

White Paper

# The Beachhead Strategy: A Theory of Change for Medium- and Heavy-Duty Clean Commercial Transportation

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March 2022



## Acknowledgments

This report will be updated on a periodic basis in support of the publication of the California Air Resources Board's (CARB's) Appendix D: Long-Term Heavy-Duty Investment Strategy.

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## List of Acronyms

BEB	Battery-Electric Bus
CARB	California Air Resources Board
CEC	California Energy Commission
EnergIIIZE	Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles
FCEB	Fuel Cell Electric Bus
FY	Fiscal Year
GHG	Greenhouse Gas
GSE	Ground Support Equipment
LIGHTS	Volvo Low Impact Green Heavy Transport Solutions Project
MHD	Medium- and Heavy-Duty
MOU	Memorandum of Understanding
RHETTA	Research Hub for Electric Technologies in Truck Applications
TCO	Total Cost of Ownership
ZE	Zero-Emission
ZECV	Zero-Emission Commercial Vehicles



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Figure 1. The Beachhead Strategy (CARB, 2021)

Figure 2. The Zero-Emission Beachhead (CARB, 2021)



# I. The Beachhead Strategy

## Overview

Zero-emission (ZE) and ZE-enabling vehicles and equipment powered by battery-electric and hydrogen fuel cell technologies are in position to transform the medium- and heavy-duty (MHD) commercial vehicle market. The deployment and development of these vehicles and equipment will provide health, environmental, and economic benefits, such as improved air quality, diminished impacts of climate change, new technological innovations, and increased opportunities for employment (Welch, 2020). However, ZE and ZE-enabling vehicles and equipment are still more costly than conventional technologies, and skepticism regarding capabilities and model availability remains high, particularly for ZE commercial vehicles (ZECVs).<sup>1</sup> Given the costs and uncertainties associated with ZE technology, transitioning all vehicle and equipment applications within a region at once, let alone at a national or global scale, is burdensome and expensive for fleets. Such an approach is therefore unlikely to achieve emission reduction goals or encourage widespread adoption of clean vehicle and equipment technology.

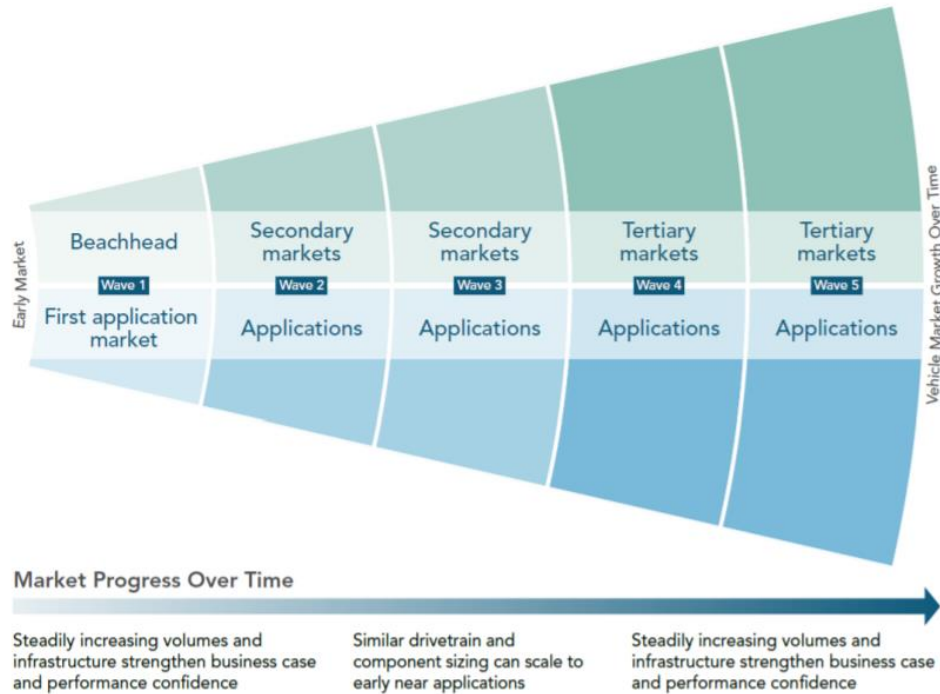
The California Air Resources Board (CARB), in conjunction with CALSTART, has developed a visual representation of its focused strategy for technology commercialization that helps to systematically address the current shortcomings of the ZE market. Based on concentrating investments on strategic applications—and on the pathways for subsequent markets or work applications—the Beachhead Strategy targets first-success applications or “beachheads”<sup>2</sup> where ZE technologies are currently viable according to duty cycle, business case, industrial capacity, and performance measures. These initial applications act as cornerstones for the development of adjacent or near-early markets for next-generation vehicle and equipment applications that follow predictable pathways. These predictable pathways, or “waves,” were first visualized by CARB in 2017; today’s most current visualization of the generic beachhead process is shown as **Figure 1** below.

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<sup>1</sup> The definition of zero-emission (ZE) includes vehicles and equipment powered by electricity or hydrogen with drivetrains that cannot emit tailpipe greenhouse gases or air pollutants.

<sup>2</sup> The term “beachhead” is most often associated with the beach landing of Allied troops in Normandy during World War II, an initial military holding that led to access to an entire continent. The commercial definition of beachhead is “a secure initial position that has been gained and can be used for further advancement; foothold” (Collins English Dictionary, 2012).

**Figure 1. The Beachhead Strategy (CARB, 2021)**



The core of the Beachhead Strategy resides in focusing resources on a smaller market segment or product and successfully deploying in or monopolizing that market, thereby helping advance the technology into larger markets or other applications (Berry, n.d.). This approach to technology commercialization has been incorporated into CARB's Appendix D: Long-Term Heavy-Duty Investment Strategy to aid in targeting its investments.<sup>3</sup> The expansion from Wave 1 to adjacent Wave 2 through 5 markets is accomplished by leveraging and adopting similar powertrains; growing supply chain volumes for common components; expanding fueling infrastructure; and building confidence in performance and business cases (CARB, 2021). This strategy defines CARB's approach to driving faster technology commercialization through Clean Transportation investments and has helped CARB target and focus Low Carbon Transportation and Air Quality Improvement Program investments around applications that have strong potential to transfer and spread to broader applications (CARB, 2021).

This white paper serves to provide further context and definition to the detailed beachhead models and graphics published in the Long-Term Heavy-Duty Investment Strategy each year. CARB's approach to implementing the Beachhead Strategy, and the corresponding graphics, are reviewed and modified (if necessary) by CALSTART and CARB on a yearly basis. As such, this report will be updated in parallel with the Long-Term Heavy-Duty Investment Strategy.

<sup>3</sup> The [Fiscal Year 2021-22 Appendix D: Long-Term Heavy-Duty Investment Strategy](https://ww2.arb.ca.gov/sites/default/files/2021-10/fy21-22_fundingplan_appendix_d.pdf) can be found at [https://ww2.arb.ca.gov/sites/default/files/2021-10/fy21-22\\_fundingplan\\_appendix\\_d.pdf](https://ww2.arb.ca.gov/sites/default/files/2021-10/fy21-22_fundingplan_appendix_d.pdf)

The rest of this section defines the first application markets in **Figure 1**'s Wave 1 above and explains how successive markets in Waves 2 through 5 consequently develop. Section II dives into the technology-specific beachhead model that is currently utilized in the Long-Term Heavy-Duty Investment Strategy: the Zero-Emission Beachhead. Section III emphasizes the importance of transferrable componentry and processes to the success of the Beachhead Strategy and provides reliable indicators of beachhead success. Finally, Section IV highlights recent examples of real-world market progress in the commercialization of ZECVs.

## Predictable Pathways to Reduced Emissions

### First Application Markets

This theory of change begins with first success beachheads, which work to catalyze clean transportation deployments in the MHD industry. By functioning as the foundation for deploying and improving technology, supply chains, and business practices, first-success applications allow clean technologies to extend to next-generation vehicles, as well as other on-road, off-road, and marine sectors.

Initial applications often cover moderate daily distances in urban settings. First beachheads for ZECVs also require established routes that end at a base for overnight charging. Given these needs, transit buses and forklifts are primed to facilitate a transition to ZE powertrains. Aligning vehicle availability with suitable duty cycles, industrial capacity, and performance often leads to success in these initial applications (Welch, 2020). In addition, ZE fleets benefit from fueling and charging infrastructure that expand from early market beachheads. These factors, as well as appropriate financial incentives, result in more favorable total cost of ownership (TCO) for clean vehicle and equipment applications.

Since components to power electric drivetrains (by both battery-electric and hydrogen fuel cell technologies) are often similar for different vehicle and equipment applications, manufacturers can concentrate efforts to build technological and business model innovations within first beachhead applications. This progress increases confidence in performance and business cases, driving demand and further technological improvements. Moreover, focused early applications in key regions allow manufacturers to increase efficiencies and streamline their products in a responsive and interested first-mover market. The large-scale and simultaneous manufacture, deployment, and service of clean trucks and buses is currently hindered substantially by cost and operational challenges. The Beachhead Strategy mitigates these hurdles by facilitating the expansion of supply chain capacity as regional and global demand increases.

### Successive Markets

As supply chain volumes increase for shared componentry and technology performance improves, secondary markets begin to develop. The transition along predicted beachhead pathways expands to larger volume, longer distance, and more demanding vehicle applications,



and these secondary and tertiary market “waves” can utilize the core component technologies, architecture, and supply chains developed during the deployment of initial applications (Welch, 2020). In the on-road ZE market for example, fuel cell electric buses (FCEB) and battery-electric buses (BEB) both use the same electric powertrain, which was originally designed from the hybrid transit bus architecture; these components are now applicable to battery-electric shuttle and school buses, battery-electric delivery vans, and FCEBs (Welch 2020). Over time, technology developments, further component volume growth, and price reductions will steadily increase market penetration and establish tertiary market viability for long-haul freight applications with heavy payloads and fewer return-to-base requirements.

Technology innovations can also transfer between on-road and off-road segments and support the expansion of successive markets, which is especially important when considering charging facilities for ZECV heavy-duty applications that require more powerful and larger fueling supplies. Long-haul freight and transit buses need large scale high-power charging and hydrogen fueling stations located in travel and freight corridors. Constructing these charging and fueling facilities to operate for multiple vehicle applications will facilitate market expansion and encourage fleet operators to deploy ZECVs given the increase in cost effectiveness. Supporting infrastructure that is critical to ZECVs and emerging technologies is discussed in more detail in Section II.



## II. Beachhead Models

### Introduction

The Beachhead Strategy has been developed to correspond to technology type. One singular category has now emerged as the most powerful example of this approach: the Zero-Emission Beachhead. The following section describes the sequential pathways from initial applications to successive markets for the Zero-Emission Beachhead Model, which is also illustrated in graphic form. Incorporating both historical and technological information, this graphic depicts the support of early clean vehicle deployments through lighter duty and return-to-base applications, the technology transfer and adoption of successive markets, and the logical forecasts for new applications that will utilize transferable technologies in tertiary waves (CARB, 2021).

The model illustrated in the following section should act as a guide for the industry, though it is subject to change. Beachhead models are not definitive and may be modified due to market conditions. It is also important to note that other beachhead models have been included in the Long-Term Heavy-Duty Investment Strategy in previous years, such as the Efficiencies Beachhead and the Combustion Beachhead. Efficiency technologies, such as connected-automated vehicles, automated guided vehicles, and stop-start systems, necessitated a separate beachhead graphic until Fiscal Year (FY) 2021-22; many of these applications can now be integrated into the Zero-Emission Beachhead to maximize reductions, particularly with new standards seeking to further reduce greenhouse gas (GHG) emissions, such as the U.S. Environmental Protection Agency's Phase 3 Heavy-Duty GHG standards. The Combustion Beachhead will no longer be included in the Long-Term Heavy-Duty Investment Strategy beginning Fiscal Year 2022-23. Market trends and regulations are increasingly targeting the adoption of ZE vehicles and ZE-enabling technologies and equipment. ZE-enabling technologies like hybrid powertrains and range extenders empower the use of zero- and near-zero emission technologies and will continue to be tracked as a part of the Zero-Emission Beachhead.

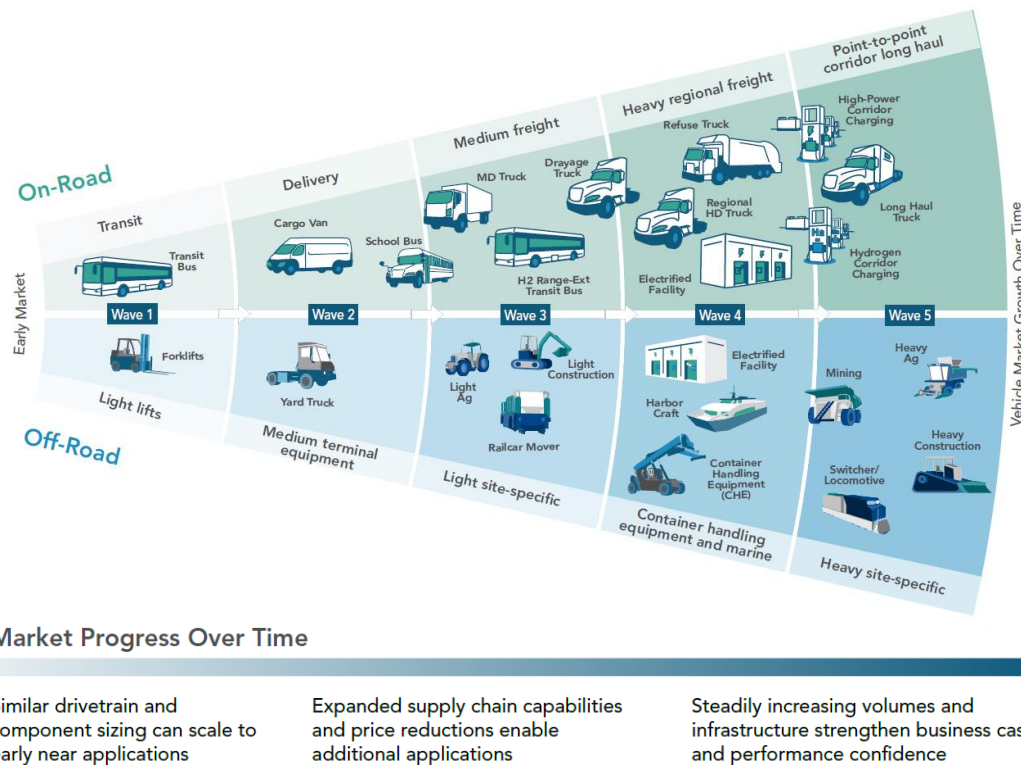
Technical assessments of the reasonable potential to progressively scale and transfer components and capabilities to additional applications and platforms are conducted by CARB and CALSTART on a yearly basis prior to the publication of the Long-Term Heavy-Duty Investment Strategy. These assessments consist of interviews with manufacturers and suppliers; assessment of component use and commonality across geographical regions and applications; and evaluations of the

transferability potential of these components.<sup>4</sup>

## Zero-Emission Beachhead

The Zero-Emission Beachhead (**Figure 2**) predicts that early success in the transit, delivery, lift, and terminal equipment markets will develop stable supply chains and reduce costs, leading to the deployment of heavier duty applications. The sequential and progressive nature of these pathways allows for effective planning for infrastructure, policies, incentives, funding, and use regulations (CARB, 2021).

**Figure 2. The Zero-Emission Beachhead (CARB, 2021)**



For the on-road sector, transit buses act as the initial beachhead application. This relatively low volume technology establishes a first marketplace and enables additional uses for core component technologies and architectures. The powertrains for FCEBs and BEBs require many of the same components, the design of which were modeled from hybrid architectures in the transit bus market. Over time, core electric drive components facilitate the electrification of other bus, truck, and van applications. This expansion leads to further technological advances and more favorable business cases for ZE drivetrains, allowing manufacturers to streamline processes to meet higher demand and for ZECVs to operate more diverse, rigorous duty cycles.

<sup>4</sup> For more information on the [Technology Readiness Level and Market Transformation Signals assessments](https://calstart.org/technology-and-market-readiness) conducted by CARB and CALSTART each year that help inform the beachhead models and the Long-Term Heavy-Duty Investment Strategy, go to <https://calstart.org/technology-and-market-readiness>

Forklifts are the initial clean transportation foothold for the off-road sector. Since these vehicles rarely stray far from their facilities, manufacturers and operators are able to install and streamline functionality improvements for next-generation vehicles and charging equipment within a closed system, such as warehouses, cargo yards, and ports. These innovations pave the way for multiple types of cargo handling applications with higher payloads.

Besides electric powertrain technology, ZECVs require charging and fueling sites for successful commercialization, making infrastructure a critical component of this beachhead. Fleets need to ensure that vehicles can charge in a depot to maximize operational efficiencies and minimize costs by charging at low speeds. In addition to on-site charging, other vehicles may need to charge along their routes given distance or battery capacity. Transit buses or drayage trucks with established routes may rely on enroute chargers or stations; vehicles that follow inconsistent or long routes, like delivery trucks and vans, may need to use publicly available chargers or stations. Hydrogen stations and high-powered direct current charging stations throughout major travel corridors will be critical to ensure on-route charging for long-haul trucks.

Infrastructure investments can also expand and support certain beachhead applications. For example, given the number of different vehicle and equipment applications that operate at shipping terminals and warehouses – marine harbor craft, cargo handling equipment, terminal tractors, drayage trucks – charging and fueling stations may be shared across applications. Regional haul trucks, terminal tractors, and other on-road ZECVs may also rely on shared-use charging facilities. Shared-use facilities are currently being demonstrated through the Volvo Low Impact Green Heavy Transport Solutions (LIGHTS) project,<sup>5</sup> which combines ZE regional haul truck applications with ZE electric forklifts and terminal tractors that operate at the shared freight facility in Northern California. In addition, subsequent benefits from infrastructure investments include labor and maintenance training and high visibility for ZE technology that can be both tested and on display, encouraging other fleets to adopt ZECVs. Investing in large site infrastructure with multiple operations, therefore, makes sense from a financial standpoint while working toward a built-in captive fleet market and testing new ZE technologies to expand to secondary and tertiary markets (CARB, 2020).

EnergIIZE Commercial Vehicles (Energy Infrastructure Incentives for Zero- Emission Commercial Vehicles)<sup>6</sup> is another example of recent investment in infrastructure for ZECVs. Funded by the California Energy Commission's (CEC) Clean Transportation Program and implemented by CALSTART, EnergIIZE is the nation's first commercial vehicle fleet infrastructure incentive project and provides incentives for ZE vehicle infrastructure equipment for MHD battery-electric and hydrogen fuel cell vehicles in California (EnergIIZE, n.d.). In addition, the CEC's creation of a Research Hub

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<sup>5</sup> For more information on the [Volvo LIGHTS project](https://www.lightsproject.com/about/), please go to <https://www.lightsproject.com/about/>

<sup>6</sup> For more information on [EnergIIZE](https://energiize.org/), please go to <https://energiize.org/>

for Electric Technologies in Truck Applications (RHETTA),<sup>7</sup> which will engage stakeholders to advance high power charging systems and to plan, design, and deploy innovative corridor charging strategies that extend the range and increase the operational flexibility of battery-electric trucks (CEC, 2020).

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<sup>7</sup> For more information on [RHETTA](https://www.energy.ca.gov/solicitations/2020-12/gfo-20-306-research-hub-electric-technologies-truck-applications-rhetta), please visit <https://www.energy.ca.gov/solicitations/2020-12/gfo-20-306-research-hub-electric-technologies-truck-applications-rhetta>



## III. Establishing Successful Beachheads

### Transferrable Componentry and Processes

The deployment of vehicle models with less predictable and longer routes, as well as heavier payloads, is supported by technology transfer between an initial beachhead and a secondary application. A self-sustaining clean vehicle and equipment market will rely heavily on the expansion of production capacity and cost reductions—all of which can be catalyzed by transferable technology. Manufacturing techniques and process improvements for components with flexible uses will create ripple effects through supply chains, reducing total production costs and in turn facilitating new applications and markets. This realization paves the way for commercially viable and mature clean vehicles and equipment far beyond first success beachheads.

To elaborate, manufacturing interchangeable or easily modified components for different models results in increased production volumes, consequently reducing the costs of production over time (CARB, 2020). The benefits associated with interchangeable parts is experienced first by local supply chains. Regional vehicle operators and servicers will no longer face difficulties with unique and expensive components for new technologies and have a steady supply of components that meet multiple vehicle and/or equipment types. Consequently, transferability accelerates manufacturers' ability to scale these components because of less expensive parts and platforms, increasing competitive advantage and access to global markets (CARB, 2020). For ZECVs, powertrains and components in ZE transit buses are similar to those needed in vans, delivery trucks, and work trucks, so original equipment manufacturers can develop new vehicle models that use existing or slightly modified components, such as motors, power electronics, and energy storage, to meet new duty cycles at low cost and with limited resources (Welch, 2020). For example, Proterra, who has developed their battery technology and begun to produce battery packs at a larger scale for their transit bus production, is now supplying batteries to Nikola Motors for use in their Tre battery-electric and fuel cell electric day cabs (Nikola, 2022).

Advancements in manufacturing and supply chain efficiencies will be important to both decrease component costs and increase performance. As production volume grows to meet new demand, these factors will increase ZE and ZE-enabling vehicle and equipment's affordability, a main barrier to complete clean vehicle adoption, and help first beachhead applications establish a market foothold. Production costs will also diminish within a beachhead market as production scales up

and supply chain management becomes more efficient. Fuel costs will also decrease as manufacturing expands: with the cost of hydrogen significantly more expensive than diesel, more fueling sites and increased fuel and technology production will help level off these costs.

Interchangeable core components also provide immediate benefits to local supply chains. By eliminating the need for unique and expensive components, operators and servicers are able to meet demand for multiple vehicle and equipment types, and technological innovations are also encouraged and easier to deploy and service. Moreover, manufacturers are able to develop and produce platforms and parts at scale with fewer costs, providing a competitive advantage and allowing for flexible production in markets around the world (CARB, 2020).

Beachheads also improve processes for vehicle manufacturers and dealers in four main areas, resulting in increased consumer confidence and desirable TCO for fleets (Welch, 2020):

- **Production Expertise:** Companies with a comprehensive understanding of local regulations and needs may have more opportunities to penetrate new markets, and companies modifying existing chassis to build custom ZE technologies for regional clients may increase process efficiencies.
- **Enhanced Customer Service:** Initial beachhead deployments will allow companies to focus in on and enhance customer service for specific technologies. Traditional manufacturers that have added electrified variants of their products or companies that are newer to widespread commercial vehicle operation and only produce ZE products will need to understand how to service ZE components or provide vehicle services unrelated to electric drivetrains.
- **Workforce Training:** Drivers and fleet owners of traditionally fueled vehicles and equipment will require training on how to charge, maintain, and safely operate ZECVs. Manufacturers may need to provide training for fleet operators given their extensive ZECV knowledge. Centralizing this training within one beachhead market will facilitate a consolidated workforce and reduce redundancies in travel and training sessions.
- **Infrastructure Improvements:** Beachhead markets allow manufacturers and fleets to revise and refine infrastructure challenges as ZECV operations expand. ZECVs require managed charging, siting and upgrading infrastructure, utility interconnections, ensuring interoperability between stations to maximize efficiencies, and improving infrastructure design to meet future demands. Right sizing these needs will economize on electrical infrastructure upgrade costs from additional distribution facilities and operating costs from lower demand charges incurred by controlling charging across vehicles and within system peaks. Installing hydrogen stations for fuel cell vehicles will likely require navigating unique regulations and technological barriers to deployment as well.

# Reliable Indicators of Beachhead Success

The following conditions help indicate whether a ZE beachhead application will successfully overcome key barriers such as higher upfront costs, insufficient model availability, lack of access to infrastructure, fleet awareness, or user demand (Welch, 2020):

- **Models are available:** Vehicle and equipment models in beachhead segments are a vital and unmistakable first step to achieving initial adoption. Model diversity also creates a more competitive marketplace and allows a greater number of fleets to participate in new markets.
- **Infrastructure is installed or available:** Charging or fueling must be affordable and available in the form most fitting for a beachhead application (i.e., depot, on-route, or opportunity) to eliminate range anxiety for fleets.
- **Vehicles achieve cost parity:** TCO is critically important to the commercial vehicle industry. Improvements in manufacturing and servicing vehicles, combined with incentives and/or penalties for diesel-powered vehicle ownership and operation, will make TCO equal or less than traditional vehicles. Removing purchase cost as a barrier is one of the most critical steps in successfully deploying ZE and ZE-enabling vehicles and equipment.
- **Governments adopt enabling policies:** Particularly with ZECVS, governments can support beachhead applications by enacting supportive policies and actions to help make operating ZECVs more attractive relative to diesel-powered vehicles (building infrastructure, lowering cost of the vehicles, increasing fleet familiarity with new technology, and placing pricing mechanisms on carbon or air pollutants). These approaches may include financial incentives that support ZECV adoption. Other examples include regulations on manufacturer ZECV sales, clean fuel standards that promote the use of ZE fuels, and ZE zones in city centers.
- **Fleets adopt ZECVs:** CARB recommends that captive fleets in sites with multiple operations, such as at freight facilities or large depots, make optimal targets for familiarizing new fleets with ZECV technologies (CARB, 2020). Fleet managers must be certain of, familiar, and comfortable with new ZECV applications before adopting them.
- **Freight users demand new ZE technologies:** Demand for new applications must be apparent for manufacturers to build those vehicles. For example, as beachhead applications expand beyond initial transit bus deployments, freight carriers must signal their intent to purchase ZE cargo vans and trucks. Similarly, shippers can signal their intent to hire carriers who operate ZECVs.





## IV. Beachhead Progress

In addition to California, the Zero-Emission Beachhead has been reviewed and adopted across the United States and abroad. For example, the Global Commercial Vehicle Drive to Zero (“Drive to Zero”) campaign uses the Beachhead Strategy as a foundational principle to drive strategic ZECV proliferation and expansion. Drive to Zero and the Beachhead Strategy have been adopted by the Clean Energy Ministerial’s Electric Vehicle Initiative and formally recognized by nine national governments. At COP26, Drive to Zero and the Government of the Netherlands announced the Memorandum of Understanding (MOU) on Zero-Emission Medium- and Heavy-Duty Vehicles,<sup>8</sup> in which leading countries have committed to working together to enable 100% ZE new truck and bus sales by 2040 with an interim goal of 30% ZE vehicle sales by 2030. The industry is already experiencing progress along the Zero-Emission Beachhead pathway.

### Real-World Examples

ZE bus applications have now been deployed in the United States, Europe, Asia, India, and South America. The success of ZE (both battery-electric and fuel cell) transit buses has resulted in deployments in many secondary markets (Welch, 2020):

- Battery-electric and fuel cell electric shuttle and school buses;
- Battery-electric delivery vehicles;
- Battery-electric terminal tractors;
- Battery-electric off-road work trucks designed for site-specific functions (in agricultural, construction, rail, and mining operations);
- Battery-electric refuse trucks;
- Battery-electric, fuel cell electric, and plug-in hybrid (sometimes operating as range extender systems) drayage trucks; and
- Battery-electric, fuel cell electric, and plug-in hybrid (and range extender) regional heavy-haul trucks.

These successive market deployments were made possible by (Welch, 2020):

- Common powertrains and components (motors, power electronics, energy storage) that can be transferred to other applications with similar power and torque needs, or scaled up

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<sup>8</sup> For more information on [Drive to Zero’s Global MOU](https://globaldrivetozero.org/mou-nations/), please go to <https://globaldrivetozero.org/mou-nations/>

or down to suit other applications;

- Supply chain expansion partially assisted by hybrid, start-stop, and idle reduction technologies;
- Steadily increasing vehicle volumes and availability of infrastructure, knowledge of business case, and consumer confidence in performance; and
- Expanded capabilities, including price reductions in energy storage/components enabling MHD applications (with some of this energy storage transferring directly from light-duty passenger car production).

Companies that were pioneers of ZE transit buses have modified these components to reach new markets and duty cycles. For example, BYD has offered several models of MHD ZE trucks (including terminal tractors) for years; shifting from transit bus operations to develop other ZECVs, including off-road applications, was part of the company's business plan dating back to 2013 (BYD, 2020). Daimler Truck North America, which is the parent organization for Thomas Built, Freightliner, Mitsubishi Fuso, and Mercedes-Benz (trucks), has begun to deploy a succession of ZE technologies in global markets: since Mitsubishi Fuso's medium-duty trucks and Mercedes-Benz's eCitaro transit/coach bus were introduced to the market, both Freightliner and Mercedes-Benz are now piloting and beginning sales of heavier-duty models.

And with demand now increasing substantially, newer manufacturers are demonstrating responsive approaches to designing ZECV models. Lion Electric, which originated from a traditional school bus manufacturer, develops all-electric school buses that have been deployed across Canada and the United States—the company now offers products such as a flexible Class 8 chassis that can serve multiple heavy-duty trucking functions (Lion Electric, 2020). Traditional automakers are also rolling out ZECV manufacturing designs that can be modified for a variety of applications. For example, Volvo developed an all-electric powertrain for transit buses that has since been adapted for vehicles with similar performance needs, such as a long-body transit bus, Class 8 tractors, and refuse trucks. In addition, the number of vehicle upfitters and modifiers that are improving ZE drivetrains is growing. GreenPower, Motiv, Lightning, Phoenix, and SEA Electric utilize parts from other large vehicle component manufacturers to redesign existing ZE vehicles into modified small shuttles, medium-duty delivery trucks, heavy-duty drayage trucks, and more.

Continued improvements in battery capacity and decreasing battery price have driven the development of extended range applications: models from major manufacturers now average 200 miles, with some models exceeding 300 miles and a few models anticipated to exceed 600 miles on a single charge.<sup>9</sup> Fuel cell trucks are also being developed by an increasing number of major manufacturers and partnerships, aiming to tackle heavy weight, charging/fueling duration, and longer distance challenges:

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<sup>9</sup> For more information on the number of [available and announced models of zero-emission heavy-duty trucks in the United States, Canada, Europe, and China](https://globaldrivetozero.org/tools/zeti-analytics), please go to <https://globaldrivetozero.org/tools/zeti-analytics>

- Nikola is currently track testing its new fuel cell electric Nikola Tre model, which uses the same Euro-style cabover cab as the battery-electric Tre model and is estimated to provide 500-plus miles of range for regional applications (HDT, 2021).
- Navistar and GM will combine their respective truck bodies and fuel cell technologies to develop a commercial-production heavy-duty FCEV for launch in 2024 (Trucks.com, 2021).
- Hyzon, a spin-off company that upfits its hydrogen fuel cell technologies into commercially available glider vehicles, anticipates producing 40,000 FCEVs by 2025, including applications (FleetOwner, 2021).
- Daimler and Volvo have formed a joint venture to undertake commercial heavy-duty FCEV production by 2025 and to harmonize FCEV policies (Volvo, 2021).
- Toyota has developed partnerships to demonstrate and bring to production its fuel cell technologies in drayage trucks with Kenworth and Hino—the latter has separately partnered with start-up Xos to develop long-haul FCEV models (Forbes, 2020).
- Cummins has also announced it will serve the fuel cell powertrain provider for Air Products global fleet of about 2,000 trucks; the pilot phase will start in 2022 (Electrify.com, 2021).
- Four of the five projects awarded funding under U.S. Department of Energy's SuperTruck 3 program include a fuel cell vehicle component (U.S. DOE, 2021).

ZE technologies have been adopted in several off-road equipment applications, such as forklifts and airport ground support equipment (GSE). For example, JetBlue operates entirely ZE airport GSE at Long Beach Airport in California and at JFK Airport in New York (Bloomberg, 2019). Fuel cell systems from the industrial lift application, such as JCB's 20 tonne hydrogen fuel cell powered excavator, will become assets for extended range and extended operation capabilities in on-road trucks and heavy-duty off-road equipment (JCB, 2020). This evolution of ZE technologies equipment branching out to subsequent applications corresponds with Figure 2 and has led to additional applications such as:

- Battery-electric and fuel cell electric GSE;
- Battery-electric and fuel cell electric sight-specific agricultural, rail, and construction applications;
- Battery-electric, fuel cell electric, and extended operations electric cargo handling equipment;
- Battery-electric, fuel cell electric, and extended operations marine harbor applications; and
- Battery-electric and fuel cell electric transport refrigeration units.

California has also acted as the testing grounds for other ZE technology. The Port of Long Beach and Toyota have operated a custom-built heavy-duty ZE fuel cell drayage truck that uses core components from its light-duty Mirai (Trucks.com, 2019). The Ports of Long Beach and Los Angeles also are testing the following ZECV technologies (Port of LA, 2020):

- Fuel cell drayage trucks that operate on freight corridors between ports;
- Converted existing fossil-fueled equipment to zero- or near-zero emissions, including nine all-electric cranes, 12 all-electric yard tractors, and four plug-in hybrid electric drayage trucks;
- Demonstrations of new ZE vehicles, including three all-electric top handlers, one all-electric yard tractor, and one fuel cell yard tractor; and
- Four all-electric retrofitted tugboats.

Beyond California, the entire West Coast is now poised to emerge as a corridor of opportunity for ZE off-road vehicles and equipment. Under the Northwest Ports Clean Air Strategy, the Northwest Ports of Seattle and Tacoma, Washington, and Vancouver, British Columbia, and the combined container operations of The Northwest Seaport Alliance announced a commitment to zero emissions by 2050 (Port of Seattle, 2021). This shift will produce an inherent increased demand for the sale and manufacture of ZE off-road vehicles, leading to technological innovations that will propel the off-road sector along its beachhead pathway. Similarly, on the East Coast, the Port Authority of New York and New Jersey has deployed 10 ZE battery-electric yard tractors as it targets halving terminal emissions by 2030 (Electrive.com, 2021a).

Technology transfer between the on-road and off-road sectors are just as critical to successful market penetration. Marine, construction, agricultural, and cargo handling equipment applications are now using similar drivetrain components from transit buses around the world:

- A hybrid-electric excursion vessel based in the San Francisco Bay area used a system that component supplier BAE Systems traces directly to the powertrain developed for a 60-foot hybrid electric articulated transit bus (CARB, 2020);
- In northern European ports, such as the ports around Copenhagen, demonstration projects are testing all-electric applications of passenger and vehicle ferries (E-Ferry, 2020);
- The Port of Stockton, California is testing 18 of the first commercially available all-electric large-capacity forklifts, which can lift from 30,000 to 70,000 pounds (CARB, 2020); and
- The world's largest all-electric vehicle is a dump truck in Switzerland that transports 60 tons of materials downhill, regenerating while laden to power its return trips uphill (Popular Mechanics, 2019).

Large marine projects have also worked to drive down the cost of large hydrogen fuel cell stacks and further help demonstrate the technology for heavy-duty trucks. In 2019, GE's Power Conversion business and Nedstack announced a collaboration to develop hydrogen fuel cell systems for powering ZE cruise vessels, and in 2018, ABB and SINTEF announced testing/modelling of technology needed to scale fuel cell power technology for main propulsion power in commercial and passenger ships (Scriven, 2019).

Though the vehicles in these examples represent a relatively small percentage of the commercial vehicle population worldwide, the diversity of ZECV applications that have now been developed

further prove the need to innovate existing ZECV components to reach new vehicle markets (Welch, 2020). However, as regions across the globe enact the Beachhead Strategy along similar timelines, global supply chains will grow and investments in ZE technologies and infrastructure will increase, further driving the market along successive pathways to achieve zero emissions.

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