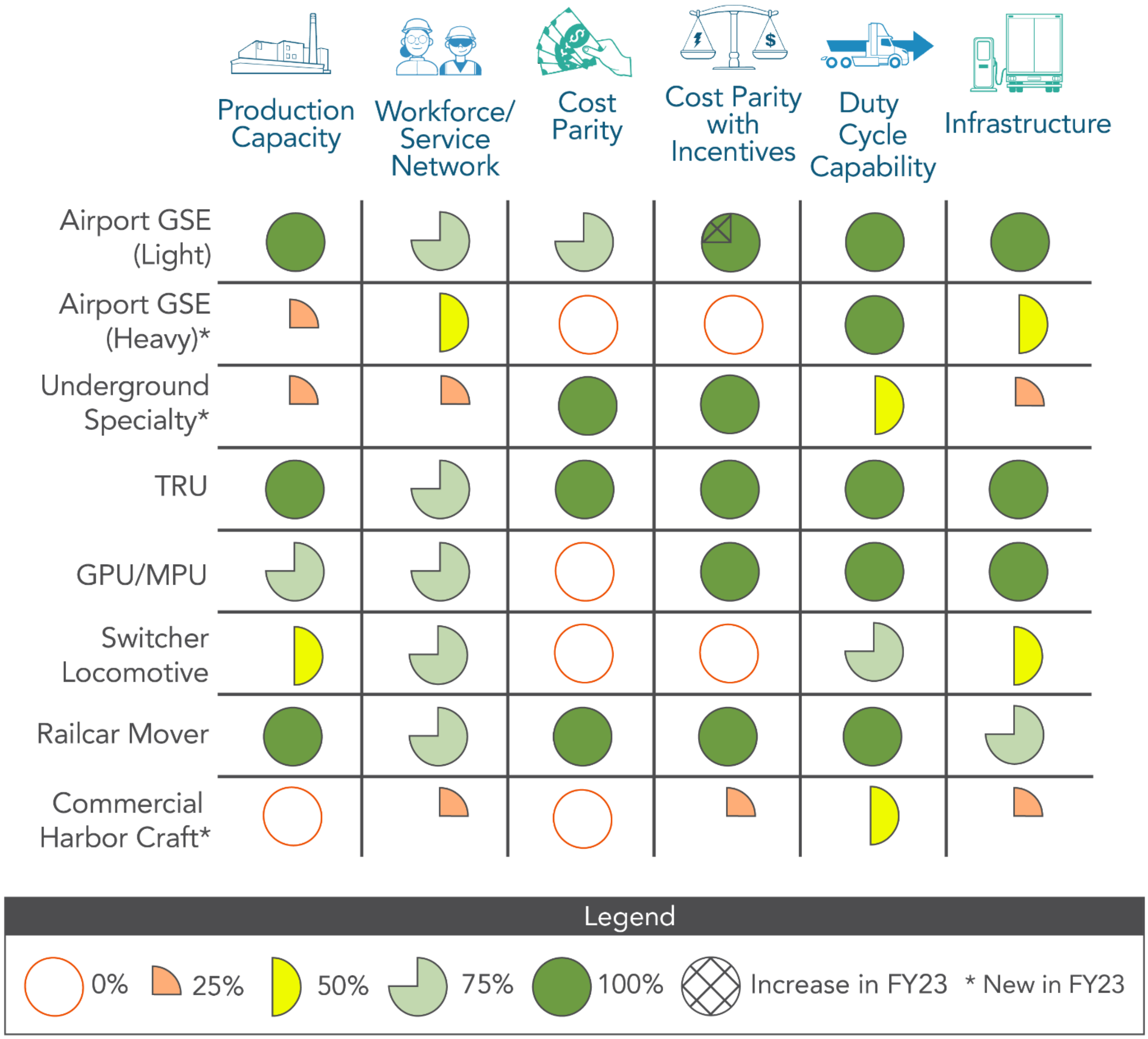


Figure 4. Market Readiness Snapshot Example: Off-Road Battery-Electric – Other (CARB, 2023)



Supply Chain Disruptions Delaying Adoption

Supply chains for ZE MHD vehicles consist of complex networks encompassing raw material extraction, component manufacturing, vehicle assembly, and distribution. This network has global dependencies with suppliers spanning continents, often relying on specialized production facilities and technologies. As the demand for ZE MHD vehicles rises, supply chain disruptions are becoming more pronounced. Such disruptions include:

- **Raw Material Shortages**: ZE MHD vehicles heavily rely on advanced battery technologies, which in turn rely on materials like lithium, cobalt, graphite, and more rare-earth elements. These materials are currently often sourced from outside of the United States and only in a limited number of regions, leading to supply shortages and price volatility.
- **Component Shortages**: ZE MHD vehicles integrate a plethora of specialized components, ranging from electric motors to power electronics. Events such as factory shutdowns, trade disputes, or transportation bottlenecks can create shortages for components.
- **Financial Instability**: Supply chain disruptions translate into financial uncertainty. Fluctuating material costs, delayed production schedules, and unexpected expenses can strain the financial viability of manufacturers and suppliers alike.
- **Labor and Workforce Issues**: Skilled labor is essential for producing cutting-edge ZE vehicles. Challenges with labor shortages, skill gaps, and workplace safety can hinder production and extend lead times.
- **Logistics and Transportation Delays**: The global nature of the ZE vehicle supply chain introduces transportation complexities. Disruptions like port closures, labor strikes, or unexpected customs regulations can delay movement of components and vehicles across borders, stalling production and deployment efforts.

Supply Chain Disruptions Delaying Adoption (continued)

Understanding these disruptions is imperative to accelerate ZE MHD vehicle adoption. Initial steps have been taken to alleviate pain points felt in the supply chain with large investments to increase domestic production in all stages of the ZE MHD vehicle's complex network. Specific examples to help solve these barriers include:

- The Inflation Reduction Act provides $2 billion to accelerate domestic manufacturing of electric vehicles and $192 million to enhance battery recycling, which will in turn reduce the need for new raw materials.
- The Electric Vehicle Infrastructure Training Program provides electricians a comprehensive training and certification process so electric vehicle service equipment can be properly installed to the highest standards.
- In the past year, 65 new projects have been announced in North America relating to the electric vehicle supply chain ranging from raw materials extraction to vehicle manufacturing.

While these investments show an increased focus to rehabilitate the supply chain, it will take years to reap the full benefits of these investments. Furthermore, most of these investments are not intended solely for the commercial vehicle sector. Greater attention is needed to 1) bridge the gap while these planned facilities become operational and 2) give the commercial vehicle sector dedicated capacity in all investments related to improve the domestic supply chain. Until these issues are addressed, the ZE MHD vehicle sector will continue to see delayed adoption due to supply chain constraints.

IV. Impact of Technology and Market Assessments

In combination, technology status and market readiness snapshots depict a holistic outlook on clean commercial vehicle and equipment platforms' readiness to perform and their readiness for the marketplace. The ultimate purpose for these technical and market assessments is to provide valuable context for agencies that have the ability to influence markets through incentives and regulations. Below is a non-exhaustive list of key incentive programs and regulations that make use of these snapshots.

Incentives

Both technology status and market readiness snapshots provide CARB with critical information to make sound decisions for incentive program planning according to technological maturity. Technology status snapshots serve as input to establish a common language and reference point to facilitate dialogue supported by well-defined measures and methods across organizational disciplines, departments, and business functions (U.S. Government Accountability Office, 2020). TRL scores help identify which vehicles and equipment would benefit from programs to further technological development: during the development process, next steps to increase a platform's TRL score are typically determined and can be utilized to scope the level of funding and effort required (Federal Highway Administration, n.d.). A standardized methodology to arrive at a platform's technological maturity, and now market readiness as well, helps improve the effectiveness of incentive programs, providing CARB with supporting documentation to affect decision-making. Below are examples of incentive programs in which CARB utilized technical and market assessments to determine which platforms were ready for commercial incentives and capable of achieving clean vehicle and equipment deployment goals.

Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project

Funded by CARB and managed by CALSTART, HVIP provides point-of-sale incentives for eligible ZE vehicles in California. To date, the program has administered hundreds of millions of dollars to accelerate the adoption of thousands of alternative fuel MHD vehicles. A first-come, first-served project with no scrappage requirement, purchasers that receive HVIP funding pay the total cost of the vehicle less the incentive amount, where HVIP-trained dealers front the incremental cost of the voucher and receive a reimbursement from CALSTART after the vehicle has been deployed.[9] Additional funding is available for vehicles deployed in disadvantaged communities and for small businesses for whom the incremental cost is particularly challenging.

The Clean Off-Road Equipment Voucher Incentive Project

CORE is a streamlined voucher incentive program funded by CARB and managed by CALSTART that encourages California freight, construction, agriculture, lawn and garden, and harbor craft equipment users to purchase or lease currently commercialized ZE off-road equipment. This program helps offset the higher cost of ZE technology with a point-of-sale discount; there is no scrappage requirement, and additional funding is available for equipment deployed in disadvantaged communities.[10]

Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles

EnergIIZE Commercial Vehicles accelerates the deployment of infrastructure needed to fuel ZE trucks, buses, and off-road equipment. This project helps lower the cost of infrastructure for fleets by using a concierge-like model to help eligible applicants plan and fund the purchase of charging and hydrogen fueling infrastructure. With an initial $50 million in funding from the California Energy Commission, EnergIIZE works with companies and public agencies to implement clean battery-electric and hydrogen vehicle technologies, benefitting communities most impacted by transportation-related pollution.[11]

[9] Learn more about HVIP at https://californiahvip.org/about/.

[10] Learn more about CORE at https://californiacore.org/.

[11] Learn more about EnergIIZE Commercial Vehicles at https://energiize.org/.

Regulations

Technology and market readiness assessments help measure technological maturity with a standard set of benchmarks or terms, in turn providing policymakers with vital information on the progress of key technologies to reduce emissions. This information and insights are therefore critical in identifying the need for climate change policies, regulations, and/or future development of resource needs. These snapshots provide valuable context to ensure that the requirements for production and/or adoption mandated in the following examples align with both technologically mature and market-ready vehicle and equipment applications, setting up OEMs and fleets for success and achievement of emissions reduction goals.

Innovative Clean Transit Regulation

Adopted in 2018, the Innovative Clean Transit (ICT) regulation requires all public transit agencies to fully transition to 100 percent ZE bus fleets by 2040. This transition will be gradual, with 100 percent of new ZE bus purchases required beginning in 2029. All transit agencies that own, operate, or lease buses with a gross vehicle weight rating greater than 14,000 pounds must comply, which includes standard, articulated, over-the-road, double-decker, and cutaway buses.[12]

Advanced Clean Trucks Regulation

The Advanced Clean Trucks (ACT) regulation aims to help accelerate a large-scale transition of ZE MHD vehicles in weight classes 2b–8. Manufacturers that certify Class 2b–8 chassis or complete vehicles with combustion engines are required to sell ZE trucks as an increasing percentage of their annual California sales from 2024 to 2035. By 2035, ZE truck/chassis sales will need to be 55 percent of Class 2b–3 truck sales, 75 percent of Class 4–8 straight truck sales, and 40 percent of truck tractor sales. Fleet owners with 50 or more trucks are also required to report information for their existing fleet operations, which provides insights for future regulations and requirements for purchasing available ZE trucks capable of meeting fleets' needs.[13]

[12] Learn more about the ICT regulation at https://ww2.arb.ca.gov/resources/fact-sheets/innovative-clean-transit-ict-regulation-fact-sheet.

[13] Learn more about the ACT regulation at https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks.

Advanced Clean Fleets Regulation

The ACF regulation aims to accelerate the market for on-road ZEVs and is part of a statewide effort to reduce emissions from transportation. Intended to help improve air quality and public health and to meet economy-wide carbon neutrality by 2045, among other climate goals, the ACF regulation requires fleets that are well suited for electrification to transition to ZE vehicles where feasible and will assist in achieving the Governor's Executive Order N-79-20 to reach:

- 100 percent ZE drayage trucks by 2035;
- 100 percent ZE off-road vehicles and equipment by 2035, where feasible; and
- 100 percent ZE MHD vehicles by 2045, where feasible.

The regulation contains an end to combustion truck sales, requiring 100 percent ZE MHD vehicle sales by 2036.[14]

[14] Learn more about the proposed ACF regulation at https://ww2.arb.ca.gov/our-work/programs/advanced-clean-fleets.

References

CARB (2019). Innovative Clean Transit (ICT) Regulation Fact Sheet. Retrieved from: https://ww2.arb.ca.gov/resources/fact-sheets/innovative-clean-transit-ict-regulation-fact-sheet

CARB (2021). Draft Advanced Clean Fleets Total Cost of Ownership Discussion Document. Retrieved from: https://ww2.arb.ca.gov/sites/default/files/2021-08/210909costdoc_ADA.pdf

CARB (2021a). Advanced Clean Trucks. Retrieved from: https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks

CARB (2021b). Advanced Clean Fleets. Retrieved from: https://ww2.arb.ca.gov/our-work/programs/advanced-clean-fleets

CARB (2023). Appendix D: Long-Term Heavy-Duty Investment Strategy Including Fiscal Year 2023-24 Three-Year Recommendations for Low Carbon Transportation Investments. Retrieved from: https://ww2.arb.ca.gov/sites/default/files/2023-10/fy2023-24lctfundingplan_appd.pdf

CARB (2023a). Advanced Clean Fleets Regulation Summary. Retrieved from: https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-fleets-regulation-summary

CORE (n.d.). About. Retrieved from: https://californiacore.org/

EnergIIZE Commercial Vehicles (n.d.). Home. Retrieved from: https://energiize.org/

Environmental Defense Fund (2021). Medium- & Heavy-Duty Vehicles Market Structure, Environmental Impact and EV Readiness. Retrieved from: https://www.edf.org/sites/default/files/documents/EDFMHDVEVFeasibilityReport22jul21.pdf

Federal Highway Administration (n.d.). Technology Readiness Level Guidebook. Retrieved from: https://www.fhwa.dot.gov/publications/research/ear/17047/17047.pdf

HVIP (n.d.). About HVIP. Retrieved from: https://californiahvip.org/about/

NASA (2012). Technology Readiness Levels. Retrieved from: https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level

U.S. Government Accountability Office (2020). Technology Readiness Assessment Guide. Retrieved from: https://www.gao.gov/assets/gao-20-48g.pdf

Appendix A: Technology Readiness Scoring Rubric

Table A-1: Technology Readiness Level Scoring Rubric

TRL Level	General Technology Level	TRL Definition	Example Technology
9	Early Market	Full commercial application. Technology in general availability for users. Manufacturing phase. Successfully operated in uncontrolled commercial environment.	Battery-Electric Bus; Fuel Cell Electric Forklift; Methane Engine 8.9 Liters
8	Large Scale Pilot	Pre-production. First of its kind commercial system. Technology ready to support commercial activity. In limited release assessment numbers. Vehicle succeeds in uncontrolled environment.	Battery-Electric Harbor Craft Vessels; Battery-Electric Mobile Power Unit
7	Early Pilot/Late Demonstration	Demonstration system. Operating in intended environment at pre-commercial scale. Unit succeeds in a relevant environment.	Fuel Cell Electric Drayage; Fuel Cell Electric Harbor Craft Vessels
6	Early Demonstration (Advanced Prototype System)	Tested in intended environment at close to expected performance. Limited vehicle builds. Vehicle succeeds in first real world scenarios.	0.02 NOx Diesel Engine; Fuel Cell Electric Automated Guided Vehicle
5	Prototype	Large scale prototypes. Tested in intended environment. Tested well enough to validate in real world scenarios.	John Deere GridCON Autonomous Tractor
4	Technology Development	Small scale (ugly) prototypes. First prototypes built and tested to perform under specific conditions.	Fully Autonomous Long-Haul Trucks
3	Research	Benefits and viability of technology confirmed in lab (Pre-Prototype).	-
2	Research	Early invention stage. Concept and application have been finalized.	-
1	Research	Scientific evidence for potential innovation.	-

Appendix B: Market Readiness Scoring Rubric On-Road

Table B-1: Market Readiness Scoring Rubric On-Road: Production Capacity, Workforce/Service Network, and Cost Parity

MRI Score	Production Capacity	Workforce/Service Network	Cost Parity[15]
0%	Production capacity is limited to prototypes or pilot/demonstration vehicles.	No service network[16] is available through OEM, dealer, or independently in California.	Model year (MY) 2025 ZE TCO is greater than 30% higher than internal combustion vehicle TCO.
25%	Production capacity is limited to small volumes of vehicles currently, although vehicles may be entering serial production soon.	Some service network is trained and available in California but not widely enough to provide ZE customers certainty that their vehicles will be repaired in a timely fashion. Customers regularly experience significant delays that prevent the full utilization of ZE vehicles and deter them from adopting future ZE vehicles.	MY 2025 ZE TCO is between 20–30% higher than internal combustion vehicle TCO.
50%	At least one OEM has begun serial production at relatively high production volumes (above specialized/retrofit manufacturing).[17]	Some workforce is trained and available in California but not widely enough to provide ZE customers certainty that their vehicles will be repaired in a timely fashion. Some customers experience significant delays that prevent the full utilization of ZE vehicles and deter them from adopting future ZE vehicles.	MY 2025 ZE TCO is between 10–20% higher than internal combustion vehicle TCO.

[15] Cost Parity includes LCFS only, no incentives; Cost Parity with Incentives includes available funding from HVIP, CORE, and federal incentives.

[16] A service network is defined as a system of professionals capable of repairing and/or maintaining ZE vehicles.

[17] This measurement is weighed against market size for each vehicle segment.

MRI Score	Production Capacity	Workforce/Service Network	Cost Parity[15]
75%	Multiple OEMs have begun serial production at relatively high volumes (above specialized/retrofit manufacturing) and are positioned to meet the entirety of current diesel market demand in the next 5–10 years if demand were to increase.	A well-trained workforce exists and is available but is unevenly distributed geographically within California.	MY 2025 ZE TCO is between 1–10% higher than internal combustion vehicle TCO.
100%	Multiple OEMs have begun serial production at relatively high volumes (above specialized/retrofit manufacturing) and are positioned to meet the entirety of current diesel market demand in the next 1–5 years if demand were to increase.	A well-trained workforce exists and is available to all customers who need it regardless of geographic location.	MY 2025 ZE TCO is at or below cost parity with internal combustion vehicles.

Table B-2: Market Readiness Scoring Rubric On-Road: Duty Cycle Capability, Infrastructure, and Supply Chain

MRI Score	Duty Cycle Capability	Infrastructure	Supply Chain
0%	Range, payload capacity, and power of ZE models are not sufficient to meet most market segments.[18]	Appropriate charging/refueling equipment is completely unavailable commercially and in pilot/demonstration projects.	Vehicle delivery timelines approach two years. Supply chain is fragile in that many parts are being impacted.
25%	Range, payload capacity, or power requirements are meeting only the minimum requirements needed for market segments.	Appropriate charging/refueling equipment is available in small quantities commercially or in pilot/demonstration projects.	Delivery of vehicles is averaging over a year with most vehicles still not delivered. Supply chain issues are frequent, and they impact OEMs' ability to deliver vehicles.
50%	Two of range, payload capacity, or power requirements are meeting minimum and average requirements needed for market segments.	Appropriate charging/refueling equipment is available commercially but has one or more significant barriers[19] which may prevent the installation of charging infrastructure or the adoption of ZE vehicles.	Delivery of vehicles is over a year and about half are delivered. Supply chain issues are frequent, but most OEMs can overcome them and still deliver vehicles.
75%	Range, payload capacity, and power are sufficient to meet the minimum and average market segments but only a few maximum requirements.	Appropriate charging/refueling equipment is available commercially but has one or more significant barriers that are on track to be overcome and do not necessarily prevent installation of charging infrastructure or adoption of ZE vehicles.	Delivery of vehicles hovers around one year and majority of vehicles have been delivered. Supply chain disruptions are limited but can require time to fix.

[18] Market segments refer to the various applications each vehicle platform can be used for.

[19] Significant barriers include high cost, difficult and long permitting process, difficult utility connection/coordination, and high utility rates.

MRI Score	Duty Cycle Capability	Infrastructure	Supply Chain
100%	Range, payload capacity, and power are sufficient to meet all known requirements for all market segments.	Charging/refueling equipment is completely available to all customers who want it with no significant barriers.	Delivery of vehicles is under a year and very few vehicles are still waiting to be delivered. Supply chain disruptions are limited and will not take long to fix.

Appendix C: Market Readiness Scoring Rubric Off-Road

Table B-3: Market Readiness Scoring Rubric Off-Road: Production Capacity, Workforce/Service Network, and Cost Parity

MRI Score	Production Capacity	Workforce/Service Network	Cost Parity[20]
0%	Production capacity is limited to prototypes or pilot/demonstration equipment.	No service network[21] is available through OEM, dealer, or independently in California.	MY 2025 ZE TCO is greater than 30% higher than combustion TCO.
25%	Production capacity is limited to small volumes of equipment currently, although equipment may be entering serial production soon.	Some service network is trained and available in California but not widely enough to provide ZE customers certainty that their equipment will be repaired in a timely fashion. Customers regularly experience significant delays that prevent the full utilization of ZE equipment and deter them from adopting future ZE equipment.	MY 2025 ZEV TCO is between 20–30% higher than combustion TCO.

[20] Cost Parity includes LCFS only, no incentives; Cost Parity with Incentives includes available funding from HVIP, CORE, and federal incentives.

[21] A service network is defined as a system of professionals capable of repairing and/or maintaining ZE vehicles.

MRI Score	Production Capacity	Workforce/Service Network	Cost Parity[20]
50%	At least one OEM has begun serial production at relatively high production volumes (above specialized/retrofit manufacturing).[22]	Some workforce is trained and available in California but not widely enough to provide ZE customers certainty that their equipment will be repaired in a timely fashion. Some customers experience significant delays that prevent the full utilization of ZE equipment and deter them from adopting future ZE equipment.	MY 2025 ZE TCO is between 10–20% higher than combustion TCO.
75%	Multiple OEMs have begun serial production at relatively high volumes (above specialized/retrofit manufacturing) and are positioned to meet the entirety of current combustion market demand in the next 5–10 years if demand were to increase.	A well-trained workforce exists and is available but is unevenly distributed geographically within California.	MY 2025 ZE TCO is between 1–10% higher than combustion TCO.
100%	Multiple OEMs have begun serial production at relatively high volumes (above specialized/retrofit manufacturing) and are positioned to meet the entirety of current combustion market demand in the next 1–5 years if demand were to increase.	A well-trained workforce exists and is available to all customers who need it regardless of geographic location.	MY 2025 ZE TCO is at or below cost parity with combustion.

[22] This measurement is weighed against market size for each vehicle segment.

Table B-4: Market Readiness Scoring Rubric Off-Road: Duty Cycle Capability and Infrastructure

MRI Score	Duty Cycle Capability	Infrastructure
0%	Range, payload capacity, and power of ZE models are not sufficient to meet the operating cycle requirements for all applications.	Appropriate charging/refueling equipment is completely unavailable commercially and in pilot/demonstration projects.
25%	There are a few available models that meet most daily and yearly operating cycles. Battery life and equipment performance need significant upgrades.	Appropriate charging/refueling equipment is available in small quantities commercially or in pilot/demonstration projects.
50%	There are a handful of available models that meet daily and yearly operating cycles. Able to start 1-1 replacing diesel equipment with ZE equipment.	Appropriate charging/refueling equipment is available commercially but has one or more significant barriers[23] which may prevent the installation of charging infrastructure or the adoption of ZE equipment.
75%	Most available models can meet daily and yearly operating cycles with a few specific market applications that cannot be met.	Appropriate charging/refueling equipment is available commercially but has one or more significant barriers that are on track to be overcome and do not necessarily prevent installation of charging infrastructure or adoption of ZE equipment.
100%	Most available models can meet the daily and yearly operating cycles for all market applications of the equipment.	Charging/refueling equipment is completely available to all customers who want it with no significant barriers.

[23] Significant barriers include high cost, difficult and long permitting process, difficult utility connection/coordination, and high utility rates.