Technology Pathways

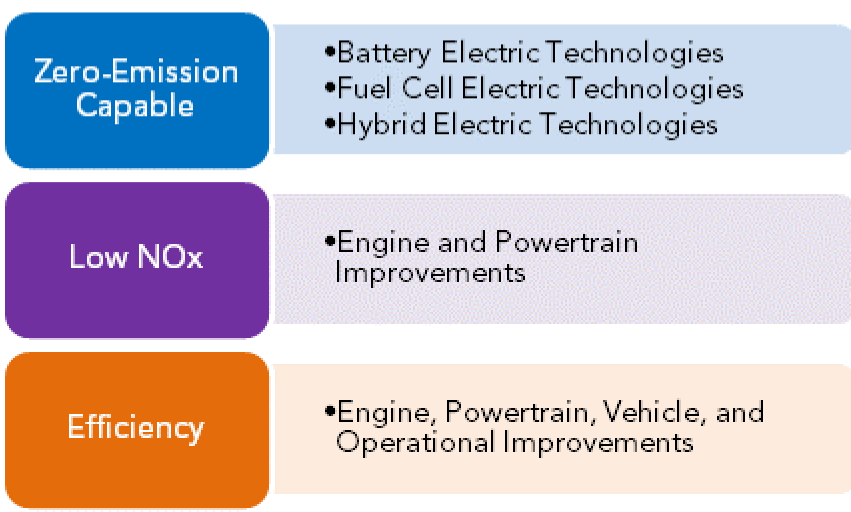
Over the previous two years, the California Air Resources Board (CARB) has been following a refined and targeted strategy for accelerating the development and market introduction of technologies critical to achieving the State's near term and longer-term climate and air quality goals.

This roadmap to develop the zero-emission and low-emission technologies needed to enable air quality and climate change goals is organized around a strategic approach for accelerating targeted technology improvement in three ways:

1. Focusing on continuing to invest Low Carbon Transportation dollars across the commercialization arc for various technologies, building on our previous investments. This includes supporting technologies through the demonstration, pilot, and commercial phases.

2. Focusing those investments on critical technology pathways necessary to meet the State's long-term climate and criteria emission goals. The three critical technology pathways identified are Zero Emission (organized around battery electric, fuel cell electric and hybrid electric technologies); Low NOx (engines and powertrains); and Efficiencies (engine and powertrain, full vehicle and system operations) (see Figure 1).

Figure 1: Pathways to Near-Term and Long-Term Goals



3. Targeting investments around the expansion of "beachhead" markets – early successful vehicle applications where the pathway technologies can best establish initial market acceptance, and then from there seed additional adjacent market applications. The beachheads will be discussed further in a later section.

The strategy of focusing on these pathways is showing success to date as measured in the significant growth in vehicle voucher requests and the improvement of technology capability being displayed in demonstration and pilot stage projects. A greater variety of platforms are becoming available and a broader cross section of industrial providers are becoming involved, including global original equipment manufacturers (OEMs) as well as innovative new manufacturers.

Technology Status Updates

To maintain the effectiveness of the investment strategy and to track progress against goals, it is important to monitor the status of the key pathway technologies. To provide a more granular view of this technology progress, CARB with its grantees and with input from industry stakeholders have conducted a high-level technology snapshot review process to assess the generalized status and progress of the key pathway technologies and representative platforms using this technology. The goal of these analyses is to provide valuable directional guidance on where important platforms are in terms of technology readiness for the market. This approach allows staff to adjust investment recommendations to help further expand market and technology success or to further assist technologies moving more slowly or facing additional barriers.

As in previous years, for each of the critical pathways and technology categories identified above staff and CARB's consultant have prepared an updated high-level overview of the technology readiness assessment of the technology as it pertains to heavy-duty vehicles and off-road equipment. Building on the baseline approach established in FY 2017-18, applications of the technology are characterized in

CARB HEAVY-DUTY VEHICLE CLASSIFICATIONS USED

For simplification, and for purposes of this document, this investment strategy refers throughout to heavy-duty vehicles. However, that designation is meant in the broader sense of commercial vehicle ranges and applications. Indeed, CARB incentives for commercial vehicles can be used from weight classes starting above 8,500 pounds Gross Vehicle Weight Rating (GVWR). This document will refer to medium-duty and heavy-duty applications but will attempt as often as possible to refer back to the CARB weight designation system where they are applicable. This consists of Light Heavy-Duty — LHD (>14,000 pounds - 19,500 pounds GVWR); Medium Heavy-Duty — MHD (>19,500 pounds - 33,000 pounds GVWR) and Heavy Heavy-Duty — HHD (>33,000 pounds GVWR). These weight class initials will be listed next to platforms being tracked to aid in understanding.

terms of general stages on the path to commercialization and the potential market penetration of the application.

With the end goal of broader market acceptance, the strategy takes a layered approach: beginning first with vehicle technology readiness, and then building on that to understand other barriers to market acceptance, such as work site rules, unique duty cycles, and infrastructure costs. Taking these steps to understand the root issues of readiness and barriers greatly assists in formulating more nuanced and effective funding recommendations and priorities.

For consistency and to track progress, these updated assessments build on the assessments presented in the previous two Three Year Heavy-Duty Investment Strategy documents and adjust them for changes in the intervening year. While these assessments originally built from technology assessments conducted by CARB staff (in conjunction with staff from other agencies and industry) over previous years[1] the updates are based on reviews of additional or updated data and information from literature, public information sources, private conversations with technology providers and field data where available.

In tracking this progress it is important to keep in mind the goals of the Low Carbon Transportation projects as laid out and planned for in this document. Fundamentally, Low Carbon Transportation is tasked with greenhouse gas (GHG) reductions through strategic investments in technologies that provide GHG and other co-benefits. With the end goal of broader market acceptance, the strategy takes a layered approach: beginning first with vehicle technology readiness, and then building on that to understand other barriers to market acceptance, such as work site rules, unique duty cycles and infrastructure costs. Taking these steps to understand the root issues of readiness and barriers greatly assists in formulating more nuanced and effective funding recommendations and priorities.

As a result, the assessments which follow evaluate technology readiness, not market readiness per se. Market readiness is driven by a variety of factors that can vary and are complicated by location and application and are not as readily quantifiable. A product may be fully technically ready for commercial introduction, but issues around infrastructure timing, knowledge of business case, training and other issues can slow introductions. Therefore, these status updates focus on the readiness of the technology generally, and then highlight those barriers or other considerations that may slow adoption.

These technology status "snap-shots" are also unique in their design. They are broadly guided by the general framework of Technology Readiness Levels, or TRLs[2].

[1] CARB, Technology and Fuels Assessment Reports, June 2015 to December 2016. https://www.arb.ca.gov/msprog/tech/report.htm
[2] NASA, Technology Readiness Levels, October 28, 2012. https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

However, the approach used in these assessments is an adaptation of the TRL process that is applied not to a component but to a full vehicle platform. Therefore, the technology readiness portrayed is not intended to be absolute, but rather directional to provide information on where pathway technologies generally reside, and what supporting tools or funding could then benefit them. For 2019-2020, the technology status snap-shots have also been refined from previous years in several ways. The chart location of each platform listed is not representative of any one specific product or vehicle, but is an aggregated average status based on the multiple platforms and manufacturers and the different stages at which each may be.

Each individual platform which contributes to the average is also provided a weighting, based on the type of manufacturer involved and numbers of units fielded, where relevant. For example, the status level of a platform from a vertically integrated global OEM would be weighted more heavily than a platform from a start-up vehicle integrator. This weighting helps provide a realistic assessment of where a platform is in overall progress toward technical and commercial readiness. These platform assessments are displayed as the general weighted average status of known platforms. This may mean a technology could be shown as generally in a pilot stage of technology readiness, even when there may be products from some manufacturers already in commercial production.

As previously noted, these assessments are an important first step but tell only part of the commercialization story. Some specific applications for a platform may present market implementation challenges. Therefore, a platform shown as technically ready for early commercial introduction (roughly corresponding to TRL 9) may not necessarily have the ability to perform every possible role in which its class of vehicle might be used. For example, a Class 8 natural gas-powered tractor cannot readily serve all long-haul truck roles. Issues of fuel availability, adequate fuel storage tanks and sufficient power may limit its use to some sub-set of Class 8 routes and duty cycles. Similarly, a battery electric transit bus today may not meet every possible transit district route or operational need for multiple back-to-back shifts. Nonetheless, each of these platforms has achieved technical readiness for commercial production and can address a meaningful portion of that application's needs.

In the technology status charts that follow, the x-axis represents how far the technology has advanced toward readiness for production, with those in the early demonstration stages shown on the left. Those that are closer to being commercially available are shown on the right. The y-axis shows generally the potential market penetration for that technology, with those technologies having a very small potential market near the bottom, and those with a larger potential market near the top. An arrow next to a technology platform shows directional changes in commercialization status since the last update. Given this is the third year of tracking, the platform names represent their positions in the 2017-2018 assessments. Each arrow shows progress tracked in each succeeding year.

Some of the progress noted is very solid year-over-year and is one signal of the early success of the investment strategy, particularly in areas where pilot and demonstration funding has helped validate vehicle designs.

Note:

- ***Applications listed are meant as reasonable examples to illustrate tech status points, but do not specifically represent investment targets.***

Technology Status Snap-Shot UPDATE: Battery Electric Vehicles

Battery-electric vehicle (BEV) technologies and key platforms are a critical element of the zero-emission pathway. They have improved continually in technology readiness in the past year across most of the platforms assessed. This progress is most pronounced in the platforms that make up the first-success applications identified in the "beachhead" strategy for the zero-emission strategy.

The full-size transit bus application (HHD weight classes) remains an important first success application as every major North American manufacturer and several new manufacturers have products available for purchase. Importantly, this is not isolated to North America but is a global phenomenon which can be seen also in Europe, China and India, with growth also in South America. There are now twelve electric bus makers with more than 25 models available in the U.S. and more than 1,650 ZEV buses have been deployed or ordered as of Fall 2018. The dominant percentage of these are BEVs, with just over half of these buses in California. As we will note in barriers, as the deployments grow and bus numbers per site increase bus operators are facing issues with the time needed to install infrastructure, adequate local charging capacity in some cases, and growing pains with best charging system designs. This is a key important topic to address and around which to develop solutions.

TECH EXAMPLE
ELECTRIC DRIVETRAIN TRANSFERABILITY

[under review]

A key secondary application after BEV transit buses is BEV delivery (MHD weight classes). This sector is also seeing progress in both its overall technical readiness and the first large volume purchase entering the market. The largest single BEV commercial vehicle order outside of China took place when FedEx Express this year placed an order for 1,000 Chanje Class 5 electric delivery vans. Additional large orders are anticipated. This overall application platform has seen a significant addition of vehicle models in early production (Fuso eCanter[3]) or in development and announced as heading to production in the near term (Freightliner eM2[4]). Overall this category ranges from later pilot stage to early commercial stage, with the weighted placement of this application moving into higher readiness but still being late pilot stage.

Steady technology progress also continues to be made in Class 7 and 8 (HHD) short haul drayage and regional haul trucks, which are both moving into the pilot stage of development. Most major truck OEMs are now actively involved in developing products and are involved in CARB-

[3] https://www.mitsubishi-fuso.com/content/fuso/en/truck/ecanter/lp.html; https://media.daimler.com/marsMediaSite/en/instance/ko/Daimler-starts-production-of-FUSO-eCanter-in-Europe--the-worlds-first-series-all-electric-light-duty-truck.xhtml?oid=23599698
[4] https://www.thedrive.com/news/25626/daimler-delivers-first-freightliner-em2-commercial-electric-truck-to-penske

funded projects around freight facilities. Additionally, several smaller powertrain providers who had been supporting such vehicles have been acquired or invested in by larger Tier 1 truck industry suppliers (Tier 1 companies are manufacturers who sell directly to the OEMs[5]), increasing the smaller firms' viability. Progress also has been made in refuse trucks (HHD) and there is clear technology transfer from bus and other truck platforms to this segment. 2021 remains a common early market production timeline for these products[6] and they are prime candidates for pilot stage deployment and validation.

At least eight school bus products are either commercially available or announced as coming to market. Public agencies have signaled tremendous interest in this application and funding is becoming available not just in California but across the U.S. It is important to note that the range of technology readiness is still fairly broad between those already producing and selling vehicles, such as Lion, and others who are still validating their powertrains. Manufacturers are rapidly working to scale their still low manufacturing capacity for these vehicles.

On the off-road side, one platform not tracked in previous years and added this year is battery electric ferries. There is global use of this technology, in particular in Northern Europe. First units are being ordered into North America[7]. In many cases these vessels use powertrain systems built up from

TECH EXAMPLE
ON-ROAD SYSTEMS TRANSFER TO HEAVY CARGO LIFTS

[under review]

[5] https://smallbusiness.chron.com/tier-1-company-21998.html
[6] https://www.greenbiz.com/article/big-truck-makers-are-starting-take-electric-trucks-seriously
[7] https://www.goodnet.org/articles/canada-adding-two-fullyelectric-ferries-to-its-fleet

on-road components. While hybrid versions are more prevalent, they share common components with the battery versions.

The technology status held steady for most applications. Class I and II electric forklifts are ubiquitous. In general, BEV ground support equipment at airports is available today as a commercially available option.

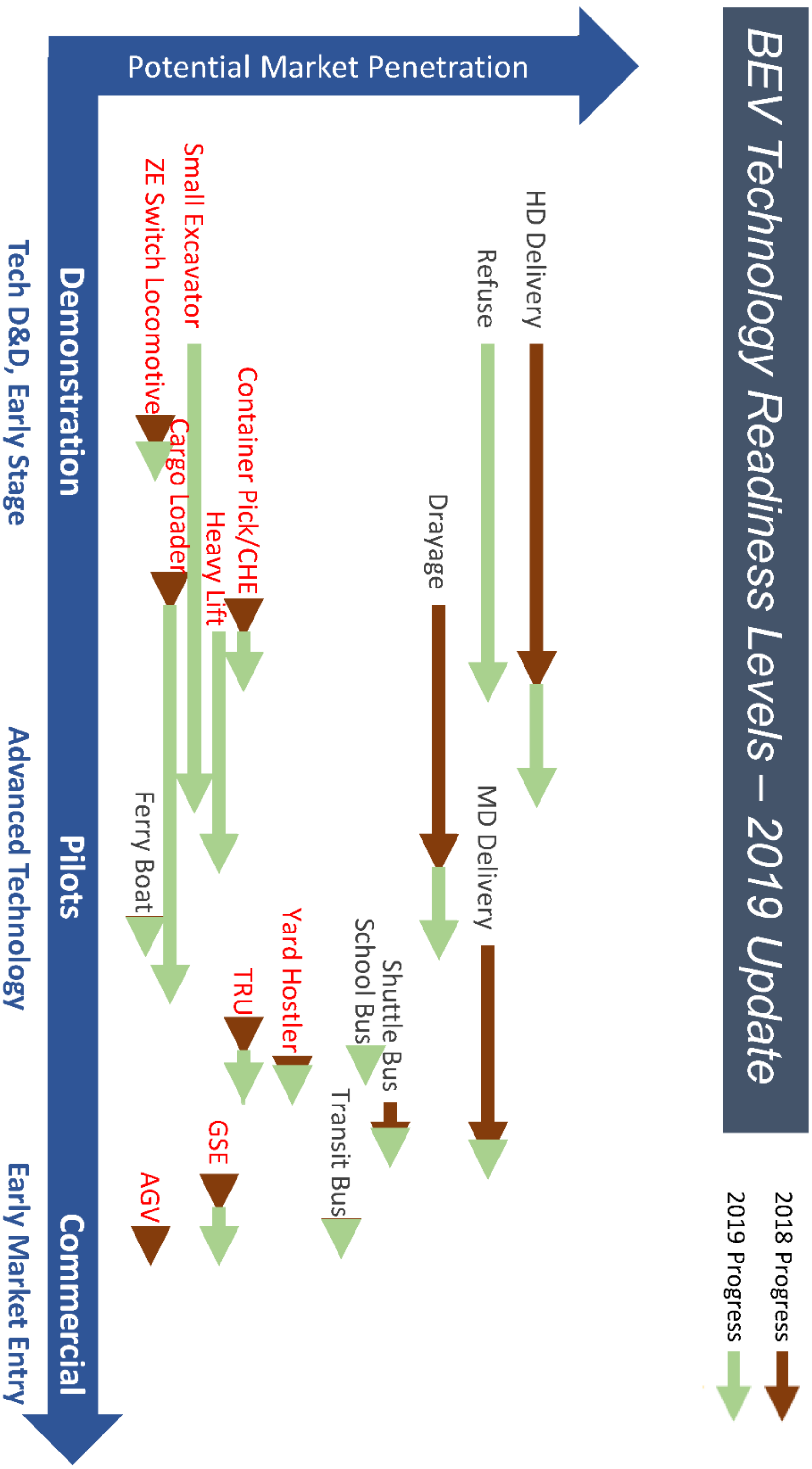
Yard hostlers (known by several names, including yard trucks, yard goats and terminal tractors) are simplified Class 8 tractors (HHD) are designed to move trailers within and between warehouse facilities, intermodal sites, port terminals, or cargo yards. They remain a category on the cusp of late pilot and early commercial market deployments with several manufacturers providing or announcing products. While some port operations remain concerned with their unique duty cycle and high utilization, that is an issue of infrastructure suitability and work rules, not technical readiness. While those are important issues for implementation, they do not change the technology readiness status of the platform.

In this year's assessment, staff separates heavy lift equipment from other cargo handling equipment (CHE) and top picks. BEV cargo handling equipment such as top picks, which are used to lift or pick up containers usually at port or multi-modal facilities, are making progress but remain at the demonstration phase. However, heavy lifts are making faster progress based on a few platforms moving past pilot to early production. Part of this is based on the ability to transfer powertrain technology from on-road applications.

Battery-electric transport refrigeration units (TRUs) are designed to function the same as units powered by small engines but they instead get their power from stored energy in batteries. Partly due to impending regulations requiring zero emission TRU operation in California, several manufacturers are developing fully battery-electric units and fielding them for pilot evaluations. Most battery electric designs have the capability to also plug in to shore power, such as at a loading dock, to operate the units as well as charge their batteries. Some TRUs now in production also have the capability of extending their daily operation by accepting power from truck body-mounted solar panels. In addition to battery electric TRU designs, there are also other technologies emerging to allow zero emission TRU operation without batteries. Such units instead harness the cooling power of cryogenic gases and pneumatic power generation.

These platforms can benefit from demonstration and pilot funding assistance to help them transition to upgraded system designs and early market stage deployments.

Figure 2: Technology Status Update – Battery Electric



Key: Off-road shown in red
AGV = automated guided vehicle
GSE = ground support equipment
CHE = cargo handling equipment
TRU = transport refrigeration unit
ZE = zero emission

Source: Based on CARB technology assessments, industry research, interviews with manufacturers, project data and status and other studies and publications.

Key Barriers to BEV Adoption

A more in-depth discussion of on-going issues impacting commercialization can be found in the last section of this document. As an overview for BEVs these barriers include:

- Infrastructure has emerged as the current largest issue requiring increased attention as fleets transition from a handful of vehicles to larger deployments. Based on field examples and comments made at several forums and meetings, fleets are facing several realities including: the long lead time needed to plan, site and install chargers; the need to increase electrical capacity at their facility; space claim for vehicle charging sites; the cost of the installations themselves; lack of understanding of utility rates and demand charges; and insufficient standardization of physical interface or communication standards. The California Public Utilities Commission SB 350 rate case outcomes for the state's major investor owned utilities will allow investor owned utilities to provide significant assistance with infrastructure costs and to modify their rate structures; this assistance is just now being seen in the market in mid-2019 as the utilities scale up to respond. HVIP has developed a direct connection to utilities to ensure better lead times by connecting fleets to utilities at the time of vehicle order. Additional detail on the work to address infrastructure issues is found in section on On-Going Issues Impacting Commercialization.
- High incremental cost of the vehicles remains a barrier in the general sense, though California has enacted several effective programs to address costs in the form of the HVIP purchase vouchers, Moyer, and VW funding as well as separate funding from air districts. Assuming sufficient funding is allocated to these programs, the State has strategies to address this barrier. Fleets do face higher sales taxes and registration fees based on the incremental cost of BEVs. While incremental costs are higher than conventional vehicles due to low production volume, energy storage, and electric powertrain costs, there are signs of improvement as energy storage costs are steadily reducing and MHDV manufacturers are starting to see those reductions. Beachhead markets are also starting to expand core component supplies which will over time help reduce costs.
- Limited vendor and product selection and the accompanying service and support network remains an issue but is improving. Workforce training efforts for maintenance technicians and infrastructure installation personnel could benefit from greater coordination and funding. These limitations should improve in the next few years as pilot programs complete and additional manufacturers enter production. Product selection is expanding in the primary and secondary beachhead markets. Major OEMs and their dealer networks are starting to enter the market. Some established fleet service providers have entered into agreements to provide maintenance support to smaller company products.

- Potential payload impacts from the size and weight of the battery electric components are no longer as much of a concern because of legislation passed in 2018 which grants a 2,000-pound weight exemption to zero and near zero emission commercial vehicles.
- Range or time of operations before refueling, while limited, is steadily improving. Energy storage capacity, and therefore longer range, continues to expand as price drops. Class 8 ranges of 150-250 miles are being announced, with some as high as 300- and up to 500-miles of reported range. However, longer-range BEVs necessarily have larger and heavier batteries, with some vehicles exceeding state axle weight limitations.
- There still exists a lack of understanding of the business case and best deployment applications. The beachhead strategy has assisted in defining where technology will provide capability and business case. Increasing demonstration, pilot, and commercial deployments are providing data to validate the fuel and maintenance savings associated with BEVs and the associated total cost of ownership. Early transit bus deployments are yielding payback periods as short as 3-5 years relative to conventional technologies, not including infrastructure costs.[8] Given that infrastructure is a long-term investment not tied to any specific vehicle model, this can be a reasonable approach. In California, there is significant funding coming available for infrastructure costs. However, even with infrastructure included, CARB staff has calculated a favorable total cost of ownership (TCO) over conventional technologies, when incentives and Low Carbon Fuel Standard (LCFS) credits are factored in.[9]

BEV Opportunities over the Next Three Years

In on-road applications, BEV technology is steadily expanding in the early beachhead market of transit buses, and emerging in medium delivery and service vehicles, shuttle buses and school buses. Heavier vehicle applications such as drayage and regional delivery trucks are now in pilot stage and refuse is entering demonstration phase with several manufacturers. In the off-road sectors BEV technology is in the commercial stage for industrial lifts and GSE. Port equipment is in the late pilot to early commercial stage for yard hostlers/terminal tractors and in the demonstration stage for heavy-duty cargo handling equipment such as top picks. High tonnage forklifts show promise to progress faster, partly due to the ready transfer of powertrains and energy storage from BEV truck platforms. TRUs are in pilot to early commercial stages. In the marine sector, electrification of ferry boats as well as harbor craft are proving themselves in European and U.S. demonstrations and can use technology transferrable from on-road. All these applications are important areas for investment funding to advance.

[8] https://ww3.arb.ca.gov/msprog/tech/techreport/bev_tech_report.pdf
[9] https://ww3.arb.ca.gov/msprog/ict/meeting/mt170626/170626_wg_pres.pdf

Technology Status Snap-Shot UPDATE: Fuel Cell Electric Vehicles and Equipment

Fuel cell electric vehicle (FCEV) technology has seen a solid and growing re-emergence at the late demonstration/early pilot phase for heavy-trucks and continues to expand in light industrial forklifts as a successful early commercial product. Demonstration activity in heavier lift and cargo handling equipment (CHE) continues.

There are expanding opportunities to leverage fuel cell systems from one application and use it in others. The fuel cell systems from industrial lift-scale devices (hydrogen fuel cell forklifts are commercially available in Class I, II, and III lift capacities) are under consideration as range extender power plants for on-road vehicles. Their benefit is they are an existing product and can tap an established supply chain and existing early production volumes. Similarly, fuel cell power plants developed for the passenger car market are expanding into heavy-duty demonstrations serving as full propulsion units in on-road drayage truck applications, with the expanded Toyota and Kenworth demonstrations as the prime example.

TECH EXAMPLE
COMMON POWERTRAINS LINK BATTERY AND FUEL CELL ELECTRIC VEHICLES

[under review]

In the on-road market, fuel cell transit buses continue to make progress and are in the late pilot to early commercial stage. There are now several fully certified commercial FCEV bus products offered in North America, and the first fuel cell buses received HVIP purchase vouchers this past year. This segment, just on the cusp of commercialization, would still benefit from a focused pilot to help with hydrogen infrastructure scaling and to further increase fuel cell component volumes.

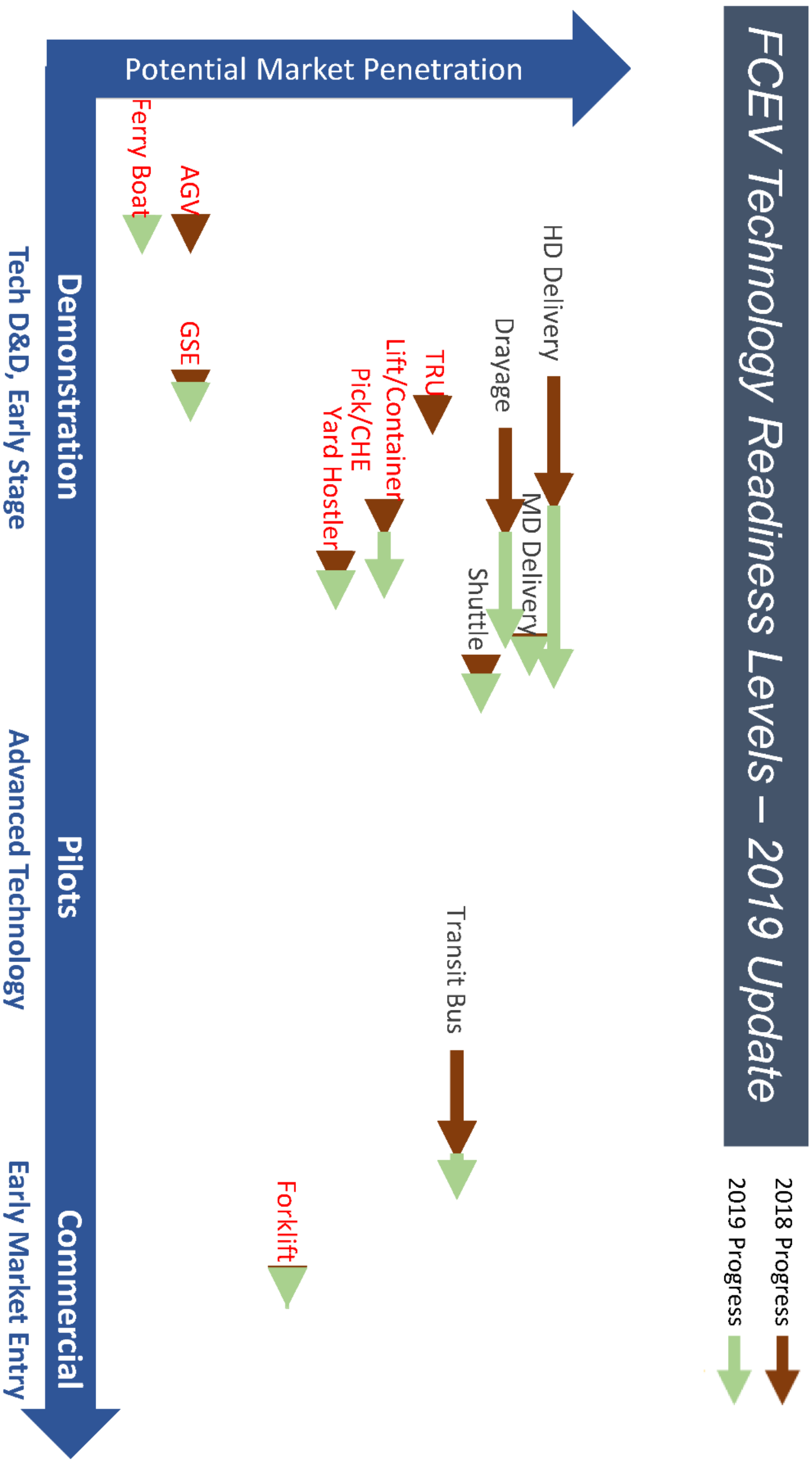
One of the reasons behind a growing interest in fuel cell electrification is the potential for providing sufficient energy for long range, heavy weight duty cycles, or those work cycles requiring continuous operation or multiple-shift operation where recharging may not be an option. Such operations can make use of centralized, high throughput fueling stations which can be sited with on-location higher capacity hydrogen production facilities. While still in the prove-out phase, such production sites may allow for much lower cost hydrogen fuel production. Such high-volume centralized fueling could serve as a base for a range of applications, such as port equipment, marine vessels and drayage trucks as well as other regional applications.

There is also an emerging clearer sense of the highly complementary nature of battery electric and fuel cell electric platforms and their uses. Both can make use of the same core powertrain components (electric motors, power electronics and energy storage) and jointly benefit from increased supply chain volumes. While battery electric capacity is increasing and therefore greater range is becoming increasingly possible, with Tesla signaling ranges to 500 miles[10], there may be a cross-over point where the fuel cell becomes the preferred option for weight and refueling considerations. Indeed, Nikola Motor Company this year unveiled both battery electric and fuel cell electric versions of their trucks, with the battery electric versions aimed more at urban and regional applications, and the fuel cell version aimed at line haul applications. While there is yet no clear guidance on the distribution of these technologies, this is an active area of exploration and research. Much depends on the ability to significantly reduce the cost of hydrogen fuel production and delivery.

The development of other fuel cell electric trucks, specialty equipment, and shuttle buses is underway at the demonstration phase. Multiple medium- and heavy-duty demonstration projects are underway in the United States. It is worth noting the potential also for fuel cell use in other off-road applications including heavy cargo handling equipment and the marine sector. CARB is funding a demonstration of a fuel cell electric top pick from Hyster at the Port of Long Beach. In San Francisco Bay, a promising demonstration of a fuel cell powered ferry boat could lead to other applications such as harbor support and work vessels. Such applications could make sure of centralized fuel production and fueling infrastructure, such as at port sites.

[10] https://www.cnbc.com/2017/11/16/tesla-semi-truck-has-a-500-mile-range-ceo-elon-musk-reveals.html

Figure 3: Technology Status Update – Fuel Cell Electric



Key: Off-road shown in red
AGV = automated guided vehicle
GSE = ground support equipment
CHE = cargo handling equipment
TRU = transport refrigeration unit

Source: Based on CARB technology assessments, industry research, interviews with manufacturers, project data and status and other studies and publications.

Key Barriers to FCEV Adoption

A more in-depth discussion of on-going issues impacting commercialization can be found in the last section of this document. As an overview for FCEVs these barriers include:

TECH EXAMPLE
CENTRALIZED HYDROGEN FUEL PRODUCTION, FUELING POTENTIAL

[under review]

- The final cost of hydrogen delivered to the pump is very high relative to current diesel prices. This remains one of the core "gating" issues for hydrogen and must be targeted aggressively for progress to be made. Projects are underway to explore multi-benefit hydrogen production facilities, co-located with fueling infrastructure, which could help reduce hydrogen cost. This allows hydrogen to be used on site and eliminates currently high distribution costs. The use of renewable feedstocks in California incented by Low Carbon Fuel Standard (LCFS) credits can help reduce hydrogen cost.
- Significant infrastructure costs and a lack of easily accessible infrastructure also remain as prime barriers. A focus on developing on-site, high capacity production facility at locations of high fuel throughput, connected by corridors to similar sites, is emerging as one potential option. Such sites could also provide local hydrogen fuel to close-by refueling sites for other users. California

continues to invest in hydrogen infrastructure, but these sites are almost exclusively focused on light-duty passenger cars and except for rare exceptions do not support medium- and heavy-duty vehicle access.

- High incremental cost of the vehicles due to fuel cell stack, balance of plant and hydrogen tank costs. Costs are slowly dropping with improved engineering and product integration though not quite as fast as battery electric costs are dropping. California has enacted several effective programs to address costs in the form of the HVIP purchase vouchers, Moyer and separate funding from air districts. Assuming sufficient funding is allocated to these programs, the State has strategies to address this barrier.
- Unknowns about the life cycle of the fuel cell and time before replacement. Recent fuel cell transit bus performance data shows that fuel cell vehicles can attain long service lives that match service intervals of a standard diesel-powered transit bus.[11]
- Lack of understanding of the business case outside forklifts and best deployment applications. The fuel cell transit bus business case is beginning to provide good data from early pilot and commercial deployments. In most cases the hydrogen fuel cost is the biggest constraint, followed by vehicle costs.
- Limited vendor and product selection and the accompanying service and support network. The fuel cell manufacturer market has a strong base of providers; the vehicle producer segment is slowly expanding and starting to grow outside a solid base in forklifts, a growing suite of transit bus providers and an emerging list of potential truck manufacturers. In trucks, production is envisioned to be 2022 or later.

<u>FCEV Opportunities over the Next Three Years</u>

In on-road applications, FCEV technology is still straddling pilot and early commercial stages for transit buses and could benefit from additional pilot stage funding, particularly to assist with building out and understanding facility infrastructure and on-site fuel production. Fuel cell heavy-duty trucks are in the early to mid-pilot stage of commercialization and show growing capabilities. This remains an important investment opportunity for state funds. Similarly, fuel cell technology is ready to demonstrate in other on- and off-road applications, including cargo handling equipment and harbor craft where shared fuel production and infrastructure can be developed and supported. Fuel cost remains a prime barrier to scaling and investments in technologies and processes for large scale on-site production and fueling facilities should be a focus of regional, state and federal fuels funding. CARB fuel cell vehicle funding has been used to leverage other agency funding of hydrogen infrastructure and fuel production. The agency is committed to finding other such project partnership opportunities that can help build a larger scale, site-based hydrogen production capacity, combined with on-site and regional fueling sites matched with multiple MHD fuel cell vehicle applications to use it.

[11] https://ww2.arb.ca.gov/news/ac-transits-fuel-cell-program-breaks-25000-hour-operating-record

Technology Status Snap-Shot UPDATE: Hybrid Electric Vehicles

TECH EXAMPLE
TRANSIT BUS POWERTRAINS ADAPTABLE TO MARINE PLATFORMS

[under review]

Hybrid electric systems share many sub-components with battery electric and fuel cell electric systems, so improvements in the core technologies generally benefit all variants. Over the past year there has been a noticeable expansion of capabilities in hybrid buses, which remain a strong and fully commercial segment of the transit bus market. Particularly in series-hybrid systems, manufacturers have added increased energy storage and the capacity to operate in extended zero-emission mode, activated via geo-fencing to protect sensitive areas or populations. These augmented systems build on the fully commercial bus design but are currently at lower volume and would be considered late pilot or early commercial stage. Additionally, all auxiliary systems (such as air conditioning, heating, steering) are being electrified to enable zero-emission operations. This variant allows buses to meet all extended range or hours of operation needs a transit operation might have while still providing meaningful emission reductions. A California electric powertrain company, EDI, was also acquired this past year by engine manufacturer Cummins as part of its strategy to bring BEV and hybrid electric vehicle (HEV) technologies to market in heavy weight class applications including delivery trucks (MHD), transit buses (HHD) and regional heavy haul trucks (HHD).

Hybrid systems are also available commercially from one major truck maker and several qualified vehicle modifiers (QVMs), sometimes referred to as up-fitters, in medium-duty delivery and service applications (MHD). These systems are in low volume but would be considered just beyond early commercial.

Hybrid systems are already in production that provide work power and engine idle reduction at worksites (electric power take-off). These systems potentially could also be used to power TRUs as well as provide ambulance and first responder power, which could be a focus of demonstration funding to extend the value of those commercial systems.

Start-stop hybrid systems that allow an engine to turn off at stop lights, traffic delays or during idle operation are becoming increasingly available in medium-duty vehicles; they are becoming very prevalent in pick-up and sport utility platforms. Start-stop systems are offered in transit, yard hostler/terminal tractors and refuse trucks (HHD) and some medium duty truck applications (MHD). The importance of this development is both in the immediate fuel savings and in building out a high-volume supply chain for components.

HEV drayage and heavy regional delivery truck applications (HHD), including plug-in hybrid electric (PHEV) and extended range series-electric designs, are in demonstration or early pilot stage. The rapid emergence of BEV technology and stringent emission certification testing has slowed some HEV development, though HEV architectures are the backbone of FCEVs.

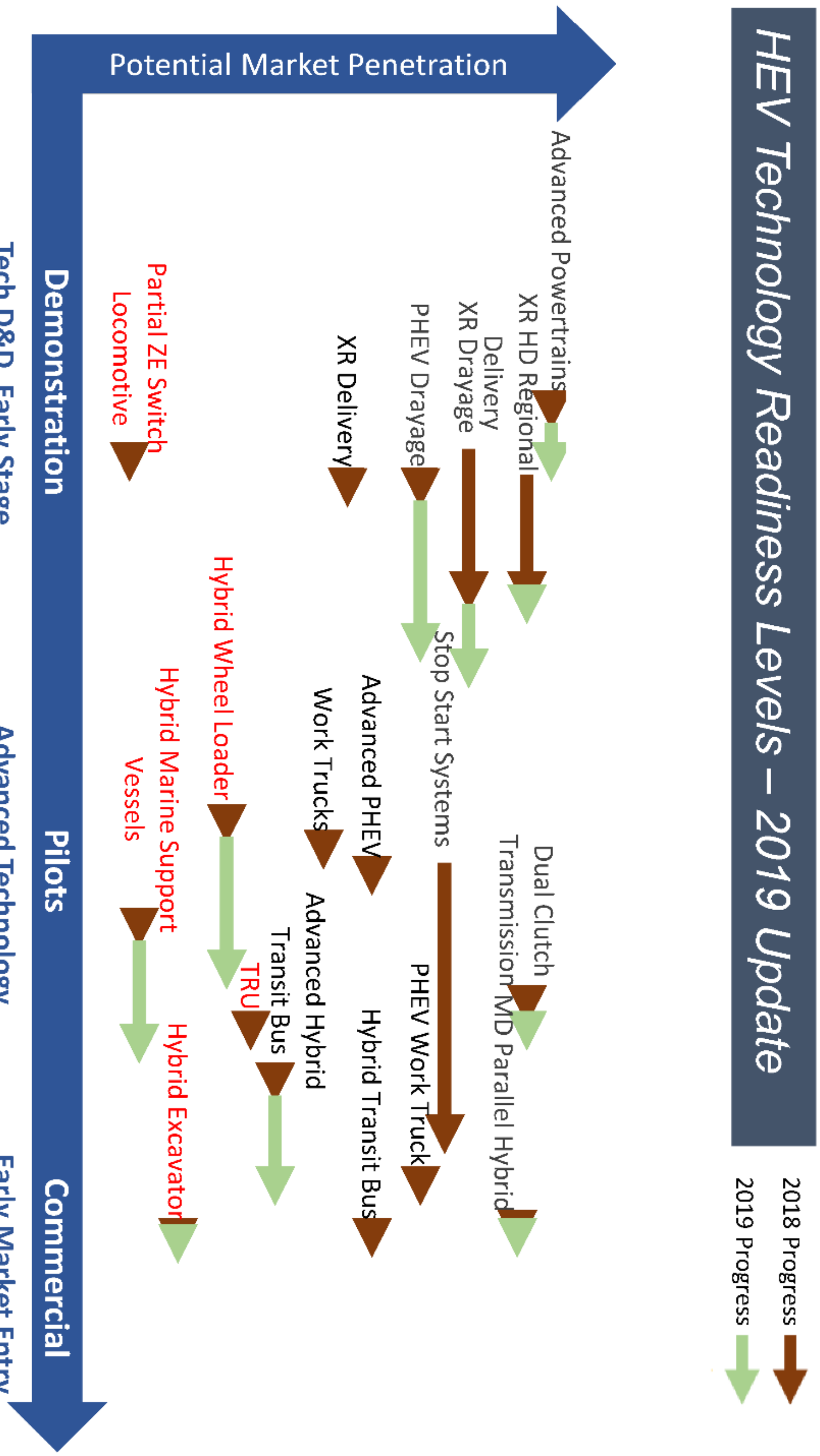
The off-road segment is increasingly promising for the use of HEV technology as these applications often require high power demands, long operational capability and are remote from electric or hydrogen refueling options. Additional factors such as the cheaper cost of HEV technology and the chassis packaging requirements for many off-road applications play a role in making hybridization a desirable option. HEV technology has the potential to meet the needs of these rigorous off-road applications and many stakeholders, including manufacturers and end-users, have expressed interest in developing and utilizing this technology.

In terms of specific platforms, hybrid excavators range from the pilot stage to early commercial stage. Hybrid wheel loaders are in the demonstration or advanced demonstration stage moving to pilot. Both products are commonly used for construction purposes. Wheel loaders also have goods movement/freight uses. Both wheel loaders and excavators, as well as other hybrid construction and agricultural equipment, are freight-enabling applications because of the common supply chain for components. Hybrid cargo handling equipment has been developed, mostly in Europe, and some is entering the very early market.

Marine vessels, particularly harbor craft but not only limited to that segment, is a rapidly emerging sector for hybridization. Several major global manufacturers have powertrains or major developments in this segment, including ABB, Siemens, BAE Systems and Volvo Penta. Hybrid ferry and support vessels are in use in Europe and in demonstration and pilot stages in the U.S. These vessels have been developed using components in some case taken directly from transit hybrid systems and are excellent examples of the potential for direct technology transfer. The systems can provide direct propulsion power, or provide auxiliary or idle power for marine vessels, some as large as cruise ships. Primary applications include tugs, tenders, ferries and other similar vessels. CARB is currently funding a hybrid tug boat as part of the Zero- and Near Zero-Emission Freight Facility (ZANZEFF) program.

Hybrid systems provide fuel savings and potential emission reductions (on a duty or work cycle basis) and also serve as an important pathway for zero-emission technologies. Hybrid electric heavy-duty vehicles help increase the production volume for components like battery packs, electric motors, and control systems by bringing down manufacturing costs, and supporting the supply chain to benefit other zero-emission technologies.

Figure 4: Technology Status Update – Hybrid Electric



Key: Off-road shown in red
PHEV = plug-in hybrid electric vehicle
TRU = transport refrigeration unit
XR = extended range

Source: Based on CARB technology assessments, industry research, interviews with manufacturers, project data and status and other studies and publications.

Barriers to HEV Adoption

A more in-depth discussion of on-going issues impacting commercialization can be found in the last section of this document. As an overview for HEVs these barriers include:

- The incremental cost of the vehicles. While it has been dropping steadily the last few years, cost is still higher because of energy storage and control system integration. It is a bigger issue for plug-in hybrids.
- Lack of understanding of the business case and best deployment applications. Relatively low conventional fuel costs have made recovery of the incremental cost from fuel savings take longer. Recent fuel price increases may help hybrids.
- Lengthy and expensive certification process for hybrid vehicles and equipment sometimes result in missing incentive funding opportunities. The Innovative Technology Regulation was partially designed to assist hybrid technologies. However, some manufacturers remain concerned about the complexity of meeting emission regulations in systems combining engines and hybrid components.
- OBD integration, and the optimization of hybrid operations with emissions control systems.
- Limited vendor and product selection.
- Infrastructure is a barrier for plug-in hybrids but not conventional designs.

HEV Opportunities over the Next Three Years

As electrification moves into heavier weight classes, more demanding duty cycles and longer periods of operations, hybrid technologies remain an extremely relevant solution for these applications. This is particularly true of some cargo handling equipment, construction equipment and agricultural equipment where there remains a need for a combustion engine for power or sustained energy and where fuel cell technology is not either available or convenient. These applications can benefit from demonstration and pilot funding as well as purchase incentive funding where they are already in the market (such as construction equipment). Construction should be considered a freight-enabling application for purposes of commercialization. Demonstration projects can then expand these capabilities for goods movement.

Extended range architectures for medium- and heavy-duty transit and delivery applications could also benefit from demonstration and pilot focus to ensure options are developed to cover needs across the entire market. Hybrid harbor craft represent a technology already in use in Europe that could have much wider application in the U.S. and pilot and incentive funding could assist. The ability to power TRUs and provide worksite engine-off operation, as well as some drive cycle engine-off operations, needs expansion as these systems can bring NOx reduction benefits as well.

Technology Status Snap-Shot UPDATE: Low NOx

Now fully developed, the natural gas low NOx (certified to 0.02 g/bhp-hr NOx) Cummins Westport 11.9-liter engine is now in mass production and beyond the early commercial stage. The low NOx version has effectively replaced the version certified to the less stringent EPA 2010 standards. Importantly, it is available as a factory installed option from all truck makers. This engine brings low NOx technology to drayage, regional delivery and many long-haul applications (HHD) where natural gas fuel is available.

As has been noted, several other low NOx gaseous fuel engines (natural gas and propane) certified to one of the optional low NOx levels are also in full commercial production for transit buses (HHD), medium-duty on-road trucks, and school buses (MHD). These include 6.8- and 8-liter propane, and 8.9-liter and 6.7-liter natural gas engines. This technology is a success story as its status has moved through the stages of the commercialization process tracked here. The natural gas engines cited above are now being sold in the United States at volumes of several thousand units per year and are past the early commercial stage.

In Europe, 13-liter natural gas engines employing compression ignition technology are available but are not currently being built for the U.S. market and do not meet any of the low NOx standards.

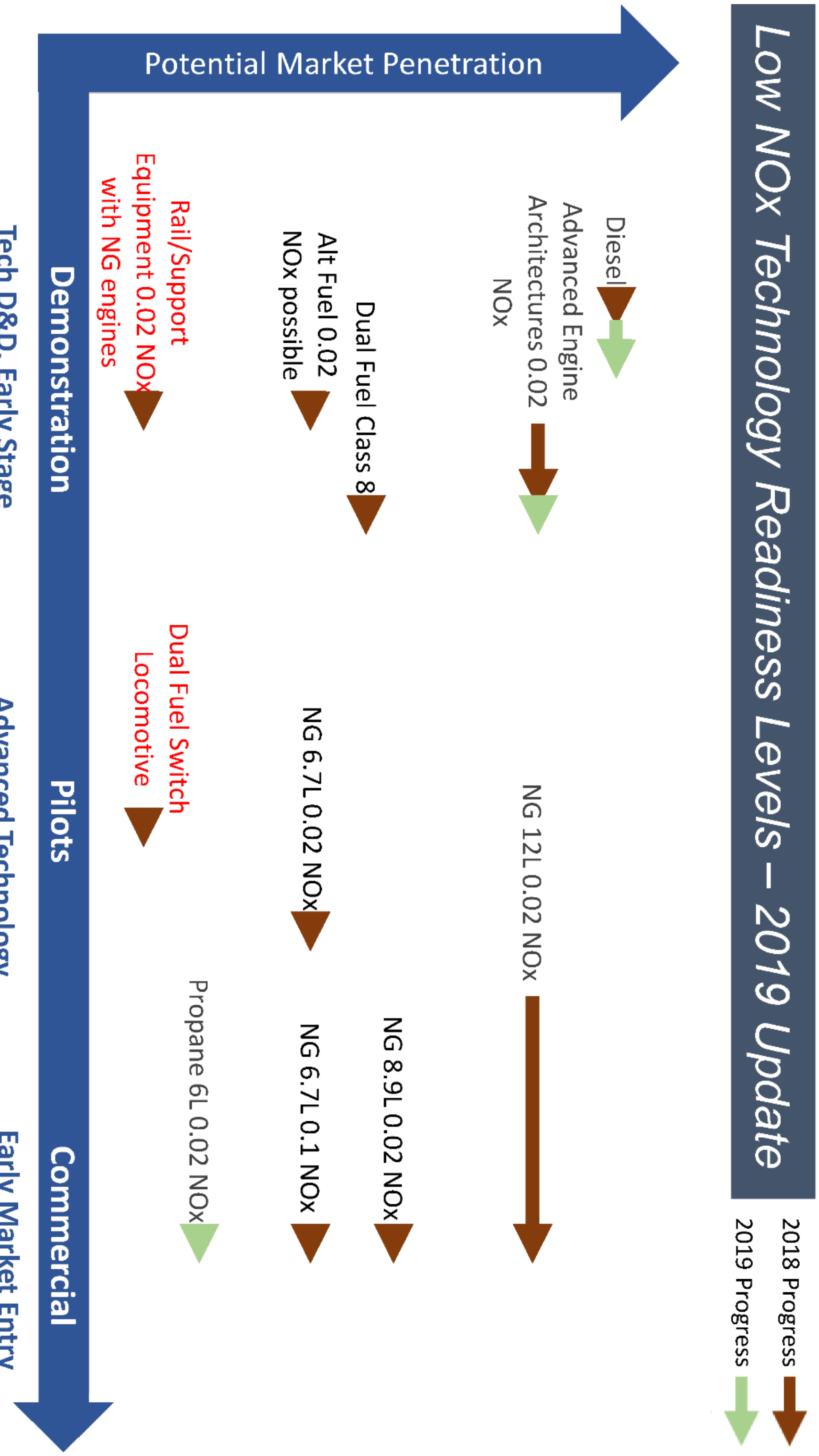
U.S. EPA has launched its Cleaner Trucks Initiative (CTI) with a stated goal of updating the federal NOx emission standards to further reduce NOx emissions from heavy-duty engines. This initiative, complementary to California's proposed rulemaking to mandate 0.0x g/bhp-hr by 2023 is putting additional pressure on diesel engine makers to look at strategies for reducing NOx. The Manufacturers of Emission Controls Association (MECA) has published a report that finds that engine makers can achieve ultra-low NOx emissions while still meeting 2027 greenhouse gas regulations. One company working to exceed this in timing and capability is Achates Power, whose high-efficiency, low NOx engine is in development and heading for demonstration. Both modeling and engine dynamometer testing have shown the capability to meet a 90 percent reduction in NOx from EPA 2010 standards while meeting or exceeding 2027 greenhouse gas standards today. Larger displacement engines for switch locomotives and some marine vessels may also show the potential to exceed Tier 4 emissions.

Expanding low NOx engine deployment into diesel-fueled vehicles and the heaviest on-road engine weight classes is important for technology transfer to off-road equipment. New low NOx engine technologies should be paired with renewable fuel use to maximize criteria and climate emission reduction benefits.

Hybrid systems also have the potential, on a duty cycle or work cycle basis, to also greatly reduce NOx emissions assuming the engines and after treatment systems are sufficiently integrated with the hybrid components and operation. This would have the further benefit of combining full powertrain efficiency improvements with emissions reductions.

In the marine sector, there are potential retrofit technologies as well as emission capture and control systems for reducing NOx, PM, and SOx emissions. In terms of supporting beachhead commercialization pathways, these technologies offer limited to no opportunity for technology transfer to other applications. However, advances in these technologies do help in meeting State climate and air quality goals.

Figure 5: Technology Status Update – Low NOx



Key: Off-road shown in red
Alt fuel = a recognized alternative, low carbon fuel other than NG
Dual fuel = engine capable of operating on diesel and NG/alt fuel
L = liter
NG = natural gas engine, either compressed or liquefied

Source: Based on CARB technology assessments, industry research, interviews with manufacturers, project data and status and other studies and publications.

Barriers to Low NOx Adoption

A more in-depth discussion of on-going issues impacting commercialization can be found in the last section of this document. As an overview for low NOx engines these barriers include:

- While moving past the early commercial stage and into higher volume production, low NOx natural gas engines and trucks still carry an incremental cost compared to diesel, largely due to fuel tanks. Low NOx engines based on propane engines do not carry as high an incremental cost. Advanced engine systems could eliminate additional fuel system costs but may carry higher costs for lower volumes in the early years.
- More than 20,000 natural gas vehicles currently operate in the state with an existing expansive network of public and private fueling infrastructure. However, fueling infrastructure availability may be an issue if there were substantial additional turnover from diesel to natural gas and propane vehicles in some regions and route structures.
- Current generations of NG engine technology are proving to be reliable. Nonetheless, fleets may still remember reliability problems from earlier generations of NG engines. Case studies shared broadly with fleet decision makers could assist transition.
- Understanding payback periods is often a barrier for alternative fuels. However, even fossil-based natural gas can be cheaper per mile than diesel; renewable natural gas (RNG) even more so. If renewable fuels are used, the Low Carbon Fuel Standard credits could provide a significant price differential.
- Reduced efficiency. Generally, natural gas and propane engines use spark-ignited engine systems which are less fuel efficient than compression-ignition engines.
- Limited vendor and product selection. For natural gas this has been mostly addressed as most truck makers offer a manufacturer-installed version of the engine.

Low NOx Opportunities over the Next Three Years

Supported by an expansive network of public and private natural gas fueling infrastructure built out over the last 30 years, low NOx natural gas and propane engines are now technical success stories that are generally beyond early commercial status. They are ready for promotion from technology transformation programs to make use of funding programs specifically designed to support fleet turnover and transition.

Given regulatory proceedings, conventional diesel engines may be required to meet a lower NOx certification level over the next several years. The State has previously invested in technologies to assist this capability. Nonetheless, advanced engine designs that can achieve low NOx emissions while also increasing efficiency remain a valuable investment. Achieving low NOx emissions in off-road equipment remains a technical challenge and more pilot and demonstration work could be warranted. Validating other innovative NOx reduction strategies involving duty cycle improvements, powertrain efficiencies, and engine-off operations would also help drive innovation. This work should be focused on areas where zero-emission technologies are significantly further behind on the commercialization arc.

Technology Status Snap-Shot UPDATE: Efficiencies

In the heavy-duty and off-road sectors, efficiency strategies can be grouped roughly into three categories: engine/powerplant and drivetrain optimization; vehicle efficiency improvements; and operational/worksite efficiency improvements. In the interest of streamlining presentation and review, those powertrain efficiencies mostly enabled through hybridization have been eliminated from this section. *Please refer to the hybrid electric section for those technologies.*

Of those systems remaining in this assessment, work-site idle reduction systems deserve notice. Most of these systems are in commercial production, with some advanced or extreme function capabilities (such as higher torque or extended time operations) still in the pilot stage. The active reduction of idling from on and off-road engines during work periods or lulls in intensive activity can be a significant fuel saver.

There are continuing advancements coming in the connected and automated technology arena. Beyond platooning of trucks – the ability of two or more trucks using sensor and control technologies to follow closely to save fuel from better aerodynamics – full automation of vehicles is in validation in several categories, both on and off-road. Of great interest are those technologies allowing much more efficient, and therefore reduced energy use and carbon – work sites. Volvo Construction Equipment has completed a quarry demonstration in Sweden that showed impressive net fuel and emission reductions per unit of work using automated and electrified work machines.[12] There are some similar technologies, though not yet as fully integrated, in the agricultural equipment sector. Such projects could show great promise for California work sites.

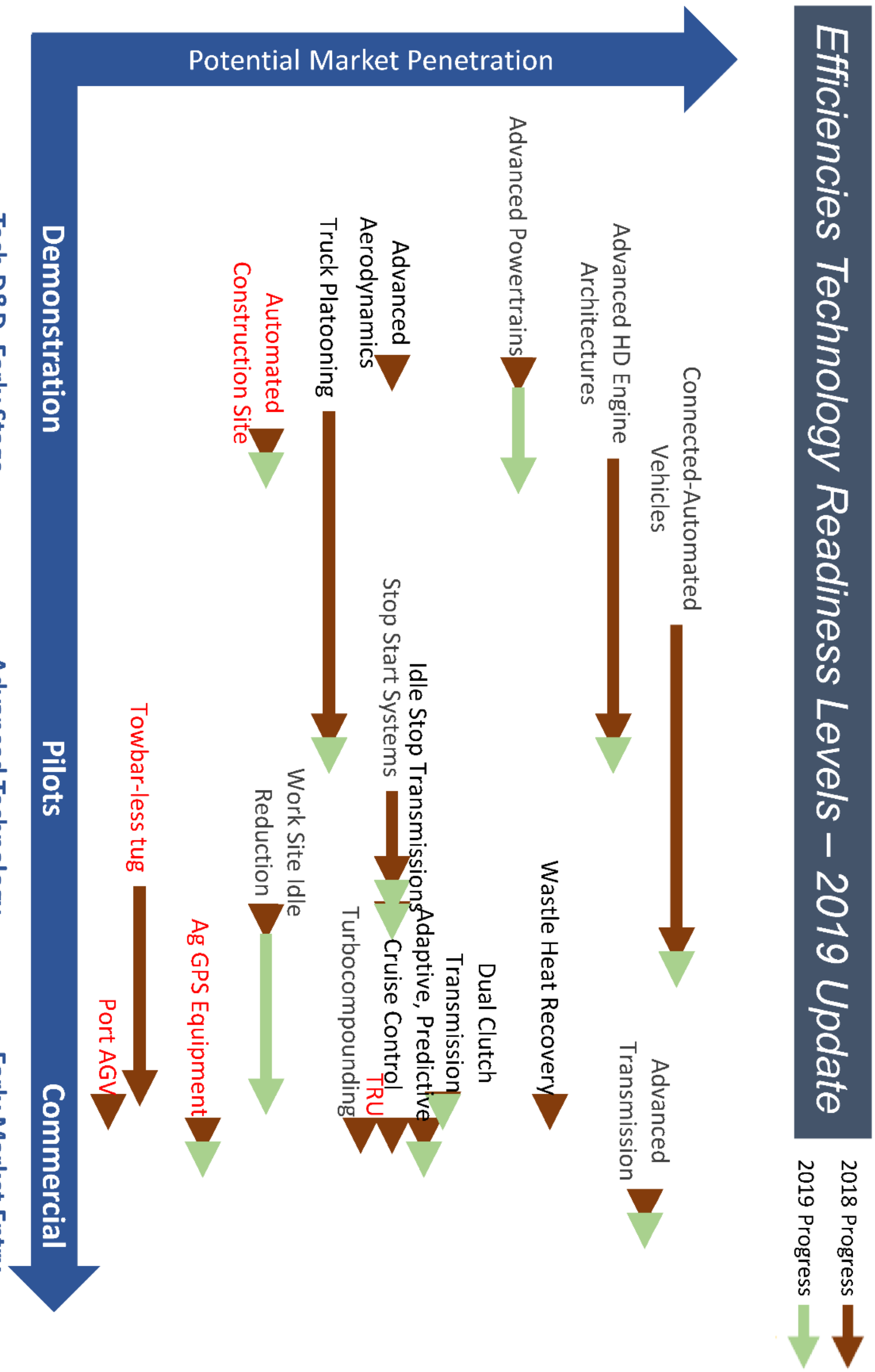
Safety as well as efficiency considerations have led connected and autonomy-pathway technologies to become increasingly commonplace in truck specifications, including adaptive cruise control, collision avoidance and lane departure warning systems. These systems are enablers of automation and also provide some of the building blocks for region-based vehicle operation, such as geo-fencing for zero emissions operations.

[12] https://www.equipmentworld.com/volvo-electric-site-quarry-test-reduced-emissions-by-95/

Towbar-less tugs for aircraft push back are becoming increasingly common and can enable aircraft to not start their engines until towed all the way to the runway, saving fuel and emissions. Zero emission versions of these tractors are in the demonstration phase and should be funded and encouraged.

Generally, CARB considers connected vehicle technologies as having a "multiplier" effect. While they may not be a large investment category on their own, their inclusion in projects paired with advanced low NOx, near and zero-emission powertrains can extend the effectiveness of these systems and should be encouraged.

Figure 6: Technology Status Update – Efficiencies



Key: Off-road shown in red
AGV = automated ground vehicle
GPS = geo-positioning satellite
TRU = transport refrigeration unit

Source: Based on CARB technology assessments, industry research, interviews with manufacturers, project data and status and other studies and publications.

Barriers to Adoption of Efficiency Opportunities

A more in-depth discussion of on-going issues impacting commercialization can be found in the last section of this document. As an overview for efficiency technologies these barriers include:

- While incremental cost is an issue, the additional cost added to the vehicles, due to cost of components and relatively expensive integration, varies greatly by technology.
- The low cost of diesel fuel creates longer payback times for any efficiency technology.
- Infrastructure may be a potential barrier for connected and automated technologies – the question is how much off-vehicle infrastructure is required.
- Lack of understanding of the business case and best deployment applications are a challenge with most new capabilities.
- There is not much familiarity yet with some of the advanced technologies. This issue is steadily being addressed as trucking fleets see the value of specific technologies and add additional connected and semi-autonomous technology to their standard truck fleets.

Efficiency Opportunities over the Next Three Years

Off-road connected and automated worksite demonstrations are ripe arenas for investment because of their ability to reduce emissions and increase productivity in otherwise hard to address sectors. Promising applications to expand this technology are ready for demonstration and pilot stage projects. Construction and agricultural sites are promising candidates and should are freight-enabling applications because of the similar components and supply chains involved.

While California funds are not generally needed to spur conventional engine efficiency gains, given U.S. Department of Energy and other investments, a technology gap remains for advanced engine development that California funding could help address because of its potential to leap-frog current designs in efficiency. Worksite and powertrain engine off technologies can be accelerated to the market via focused pilots or commercial incentives. Combining connected technology with the above strategies, such as geo-fenced powertrain management, provides a highly-leveraged strategy to move multiple technologies forward.

Other Emerging Technologies

There are additional applications that represent opportunities, including locomotives and ocean-going vessels, such reducing the operations of auxiliary or secondary engine systems on vessels. Early demonstration projects utilizing zero-emission or near zero-emission technologies are underway and should be expanded in the rail sector.

Staff anticipates working with other CARB divisions, other State agencies and stakeholders to coordinate on funding developments in these areas.