GATEWAY CITIES

I-710 Project Zero-Emission Truck Commercialization Study Final Report

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Executive Summary

CALSTART was tasked to evaluate which zero-emission (ZE) truck technologies might primarily meet the needs of the I-710 Corridor Project and drayage users, develop a preliminary business case for the more feasible technology alternatives, and describe a commercialization plan for these zero-emission capable trucks based on the technologies recommended. A number of reports and studies were used to develop the analyses. (Please see the appendices for this reference material.)

The truck technologies evaluated in this report will enable a truck to operate in zero-emission mode while being driven in the I-710 Corridor. The mileage driven in a zero-emission mode has been grouped into logical ranges, and represents "Clean Corridor Capable (3C)" trucks.

While the focus of this study is assessing the potential for commercialization of zero-emission capable Class 8 drayage trucks, the ultimate commercialization pathway of zero-emission trucks needs to be extended to intermodal and domestic trucks as well to improve market adoption, increase sales numbers of these types of trucks, and reduce their costs.

User surveys and interviews with drayage operators showed a desire for at least 100 miles in range capability, before refueling is needed (one-tank range), and preferably 200 miles. Additional user requirements were identified, and these user needs can be expressed as "Key Performance Parameters (KPP)". The KPPs were listed and, regardless of fuel technology, a drayage truck must deliver three properties:

- The vehicle must have sufficient power for operation—400 horsepower (HP), 1,200 to 1,800 foot-pounds (ft.-lbs.) of torque;
- The vehicle must achieve the necessary daily range (100+ miles) before refueling; and
- The vehicle must have the capability to be used on all delivery routes.

There are five fundamental zero tailpipe-emission capable truck architectures that could be used for Class 8 drayage trucks.

1. Dual-Mode Hybrid Electric Vehicle (HEV);
2. Dual-Mode Plug-in Hybrid Electric Vehicle (PHEV);
3. Range Extended Electric Vehicle (REEV) with Engine;

4. Range Extended Electric Vehicle (REEV) with Fuel Cell; and
5. Battery Electric Vehicle (BEV).

The optimal technology for a zero-emission capable Class 8 drayage truck depends upon the zero-emission range required. Logical categories for this capability are:

- 20 miles ZE range: Any of the five architectures,
- 50 miles ZE range: Both REEV and BEV designs,
- 100 miles ZE range: Both REEV and BEV designs, and
- Over 100 miles ZE range: REEV with Fuel Cell is the primary viable option.

Therefore, one of the major assumptions used in this report is that in order for a ZE technology to be considered for evaluation, it must be able to perform equivalent to current diesel trucks, and **must have a zero-emission range of at least 50 miles**. A truck with these capabilities can be considered a 3C vehicle. Based on these requirements, the current technological solutions possible are:

- REEV with Engine,
- REEV with Fuel Cell, and
- BEV.

There are only two fuel options that are inherently zero tailpipe-emission:

1. Electricity (via batteries in EV or REEV), and
2. Hydrogen (via fuel cells in REEV with Fuel Cell).

Each has pros and cons, and each requires infrastructure build-out to support a fleet of ZE drayage trucks. Both REEV and BEV designs use electricity, and REEV with Fuel Cell also uses hydrogen. Electricity has the following infrastructure options:

- Catenary power supply (overhead contact).
- In-road power supply (contact or wireless).
- Ultra-fast chargers (over 90kW; overhead, wireless, or plug-in).
- Fast chargers (11 to 90kW; wireless or plug-in).
- Battery Swapping.

Within the I-710 Corridor, hydrogen is readily accessible as a fuel source. A steam reformation hydrogen production plant is located in one of the Gateway Cities, and a pipeline delivers hydrogen to customers, specifically the nearby oil refineries. Arrangements can be made to tap the pipeline, and bring that hydrogen to dispensing stations for new customers (i.e., REEV with Fuel Cell truck users).

Infrastructure is one of the keys to the successful deployment of zero-emission capable trucks. First, and foremost, there need to be sufficient sources and adequate distribution of electricity and hydrogen. Refueling and recharging stations have to be included in the plan. Infrastructure development must proceed concurrently with the development and deployment of zero-emission trucks for the introduction of ZE truck operations to be successful. Additional partners and stakeholders will be needed to participate and assist as the project moves forward.

Costs for the key components of ZE trucks—batteries and fuel cells—are expected to fall dramatically as technology advances and volumes increase. However, these components will remain expensive, particularly in the early deployments, and ZE trucks can be more than double the cost of a conventional truck, even in the 2020 or 2030 time frames. Sensitivity analyses of component costs showed dramatic changes in the business case based on changes in costs, with 60 percent to 90+ percent increases in payback time when higher future estimates for component costs were used. Wider development of zero-emission trucks and deployment of both other size trucks and other applications for Class 8 drayage 3C trucks would help bring costs down more quickly and should be studied and evaluated as this commercialization effort continues to expand uses and users of zero-emission trucks.

There are a wide variety of potential ZE truck architectures, with numerous variables that are still under engineering investigation. The variables impact the costs and performance of the trucks, and the examples in this report are not intended to represent ideal solutions. The sets of parameters chosen are based on reasonable assumptions but are not exhaustive, and are only for internal comparison, not comparison to estimates from other reports or to current truck costs.

The following five architectures and scenarios were examined:

1. BEV with 100 mile range before recharging, all ZE, driven 100 miles per day;
2. REEV with Engine (CNG); 200-mile range on battery plus CNG; 50 miles ZE (battery only)—low utilization (driven 100 miles/day);
3. REEV with Engine (CNG); 200-mile range on battery plus CNG; 50 miles ZE (battery only)—high utilization (driven 200 miles/day);
4. REEV with Fuel Cell; 200-mile range on battery plus hydrogen, all ZE—low utilization (driven 100 miles/day); and
5. REEV with Fuel Cell; 200-mile range on battery plus hydrogen, all ZE—high utilization (driven 200 miles/day).

As noted, these architectures and scenarios shown were selected based on initial 3C requirements; they do not represent ideal solutions and are by no means exhaustive. Future projects must review many more alternatives and conduct an optimization analysis.

Under the assumptions and criteria used in this analysis the BEV design shows a challenging business case, with the REEV options offering easier pathways. Utilization (miles driven per day) is critical, particularly when the fuels (electricity, CNG, or hydrogen) are notably less costly than diesel. With the assumptions used for this analysis, the lowest incentives needed to meet a 5-year payback were for the Fuel Cell REEV at $17,142 when driven 200 miles/day, followed by the CNG REEV at $20,692 when driven 200 miles/day.

Infrastructure must be considered in parallel, because electrical infrastructure may have local grid impacts due to the large electrical loads that would occur in certain scenarios. Hydrogen and CNG infrastructure may have suppliers willing to cover distribution and dispensing costs in order to profit from the fuel sales, but planning for fueling station supplies and locations is essential. In all cases, additional studies and demonstration/deployment projects are needed for infrastructure.

In summary, zero-emission capable drayage trucks can be developed, demonstrated, validated, and moved into production by a 2025 target timeline. These trucks can be designed to meet the key performance requirements for port drayage operations, including range, power, and duty cycle. These trucks can show a viable business case assuming appropriate, timely and targeted incentive support, and appropriate infrastructure deployment.

The core issues that need to be addressed for commercialization of ZE freight vehicles to be successful include:

- **Flexibility.** Vehicles must be able to perform full drayage duties, including a range of up to 200 total miles per day and power to handle up to 80,000-pound loads and regional grades.
- **Operations.** Trucks must have the ability to go a minimum distance (possibly 20 and up to 50 miles) in zero-emission mode and then potentially continue to operate in a reduced emission mode outside the core port region.
- **Manufacturability.** To be successful, the manufacturing process would be based on a core, high-volume truck platform of which the ZE version is a producible variant.
- **Infrastructure.** Given the level of "new" fuel that may be required to meet the needs of up to 10,000 ZE trucks, particularly for electricity and hydrogen, planning for capacity, distribution, and siting of ZE truck infrastructure needs to start immediately and include utilities and fuel providers
- **Regulations/Inducements/Incentives/Business Case.** Given the rapid timing for the rollout of an entirely new category of vehicle, it is unlikely market forces alone will be sufficient. Therefore, regional and state air quality and transportation agencies need to quickly develop a regulatory framework in which ZE trucks will be both required and rewarded.

- **Clear Requirement Definition: Fixed Corridor or Broader "Zone"?** OEMs and suppliers need to know clear requirements to successfully design a product. This needs to be determined soon to engage manufacturers.

3C trucks cannot operate in a vacuum; they must be part of a full ecosystem that has an established framework for their operations. Therefore, several paths of parallel activity are required. They are:

- Focused vehicle and infrastructure development, demonstration, validation, and deployment process;
- Early action deployments of ZE vehicles and infrastructure in the Gateway Cities and port communities;
- Regulatory framework for ZE drayage trucks;
- Enhanced operational and business case assessment; and
- Fleet training, maintenance training, and decision support.

The development and deployment leading to the commercialization of 3C trucks will take a concerted effort if there is to be a fleet of them when the I-710 zero-emission freight corridor is projected to open about 2025. This report lays out the future stages needed to achieve this deployment. The proposed commercialization stages are described below.

Stage 1. Expand the Technology Capability, Establish the Infrastructure Framework, Build Supporting Markets and Design the Business and Operational Model, 2014-2016

- Expand tech capability beyond prototype.
- Plan and develop infrastructure framework.
- Validate the business cases and operational models.
- Build supporting markets and market structure to build ZE volumes, supply chains, and infrastructure.
- Begin development of regulatory framework.
- Develop incentive funding sources and scenarios.
- Develop Product Definition Document (PDD) for truck development.
- Develop or obtain more detailed information on drayage truck origins/distribution patterns for extended periods of time.
- After-market (or secondary market/used truck market) analysis for Zero emission trucks.
- Set up OEM working group for ZET development.

Stage 1 Goals: Deployment of several thousand ZE trucks (including work trucks and vocational trucks) in the targeted region. Achievement of "Stage 2 technology" from CalHEAT Roadmap (see Appendix F) in demonstration actions. Development of future fleet regulation for ZE drayage trucks by the appropriate government agency.

Stage 2. Deploy Pre-Production ZE Drayage Trucks and Infrastructure, Expand Supporting Markets, 2017-18

- Pre-commercial pilot projects start with 20 to 50 truck pre-commercial pilot projects aiming for production intent designs in 2019.
- ZE yard hostlers begin phasing in with electric yard hostlers.
- Drayage to near-dock rail should begin transitioning to either low NO_x vehicles or full ZE vehicles for the near-dock rail.
- Develop ZE training curriculum.
- Begin development of backbone infrastructure for ZE trucks.
- Further develop business case and operational models.
- Finalize incentive funding scenarios.
- Further develop regulatory framework.

Stage 2 Goals: Deployment of more than 2,500 ZE trucks in targeted region. Begin deployment of ZE yard hostlers in I-710 region terminals and distribution centers. Begin transition to ZE drayage for near-dock activities based on demonstration fleets. Begin pre-commercial volume validation deployments of the most promising ZE drayage trucks (multiple designs).

Stage 3. Down-Select: Pre-Commercial ZE Drayage Assessment and Validation; Infrastructure Deployments Expand, 2019-22

- Multiple parallel assessments of pre-commercial drayage trucks with fleets throughout port region.
- Expanded installation of needed infrastructure for the full rollout of trucks in Stage 4.
- Deployment of ZE trucks, yard hostlers, and drayage near-dock rail.
- ZE technology maintenance training.
- Finalize regulatory frame work based on deployment results.

Stage 3 Goals: Complete deployment and assessment of several hundred more ZE drayage trucks with leader fleets in I-710 zone. Complete deployment of ZE yard hostlers and near-dock ZE drayage vehicles. Establish infrastructure

deployment sites for Stage 4. Train current maintenance personnel, launch workforce training for new workers.

Stage 4. Commercial ZE Drayage Production, Deployment Ramp-Up, 2020-25

- Infrastructure siting and construction.
- Additional training.

Stage 4 Goals: Phase up production over 5-year period for a cumulative number of roughly 10,000 cumulative zero-emission drayage trucks by 2025. Deploy sufficient infrastructure to support those trucks as needed in their daily operation in the ZE zone. Stage ongoing training and support for impacted fleets. Have in operation an incentives-based purchase or lease system for fleets to obtain ZE trucks for their operations (with additional incentives provided for early mover fleets in the first few years of the ramp-up).

1.0 Introduction

Interstate Highway 710 (I-710), the Long Beach Freeway, is a north-south interstate highway that connects the City of Long Beach with the San Pedro Bay Ports and central Los Angeles. I-710 is the principal route for trucks transporting marine cargo containers from the Ports to near-dock (approximately five miles from the ports) and off-dock (approximately twenty miles from the ports) intermodal facilities, where they are loaded onto trains for shipment beyond the Los Angeles basin. Trucks also carry containers via I-710 and other regional freeways to other local and regional destinations, including warehouses, distribution centers, and end users of the products being shipped.

Trucks using I-710 contribute to congestion on the highway and adjacent surface routes, and have generated high levels of air pollutant emissions (e.g., diesel particulate matter, nitrous oxides). The high ratio of heavy trucks to personal automobiles on I-710 has been correlated to higher than average traffic accidents and poses a considerable safety risk to all users of the facility. The health effects of diesel emissions are felt keenly among the communities adjacent to the I-710.

In response to these concerns, the Los Angeles County Metropolitan Transportation Authority (Metro) and its partner agencies are preparing an environmental document which identifies alternatives that improve the I-710 with respect to mobility, public health, and safety, while providing the capacity needed to accommodate forecast passenger travel and goods movement.

An important element of the alternatives is to move goods from the Ports to/from the rail yards with zero-emissions trucks. For the purposes of this work, "zero-emissions" means zero tailpipe emissions. Zero tailpipe emissions means that the vehicle emits no tailpipe pollutants from the onboard source of power. Harmful pollutants that have been identified as risks to health and environment include diesel particulates (soot), hydro- carbons, oxides of sulfur, oxides of carbon, ozone, lead and various oxides of nitrogen. Volatile Organic Compounds (VOC) and several air toxins can also be classed as pollutants, including carbon dioxide and other greenhouse gases. Emissions from power generation and distribution, fuel generation and distribution, and manufacturing process (or the ultimate disposal of the used vehicles) are ignored in this report.

There are several technologies under development that could be applied to Class 8 drayage trucks and potentially enable goods movement with zero tailpipe emissions for distances greater than the length of the I-710 from the ports to the rail yards (20 miles). Figure 1.1 shows the location of all warehouse and

transload facilities in Gateway Cities, demonstrating a cluster of facilities near the downtown yards.

Metro retained CALSTART to assess the commercial viability and development requirements for truck-based technologies that would enable drayage operations with zero tailpipe emissions. As work on recirculating the I-710 environmental document continues, zero-emission goods movement is a key component of the alternatives being studied.

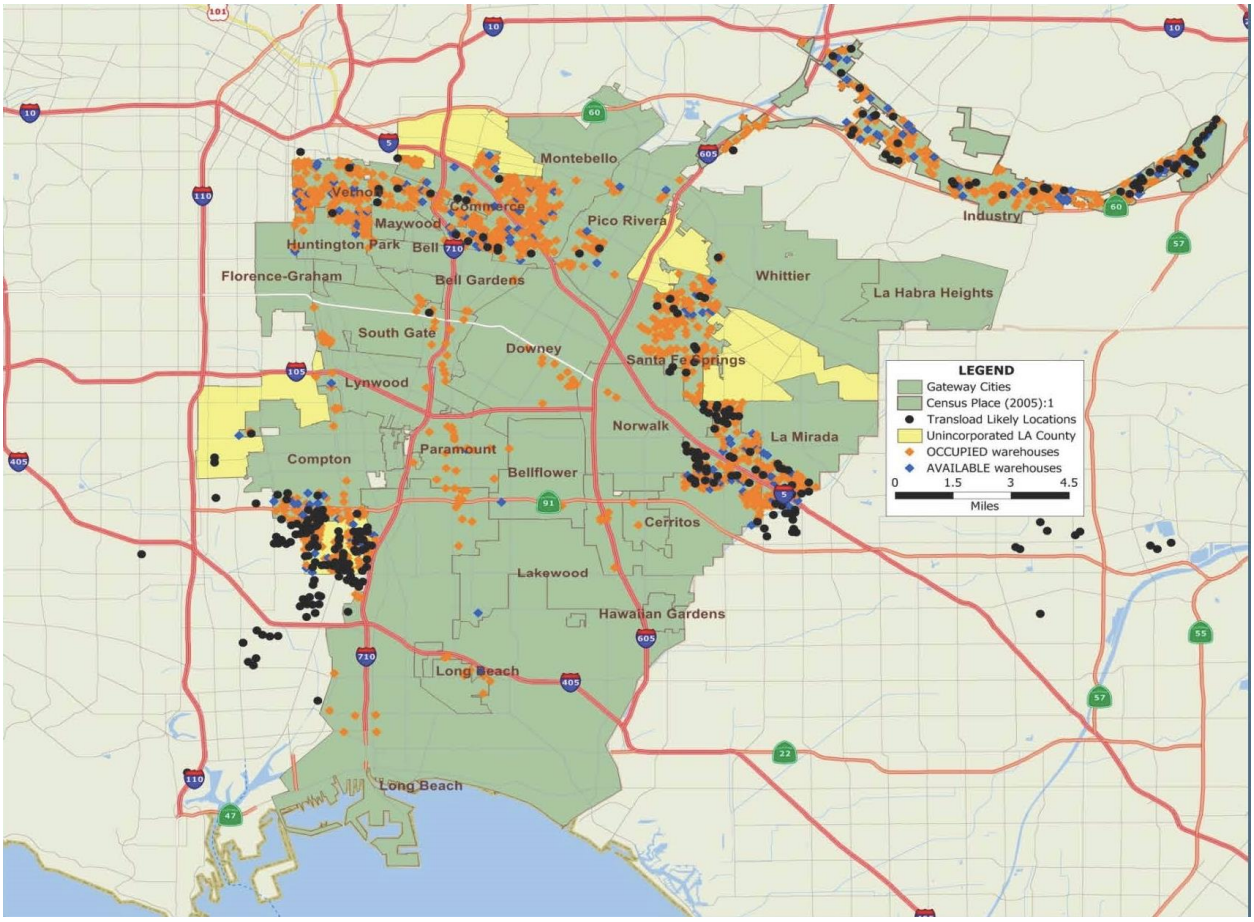
The set of tasks assigned to CALSTART as part of the Gateway Cities Strategic Transportation Plan (STP) includes this Zero-Emission Truck Commercialization Study (Final) Report, in which the barriers, costs and feasibility, and path to commercialization for various technology solutions are examined and initially developed.

This report will outline the stages and work efforts needed to address the barriers identified, define the steps to be carried forward to deployment and help set in motion the process to achieve zero-emission goods movement (port-related drayage) in the I-710 study area.

Figure 1.1 I-710 Project Study Area

Source Metro.

Figure 1.2 Warehouse and Transload Locations in the Gateway Cities Region



Source Cambridge Systematics and Metro.

2.0 Technology assessment

2.1 KEY PERFORMANCE PARAMETERS (KPP)

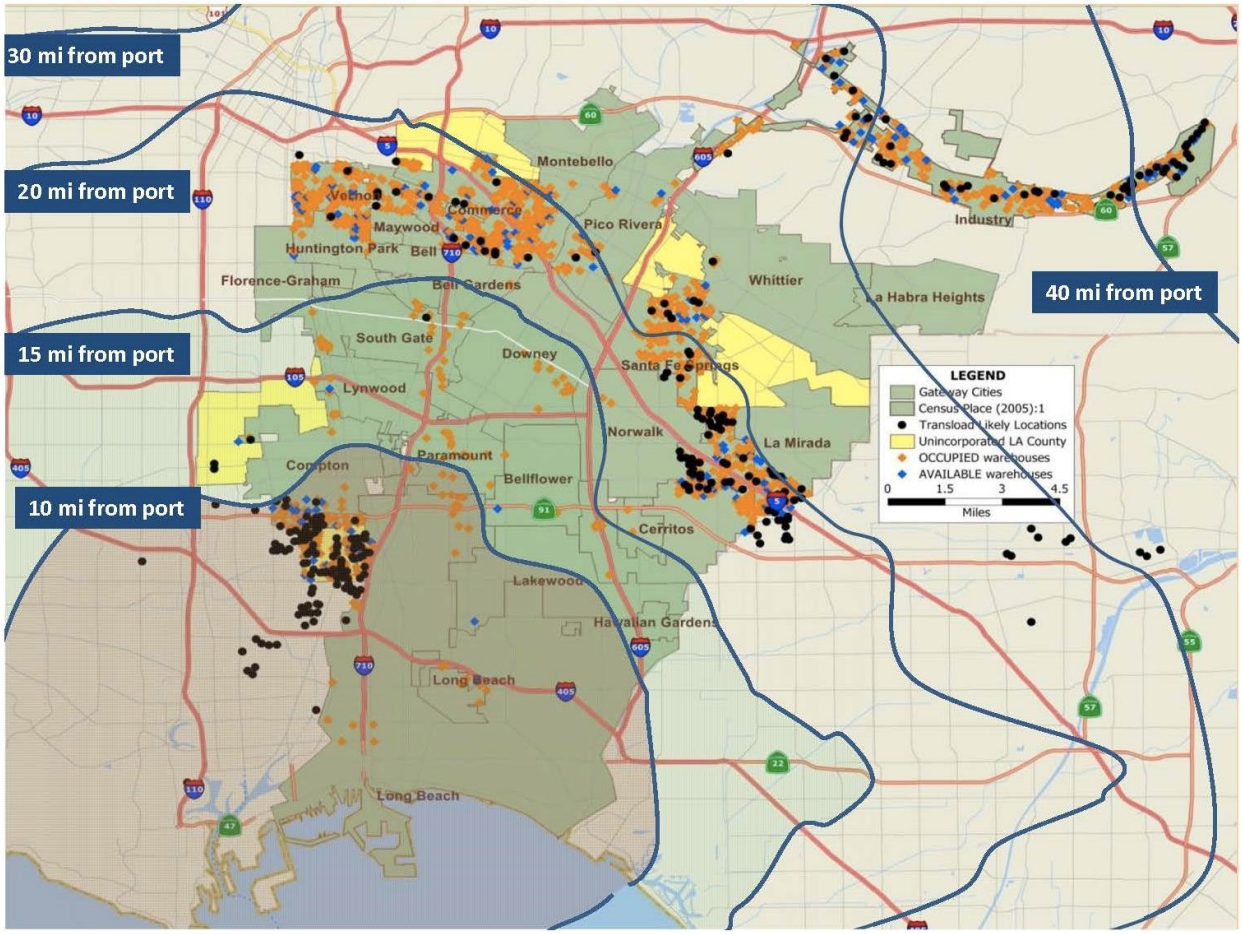
Needs of Drayage Truck Operators

In order to develop key performance parameters, it is necessary to understand the users of the I-710 corridor and their needs. Who will be moving freight through the region using I-710 and its neighboring roads? How do these users operate and what equipment do they use? The analyses conducted are fully summarized in the Drayage Truck Key Performance Parameters Report, included here as Appendix E.

The freeways in this region serve a wide variety of users, with major drayage related origin and destination points at the ports, rail yards, local and regional distribution centers, and points outside the immediate region, such as Bakersfield or Mexico. A comprehensive analysis of all drayage user groups would be broad but less relevant to I-710 related discussions because the users are varied. It would be difficult to distill into regionally specific results.

This analysis is focused on drayage trucks moving containers to and from the Port of Los Angeles and the Port of Long Beach (POLA/POLB), as well as related trips (for example, moving containers from temporary transloading warehouses to the final destination or to and from a rail yard). These movements account for the majority of truck trips along the I-710 corridor, especially in the southern half. As show in the figure below, a large number of warehouses, rail yards, and other drayage destinations are within 50 miles of the ports.

Figure 2.1 Distances to Warehouses and Transload Locations in Gateway Cities Region



Source CALSTART.

The attached KPP Report offers in-depth information and insights into local dray user needs taken from a variety of sources. First, a summary of typical drayage truck duty cycles is presented, based on prior research and truck measurements. Next, a survey of drayage truck operators and fleet managers reveal typical characteristics of drayage truck operation. Lastly, follow-up interviews with key stakeholders in this field provide more specific information about needs of the drayage trucking industry in the I-710 region.

Each of these contributing analysis components are used to develop truck-related KPPs. These KPPs can be future developed into a Product Definition Document (PDD) which OEM truck makers can use to design vehicles. The KPPs discussed here do not directly address business case factors, or the important parameters for the investment decisions involved in purchasing a truck. Those aspects of the project are covered in Section 4 of this Report.

Characterization of Port Drayage Truck Duty Cycles

A recent TIAX study[1] (attached here as Appendix H) measured operation of each truck in several scenarios: near-dock operation, local operation (less than 20 miles from the ports), and regional operation (between 20 and 120 miles from the ports). Vehicle data loggers collected engine parameters such as speed and distance, GPS positional data, and acceleration/deceleration. For each trip, an analysis characterized average speed and other trip statistics. The TIAX report defined drayage truck trips as near-dock, local, and regional.

I-710 Freight Operator Usage Survey Results

In June 2013 CALSTART conducted a survey of freight operator needs. The purpose of the survey was to better understand the needs and usage patterns of a wide variety of freight stakeholders who move drayage from and to the rail yards and the San Pedro Bay ports.

The survey document was developed in consultation with Gateway Cities Council of Governments, Arellano Associates, the Harbor Trucking Association (HTA), and the California Trucking Association (CTA). The survey was distributed electronically to members of HTA and CTA, through the organizations' group email lists. In total, over 1,000 CTA and HTA members received notices about the survey. We then filtered the responses to limit our data set to trucks that regularly pick up or deliver loads to the two San Pedro ports (POLB and POLA), in order to eliminate other freight uses that are outside of our scope.

The survey addressed several topics relevant to this analysis: information on fleet composition, industry focus, operator shifts and refueling practices, vehicle service life and turnover, and alternative fuels usage. The findings indicate several insights relevant to this report:

- The length of each trip for a port drayage truck varies greatly, from short local runs to longer regional runs.
- Trucks maintain a long service life of over 600,000 miles on average.
- Fleet refueling needs (every shift or day) will place large requirements for alternative fuel infrastructure.
- There has been very little adoption of ZE trucks to date, although there is interest in pursuing the technology further.

These results indicate the need for more detailed information on drayage trucks patterns and routes over an expanded and lengthy time period.

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[1] See Appendix H. Characterization of Drayage Truck Duty Cycles at the Port of Long Beach and Port of Los Angeles," TIAX LLC, March 2011.

Inputs from Stakeholder Interviews

The survey results described above provide information on broad industry trends. Survey results were validated and expanded upon through interviews with key stakeholders in the dray community (fleet managers, operators, dispatchers, and executives). The specific comments from these interviews informed this report's list of drayage KPPs.

Key Performance Parameters for Drayage Trucks

KPPs represent a quantification of user needs and show the minimum requirements that a drayage truck must achieve to meet the operational needs of a driver. For this report, draft KPPs were identified through the initial survey and research, then validated and expanded upon through stakeholder interviews. The KPPs were limited to factors that would be relevant for zero-emission vehicle technologies. Factors influencing the business case are only tangentially included here, as the purpose of KPPs are to inform truck makers about the performance parameters of a vehicle. Section 4 of this report covers the business case parameters, some of which are impacted by the KPPs, and some KPPs have relevance to the business case analysis.

All inputs coalesced around four KPP categories: driving range and refueling, scheduling and operation, truck performance, and vehicle lifetime and service requirements. For the full discussion of the KPPs, please refer to the KPP Report included here as Appendix E.

Of all the KPPs below, interviewees were very clear about which KPPs are required, or cannot be missed. According to interviewees, regardless of fuel technology a drayage truck must deliver three properties:

- The vehicle must have sufficient power for operation (400 horsepower [HP], 1,200 to 1,800 foot pounds [ft.-lbs.] of torque);
- The vehicle must achieve the necessary range (200+ miles); and
- The vehicle must have the capability to be used on all delivery routes.

Table 2.1 Key Performance Parameters Related to Driving Range and Refueling

Key Performance Parameter	Baseline Values
Daily Range	Up to 200 miles.
Distance per trip	40 miles, for example from the ports to the Inland Empire.
Number of turns per day	3 is typical, 4-5 on a good day
Refueling interval	Baseline 2-4 days for diesel, daily for LNG. Varies greatly on number of turns daily and the container destinations.
Fuel economy	4.5-5.5 MPG is typical; some new trucks up to 8 MPG.
Range per tank of diesel	400 miles typical for diesel trucks
Availability of refueling infrastructure	On-site refueling is best, either through depot fueling infrastructure or a contractor traveling to the yard to fill up the trucks. Otherwise centralized infrastructure is important.

Source CALSTART.

Table 2.2 Key Performance Parameters Related to Truck Scheduling and Operation

Key Performance Parameter	Baseline Values
Operating time per day	10-14 hours. Limited by federal Hours of Service (HOS) limitations on drivers
Shifts per day	One shift primarily; 10-15% of owner/operators do two shifts.
"Turns" per day	3 turns typically, 4-5 on a good day.
Capital costs	$110,000 for new diesel truck; perhaps room for a $50-70k increment for alternative fuel trucks, based on interview input.
Flexibility to assign to a subset of routes	All trucks must be "full service" trucks. Due to labor and other limitations, a driver can't be assigned to serve only a subset of routes (for example, just routes between the ports and the near-dock rail yards).
Overnight storage	80-90% of trucks return to operator yards near the ports.

Source CALSTART.

Table 2.3 Key Performance Parameters Related to Truck Performance

Key Performance Parameter	Baseline Values
Engine parameters	400HP, 1,200-1,800 ft.-lbs. torque expected for diesel.
Top speed	Operators limit truck capability to 62-65 MPH.
Acceleration requirements	Sufficient for operation on local roads and freeways. The necessary acceleration can be achieved in a truck with the specified engine parameters.
Gradeability and startability	Maximum grade of 6% occurs on the bridges entering/leaving the ports. Trucks must be able to start from zero while fully loaded when stuck in traffic on the bridge, and climb this grade at 40MPH when traffic is moving freely.
Idling capability (hours of idling at one time or over a day)	Very little idling time—regulations limit idling to 5 minutes before shutoff. But creep time can be 30 mins-1 hour at the ports (for example, trucks waiting in queues).
Capacity for freight load	Containers can vary from 10,000 lbs. to 44,000 lbs.
Operating temperatures	The lowest and highest recorded temperature in the Los Angeles region is a low of 24 degrees to a high of 113 degrees Fahrenheit.
Accessory loads	Drivers expect all ‘‘creature comforts’’ including A/C, sound system, and lighting.
‘‘Urge to move’’/creep mode	Required due to the time trucks spend in line at the ports.

Source CALSTART.

Table 2.4 Key Performance Parameters Related to Vehicle Lifetime and Service Requirements

Key Performance Parameter	Baseline Values
Durability: vehicle lifetime in miles	Survey and interviewees indicated approximately 500,000 miles.
Durability: vehicle lifetime in years	Survey shows at least 8 years for diesel trucks. Interviewees specified a target of at least 10 years minimum.
Uptime or availability—compare frequency of issues against the service time.	Diesel trucks typically achieve 90% uptime. Down 2-3 days per month for maintenance and service. The industry target for this KPP is at least 90%.
Serviceability—availability of diagnostic tools and manuals. Location for servicing.	Not a concern— except for the largest companies, maintenance is contracted out.
Warranty	Typical diesel warranty is 3 years/300,000 miles. Longer warranty for alt fuel trucks helps to alleviate concerns about reliability.

Source CALSTART.

2.2 POTENTIAL SYSTEM DESIGNS MEETING PROJECT REQUIREMENTS

The highly dynamic and variable nature of drayage trucking in the I-710 area presents a challenge to defining requirements for zero-emission trucks. Changes in how goods are moved and delivered in the region are resulting in more truck trips that don't use the I-710 freeway itself, or use it for only short sections. More drayage trucks use the southern section of the I-710, nearest the ports, than use the northern part of the freeway. It can be confidently stated that changes will continue into the future, and so the best approach is to design for maximum flexibility.

In addition, interviews conducted with users (dray truck companies) have made it clear that their business models are different than other truck fleet operations—every truck has to be able to handle every job. This need for flexibility is reinforced by the local business model, in which many dray truck drivers are independent owner/operators who contract with a trucking company. Those drivers must be given a job when they come to the assignment window of the company with which they have contracted. Since the jobs could be short, medium, or longer range, and encompass light or heavy loads, it is again essential that all trucks be able to handle all jobs.

In sum, all zero-emission capable trucks need to have the same performance ability as current diesel drayage trucks. Given this, the forcing criterion for defining a truck that meets the project requirements is establishing a reasonable zero-emission range.

There are five fundamental zero tailpipe-emission capable truck architectures that could be used for Class 8 drayage trucks in the context of this report:

1. Dual-Mode Hybrid Electric Vehicle (HEV);
2. Dual-Mode Plug-in Hybrid Electric Vehicle (PHEV);
3. Range Extended Electric Vehicle (REEV) with Engine;
4. Range Extended Electric Vehicle (REEV) with Fuel Cell; and
5. Battery Electric Vehicle (BEV).

There are only two fuel options that are inherently zero tailpipe-emission:

1. Electricity (via batteries in EV or PHEV); and
2. Hydrogen (via fuel cells in REEV with Fuel Cell).

The optimal technology for a Class 8 drayage truck in the I-710 corridor area depends upon the zero-emission range required. Based on daily driving distance (distance before being recharged), some logical categories for this capability are:

- 20 miles ZE range: Any of the five architectures;
- 50 miles ZE range: Both REEV and BEV designs;
- 100 miles ZE range: Both REEV and BEV designs; and
- Over 100 miles ZE range: REEV with Fuel Cell is the primary viable option.

These ranges are defined by the approximate technological breaks between the system engineering approaches to ZE drayage trucks. Some can do up to 20, but above is impossible. Some can do up to 50, but above that is costly. Some can do up to 100 but above that is also costly or impossible, and some can do over 100. These range categories therefore reflect technological breaks that align with logical breaks in travel length before refueling is needed.

Therefore, based on our understanding of the project requirements, it is believed all trucks must deliver performance equivalent to current diesel trucks, and **must have a zero-emission range of at least 50 miles**. The description of a 3C truck, one capable of meeting the requirements of the I-710 Corridor project, includes a minimum of 50 miles ZE operation fully loaded. This requirement is being used to define the technology alternatives for the following analyses.

Please refer to Appendix D, the TCO Report, for a more complete description of each of the potential technologies. Each requires a set of tradeoffs that must be made in developing a truck that can perform at the same level as an existing diesel vehicle.

HEVs are too limited in their ability to operate with zero tailpipe emissions. As with the light-duty Toyota Prius, there are speed and range limits, and the conventional engine has to switch on quite regularly to maintain the desired performance. These designs are less costly and do deliver benefits in other applications, but lack sufficient zero-emission range for the needs of this project.

PHEVs have greater zero-emission range than HEVs because of their larger batteries, but in virtually all standard designs, PHEVs still lack enough zero-emission capability to meet our understanding of the project requirements. Drawing the same analogy as with HEVs, the Toyota Plug-In Prius (a light-duty PHEV) has much more zero-emission capability than the conventional Prius, but can only go about 11 miles on batteries alone, and has speed and power limits in zero-emission operation.

Most HEV and PHEV designs are parallel hybrids, meaning both the gasoline engine and the electric motor can power the wheels. There are many circumstances where the gasoline engine must come on to provide the power needed. The same is true for current PHEV trucks and PHEV truck prototypes we know in sufficient detail. Full "diesel truck equivalent" performance is not

available from most PHEV designs in ZE mode, making them inappropriate for this project. Future PHEV designs could very easily have expanded capabilities, and their greater similarity to conventional trucks could give them a cost advantage. Follow-on analyses in later projects can address this if changes do occur.

There are infrastructure dependencies for each of the potential truck architectures, meaning the demands inherent in creation, distribution, storage, and dispensing of the zero-emission fuel required. The operational requirements of a 3C drayage fleet place heavy demands on infrastructure systems. These issues will be discussed further in Section 3.0 of this report.

2.3 TECHNOLOGIES THAT CAN MEET PROJECT REQUIREMENTS

This section discusses the technologies that could meet the requirements of a 3C Truck as discussed above and their pros and cons. The technology analyses conducted were summarized in the Technologies, Challenges, and Opportunities Report, which is attached here as Appendix D.

Range-Extended Electric Vehicle (REEV) with Engine

A REEV with engine is a truck that has an electric motor as the primary source of power, batteries for energy storage, and a fuel-burning engine (usually a piston or turbine engine, burning diesel or compressed natural gas (CNG) which runs a generator to produce electricity when the batteries are depleted. The engine is called a "range extender" because it extends the possible range of the electrically driven truck beyond what onboard batteries can provide. The truck is zero-emission when the range extender engine is off, but does create emissions when the engine is running.

A good way to envision this type of truck is as "**the Chevy Volt of Trucks**." Much like the basic Chevrolet Volt design (overlooking a few technical details for the sake of simplicity), the vehicle is driven by an electric motor big enough to provide the performance required. A battery pack contains the energy storage for the electric motor, and there is a connector for charging that battery pack from the electrical grid. There is also an internal combustion engine (ICE) that runs when needed to operate a generator and recharge the batteries as they are depleted. **The range a REEV can run in a ZE mode is less than 100 miles in one charge.**

There are many possible designs and variations in operating modes, but most often a REEV works in charge depleting mode, meaning the batteries are used first. In charge depleting mode, the vehicle is fully zero-emission until the batteries are depleted, equipping the vehicle with a larger battery pack will result in greater zero-emission range. When the batteries are drained, the ICE starts

and operates a generator to run the primary motor (electric) and recharge the batteries, until the vehicle is parked and plugged into the electrical grid to recharge the batteries.

Since the range extender engine does not actually move the vehicle, the types and sizes of engine can be very different than conventional trucks. The REEV designs in prototype form today use a microturbine burning CNG as a range extender. Alternatives under consideration include low-NO_x natural gas piston engines and small diesel engines.

REEV with Engine Facts

- Zero Emission Capability. Can operate as a zero-emission vehicle for as long as the battery pack size allows. Full performance while in zero-emission mode. After ZE-mode batteries are exhausted, the REEV operates in a mix of zero and non-zero emission. When running on engine power, natural gas REEVs would probably produce lower emissions than diesel REEVs.
- A type of hybrid truck, usually a series hybrid with sufficient battery energy storage and electric motor power to operate in EV-only mode for as long as the batteries allow. A REEV almost always requires a larger electric motor and/or greater energy storage capacity than a dual-mode hybrid, and usually has no performance limitations when in ZE mode. In some cases, the engine/generator has enough power to drive the vehicle via the electric motor. Other designs only enable recharging of the batteries, and then depend on plugging into the electrical grid to fully recharge.

Pros

- Early stage demos have begun. System is based on technology ready today; zero-emission mode has uncompromised performance, and ranges up to the battery capacity provided. Can replace a conventional truck in ZE mode up to a certain range (current designs are less than 100 miles ZE).
- REEV platforms can be built in variants to spread the cost across applications with different power, ZE range, engine types, and other criteria. This enables much greater sales in multiple uses beyond the I-710 region.
- Many options for range extender engine types, fuel sources, and levels of emissions.

Cons

- Battery cost/size/weight constrains zero-emission range. Current designs are built to maximize fuel economy rather than minimizing emissions. Designs are still in prototype stages, with limited testing of alternative range extender engines so far.

- Cost: additional equipment, especially batteries, raises the cost of the system well above conventional trucks, and the increase in fuel economy may or may not deliver an acceptable return on investment. The larger the battery pack (and hence the longer the ZE capacity), the higher the incremental cost.
- Emission certifications are still undefined. Since the vehicle is sometimes zero-emission and other times not, the testing cycle and other factors become important. Regulatory agencies are still working on test protocols.

Figure 2.2 Turbine Range-Extender Electric Truck (Artisan/Capstone/Parker on a Freightliner Chassis)

Range Extended Electric Vehicle (REEV) with Fuel Cell

A REEV with Fuel Cell is a truck that has an electric motor as the primary drive for the vehicle, batteries for energy storage, and a fuel cell, typically consuming hydrogen, which generates electricity when the batteries are depleted. In this case, instead of an engine as range extender, a zero-emission fuel cell is used. A fuel cell REEV truck produces zero emissions 100 percent of the time, as fuel cell byproducts are only water.

A good way to envision this type of truck is as the "**Honda Clarity of Trucks**." Much like the Honda Clarity, a REEV with Fuel Cell is driven by an electric motor big enough to provide the performance required. A battery pack contains the energy storage for the electric motor. A fuel cell generates electricity from hydrogen stored onboard in a cryogenic tank, which keeps the batteries charged, and there is a connector for charging the battery pack from the electrical grid.

There are many possible designs and variations on operating modes. The vehicle uses only the stored battery energy until the batteries are depleted. When the batteries are drained, the fuel cell starts and provides power to the motor and/or recharges the batteries, until the stored hydrogen is consumed. At that point the vehicle needs to be refueled with hydrogen and/or plugged into the electrical

grid to recharge the batteries. **The range a REEV with Fuel Cell can run in a ZE mode is limited only by the amount of onboard hydrogen storage. Current designs and technologies typically allow up to 400 miles.**

REEV with Fuel Cell Facts

- Zero Emission Capability. Fully zero-emission at all times. It performs as well as a standard diesel truck while generating zero emissions. After batteries are exhausted, it consumes hydrogen from an onboard storage tank. Hydrogen range is limited only by onboard tank size/capacity.
- A type of hybrid truck, usually a series hybrid, where there is sufficient battery energy storage and electric motor power to run in EV-only mode for as long as the batteries and onboard hydrogen storage allow. In some cases, the fuel cell has enough power to drive the vehicle via the electric motor. Other designs only enable recharging of the batteries, and then depend on plugging into the electrical grid to fully recharge. As with other REEV designs, this is an engineering tradeoff based on costs for batteries, fuel cells, and other range-extender technology.

Pros

- Early stage demos have begun. System is based on technology ready today. Transit bus work is ahead of truck development and is making good progress, with some fuel cell REEV bus designs already operating in transit service.
- Zero-emission mode has uncompromised performance. It can range up to the hydrogen capacity provided (current designs typically allow up to 400 miles). Can replace a conventional truck while being fully zero-emission.
- REEV platform can be built in variants to spread the cost across applications with different power, ZE range, fuel cell size, onboard storage, and potentially include fuel reforming (converting CNG or diesel into hydrogen). This flexibility enables many more sales for multiple uses beyond the I-710 region.
- Battery storage can be quite small (covering fuel cell startup/shutdown) depending on electric generation capacity of fuel cell—larger fuel cells are higher cost (another engineering tradeoff).
- Because it is fully zero emission, regulatory certifications are easier.

Cons

- Battery cost/size/weight and fuel cell cost lead to very high initial costs and challenging design requirements.
- Fuel cell reliability is improving but not proven in truck applications. Life cycle and maintenance costs are unknown.

- Fuel is widely available in some areas, particularly near oil refineries and other heavy users of hydrogen. Pipeline access makes fuel access much more direct. Outside of those areas, however, fuel access is limited.

Figure 2.3 Vision Fuel Cell Electric Hybrid Truck (Early Prototype)

Battery Electric Vehicle (BEV)

A Battery Electric Vehicle (BEV) has only an electric motor to move the vehicle, and energy stored onboard via batteries. No fuel other than electricity is used to operate the truck. It is fully zero emission at all times.

A good way to envision this type of truck is as "**the Nissan Leaf of Trucks**." Much like the Leaf, a BEV truck is driven by an electric motor big enough to provide the performance required. A battery pack contains the energy storage for the electric motor. As with other designs, regenerative braking captures energy from the brakes and helps charge the batteries, plus there is also a connector for charging the battery pack from the electrical grid. When the batteries are depleted the truck must plug into the electrical grid to recharge. **The range a BEV can run in a ZE mode with current technology is typically less than 100 miles with one charge.**

BEV Facts

- Zero Emission Capability. Fully zero-emission at all times, it can perform equivalent to a standard diesel truck while generating zero emissions. After batteries are exhausted, vehicle must plug into the electrical grid to recharge.
- A type of truck where there is sufficient battery energy storage and electric motor power to perform equivalent to a conventional truck for as long as the batteries allow.

Pros

- Early stage demos have begun. System is based on technology ready today. Transit bus work is ahead of truck development and is making good progress, particularly in fast chargers. Some BEV bus designs are already in transit service.
- Fully zero-emission all the time, and when designed properly, has uncompromised performance equal to a conventional truck. No petroleum use; good for fixed route and circulator operations.
- Can be combined with infrastructure power (catenary or in-road) to minimize or eliminate need for recharging.
- Because it is fully zero-emission, regulatory certifications are easier.

Cons

- Range is limited by battery cost/size/weight. Current technology makes it challenging to provide more than 100 miles of range before needing a recharge.
- Large battery pack life-cycle and maintenance costs are unknown.
- Although electricity is obviously available almost everywhere, the quantities required for a fleet of BEV drayage trucks are very high and could require significant infrastructure. Multiple high-power and/or fast-charging stations will be required and may be costly. Electrical costs are dependent upon local utilities and rate structures.
- The time for plug-in recharging also needs to be addressed—fast charging is probably a must in order to meet drayage operational needs. Fast charging and supporting infrastructures need further development. (This concern applies to all zero emission trucks that use a battery).
- Roadway power infrastructure is complicated and expensive, and may be appropriate only in certain areas or applications. Further study and analyses are required to determine the feasibility of roadside power and its costs, issues and applications. Again, this concern applies to any ZE truck that uses batteries.

Figure 2.4 Balqon BEV Drayage Truck

Figure 2.5 Transpower BEV Drayage Truck

Technology and Business Case Parameters

Many of the business case model assumptions will be described in the Business Case Analysis section (Section 4.4) but some other broad parameters are discussed here, to emphasize the need for future projects to conduct optimization analyses. It must also be pointed out that this report is discussing the leading edge of truck technology development—many facts are not yet known, and many critical decisions regarding technology architectures cannot be made without facts that are still to be uncovered. Ambiguity and potential contradictions are commonplace when predicting future technology developments such as these.

REEV with Engine

A REEV with Engine can have essentially comparable range to an existing (diesel) truck simply by refilling with engine fuel—CNG, Diesel, Di-Methyl Ether (DME), or other. While they can achieve very low emissions, a REEV with Engine is not ZE when the engine is running. It utilizes the battery and is ZE when there is battery energy, but does not need the battery to deliver the same performance as a diesel dray truck.

Our analysis focuses on a CNG-powered piston engine as the range-extender. Many other alternatives are possible, including a piston engine burning propane, diesel or even gasoline. A piston engine using DME is another good option, as DME will have lower tank costs and engine conversion costs versus CNG, although the fuel itself may be more costly (and is currently only in prototype development stages). Most of the REEV with Engine truck designs in prototype form today are using a CNG-fueled turbine as the range extender. Turbines are more costly than piston engines, but have the ability to run on a number of fuels, and deliver some emissions benefits.

It is important to note that other REEV with Engine truck architectures need to be examined, beyond those modeled here. Timing and project scope prohibited examination of multiple configurations. The sizing of batteries and range extender engines, engine types, and fuel system designs/costs are areas of ongoing engineering development, and in no way does our selection of model assumptions imply we have determined the optimal designs. Our modeling uses a 350kW range-extender engine, which is almost certainly too big, and hence more expensive than necessary. Fuel consumption, system weight, and costs could be reduced by using a smaller range-extender engine. Significant engineering work must be done, and this is an important area where funding from governments and other entities must be focused to advance REEV designs to commercialization.

REEV with Fuel Cell

As with REEV with Engine designs, our selection of parameters does not imply the optimal solution. An area of ongoing engineering work is the balance of fuel cell capacity and battery capacity in REEV with Fuel Cell designs. Our choices of a 60Kw fuel cell and 60kWh battery pack were made based on internal CALSTART expert input, which combines the knowledge of leading industry experts. Future studies must examine the tradeoffs.

The relationship between the size/power of the range extender and the size/power of the battery pack for both the REEV with Fuel Cell and REEV with Engine is very much worthy of study. A recent National Renewable Energy Lab (NREL) analysis looked at this tradeoff for Class 3 to Class 5 parcel delivery trucks, determining that for this application a 24kW fuel cell and a 30kWh battery were optimal, but the balance was very sensitive to duty cycle and

economic conditions...[2] An analysis for Class 8 drayage is an important subsequent task, along with examination of modular fuel cell and battery pack designs. Simultaneous changes in fuel cell and battery pack technology, costs, production volumes, and support systems, makes for a dynamic and rapidly changing equation.

BEV

BEV designs are evolving as more is learned from prototype demonstrations, and as battery technology and production processes mature.

Because all the miles are ZE, the 50-mile ZE criterion does not apply, but current BEV technology will not allow meeting the user preference of 200 miles range before refueling. To partially mitigate this limitation, the recharging assumption has been set to "less than 30 minutes" (ultra-fast charging).

BEVs can be capable of delivering 100-plus miles of range while performing equivalent to current diesel trucks. This is at the limits of current technology and design, but advances will likely be made before the 2025 deployment date.

For BEVs, as with REEV with Fuel Cell trucks, infrastructure requirements are important. Arguably, infrastructure is more critical for BEVs, as each truck will need to charge at least daily, or more than once a day if more than 100 miles of travel is needed. Charging without interruption of the daily work required, often called "opportunity charging" (such as wireless charging while waiting in port queues or loading docks) is possible, and ultra-fast chargers are a necessity. These chargers could potentially be located at terminals, rail, trans-loading, and distribution warehouses.

Factors that need to be examined in subsequent work are the grid impacts of multiple ultra-fast chargers in one region, and how the electrical power can be supplied. A project should be undertaken as part of moving ahead with BEV development to examine the impact on battery lifespan from frequent ultra-fast charging. Generally it is believed there is negative impact on battery life when lithium-ion packs are charged very quickly on a regular basis. This risk is noted in our business case modeling, where we are presuming the battery packs will not have to be replaced during the lifetime of the truck. Degradation due to frequent ultra-fast charging could require pack replacement, with very negative impacts on the business case. All trucks with batteries that are ultra-fast charged, including REEV designs, could face this concern.

[2] Analysis of Continuous On-Board Recharging Applications (COBRA) Initial simulation Results, Webinar Presentation, May 7, 2013, NREL.

3.0 Infrastructure Dependencies

3.1 Fuels and Infrastructure

In addition to zero-emission technologies applied to trucks themselves, each truck design comes with what can be termed "infrastructure dependencies." All zero-emission vehicles need some kind of fuel, and that fuel has to be distributed and dispensed to the trucks. The fuel, of course, has to be created as well, but that step is beyond the scope of this report. Future projects will need to investigate the production and distribution of the required ZE-capable fuels.

Once the fuel is generated, distributed, and dispensed to a truck, there also has to be a way to store enough energy on the truck to meet operational requirements. Less onboard storage places higher demands on the dispensing infrastructure or other means of energy supply (e.g., roadside power). As a result, there are many tradeoffs in the way fuels are provided for use - chosen, stored, delivered and dispensed.

All of the hybrid designs (HEV, PHEV, and REEV with Engine) can use diesel or CNG/liquefied natural gas (LNG) as a fuel along with electricity. The distribution, dispensing, and storage of diesel, CNG, and LNG are well developed and present no new challenges. More widespread use of CNG/LNG will require additional infrastructure, but the challenges of this expansion are well understood, and a number of companies stand ready to build out the needed systems.

Other fuels, like di-methyl ether (DME), propane, or gasoline could also be utilized. Some new fuels, such as DME, promise significantly reduced emissions (virtually zero with exhaust after-treatment) and require less costly after-treatment systems than diesel. These fuels are promising in hybrid designs, and for use in areas without a zero-emission requirement, but are not further discussed here because they are not truly zero-emission fuels.

This section will focus only on fuels that can deliver zero-emission operations. As mentioned earlier, there are only two fuel options that are inherently zero tailpipe-emission:

- Electricity (via batteries in BEV or either type of REEV); and
- Hydrogen (via fuel cells in REEV with Fuel Cell).

Onboard Energy Storage Options – Energy Density Challenges

For both relevant zero-emission fuels, electricity and hydrogen, there is tremendous R&D activity in the area of onboard energy storage. The ability to carry large amounts of fuel energy onboard the truck is a critical factor for zero-emission vehicles, especially because the onboard energy of a large diesel fuel tank is significant and has set an expectation level. This report will not delve very deeply into the many energy storage options available and under development because other reports have done so (see CE Delft[3], NPC[4], and others). In addition, new technological approaches are being announced almost daily so any summary would be out-of-date immediately.

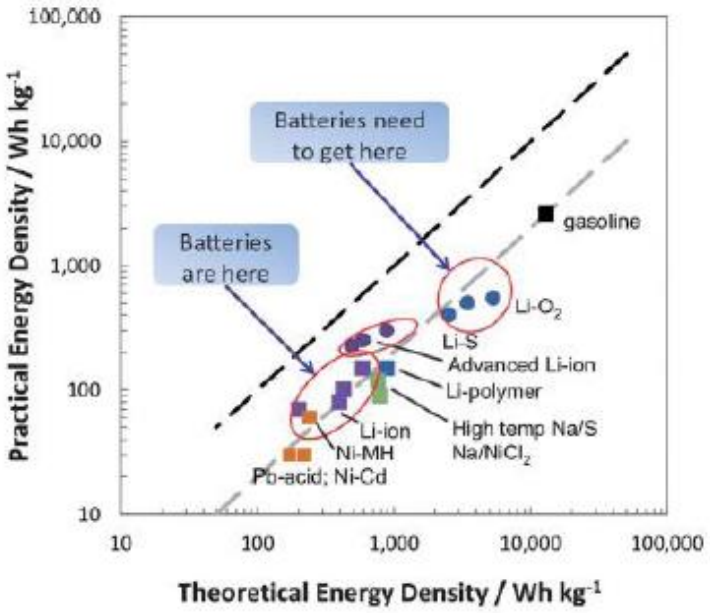
The most important factor for energy storage of any kind is the energy density that can be achieved. Liquid fuels like gasoline and diesel have come to prominence in large part because they have very high energy density. Figure 3.1 compares the energy density of batteries to gasoline. Energy density is measured in watt-hours per kilogram (Wh/Kg), a ratio of the mass (kilograms) and the energy being stored (watt hours), the amount of energy in a given quantity of the substance. Diesel is not shown on this particular chart, but diesel is very slightly higher than gasoline in energy density, and both are currently well above batteries.

For hydrogen, the critical issue is how much fuel can be stored in onboard tanks. There are variations in tank pressure and tank technology that affect capacity. Hydrogen can be compressed, cryogenically compressed (low temperature and high pressure, respectively) or can be physically or chemically adsorbed into a specially designed material. The CE Delft report provides a good examination of the various technologies and their energy density potential. (See Appendix C for that detail.)

[3] See Appendix C. Zero Emissions Trucks – An Overview of State-of-the-Art Technologies and their Potential; CE Delft, July 2013.

[4] Advancing Technology for America's Transportation Future; National Petroleum Council, 2012, www.npc.org.

Figure 3.1 Energy Density of Battery Systems vs. Gasoline[5]



Note: The difference between theoretical and practical energy density relates to the weight of the steel battery case, other inactive components (heating/cooling devices) and inefficiencies.

Source: Thackeray, 2012.

Again as a function of energy density, hydrogen stored at 700 bar (the current state-of-the-art) requires roughly 8.46 times more space than diesel fuel for equivalent energy storage.[6] These tanks also add weight, on the order of an additional 2,900 pounds compared to diesel.[7] It is worth noting that the development of 700 bar storage tanks has been led in part by firms based in Southern California, notably Quantum Technologies. We should also note that parity to gasoline or diesel is not necessary for these technologies to be valuable and deliver benefits within certain business case situations.

For electricity, the primary onboard energy storage technologies are batteries and ultra-capacitors. However, the two technologies have quite different uses: batteries are primarily energy (storage) devices; ultra-capacitors are primarily power (storage) devices. For the applications under discussion here (large vehicle energy storage) ultra-capacitors are not being used in the designs

[5] Appendix C. CE Delft, page 24.

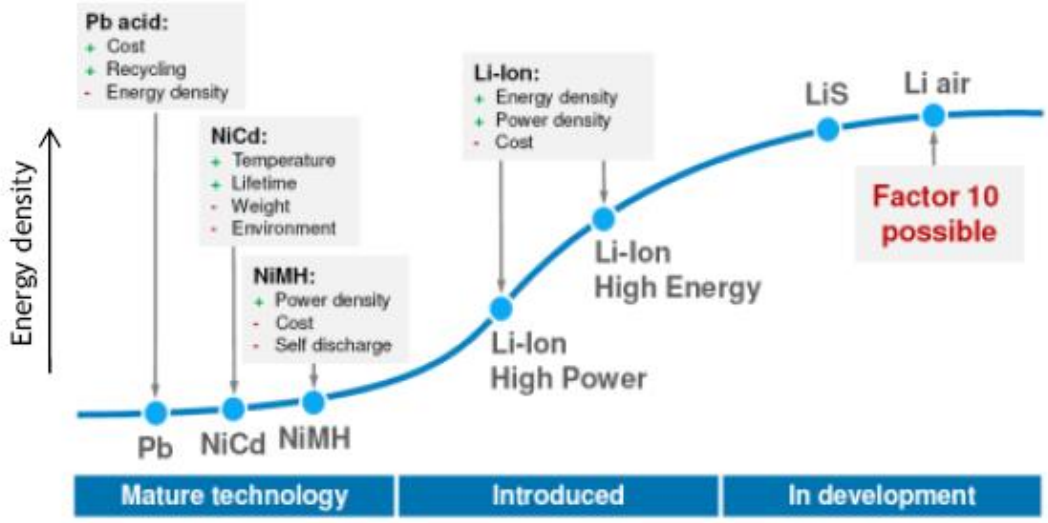
[6] Ibid, page 54.

[7] Ibid, page 55.

currently under development. Ultra-capacitors are in use for capturing regenerative braking power, and in engine start-stop uses, especially in hybrid systems on transit buses. The primary benefit of ultra-capacitors is their ability to very quickly absorb and store energy and to release that energy quickly as well—they are "power" storage systems. Batteries have much greater limitations in how fast energy can be pushed into the battery and stored, but are better at longer-term storage. It is certainly possible that given the large and rapid regenerative braking energy flows created by a fully loaded drayage truck, an ultra-capacitor could be a solution to some engineering challenges. The technology has not come up in heavy truck applications thus far, but ongoing developments and falling costs could change that situation.

The development of batteries is very much a focus of attention across the industry, from research scientists to policy-makers. Within the vehicle industry, the expected path for battery development is well defined, although there is always the potential for an unforeseen disruptive technology to appear. Figure 3.2 shows a graphic from the CE Delft report (sourced from a report prepared by consulting firm ICF) that is a good summary of the battery development pathway.[8]

Figure 3.2 Battery Development Pathway



Source: ICF, 2011.

According to the CE Delft researchers, the current best technology battery (high energy lithium-ion) has an energy density 12 times lower than diesel fuel. However, since electric drivetrains are more efficient than internal combustion

[8] Ibid, page 22.

engines, CE Delft further estimates that batteries need only be 3 times lower in energy density to reach "parity."[9]

Extrapolating from CE Delft calculations,[10] an advanced lithium-air battery that could provide a BEV drayage truck with roughly 300 miles of range would weigh over 2,500 pounds, and occupy 150 cubic feet of space. Obviously, that would be unacceptable on a drayage truck.

These expectations for battery development align with our industry expert interviews and other research reports. Again, parity with diesel is not necessary for these technologies to deliver value and to have a business case in the I-710 region and elsewhere.

3.2 FUEL OPTIONS: HYDROGEN

Hydrogen (H2) Fuel Facts

As a fuel, H2 has been in development for many years. Hydrogen is a plentiful element, and to be used as a fuel it is turned into a liquid at high pressure and low temperature (cryogenic). Importantly, hydrogen is a good energy carrier, contains no carbon, and creates no GHG emissions. It can be used in specially modified internal combustion engines (ICEs) or more commonly, in a fuel cell to create electricity. Currently, the large volumes of hydrogen needed are made from natural gas, but a number of new methods of generation, transport, and storage are being developed. Renewable sources are also being developed, and systems that can create hydrogen from diesel fuel on a vehicle are being researched.

Pros

- H2 delivers zero emissions in fuel cell use; it matches some state future fuel goals. In the Los Angeles basin, it can be sourced from large steam reformation plants that serve area refineries and can use the distribution trunk lines set up to serve those refinery clients. There are strong efforts to expand H2 distribution for light-duty (car) applications and H2-powered transit buses are forecast for the LA region as well.

Cons

- High fuel volumes are needed for truck use; limited infrastructure capacity and very limited infrastructure at the moment. Fuel costs are not well

[9] Appendix C. CE Delft, page 25.

[10] Ibid, page 28.

documented at present. To be widely used, hydrogen fuel needs to be widely distributed and available throughout Southern California. For trucks to use this fuel outside of Southern California will require further study to make fuel cell trucks commercially viable and marketed beyond Southern California. These steps will require further analysis and study by others.

The main issues around the use of hydrogen fuel cell technology are:

- **Costs.** The costs for fuel cells are still quite high, but expected to fall significantly within the time frame of the project (up to 2025).[11] The costs for hydrogen fuel itself are not well documented at this time, as the infrastructure and volume of hydrogen sold as a vehicle fuel is currently very small. In areas near oil refineries, such as the I-710 region, or Houston/ Galveston, there are often steam-reforming hydrogen production plants, which generate hydrogen from natural gas. Those facilities can supply vehicles in the region, but limitations, volumes, costs, and availability have yet to be established. Ongoing costs for this fuel source are unknown, as only a Houston-area demonstration program has explicitly planned to work in this way. The National Petroleum Council (NPC) report (not included here due to its length) contains an in-depth analysis of potential future hydrogen costs as they relate to light-duty applications and national distribution makes it less relevant for I-710 region forecasts.[12] It is expected that this will be an area of growing research and discussion in the upcoming years.
- **Onboard tank pressure and sizing.** As discussed in the CE Delft report[13] and above, the amount of onboard storage is one of the variables in the tradeoffs to designing the most cost-effective ZE truck. The technologies for higher pressure H2 delivery and storage, and advanced storage techniques will impact this tradeoff.

  Hydrogen is an off-gassing fuel, meaning that like LNG, as the fuel in the tank warms up the pressure increases and fuel must be vented at a certain point to ensure safe operation. This does result in fuel loss if vehicles are parked for long periods of time. Long parking time is rarely an issue with drayage trucks, but should be considered as more detailed calculations are conducted to confirm the business case in future project analyses.
- **Fuel Cell Longevity.** As also discussed in the CE Delft report, "The durability of fuel cells is a critical barrier for commercialization and, therefore, needs substantial improvement before widespread

[11] Appendix C. CE Delft, pages 51-54.

[12] National Petroleum Council, page 15-17 and 15-50.

[13] Appendix C. CE Delft, pages 51-54.

implementation..." [14] Fuel cells do require highly purified H2, which means pipeline hydrogen or hydrogen from bioreactors (e.g., wastewater treatment plants) and must be further cleaned and purified before using in a fuel cell. The impact of "dirty" hydrogen is still being investigated. The same applies for the air used in the fuel cell, and regular air filter maintenance is a necessity for vehicle uses of fuel cells, adding to operations and maintenance costs.

- **Infrastructure Needed.** Focusing only on the I-710 region, where quantities of H2 are available from the production plant owned by Air Products, we can potentially remove issues of production or distribution capacity. Further examination and discussion with hydrogen producers in the area are required, as part of future project efforts. If all the ZE trucks in the drayage fleet (estimated to be 10,000 trucks by 2025[15]) were REEV with Fuel Cell, we can make the following simplistic calculation: 4 trucks per hour per pump (15 minutes each to fill); open for 20 hours/day => each dispenser could service 800 trucks per day. Therefore, roughly 12 pumps would be required. There could be multiple pumps per station, but the physical layout and space required for truck processing must be considered in future projects on infrastructure. Light-duty H2 stations cost roughly $2 million, without including fuel production.[16] However, we can envision a situation similar to CNG, where the station cost is absorbed by the distributor based on a promised level of fuel throughput and hence profitability. This is a VERY SIMPLISTIC analysis intended only to briefly outline parameters. Location and access to hydrogen fuel have to be assessed, determined and analyzed. It is doubtful that a thorough analysis would actually result in just 12 pumps for a fleet of 10,000 zero emission trucks powered by hydrogen fuel. Therefore, a full infrastructure analysis is needed to determine siting for these pump stations along with how many pumps, level of throughput capability, number of supply locations, and the necessary distribution system. All will add costs to using this fuel.

3.3 FUEL OPTIONS: ELECTRICITY

Electricity Fuel Facts

- Electricity as a fuel for vehicles has been in use since the earliest days of motor vehicles. Vehicles running on electricity have an electric drivetrain

[14] Ibid, page 51.

[15] Personal Communications with Gill Hicks, Cambridge Systematics I-710 Project Leader.

[16] National Petroleum Council, page 15-39.

(i.e., motor) and generate no tailpipe emissions. Emissions are created when the electricity is generated, as is the case for other fuels including diesel, gasoline, and hydrogen. The generation of electricity on a large scale is well developed, and pollution from those plants is being reduced over time, dramatically in in some areas. As coal plants are being phased out, natural gas plants and renewable energy sources are becoming more common. Therefore, as the electric generation grid becomes cleaner the electricity life cycle becomes cleaner, and hence BEVs become cleaner. Many large and heavy vehicles operate on electricity (e.g., locomotives, mining trucks). The technologies around electric motors and batteries are well developed, but replacing gasoline or diesel engines is a challenge because of the energy density of those liquid fuels and the need to store large amounts of electric energy onboard a truck (or deliver it via roadway power systems).

Pros

- Readily created and distributed, but power levels, locations, transmission, and distribution must be carefully planned to avoid localized grid impact.
- Zero-emission BEV vehicles, and a cleaner electric generation grid network is developing over time.
- Highly efficient engines, with significant torque at all speeds.

Cons

- Energy storage (batteries, ultra-capacitors) are currently expensive, heavy, and do not have the energy density of liquid fuels, meaning they take up more space on a vehicle.
- For a large fleet of trucks, a large amount of electricity would be needed, either for driving the vehicles (e.g., via catenary, in-road or roadside distribution) or for recharging batteries (e.g., via charging stations). Producing and distributing this electricity may be challenging and costly; the timing of power demand must also be considered because of its effect on local electric grid supply and stability.
- Ultra-fast charging stations would be needed as a minimum at a variety of locations to meet drayage operational requirements.
- The infrastructure to supply electricity will have to be developed, and analyzed, and costs determined, along with the method(s) of dispensing electricity to the trucks in order to determine commercial viability and recharging locations.

The main issues around the use of battery electric technology are:

- **Range.** The energy density of battery technology and the development projected in this area are critical. Even with forecast improvements, it will remain a challenge to build a battery electric drayage truck with more than

100 miles of range before recharging. Recharging while in use, either opportunity charging (e.g., wireless connections at port queues) or roadside power (e.g., catenary) could help address this concern. The size and weight of the required battery pack, and the cost, make for an untenable business case. If advanced information sharing and intelligent transportation systems (ITS) enable drayage operators to segment their loads, and use BEVs only for short range trips, then the BEV can be part of an effective overall solution.

- **Costs.** As covered in detail elsewhere the costs for batteries are expected to fall. This path is fairly well defined so future cost reductions are already built into the analyses and the planning of truck OEMs. Even with expected dramatic cost reductions, the battery pack will remain the largest cost element for a BEV truck, and likely more than half of the total cost.
- **Size and weight.** Current batteries weigh about 22 pounds per kWh, as outlined by CE Delft (see Appendix C). Future advanced batteries could cut this to only 4.5 pounds per kWh. Due to the large energy storage capacity needed for a full BEV Class 8 truck, a battery pack sized for 100-mile range (about 350kWh) would weigh 7,700 pounds—nearly 4 tons. This cuts into the load capacity of the vehicle, since total gross vehicle weight is limited by state regulation.
- **Recharge (refueling) time.** Diesel and LNG trucks can refuel at 12 or more DGEs (diesel gallon equivalents) per minute. Filling a 100-gallon diesel tank takes 15 minutes or so. Yet even this small interruption in active work has been a focus of reduction efforts by drayage companies (via mobile refueling, etc.). Electric trucks measure refueling time in hours, not minutes. Ultra-fast chargers can cut this time to less than 30 minutes, but repeated ultra-fast charging is believed to cause damage to the battery pack lifespan, and would require more advanced pack cooling systems due to the heat generated by rapid recharging. Recharging would have to be planned for and built into the truck usage patterns, and the recharging routine would have to be staggered and aligned with the infrastructure and grid demand. Obviously it would be essentially impossible to recharge all the BEV fleet during the four or five hours that they are not in operation (presuming two shifts per day, at 10 hours total time per shift). Addressing this challenge will require extensive study and development efforts.
- **End-of-life usage.** Over the course of a presumed 10-year lifespan, lithium-ion battery packs lose capacity, reflecting a challenging tradeoff for size/ weight and range. When a battery pack has lost 20 percent of its useful capacity, usually after 7 to 10 years with current technology, it is typically necessary to replace that battery pack. However, the high cost of the battery pack means there is significant residual value to be captured in the old pack. Much work is currently underway to find appropriate uses for end-of-life (after-market) vehicle battery packs. Recycling and rebuilding are one option, as are stationary applications with power draw demands that are not

as great as in a vehicle. Capturing the intermittent energy from solar or wind power renewable energy plants is a promising application for old vehicle battery packs. For a good business case, these end-of-life supply chains will have to be well developed and functional. Another factor in considering this technology is the eventual final disposal of these batteries, which needs to be safe and environmentally sensitive.

- **Infrastructure needed for support.** Batteries need to be charged from the electrical grid. Similar to the challenges of creating and distributing electrical power to in-road systems, the grid impact of large numbers of ultra-fast BEV chargers in one region will be significant. The challenge is that large numbers of trucks with large battery packs will have to be recharged every day. Small numbers of trucks, demonstration projects, and transit bus operations are a very different situation than the needs of the I-710 Corridor, where there could be up to 10,000 or more trucks operating continuously and simultaneously. Potentially all of these trucks have some quantity of battery onboard that needs recharging from the grid at some point. The challenges are not insurmountable, but will be costly and require major infrastructure design efforts. The infrastructure would have to accommodate staggered charging, and multiple vehicles charging at once. It would have to include some generation and some storage to minimize grid impacts and help balance the loading. Obviously, this situation requires a significant study, conducted as a separate project and involving a number of stakeholders.

3.4 INFRASTRUCTURE OPTIONS: HYDROGEN FUEL

For the needs of the I-710 Corridor, hydrogen is readily accessible as a fuel source. There are oil refineries in the region, and refineries use large amounts of hydrogen. For example, Air Products has a facility located in the Gateway Cities sub-region and owns a steam reformation hydrogen production plant, which delivers hydrogen to users in the region via pipelines. Similar companies and infrastructure exist at the Port of Houston, due to proximity to refineries.

Arrangements can be made to tap the pipeline and bring that hydrogen to dispensing stations located appropriately for potential fuel cell REEV truck users. Discussions with the hydrogen producers and other stakeholders are required, as a separate future effort.

There are hydrogen-dispensing stations in commercial service in several locations in the United States and Europe. The technology is well understood, although high volume fueling is less common and deployed primarily in a few locations of fuel cell transit bus operations, such as AC Transit in northern California.

Typically pipeline hydrogen needs to be further cleaned and compressed at the dispensing site in order to be pure enough for vehicle fuel cell use, adding to the costs for each station.

Further study and analysis is needed, as previously discussed, to determine fueling locations, distribution facilities and ultimately costs.

Figure 3.3 Light-Duty Hydrogen Fueling Station

Figure 3.4 AC Transit Fuel Cell Bus at Chevron H2 Station, Oakland, CA

Figure 3.5 Typical Onsite Compression, Dispensing, and Storage Equipment for H2

Source: These photos courtesy of the National Renewable Energy Laboratory.

Source: National Petroleum Council, page 15-32.

3.5 INFRASTRUCTURE OPTIONS: ELECTRICITY

This section will cover electrically powered infrastructure without evaluating the applicability and/or viability to the I-710 Project. Matching of potential technologies to project and user requirements is discussed in Section 2.2.

In considering the infrastructure options for electricity, this report will discuss the following possible technologies:

- Catenary power supply (overhead contact).
- In-road power supply (contact or wireless).
- Ultra-fast chargers (over 90kW; overhead, wireless, or plug-in).

- Fast chargers (11 to 90kW; wireless or plug-in).
- Battery swapping.

Electricity Infrastructure: Catenary Power Supply (Overhead Contact) Technology

Overhead wires are charged, and a pantograph device on the truck cab extends and slides along the wires to deliver power from the overhead wires to the moving vehicle. The pantograph can be automated to recognize when it is below a catenary system and automatically raise and connect, or lower when not connected to the catenary.

Pros

- A well-known technology from transit and mining operations, it reduces per-vehicle costs by eliminating the need for larger battery packs, traded off against the costs of a possibly complex pantograph.

Cons

- Additional infrastructure costs must be built into roadway design. A business structure is needed for payment/use. A vehicle connection system adds cost and integration expense to vehicles. Some consider overhead wires a nuisance or visually unattractive There are also concerns about power requirements under heavy traffic, and the associated distribution of power and costs for substations and distribution facilities.

Notes: The South Coast AQMD is planning a demonstration test of a Siemens catenary system design with trucks developed by Volvo and Transpower. Permits and construction will take over a year, and the actual demonstration is expected to begin in 2015. Studies directed by Metro and the Gateway Cities COG are examining the power requirements and potential costs for a catenary system for the Zero-Emission Freight Corridor. The critical issues are the density of trucks (headway between vehicles using the catenary) and the ability to deliver and distribute adequate power through the catenary system. This is a new situation; transit applications obviously use catenary, but those uses have headway times of 10 minutes or more. Current traffic models have truck headways of five seconds or less in the I-710 corridor, which significantly increases power demands and complicates the distribution of power to the catenary wires.

Figure 3.6 Siemens eHighways Concept (in prototype form, diesel-electric hybrid truck on the right)

Electricity Infrastructure: In-Road Power Supply (Contact or Wireless) Technology

A system of embedded wires or cables would carry electric power within the roadway. Trucks would have pick-up devices that receive power from the road as the truck drives over them. Options include "inductive" designs where there is no physical contact, and "conductive" designs where a pick-up device touches a conductor embedded in the roadway surface.

Pros

- No "visual pollution." The technology is known but less well developed than overhead power. Train transit system using in-road power in Bordeaux France is highly sophisticated. Truck-based system(s) are currently under development in Europe and Korea.

Cons

- Infrastructure costs may be higher than for an overhead system. The technology must be built into design of corridor. A business structure is needed for payment/use, and a vehicle connection system adds cost and integration to vehicle.
- Power distribution of sufficient quantity could be an issue.
- Safety could be an issue along with ease (or difficulty) of maintenance.

Notes: The Swedish Energy Agency and Swedish Road Administration are studying various methods of electric power supply to roadways for goods movement. Volvo is part of this work and has other projects of its own as well.

Prototypes of electrified roadway trucks are in demonstration form in Sweden. The KAIST system (photos below) is high power (over 90 kW) and in full-time use today near Seoul. It is a significant innovation as it recharges the buses while they are in motion, driving over recharging "pads" in the roadway. As with catenary systems, however, the same vehicle headway challenge applies to in-road approaches. The amount of power needed for multiple trucks travelling close together is far greater than in transit operations and presents a major barrier for roadway electrification.

Roadway power such as catenary or in-road may be too problematic and costly to be viable in this application. A separate report for Metro and the Gateway COG has been prepared to examine the power requirements and distribution challenges. Please contact the Gateway COG for a copy of that report.

Figure 3.7 The Korean Advanced Institute of Science and Technology (KAIST) Buses[a]

[a] KAIST deploys these buses on a 7.5-mile route with in-road wireless charging while in motion.

Electricity Infrastructure: Ultra-Fast Chargers (Over 90kW, Overhead, Wireless, or Plug-In) Technology

- High current chargers are usually direct current (DC) and can deliver over 90 kW of power flow, which accelerates the battery recharging process. Some are able to deliver over 400 kW, which can charge a small pack (25 kWh) in

under 5 minutes. For BEV truck packs of 300 kWh or more, this level of charging may be important for operational effectiveness.

Pros

- Known basic technology;
- Systems for transit use are in operation; and
- Fast charging times will improve acceptance and usefulness.

Cons

- Infrastructure systems, like the trucks using them, need to be developed, demonstrated, and proven effective. Costs, complexity, and appropriate applications need to be examined.
- High pulse power demand on grid is potentially significant if multiple chargers are deployed in one area. As stated in reports, "charging of a 25 kWh battery pack in 5 minutes would require a power flow rate of approximately 300 kW, which is approximately equivalent to the peak power requirements for a 100,000 square foot office building."[17] The impact of longer charging times and more frequent charging require further analysis and planning. Grid demands, electricity supply, and charging locations are in need of further analysis as separate project efforts.
- Possible reduction in life cycle of batteries; advanced cooling needed due to heat generated. Additional development and validation are necessary.
- Wireless systems may have lower efficiency. KAIST system allows 100kW at 85 percent efficiency, but it was unclear if this was while in motion. Presume it is stationary charging.

Notes: Conventional chargers (under 10kW) are generally not applicable for heavy-duty applications – the charge times would be too long given the large battery pack sizes. One potential approach is multiple conventional chargers with multiple connectors, but this is seen as a stop-gap system for prototypes only.

[17]National Petroleum Council, page 13-26.

Figure 3.8 Proterra BEV Transit Bus Overhead Ultra-Fast Charger, Stockton, California

Figure 3.9 ABB "TOSA" Hybrid Transit Bus Overhead Ultra-Fast Charger, Geneva, Switzerland

Figure 3.10 Ultra-Fast Plug-In Charge Transit Buses, China

Electricity Infrastructure: Battery Swapping Technology

- Batteries are made in standard sizes, with standardized dimensions and connectors, allowing reserve packs to be housed and charged in a swapping station. Vehicles enter and an automated system removes the discharged batteries and replaces them with fully charged packs.

Pros

- Enables charging at off peak periods.
- Potentially similar equipment to other shipping container loading. Ports could theoretically serve as host to swapping stations.
- Potentially lowers the cost of trucks. The batteries could be owned by someone other than the truck purchaser.

Cons

- Requires industry standardization and 'ruggedization' of battery packs.
- Requires standardized software and communication protocols for batteries and system integration.
- Need sufficient locations, storage space and operating space for multiple vehicles and hundreds of large battery packs.

Notes: This approach has been tried in light-duty vehicles (the now bankrupt Better Place was using this model) and for transit buses in China. Again, the volumes and pace of truck traffic in the I-710 region are far different than a transit application. The Chinese system operated 100 buses on fixed routes. The drayage fleet could be 100 times as large, operating in multiple routes and areas.

Figure 3.11 Battery Swap Systems, Automated System, China

Figure 3.12 Battery Swapping for Transit Buses, China

4.0 Economic Factors and Business Case

4.1 Vehicle Costs

The costs of the ZE Trucks are driven by their components. Some components, such as batteries or fuel cells, are especially expensive currently, and there is uncertainty around the future costs of these components. Although costs will come down, these components will remain a large portion of the total truck bill of materials and additional costs for ZE trucks over and above conventional diesel trucks.

The CE Delft report did an excellent analysis of future component costs, building them up from baselines. For this section, we will use their analysis, converted to U.S. measures.

As discussed elsewhere, we are presuming a zero-emission range of at least 50 miles. This implies the technological solutions possible are:

- REEV with Engine;
- REEV with Fuel Cell; and
- BEV.

For any BEV or REEV design to meet the key performance parameters (KPPs) described earlier, the following are required:

- 350 kW electric motor = roughly 470 horsepower; and
- Sufficient onboard energy storage to meet the required ZE range.

For the REEV with engine, there would be a requirement for additional fuel storage for the emission-creating range extender engine (CNG, diesel, gasoline, or other). The fuel cell REEV would have batteries and H2 storage, and the BEV would have only batteries. The table below from the CE-Delft report provides an excellent summary of estimated costs for ZE Truck elements.[18]

[18] Appendix C, CE Delft, Table 14, page 70.

Table 4.1 CE Delft Estimated ZE Truck Element Costs

Component		2012	2020	2030
Diesel ICE	$/kW	70	79.2	88.4
Battery System	$/kW	594	316.8	212.5
Electric Motor	$/kW	25.1	22.4	19.8
Fuel Cell System	$/kW	1,287	250.8	105.6
H2 Storage	$/kW	34.3	23.8	13.2
BEV BoP (balance of plant components)	$/kW	34.3	28.4	22.4
FC REEV BoP	$/kW	25.1	21.1	17.2

Source CE Delft (conversion to U.S. measures by CALSTART).

There are several key points that can be made regarding the CE Delft analysis and the resulting cost assumptions:

- Diesel engine costs rise due to "tightening exhaust after-treatment regulations."[19] For California, this factor is especially important, and could even be larger than the EU estimate in the CE Delft report. It is highly likely California will require an ultra-low NO_x engine as the new baseline. Such engines will almost certainly be more expensive than today's engines to meet an 80-percent NO_x reduction over today's trucks.
- Fuel cell costs are expected to drop dramatically between today and 2030 (by more than a factor of 12).
- Battery costs are also expected to drop significantly, by a factor of nearly 3.

Balance of plant (BoP) components for the diesel truck (such as fuel tanks) are estimated to remain unchanged from 2012 to 2030[20] while the fuel cell and BEV components show gradual declines in prices due to improvements in manufacturing, volume increases, and value engineering.

The baseline diesel truck costs used by CE Delft were for a Class 8 truck with 1,000-km (about 621 miles) range.[21] Those costs, converted to U.S. measures are shown in Table 4.2.

[19] Ibid, page 71.

[20] Ibid, page 71.

[21] Ibid, Table 18, page 74.

Table 4.2 Baseline Diesel Truck Cost Estimates

Baseline Diesel	2012	2020	2030
Total truck cost	$105,336	$108,570	$111,804

Source CE Delft (currency conversion by CALSTART).

This baseline value can be used to compare the incremental capital costs for each ZE truck option, even though C3 capable trucks do not need as much range. Vehicle costs are not the only factor in an investment decision, and more in-depth analysis is conducted in later sections (see Section 4.4) of this report.

Please note that our analyses have used additional data for sensitivity analysis. CE Delft often used very aggressive assumptions for cost reductions, and so we have conducted analyses with a higher battery cost and higher fuel cell costs. See the following sections for additional description.

REEV with Engine

Note that a REEV with Engine can have a mileage range between refueling comparable to existing diesel trucks, simply by refilling with engine fuel (CNG, Diesel, Gasoline, or other). It utilizes the battery when there is battery energy, but does not need the battery to deliver the same performance as a diesel truck. It is not zero-emissions when operating in engine-on mode, however.

Costs for a REEV with Engine were not estimated in the CE Delft report. We will make the assumption that a REEV with Fuel Cell would be very similar in costs and use those values for REEV with Engine, except that a range extender engine would replace the fuel cell, and so our business case analyses will follow this approach.

REEV designs can have a huge variety of component combinations. The parameters used here are in no way presented as the optimal solution. However, future projects should conduct an optimization calculation to determine the best combination of battery size and range extender engine size. There are multiple types of range extenders that could be used, and many sizes of battery packs. For the I-710 region, an optimum mix could be determined to enable more accurate business model calculations.

In addition, the engineering work to select the best combinations of size/ capacity for battery, fuel, range extender, and overall architecture is currently ongoing and changing based on findings from demonstration projects. The assumptions used are the best estimates of CALSTART experts at this point in time.

Further details and parameters used are outlined in the following sections. It is essential to remember that the examples presented here can be used for internal comparison only, not for comparison to current truck costs or other cost estimates.

REEV with Fuel Cell

As mentioned previously, we used CALSTART expert input to select the parameters for the REEV with Fuel Cell modeling. The same conditions and caveats apply as with the REEV with Engine. Most importantly, an optimization analysis is needed, and the outcomes cited here can only be used for internal comparison.

BEV

CE Delft did not specifically examine a full-performance BEV, in that they focused on BEV designs with grid connections and smaller battery packs. For the I-710 corridor project, a C3 capable BEV must be examined, as the availability of roadway power cannot be assumed. The ability to operate without grid connection requires a larger battery pack, on the order of 350 kWh (versus 166 kWh for the CE Delft grid-connected trucks) in order to deliver roughly 100 miles in range with a full load and safety buffers.

Note that since a BEV is always zero-emission, the forcing parameter is the daily range needed for drayage operation, which our analysis shows to be roughly 200 miles based on operator preference. BEVs cannot currently meet that range, so we are using 100 miles, as that is the current limit of technology.

Infrastructure Impacts on Vehicle Cost

Both catenary and in-road power infrastructure systems are discussed more in other sections, but here we look specifically at the vehicle-related cost component. The "pick-up" mechanism for getting the power from the roadway into the truck is a vehicle component. Note that these costs may change if the voltages or other roadway power parameters change from the CE Delft assumptions.

Table 4.3 Catenary System Estimated Costs*

2012	2020	2030
$52,800	$30,800	$13,200

Source CE Delft.

[a] Pantograph only.

For the in-road inductive system, the costs are shown in Table 4.4.[22]

Table 4.4 In-Road Inductive System Estimated Costs[a]

2012	2020	2030
$12,210	$11,253	$10,296

Source CE Delft.

[a] Pantograph only.

These costs must be added to any of the vehicle designs (REEV or BEV) if roadway power is part of the project solution. Further separate analyses, as part of future projects, will be required to examine roadway power systems, their optimal design and application, and their costs.

4.2 OPERATING AND MAINTENANCE COSTS

One of the unknowns in this project effort is operating and maintenance costs. Operating costs (i.e., primarily fuel costs) can be estimated fairly well using expected fuel consumption and predicted fuel costs. Maintenance costs, however, cannot be accurately determined until enough ZE Drayage trucks are in operation for long enough to collect data and ascertain maintenance needs. Therefore, surrogates will be used for the business case analyses.

One good summary of the potential costs was done for the CalHEAT Parcel Truck Evaluation project. While the values are estimates for a parcel truck, the areas of costs will be comparable for a Class 8 drayage truck. Subsequent projects should conduct a detailed examination of drayage truck maintenance and savings from ZE designs.

The operating and maintenance (O&M) cost estimates used are from CALSTART experience on the CalHEAT project, and general expertise in e-trucks. The values used in the analysis are described Appendix B: Business Case Analysis Assumptions. O&M costs are outlined in each of the business case models that follow.

4.3 INFRASTRUCTURE COSTS

Infrastructure is critical for the successful implementation of C3 trucks in the I-710 region, and their successful expansion to other markets.

As discussed in Section 3.0 Infrastructure Dependencies, there are some C3 truck architectures that will create emissions some of the time, using fuels that are not

[22] Ibid, Table 19, page 76.

inherently zero-emission. These are the REEV with Engine designs, and CNG is a leading candidate for a non-zero-emission fuel that will be used in the I-710 region and elsewhere. We believe the CNG infrastructure will be growing due to factors other than those from the ZE Truck initiatives, largely the current low cost of natural gas, and the efforts of natural gas distributors to expand market share. While a high-volume CNG station can cost over $1 million, we also feel the distributors will absorb that cost based on projected high fuel volume sales.

Such a business model is already being used by the major CNG provider Clean Energy, in the deployment of their CNG stations, in which the station costs are built into a package based on projected fuel consumption, with high volume stations (as would be the case in the I-710 region) delivering sufficient revenue to make the station costs negligible in the overall infrastructure funding. In other words, CNG infrastructure costs will not impact the I-710 ZE Truck Commercialization project and can be left to other entities and future analyses.

Our business case analyses uses costs based on the above assumptions, and further presumes the same business model will be developed for Hydrogen. Costs for CNG and H2 infrastructure are built into the fuel costs used for the analyses that follow.

Electricity will play a role in virtually every ZE truck design. The electrical infrastructure in the I-710 corridor will almost certainly need to be strengthened to support the rollout of ZE trucks. A thorough analysis of electrical infrastructure is a necessary future step.

For trucks not dependent upon roadway power (i.e., those with batteries onboard to hold electrical energy) recharging requires stations or other locations where charging infrastructure can be deployed. Only this condition was examined in this report; roadway power was not evaluated. Broader analyses of overall electrical charging requirements, locations, and methods, must be conducted in future project efforts.

Our business case model uses costs for charging infrastructure driven by the time required/allowed for charging. Shorter recharge times require higher power charging. The recharge times allowed were estimated based on our understanding of drayage operations in the I-710 region and the battery size of the vehicle. The parameters are described in Section 4.4 below. The costs are estimated based on CALSTART expert input regarding charging infrastructure costs. CALSTART has worked with charging systems from ultra-fast 500 kW to Level 1 light-duty chargers, and we believe the values listed in the following business case analyses are appropriate for the calculations.

Future projects must conduct more detailed evaluation of charging needs, infrastructure requirements, and battery swapping technologies, which were not covered here.

4.4 BUSINESS CASE ANALYSIS

Model Simulations

The truck architectures selected for simulation here are examples only. The output of the models can be compared against each other, but they are NOT absolute values, and should not be compared to current pricing or other estimates of costs. We made no optimization analysis, but selected parameters that seem reasonable, and are designed to be comparable against each other.

Technology Option #1: Zero-Emission Battery Electric Drayage Truck (BEV)

Table 4.5 Key Performance Parameters for Technology Option #1

Total Range	100 miles
Electric Motor Size	350 kW
Charging Time	2 hours

Source CALSTART.

Table 4.6 Analysis Parameters and Assumptions for Technology Option #1

Analysis Parameters	Assumptions
Vehicle life	10 yrs.
Days in operation per year	250 days/year
Total daily range	100 miles
Electric vehicle energy consumption	2.50 kWh/mile
Energy charge	$0.15/kWh
Demand charge	$15.00/kW
Electricity escalation rate	0%
Desired time to recharge vehicle from 0 to 100% SOC	2 hours

Source CALSTART.

Note: Analysis parameters and other assumptions are explained in further detail in Appendix B.

Table 4.7 Zero-Emission Battery Electric Drayage Truck Element Costs

Components	BEV (Year 2012)	BEV (Year 2020)	BEV (Year 2030)
Glider	$79,200	$79,200	$79,200
350 kW motor	$8,785	$7,840	$6,930
Power electronics, battery management system and additional required BEV systems	$12,005	$9,940	$7,840
Battery system (350 kWh)	$207,900	$110,880	$74,375
Total vehicle cost	**$307,890**	**$207,860**	**$168,345**
Baseline diesel cost	$104,360	$107,580	$110,800
Incremental cost	$203,530	$100,280	$57,545

Source CALSTART.

Incremental Cost

Battery electric truck incremental cost was calculated from CE-Delft ZE Truck element costs. For the year 2020, a 100-mile range zero-emission battery electric drayage truck would cost $100,280 more than an equivalent diesel drayage truck. For the purposes of calculation, the zero-emission battery electric drayage truck incremental cost was rounded down to $100,000.

Maintenance Cost

Electric vehicles will typically have lower maintenance costs than conventional fossil-fueled vehicles for the following reasons[23]:

- The battery, motor, and associated electronics require little to no regular maintenance;
- There are fewer fluids to change;
- Brake wear is significantly reduced, due to regenerative braking; and
- There are far fewer moving parts, relative to a conventional internal combustion engine.

The CalHEAT e-truck report[24] estimated maintenance cost savings for Class 4 to Class 5 parcel delivery battery electric vehicles between 0.3 to 10 cents per mile.

[23] U.S. Department of Energy, Energy Efficiency and Renewable Energy, Alternative Fuels Data Center, Maintenance and Safety of Hybrid and Plug-In Electric Vehicles, http://www.afdc.energy.gov/vehicles/electric_maintenance.html. (Accessed on 2013-07-16.)

We assumed the higher end of that range (10 cents per mile) since drayage trucks are larger Class 8 vehicles with larger and more expensive braking systems. Larger diesel engines use more cooling fluids and lubricant oil.

Battery size

The zero-emission battery electric drayage truck can drive 100 miles per day, using 2.5 kWh per mile driven. Battery life decreases dramatically when batteries are fully discharged (from 100 percent to 0 percent SOC); therefore, we added a 20-percent buffer for battery life. With limited charging infrastructure and longer charging time, "range anxiety" remains an issue with battery electric vehicles, so based on CALSTART experience and knowledge of e-trucks, we have added an additional 20-percent buffer. The result adds up to a 350 kWh battery size to deliver 100 miles of range.

E-Truck Infrastructure

Recharging in 2 hours requires using a 150 kW charger. For purposes of this analysis, we assumed such a charger would cost $150,000. (See Appendix B for more details on business case assumptions.) This charger could be used by more than one vehicle, making it possible to spread costs over each vehicle using the charger. We assumed that 6 vehicles could use this charger every day, which translates to the charger being used 12 hours per day.

Battery Change

We assumed no battery change throughout the life of the vehicle. A battery change midway through the life of the vehicle would be costly ($110,880 to replace the 350 kWh battery system).

[24]See Appendix G. Gallo, Jean-Baptiste, Jasna Tomić (CalHEAT), 2013, Battery Electric Parcel Delivery Truck Testing and Demonstration, California Energy Commission.

Table 4.8 Business Case Analysis Results for Technology Option #1

Economic Analysis Parameter (Amounts in 2013 U.S. Dollars)	Result
Truck Incremental cost (in 2020)	$100,000 per truck
Infrastructure cost	$25,000 per truck
Simple payback period (without incentives)	17 years
Net present value (without incentives)	-$57,202
Incentive level needed to meet 5-year payback period	$87,708 per truck
Net present value (with incentives)	$30,506
10-yr. operation & maintenance savings	$67,798
Fuel savings	$49,010
Maintenance savings	$18,788

Source CALSTART.

These results rely on the following key assumptions:

- Aggressive reductions in costs for motor, power electronics, battery management systems, additional required systems and battery packs.
- Battery pack will last the life of the vehicle (10 years) without needing to be replaced; risk is higher due to frequent ultra-fast charging, as ultra-fast charging is known to cause battery life degradation of an uncertain amount.
- Fast charger used by 6 zero-emission battery electric drayage trucks.
- The zero-emission battery electric drayage truck is used 250 days per year and drives an average of 100 miles per day.

Technology Option #2: CNG Range Extender Electric Drayage Truck (CNG REEV)

Table 4.9 Key Performance Parameters for Technology Option #2

Total Range	200 miles
Zero Emission Range	50 miles
Electric Motor Size	350 kW
Range Extender Size	350 kW
Charging Time	2 hours

Source CALSTART.

Table 4.10 Analysis Parameters and Assumptions for Technology Option #2

Analysis Parameters	Assumptions
Vehicle life	10 yrs.
Days in operation per year	250 days/year
Total daily range	100 or 200 miles
CNG vehicle fuel efficiency	6 MPG
CNG fuel price	$3.45/diesel gallon equivalent (DGE)
CNG fuel escalation rate	3%
Electric vehicle energy consumption	2.50 kWh/mile
Energy charge	$0.15/kWh
Demand charge	$15.00/kW
Electricity escalation rate	0%
Desired time to recharge vehicle from 0 to 100% SOC	2 hours

Source CALSTART.

Note: Analysis parameters and other assumptions are explained in further details in Appendix A.

Table 4.11 CNG Range Extender Electric Drayage Truck Element Costs

Components	CNG REEV (Year 2012)	CNG REEV (Year 2020)	CNG REEV (Year 2030)
Glider	$79,200	$79,200	$79,200
350 kW NG ICE + CNG tank (25 DGE)	$45,000	$23,000	$18,000
350 kW motor	$8,785	$7,840	$6,930
Power electronics, battery management system and additional required BEV systems	$12,005	$9,940	$7,840
Battery system (150 kWh)	$89,100	$47,520	$31,875
Total vehicle cost	**$234,090**	**$167,500**	**$143,845**
Baseline diesel cost	$104,360	$107,580	$110,800
Incremental cost	*$129,730*	*$59,920*	*$33,045*

Source CALSTART.

Incremental Cost

CNG range extender electric truck incremental cost was calculated from CE-Delft ZE Truck element costs. For the year 2020, a CNG range extender electric truck would cost $59,920 more than an equivalent diesel drayage truck. For the

purposes of calculation, the CNG range extender electric truck incremental cost was rounded up to $60,000.

Maintenance Cost

To be conservative, we assumed no maintenance savings.

Battery Size

The CNG range extender electric truck can drive on electricity-only mode 50 miles per day, using 2.5 kWh per mile driven. Battery life decreases dramatically when batteries are fully discharged (from 100 percent to 0 percent SOC); therefore, we added a 20-percent buffer for battery life. The result adds up to a 150 kWh battery size to deliver 50 miles of range.

E-Truck Infrastructure

Recharging in 2 hours requires using a 63 kW charger. For purposes of this analysis, we assumed such a charger would cost $50,000. (See Appendix B for more details on business case assumptions.) This charger could be used by more than one vehicle, making it possible to spread costs over each vehicle using the charger. We assumed that 6 vehicles could use this charger every day, which translates to the charger being used 12 hours per day.

Battery Change

We assumed no battery change throughout the life of the vehicle. A battery change midway through the life of the vehicle would be costly ($47,520 to replace the 150 kWh battery system).

These results rely on the following key assumptions:

- Aggressive reductions in costs for motor, power electronics, battery management systems, additional required systems and battery packs.
- Battery pack will last the life of the vehicle (10 years) without needing to be replaced; as ultra-fast charging is known to cause battery life degradation of an uncertain amount.
- Fast charger used by six CNG range extender electric trucks.
- The CNG range extender electric truck is used 250 days per year and drives an average of 100 or 200 miles per day.
- CNG cost at $3.45 per DGE.

Table 4.12 Business Case Analysis Results for Technology Option #2

Economic Analysis Parameter (Amounts in 2013 U.S. Dollars)	Result (100 mi/d)	Result (200 mi/d)
Truck Incremental cost (in 2020)	$60,000 per truck	$60,000 per truck
Infrastructure cost	$8,400 per truck	$8,400 per truck
Simple payback period (without incentives)	13 years	7 years
Net present value (without incentives)	-$25,349	$6,107
Incentive level needed to meet 5-year payback period	$42,983 per truck	$20,692 per truck
Net present value (with incentives)	$17,634	$26,799
10-yr. operation & maintenance savings	$43,051	$74,507
Fuel savings	$43,051	$74,507
Maintenance savings	$0	$0

Source CALSTART.

Technology Option #3: Zero Emission Fuel Cell Range Extender Electric Drayage Truck (FC REEV)

Table 4.13 Key Performance Parameters for Technology Option #3

Total Range	200 miles
Fuel Cell Size	60 kW
Battery Size	60 kWh
Electric Motor Size	350 kW
Charging Time	2 hours

Source CALSTART.

Table 4.14 Analysis Parameters and Assumptions for Technology Option #3

Analysis Parameters	Assumptions
Vehicle life	10 yrs.
Days in operation per year	250 days/year
Total daily range	100 or 200 miles
Fuel cell vehicle efficiency	5.0 mile/kg H2
H_2 fuel price	$3.50/kg
H_2 fuel escalation rate	3%
Electric vehicle energy consumption	2.50 kWh/mile
Energy charge	$0.15/kWh
Demand charge	$15.00/kW
Electricity escalation rate	0%
Desired time to recharge vehicle from 0 to 100% SOC	2 hours

Source CALSTART.

Note Analysis parameters and other assumptions are explained in more detail in Appendix B.

Table 4.15 Zero Emission Fuel Cell Range Extender Electric Drayage Truck Element Costs

Components	FC REEV (Year 2012)	FC REEV (Year 2020)	FC REEV (Year 2030)
Glider	$79,200	$79,200	$79,200
Fuel Cell System (60 kW)	$77,220	$15,048	$6,336
350 kW motor	$8,785	$7,840	$6,930
Power electronics, battery management system and additional required FC systems	$1,506	$1,266	$1,032
Battery system (60 kWh)	$35,640	$19,008	$12,750
H_2 Storage (30 kg)	$24,010	$16,660	$9,240
Total vehicle cost	**$226,361**	**$139,022**	**$115,488**
Baseline diesel cost	$104,360	$107,580	$110,800
Incremental cost	$122,001	$31,442	$4,688

Source CALSTART.

Incremental Cost

Zero-emission fuel cell range extender electric truck incremental cost was calculated from CE-Delft ZE Truck element costs. For the year 2020, a zero-

emission fuel cell range extender electric drayage truck would cost $31,442 more than an equivalent diesel drayage truck. For the purposes of calculation, the zero-emission fuel cell range extender electric drayage truck incremental cost was rounded up to $31,500.

Maintenance Cost

To be conservative, we assumed no maintenance savings.

Battery Size

The zero-emission fuel cell range extender electric drayage truck can drive an equivalent of 20 miles in electricity-only mode per charge, using 2.5 kWh per mile driven. Battery life decreases dramatically when batteries are fully discharged (from 100 percent to 0 percent SOC); therefore, we added a 20-percent buffer for battery life. The result adds up to a 60 kWh battery size to deliver 20 miles of range.

E-Truck Infrastructure

Recharging in 2 hours requires using a 25 kW charger. For purposes of this analysis, we assumed such a charger would cost $20,000. (See Appendix B for more details on business case assumptions.) This charger could be used by more than one vehicle, making it possible to spread costs over each vehicle using the charger. We assumed that 6 vehicles could use this charger every day, which translates to the charger being used 12 hours per day.

Battery Change

We assumed no battery change throughout the life of the vehicle. A battery change midway through the life of the vehicle would be costly ($19,008 to replace the 60 kWh battery system).

Table 4.16 Business Case Analysis Results for Technology Option #3

Economic Analysis Parameter (Amounts in 2013 U.S. Dollars)	Result (100 mi/d)	Result (200 mi/d)
Truck Incremental cost (in 2020)	$31,500 per truck	$31,500 per truck
Infrastructure cost	$3,350 per truck	$3,350 per truck
Simple payback period (without incentives)	16 years	10 years
Net present value (without incentives)	-$19,943	-$14,971
Incentive level needed to meet 5-year payback period	$23,808	$17,142
Net present value (with incentives)	$3,865	$2,170
10-yr. operation & maintenance savings	$14,907	$19,879
Fuel savings	$14,907	$19,879
Maintenance savings	$0	$0

Source CALSTART.

These results rely on the following key assumptions:

- Aggressive reductions in costs for motor, power electronics, battery management systems, additional required systems, battery packs and fuel cell stack.
- Battery pack will last the life of the vehicle (10 years) without needing to be replaced; as ultra-fast charging is known to cause battery life degradation of an uncertain amount.
- Fast charger used by 6 zero-emission fuel cell range extender electric drayage trucks.
- The zero-emission fuel cell range extender electric drayage truck is used 250 days per year and drives an average of 100 or 200 miles per day.
- H_2 cost at $3.50 per kg.

These analyses can be summarized as follows:

Table 4.17 Summary of Business Case Analysis Results

	Total Range (ZE Range)	Daily Driving	Simple Payback Period (Years)	Incentive for 5-Year Payback Period	10-Year O&M Savings	2020 Truck Incremental Cost (Dollar per Truck)	Infrastructure Cost (Dollar per Truck)
#1 BEV	100 (100)	100	17	$87,708	$67,798	$100,000	$25,000
#2L CNG REEV *Low Utilization*	200 (50)	100	13	$42,983	$43,051	$60,000	$8,400
#2H CNG REEV *High Utilization*	200 (50)	200	7	$20,692	$74,507	$60,000	$8,400
#3L Fuel Cell REEV *Low Utilization*	200 (200)	100	16	$23,808	$14,907	$31,500	$3,350
#3H Fuel Cell REEV *High Utilization*	200 (200)	200	10	$17,142	$19,879	$31,500	$3,350

Source CALSTART.

These results rely on the following key assumptions:

- Aggressive reductions in costs for motor, power electronics, battery management systems, additional required systems and battery packs.
- Aggressive reductions to costs of motor, power electronics, battery management systems, additional required systems, battery packs and fuel cell.
- Battery pack will last the life of the vehicle (10 years) without needing to be replaced; as ultra-fast charging is known to cause battery life degradation of an uncertain amount
- Fast charger used by 6 drayage trucks.
- The drayage trucks are used 250 days per year and drive an average of 100 or 200 miles per day.
- CNG cost at $3.45 per DGE.
- H_2 cost at $3.50 per kg.

We then looked at the cost estimate to replace 10,000 drayage trucks. We assumed a combination of the three technology options.

Table 4.18 Summary of Business Case Analysis Results for Fleet of 10,000 Trucks

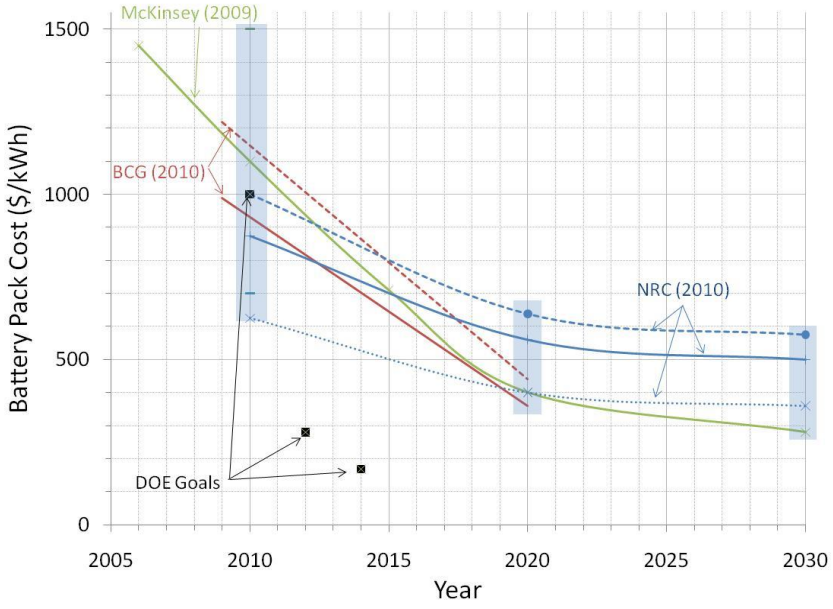
	#1 BEV	#2 CNG REEV	#3 Fuel Cell REEV	Total
Number of Units	2,500	5,000	2,500	10,000
2020 Truck Incremental Cost ($ per truck)	$100,000	$60,000	$31,500	–
Infrastructure Cost ($ per truck)	$25,000	$8,400	$3,350	–
Total Cost	**$312,500,000**	**$342,000,000**	**$87,125,000**	**$741,625,000**

Source CALSTART.

Impact OF Battery Costs

To illustrate the importance of battery prices in the business case analysis above, we carried out a sensitivity analysis on battery prices.

Figure 4.1 Estimated Reductions in Battery Costs[a]
Dollars per kWh, Nameplate



Source ICF International.

[a] See Appendix I, The Gateway Cities Air Quality Action Plan, Task 7, New Measures Analysis, Draft Report, ICF International, March 2013.

Table 4.19 Summary of Battery Prices from CE-Delft Study and Highest Prices Reported by ICF

	CE-Delft	Highest Price
2012	$594.0/kWh	~$1000/kWh
2020	$316.8/kWh	~$650/kWh
2030	$212.5/kWh	~$575/kWh

Source CE Delft and ICF International.

We chose to use $650 per kWh as a high battery price point. Table 4.20 below summarizes the results of the business case analysis with high battery prices.

Table 4.20 Summary of Business Case Analysis Results with High Battery Prices

High Battery Prices ($650/kWh)	Total Range (ZE Range)	Daily Driving	Simple Payback Period (Years)	Incentive for 5-Year Payback Period	10-Year O&M Savings	2020 Truck Incremental Cost ($ per Truck)	Infrastructure Cost ($ per Truck)
#1 BEV	100 (100)	100	32 yrs.	$204,708	$67,798	$217,000	$25,000
#2L CNG REEV Low Utilization	200 (50)	100	23 yrs.	$92,983	$43,051	$110,000	$8,400
#2H CNG REEV High Utilization	200 (50)	200	12 yrs.	$70,692	$74,507	$110,000	$8,400
#3L Fuel Cell REEV Low Utilization	200 (200)	100	25 yrs.	$44,308	$14,907	$52,000	$3,350
#3H Fuel Cell REEV High Utilization	200 (200)	200	16 yrs.	$37,642	$19,879	$52,000	$3,350

Source CALSTART.

Impact of Fuel Cell Costs

To illustrate the importance of fuel cell component prices in the business case analysis above, we carried out a sensitivity analysis on fuel cell component prices (fuel cell system, power electronics, battery management system and additional required fuel cell systems and H_2 storage). Thorough research uncovered no supportable estimates for future fuel cell component pricing, so we chose to double the fuel cell component prices from the CE-Delft ZE Truck study, as a representation of conservative "high" pricing.

Table 4.21 below summarizes the results of the business case analysis with high fuel cell component prices.

Table 4.21 Fuel Cell Component Cost Assumptions

Year 2020	CE-Delft	High Prices
Fuel Cell System	$250.8/kW	$501.6/kW
H_2 Storage	$23.8/kWh	$47.6/kWh
Power electronics, battery management system and additional required FC system	$28.4/kW	$56.8/kW

Source CALSTART and CE Delft.

Table 4.22 Summary of Business Case Analysis Results with High Fuel Cell Components Prices

High FC Prices	Total Range (ZE Range)	Daily Driving	Simple Payback Period (Years)	Incentive for 5-Year Payback Period	10-Year O&M Savings	2020 Truck Incremental Cost ($ per Truck)	Infrastructure Cost ($ per Truck)
#3L Fuel Cell REEV Low Utilization	200 (200)	100	31 yrs.	$56,808	$14,907	$64,500	$3,350
#3H Fuel Cell REEV High Utilization	200 (200)	200	19 yrs.	$50,142	$19,879	$64,500	$3,350

Source CALSTART.

Infrastructure Impacts and Fuel Needs

To approximate the total fuel needs for the I-710 region drayage fleet in the future, we looked at the fuel needed (electricity, CNG and H_2) to run these 10,000 drayage trucks every day.

To give a sense of scale, for reference, in 2011 the Los Angeles County Metropolitan Transportation Authority consumed an average of **489,000 kWh per day** for its light and heavy rail system and **120,525 DGE per day** for its transit CNG bus system.[25] This would indicate that the natural gas requirements are high but not unprecedented. Electrical requirements however are extremely high and focused only on the small area around the I-710 and ports. A fleet of 10,000 trucks, all of which use some amount of electrical power, will pose a challenge to the local grid and to electrical production capacity. The use of hydrogen for vehicle fuel is so new that no references can be made.

[25]National Transit Database 2011, http://www.ntdprogram.gov/ntdprogram/datbase/2011_database/NTDdatabase.htm. (Accessed 10/16/2013.)

Table 4.23 Estimate of kWh, CNG and H_2 Needed per Day

	BEV	CNG REEV		Fuel Cell REEV		Total
Daily Mileage (miles/day)	100	100	200	100	200	**N/A**
Number of Trucks	2,500	2,500	2,500	1,250	1,250	**10,000**
Cumulative Daily Electric Miles (miles/day)	250,000	125,000	125,000	25,000	25,000	**550,000 miles/d**
Cumulative Daily Charging Energy (kWh/day)	625,000	312,500	312,500	62,500	62,500	**1,375,000 kWh/d**
Cumulative Daily CNG Miles (miles/day)	N/A	125,000	375,000	N/A	N/A	**500,000 miles/d**
Cumulative Daily CNG Needed (DGE/day)	N/A	20,800	62,500	N/A	N/A	**83,300 DGE/d**
Cumulative Daily FC Miles (miles/day)	N/A	N/A	N/A	100,000	100,000	**200,000 miles/d**
Cumulative Daily H_2 Needed (kg H_2/day)	N/A	N/A	N/A	20,000	20,000	**40,000 kg H_2/d**

Source CALSTART.

In addition to the quantity of electricity being used, there is also the recharging infrastructure. We looked at the recharging infrastructure needed to recharge these 10,000 drayage trucks every day.

Table 4.24 Estimate of Recharging Infrastructure Needed

	#1 BEV	#2 CNG REEV	#3 Fuel Cell REEV
Shifts per day (10-hour shift)	1	1	1
Time to recharge	2 hours	2 hours	2 hours
Charging Power Needed per Vehicle	150 kW	63 kW	25 kW
Number of Vehicles Charging Simultaneously	417	833	417
Maximum Grid Charging Power	62.6 MW	52.5 MW	10.4 MW

Source CALSTART.

This combination of 10,000 drayage trucks (2,500 BEV/5,000 CNG REEV/2,500 FC REEV) could represent a 125.5 MW maximum grid charging power.

5.0 Phase-In Plans and Commercialization Approaches

5.1 Areas of Needed Development and Demonstration

Current Development and Demonstration Projects

Many companies and entities are involved in developing, funding, or promoting zero-emission truck vehicles and technologies. It is important to note, however, that while these companies do include the major truck original equipment manufacturers (OEMs), these OEMs do not currently consider ZE trucks to be a core product focus for them. They are concerned with the reality of future demand for ZE trucks. They want to know whether government rules will require ZE trucks, what it will cost to produce these trucks, and what incentives will be offered to encourage their use. Nonetheless, several OEMs are involved in development efforts. Taken together, these companies and programs are advancing ZE truck capabilities and bringing the technology closer to deployment in the marketplace.

The following sections describe key companies in the ZE truck industry, and the most influential government and private programs for furthering ZE truck development.

Key Industry Players

The zero-emission truck industry is dominated by a set of leading-edge companies, spread over several industry groups. This section provides a brief compendium of companies that are active in the zero-emission space, broken into functional groups.

Established Truck Manufacturers

Major truck makers are currently exploring an expansion into new technology trucks, although some companies are moving faster than others. The sales volume of trucks that would constitute a viable market for each of the major truck makers varies, much as their business plans vary. Sales of 1,000 units per

year could be enough to attract interest. Class 8 truck sales are not large, relative to other types of vehicles. For these established truck makers (of which there are 7 or 8 major brands) the number of Class 8 trucks sold in 2012 was 194,715. This is up from 171,358 in 2011 and 107,152 in 2010.[26] The leading manufacturer has one-third of the market, indicating that 10,000 units per year would constitute good sales for many Class 8 brands.

Table 5.1 Truck Makers New Technology

Company	Activities
Kenworth	Focusing on Classes 6/7 trucks. Includes REEV truck. Technologies may transfer well to Class 8.
Navistar	Investigating parallel hybrid trucks using Meritor drivetrains. Developed Classes 4-6 "eStar" BEV; working on additional developments through DOE SuperTruck program.
Freightliner	Through the SuperTruck program, Freightliner has partnered with DTNA (Daimler Truck North America) to develop a mild hybrid truck platform. This vehicle is not zero-emission, although the technology developed for this truck may be extended or further developed for zero-emission use.
Volvo	The company has a Class 8 plug-in hybrid drayage truck, developed in parallel to the SuperTruck. The vehicle is currently being demonstrated by AQMD and will also be demonstrated by CEC.

Source CALSTART.

New Entrants

CALSTART has partnered with several new entrants into the zero-emission truck field either through membership activities or as joint participants in several grant programs. Some of these companies are highlighted below, although other firms also may be exploring this market.

[26] 2012 "Class 8 truck sales fall short of 200,000 mark at 194,715," The Trucker News Services; 1/11/2013, http://www.thetrucker.com/News/Stories/2013/1/11/2012Class8trucksalesfallshortof200Kmarkat194715.aspx.

Table 5.2 New Technology and Truck Makers

Company	Product	Market	Technology Readiness	Description
Transpower	Battery-electric Class 8 drayage truck	Testing plan in POLA/POLB	Pilot demonstration stage	Seven pilot trucks under construction with funding from CEC, DOE, and AQMD. Plans for testing with companies serving POLA/POLB. Trucks to be tested with TTSI.
Artisan VS	Battery-electric and CNG range-extended electric drayage trucks	Testing plan in POLA/POLB	Pilot demonstration stage	Artisan has secured CEC funding for further development of drayage trucks in full electric and hybrid electric configurations. Testing with WCCS.
Smith Electric	Deployment phase for Classes 4/5 trucks (delivery vans, etc.)	USA & Global	Deployment stage, approx. 700 units delivered	Smith Electric has found success in delivery fleets. Its trucks are eligible for significant discounts from California's HVIP incentive program.
Motiv	BEV powertrains in several Classes 6-7 configurations	4 vehicles tested through CEC grant in Bakersfield and San Francisco	Vehicle development stage; powertrain is better established	Motiv's powertrain control systems can be scaled up for battery trucks, currently in demonstration phase.
ZeroTruck	Battery medium-duty truck (Classes 3-5), 70-mile range	Nationwide distribution available, sales focused in CA	Demonstration phase, though private investment combined with public grants	ZeroTruck is deploying up to 18 medium-duty trucks to California fleets through a 2011 CEC grant.
Creative Coach Works	Battery-electric full size bus with 120mi+ range	Publicly funded pilot tests in Washington state, Utah	Testing stage. CEC grant for further technology development	CCW, an established bus remanufacturer, built an electric drivetrain on an existing bus chassis, enabling a full electric bus at dramatically lower cost.
Proterra	Battery-electric "fast-charge" bus with 35mi+ range	CA, nationwide	Deployment stage. CEC grant for further technology development	Proterra fast-charge buses are paired with rapid chargers, for a 35-mile range and 10-minute recharge. Compatible with bus routes and schedules.

Source CALSTART.

Fuel Cell REEVs are under development in the U.S. and Europe. In addition to Vision working in California, there are California Energy Commission projects for smaller (Class 6 vehicles).

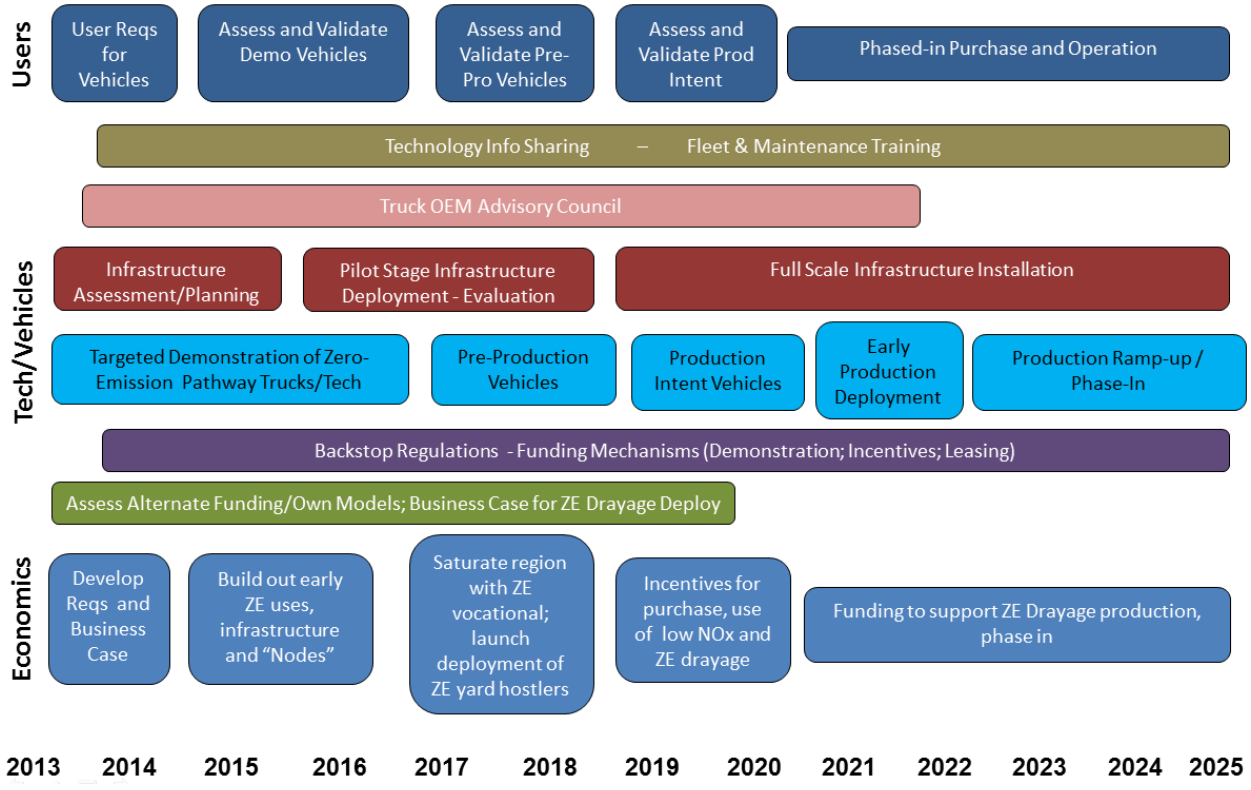
There are several fuel cell transit bus projects, both in the U.S. and in Europe. These developments can be transferred to Class 8 trucks if efforts are expended to link the manufacturers and technology suppliers. Additional work in the United States and Europe involves auxiliary power units (APUs), which are less relevant to this project.

5.2 COMMERCIALIZATION APPROACHES

Overview

As identified in the report findings, while achieving the outcomes will require following a significant and aggressive commercialization plan, it is feasible for zero-emission capable drayage trucks to be developed, demonstrated, validated and moved into production by a 2025 target timeline. These trucks can be designed to meet the key performance requirements for port drayage operations, including range, power, and duty cycle. They can also show a positive business case, assuming there is appropriate and targeted incentive support and concurrent infrastructure deployment as shown in Figure 5.1. This business case will be easier to make due to an anticipated increase in costs for conventional vehicles, in part, to meet federal efficiency and regional emissions requirements, specifically in the South Coast Basin. In addition, costs for core zero-emission technologies are expected to decrease during this time period.

Figure 5.1 ZE Truck Commercialization Phase-In Plan



Source: CALSTART.

However, achieving this outcome is not assured and will require a comprehensive approach combining technology development, regulatory requirements, innovative incentives and potentially revised business models, perhaps including public-private partnerships. Over the next decade, achieving

the ZE truck deployment will necessitate following an aggressive and highly focused commercialization and phase-in plan. It will require regional, state and federal government support in providing multi-year funding and the necessary regulatory framework and operational requirements. This effort must begin immediately by initiating, several multi-truck demonstration projects in 2014 to assess the architectures and ZE range options outlined in this report.

The plan will also need to build on the expected truck turnover timeline already set in motion by the San Pedro Bay Ports Clean Truck Program. The initial investment that was made to facilitate a rapid transition to trucks compliant with EPA 2007 and later emissions standards has resulted in a significant quantify of trucks ready for replacement by 2020 and later.

Achieving ZE truck deployment success will also require the involvement of the major truck OEMs. Each has its own current strategy on ZE-enabling technology based on their product mix, plans for fuel economy, and global market considerations. Full ZE technology is not central to their current product plans – though several have intriguing internal development efforts. In general, they are not so much skeptical of the feasibility of the technology as they are of the reality of the market for its use. However, meeting ZE truck deployment needs will not necessarily require every OEM to offer a product. A possible scenario is for one or two OEMs to be active participants, and potentially approach the market via a partner that may provide the ZE technology integration on the OEM truck platform while initial volumes remain low. This approach is already being used with medium-duty ZE trucks and can reduce the risk to both supplier and OEM.

No matter the scenario, however, truck OEMs need to be active participants in the commercialization process. At a minimum this would require the formation of an OEM Advisory Council to take part in the process starting in the first phase of activity outlined in Commercialization: Phase-In Stages, page 5-15. Such a council would directly connect OEMs to the status of the I-710 ZE corridor and could assess ZE truck requirements, identify gaps and needs based on their business cases, and make suggestions for refined development activities. Given competitive realities, such a council is only one of the needed tools. A structured and ongoing private consultative process with OEMs will also need to be maintained. This will be imperative to help convince OEMs of the region's commitment to supporting a ZE truck market.

Smart, adequate and timely infrastructure development is another one of the keys to the successful deployment of zero-emission trucks. First, and foremost, there need to be sufficient sources and adequate distribution of power and fuel: electricity, hydrogen, and to a lesser extent, natural gas. Refueling and recharging stations have to be included in this plan to assure commercialization for these trucks. These infrastructure dependencies are discussed in Section 3.0 of this document. Infrastructure development must proceed concurrently with the development and deployment of zero-emission trucks for the introduction of ZE truck operations to be successful. These trucks cannot work without fueling

infrastructure, and fueling infrastructure cannot be supported without enough trucks to use it. Additional partners and stakeholders will be needed to participate and assist.

Given the objective—of such a rapid shift over the next thirteen years—it is imperative that the zero-emission drayage trucks do not roll out into or operate in a technology vacuum. Addressing this, while ZE drayage trucks are in development, will require the accelerated early deployment of existing medium-duty ZE trucks. Therefore, an important component of a successful commercialization plan will include encouraging and incentivizing a parallel rollout of zero-emission and ultra-low emission vehicles in advance of the drayage trucks. This will help establish the needed infrastructure, demonstrate the viability of ZE technology, increase production of components, create more supply chains and increase the visibility of zero-emission vehicles.

This early implementation should be focused on the port and the I-710 region and communities, particularly the Gateway Cities. Initially, it will target those zero-emission vehicles already in early production and ready for deployment in medium-duty vocational applications, including food, beverage, parcel and some freight delivery. Such vehicles already are in early production and eligible for state incentive funds through the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP). With a regional deployment partnership and a commitment to an accelerated deployment of such vehicles in the Gateway Cities and surrounding region, and with additional incentives to encourage targeted deployment from South Coast regional agencies, communities along and near the I-710 can begin to create a zero-emission supporting zone – an "ecosystem" – that can serve as the early backbone to support the successful implementation of zero-emission drayage trucks.

Key Issues Impacting Commercialization

Based on the user requirements expressed in the initial Key Performance Parameters report (see Appendix E), it is clear that drayage operators today need a multi-functional vehicle with a daily range of as much as 200 miles. Given the potentially high costs of infrastructure and the highly variable (non-corridor specific) nature of port drayage trips, road-provided power may or may not be an option. Therefore, this places more cost and requirements on the vehicle alone to attain zero-emission operation. To summarize, the core issues that need to be addressed for successful commercialization of ZE freight vehicles include:

Flexibility

- Vehicles must be able to perform full drayage duties, including a range of up to 200 total miles per day and power to handle up to 80,000-pound loads and regional grades.

Operations

- Trucks must have the ability to go a minimum distance (possibly 20 and up to 50 miles) in zero-emission mode and then potentially continue to operate in a reduced emission mode outside the core port region.
- Trucks should be able to switch back and forth—between zero emissions and reduced emissions—several times per day as they enter and exit this zone.
- As noted, this capability implies the need for a fast charging or refueling capability and/or a ZE range extender function.

Manufacturability

- To be successful, the manufacturing process would be based on a core, high-volume truck platform of which the ZE version would be a producible variant.
- The more common the base truck is to established vehicles the easier it will be to produce.
- New components (such as batteries, electric drivelines) ideally need the support of a broader market to help reduce costs. This market can come from additional truck applications (such as ZE vocational trucks and buses) and from additional markets for ZE drayage trucks in the U.S. and globally.
- OEMs and ZE truck component manufacturers need to participate in manufacturing development of ZE trucks, with clear roles, requirements, and expectations.

Infrastructure

- Given the level of "new" fuel that may be required to meet the needs of up to 10,000 ZE trucks, particularly for electricity and hydrogen, planning for capacity, distribution, and siting of ZE truck infrastructure needs to start immediately and include utilities and fuel providers.
- Demonstration evaluations will identify tradeoffs between speed of refueling, costs of installation and equipment, and the impacts to the power grid and local distribution capacity.

Regulations and Operating Structure

- Given the rapid timing for the rollout of an entirely new category of vehicle, it is unlikely market forces alone will be sufficient motivation. Therefore, regional and state air quality and transportation agencies need to quickly develop a regulatory framework in which ZE trucks will be both required and rewarded.

- Air quality regulations can form a structure for the existence and need for ZE drayage trucks and establish timing requirements. Such rules can then be used as a "backstop" should incentive and use benefits not prove sufficient.
- An operating structure is needed that can create economic benefits for those operating ZE trucks and disincentives for those who do not. Such a structure needs to be in place within the next two to three years.
- Such an operating structure may require new business models or ownership structures to be successful.

Define Clear Requirement: Fixed Corridor or Broader "Zone"?

OEMs and suppliers need to know clear requirements to successfully design a product. This needs to be determined soon to engage manufacturers. Planners should decide whether to create a zero-emission corridor only or a larger zero-emission zone that includes mileage rings around the ports in addition to the I-710 corridor. Given recent findings on truck driving patterns, such a ZE "zone" may address how trucks actually operate more effectively than a corridor. However, creating such a zone raises several operational issues:

- Would compliance with the zero-emission freight zone (operating a zero-emission drayage truck) be required?
- How would compliance with the zero-emission freight zone or corridor be enforced or validated?
- What would be the rules for operating vehicles in the zone?

Framework for Commercialization

To be successful in building out and introducing a ZE freight truck, particularly in the absence of a defining and controlling corridor, requires establishing a framework for accelerated product and technology development, infrastructure deployment, user acceptance, regulation, and business case. These trucks cannot operate in a vacuum; they need an ecosystem with an established framework for their operations. Therefore, several paths of parallel activity are required. They are:

- A focused vehicle development, demonstration, validation, and deployment process;
- Early action deployments of ZE vehicles in the Gateway Cities and port communities;
- A regulatory framework for ZE drayage trucks;
- Enhanced operational and business case assessment; and
- Fleet training, maintenance training, and decision support.

The following section describes these activities in overview.

The Focused Vehicle Development, Demonstration, Validation, and Deployment Process

Achieving a rapid change in heavy truck technology, as well as spurring the adoption of that technology in an application segment, will require a high degree of focus, cooperation, and consensus among public and private entities. In the near term, it will require a much higher degree of focused technology development funding and outcome setting than typically occurs for a single drayage truck application. The State of California and regional agencies currently have several funding programs that enable such investments in advanced vehicle technology and alternative fuels to help the state meet its climate change and emissions goals. Those programs have been reauthorized and extended through the 2023 timeframe. Additional funds can include unallocated Prop 1B funds, GHG cap and trade revenues and other sources. However, having the funds available is only one part of the issue: the state and regional agencies must agree to follow a clear roadmap for pooling those resources on the specific technologies, vehicle architectures, and fuels that can achieve the 2025 outcomes needed. This will require an unprecedented level of agency cooperation. A subset of the CalHEAT roadmap, cited earlier in this report, can serve as an important guide in these activities.

To succeed, this intensive development process must leverage and include the truck OEMs.

Over the next three to five years, focus must be placed on using state and regional funding to develop and field truck demonstration projects that are designed to support and drive zero-emission drayage truck capability and product development. These projects must be targeted at developing and validating the functionality to meet zero-emission performance requirements as well as drayage users' operational needs.

This phase will focus on electric drive trucks with range extender capabilities (natural gas, fuel cell and other). Analysis shows that these trucks together with all battery electric and plug-in hybrid systems will be the optimal technology for zero-emission operations. California Energy Commission transportation funding, port TAP funding, and regional air quality funds can be assets for accomplishing this work.

Over the next three years, demonstration programs should focus on fielding and assessing the architectures and different range capabilities outlined in the business case Section 4.4 of this report. This includes full battery electric designs and range extended designs (natural gas and fuel cell) in different configurations for energy storage size and range extender capabilities.

It will also be critical to encourage development of the new technology's supporting systems, such as electrified auxiliary components, high-power rapid charging, lightweight natural gas and hydrogen storage systems, optimized

alternative fuel engines and modular battery packs by working with OEM's and component manufacturers.

Given its critical role in ZE truck deployment, significant immediate and continuing work is required to evaluate and plan infrastructure requirements. This should include development and demonstration projects to validate high-power, multi-vehicle recharging systems. This report quantified the potential power and fuel needs to field ZE capable trucks. Electric and natural gas utilities and future fuel providers (natural gas and hydrogen) need to be involved in planning how to meet these needs.

At the same time these demonstrations are proceeding, investment in developing a secondary market with the ability to directly support drayage trucks should be made. This market is zero-emission yard hostlers, which have high utilization rates but low mileage and fixed operational and fueling locations, making them useful for zero-emission technology. They also use vehicle platforms that are comparable to those of drayage trucks, though their power needs and flexibility of routing requirements are not nearly as great. Yard hostlers could represent both an early deployment commitment in the region (by the terminal operators) and build initial knowledge and component volumes, also of value to ZE drayage trucks development.

It will be equally important to start to identify and work with other regions—nationally and internationally—that have an interest in this or similar technology. While the vehicle volumes anticipated by 2025 are acceptable for an early market, there will be greater opportunities for reduced cost and market competition if additional markets for this technology are developed. This can include zero-emission transit buses, already being deployed in some fleets.

By 2017 and 2018, several validated systems should start moving into the production intent and pre-production stages of product development. At these stages, ten to several hundred of each going-forward design should be fielded in real-world conditions with I-710 region drayage fleets.

The rapid iteration from these deployments sets the stage for early production deployment and acceleration of volume production, starting as early as 2020 but no later than 2022. During this period ZE truck volumes will increase from several hundred per year to more than 2,000 per year by 2025 to meet the need for roughly 10,000 fielded units. Concurrently, the supporting infrastructure will be developed and installed, built around early fleet adopter locations, selected freight terminals, and shipment points.

Early Action Deployments of ZE Vehicles in the Gateway Cities and Port Communities

In parallel with an aggressive ZE drayage product development process, it is imperative to start establishing successful "nodes" of ZE operation and infrastructure within the I-710 goods movement system and region. These

targeted areas can, in fact, be first adopters of the technology in other appropriate applications, such as electric medium-duty weight trucks for food, beverage, parcel, and freight movement. By focusing these deployments on the Gateway Cities and other port-adjacent regions, this approach can create many benefits and establish the outlines of an ecosystem for zero-emission vehicles.

Early deployments will raise the profile of the reality of zero-emission technology today, highlight the roles it can already perform, and showcase the Gateway Cities and other adopting communities as leaders. These vehicles provide immediate emissions and air quality benefits to the community. They can also produce new jobs as vehicle and component makers currently explore assembly sites close to their first markets.

These very-focused deployment regions can help with the first placement of ZE-supporting infrastructure and create key "anchors" for establishing recharging and refueling sites. These early ZE vehicle deployments can also help cities and utilities understand and address siting, permitting and distribution issues in advance of the installation of the high power systems that may be required for ZE drayage trucks.

These early deployments can help increase volumes and demand for core components that are important to ZE drayage trucks, such as electric drivelines, batteries and energy storage systems, and other balance of plant power electronics. Such volumes can help build up a stronger supply chain to support the larger trucks and assist with expanding the market and reducing costs for systems that will be required to help support its commercialization.

Existing state incentive programs (HVIP) do provide funding for zero-emission commercial vehicles, although ideally HVIP program funding would be increased to support this early deployment. It could be expanded or augmented using local and regional funds to truly create an early deployment success, supporting both vehicles and infrastructure. The funds could come from regional air quality programs, the port TAP program, Los Angeles County Metro Congestion Mitigation Air Quality (CMAQ) funds, Greenhouse gas (GHG) cap and trade revenues and other sources.

Gateway Cities and other port communities would ideally commit to shifting their public fleets to zero-emission vehicles. In and of itself this is probably not a large number, but it signals the commitment of the region and can help set the tone for private fleets to adopt. Public agencies can also adopt supporting policies, including calling for zero- or low-emission vehicle use in municipal or agency contracts.

Regulatory Framework for ZE Drayage Trucks

While fleets and manufacturers will often not publicly call for new rules or requirements for more stringent vehicle emissions standards, privately several manufacturers have shared with CALSTART that they believe a regulation or

requirement of some type will be required to propel adoption of zero-emission truck technology on the aggressive timeline being proposed. Voluntary action and incentives alone are insufficient; a potential business case, with assistance (such as incentives), exists but is evolving and will take time to develop. To create a level playing field and to show manufacturers their investments are justified because the region is serious about zero-emission operations, some type of ZE drayage fleet rule or backstop regulation on I-710 regional emissions is likely required.

A backstop regulation has been cited by participants as highly effective in supporting the rapid transition to 2007 to 2010 clean trucks as part of the Port of LA and Long Beach Clean Truck programs. It focused attention on the need for the transition and the timeline established for it. It allowed the ports and their partners to focus on solving deployment issues. The incentives that came with the regulation were effective because the program implementation timeline came in advance of the regulation's deadline. (Generally incentives cannot be used for compliance with a requirement once the requirement deadline has occurred.)

A similar structure for an I-710 ZE freight requirement could be set, using either a fleet rule precedent or a regional emissions reduction structure. The deadline would ideally be set for some point after 2025 to allow incentive and other support funding to be used to help fleets and manufacturers in the transition.

The South Coast Air Quality Management District and the California Air Resources Board have both published extensive data showing the need for achieving zero emissions from most transportation activities in the South Coast Basin by 2031 in order to meet federal health-based air standards. Zero-emission freight trucks have been cited as one of the targeted actions in the near-term for nitrogen oxide (NO_x) reductions, and over the longer term for greenhouse gas reductions. To meet the air standard goals on such a timeline, these agencies probably will need formal requirements, which would align with the I-710 timeline.

Enhanced Operational and Business Case Assessment

The drayage truck marketplace is complex, disaggregated, and competitive. Vehicle use is driven by daily needs, and while there appear to be general vehicle use profiles, there also seem to be no set patterns or daily predictable routes. Better understanding this dynamic will be critical to manufacturers and suppliers as the succeeding generations of zero-emission drayage truck systems are designed and validated. Meeting the needs of users with the most optimized solution is of paramount importance to the business case.

As noted in the report, additional data collection, analysis and validation of truck use profiles, truck delivery distribution, trip patterns, and performance needs will be of significant value and will help refine technology selections and vehicle design architectures. In addition, a project to gather a broader cross-section of

truck and fleet data from drayage operators serving the I-710, South Coast ports, and regional freight movement should be launched concurrently.

A second and enhanced iteration of the business case assessment also needs to be performed, with additional testing of specific technology packages and more discrete identification of expected component costs and operational benefits of ZE trucks.

An important consideration for zero-emission trucks, given their increased incremental cost, is to consider which ownership models might make it easier for fleets to make a rapid transition without incurring substantial upfront capital costs. Even with incentives, many drayage operators are hard pressed to make new truck purchases, even at costs at par with current conventional technology.

One possible approach would be to establish a lease process for the trucks. This could be public or private with public underwriting. In such a case, fleets would be required to operate ZE trucks but would not be required to purchase the trucks. Rather, they could choose to lease them from either a private lease pool or a publicly operated lease authority. In either case, the leasing entity could use public funds to help reduce the lease basis (the cost of the truck, reduced by incentives) as well as the lease rate. Such an entity or market could also establish an agreed residual value for the vehicles, possibly back-stopped by public funds or through lease fees, adding greater certainty to the business case. If leased over the full lifecycle of the vehicle, such a leasing approach could become self-funded as the vehicles pay for themselves from long-term operational savings. (Most business cases assessed showed net present value assuming initial incentives.)

An alternative approach, and one that is succeeding in the photovoltaic market, is the performance lease. Such a lease allows higher cost assets with longer term returns to be paid incrementally out of the operational savings accrued monthly. As in the above case, public or private seed funding would be needed to purchase all, or potentially just pay the incremental cost, of the zero-emission trucks. Fleets would then repay the incremental cost in part or in whole out of their operational savings. The business case for ZE drayage trucks is still an estimate and a work in progress; this ownership approach would need to be developed as vehicles are developed and specific costs are better understood.

The business case for these different ownership models needs to be explored. For example, the role for government may involve more than legislation but could also involve becoming an infrastructure and/or asset manager. Given the low volume nature of the early ZE truck market, private industry may be unwilling to make significant production or purchase investments until critical mass is reached for deployment. A possible scenario could see government, or a public-private partnership (PPP), assume the role of purchasing the first few thousand ZE trucks and providing them to users via a lease; and/or reducing purchase risk by providing incentives to guarantee residual value or repurchase. Such approaches need to be developed and validated as they may provide critical impetus for faster deployment of the initial volume of ZE trucks. The use

of a PPP has been successful in other large infrastructure projects, and while this situation would be unique, the broad set of stakeholders in this effort may be effectively represented by a PPP solution. While beyond the scope of this report, future projects should directly investigate PPP options.

An assessment needs to be made of how the drayage business case may be changed – and zero-emission truck capabilities and limits better utilized – as part of the transition to more efficient drayage truck operations. The Gateway Cities and Metro are developing a Strategic Transportation Plan (STP), of which this report is one component. The complete STP will be composed of multiple elements, including connected vehicle and intelligent transportation system capabilities. Implementation over the next several years should enable better, real-time traffic, cargo, and vehicle location information. Such information, used in a system rather than a vehicle-only approach, can also be used to streamline drayage dispatch and routing decisions, reduce idle and dwell time and potentially allow more discrete truck use decisions to be made. It may be possible to select specific truck capabilities for specific jobs, allowing fleets to dispatch a longer range truck for some jobs, but selecting a shorter range (and possibly lower cost) truck for another. Such flexibility is entering other truck application segments; its potential in drayage could allow a more varied, flexible and ultimately lower cost zero-emission fleet.

Fleet Training, Maintenance Training and Decision Support

For the transition to be successful, drayage fleets need to be engaged in the development of zero-emission freight truck operations as they progress. This will not only lead to better vehicle design and operation decisions, but also to a better integration with the fleet business case. Fleets need to have information on best practices for operation, maintenance, and deployment of the vehicles. They need to know how to select and use the best options for their business needs. Fleet maintenance will need to learn new skills to manage the transition to higher voltage systems and new driveline architectures.

Yearly fleet workshops on zero emission technology will be important ground builders for the transition. Such workshops should provide good information on the value and need for zero-emission technology, and on the status of zero-emission vehicle demonstration and deployment activities. These workshops would also showcase the emerging support programs that will assist the transition to zero-emission trucks.

Fleet maintenance training programs, as well as technician workforce education activities at community and vocational schools, can be of great value in starting to build the capacity for zero-emission trucks and make users more familiar with their operation as they come to market. Such programs can be offered by traditional fleet support associations, state and regional trucking associations, and by the community college network.

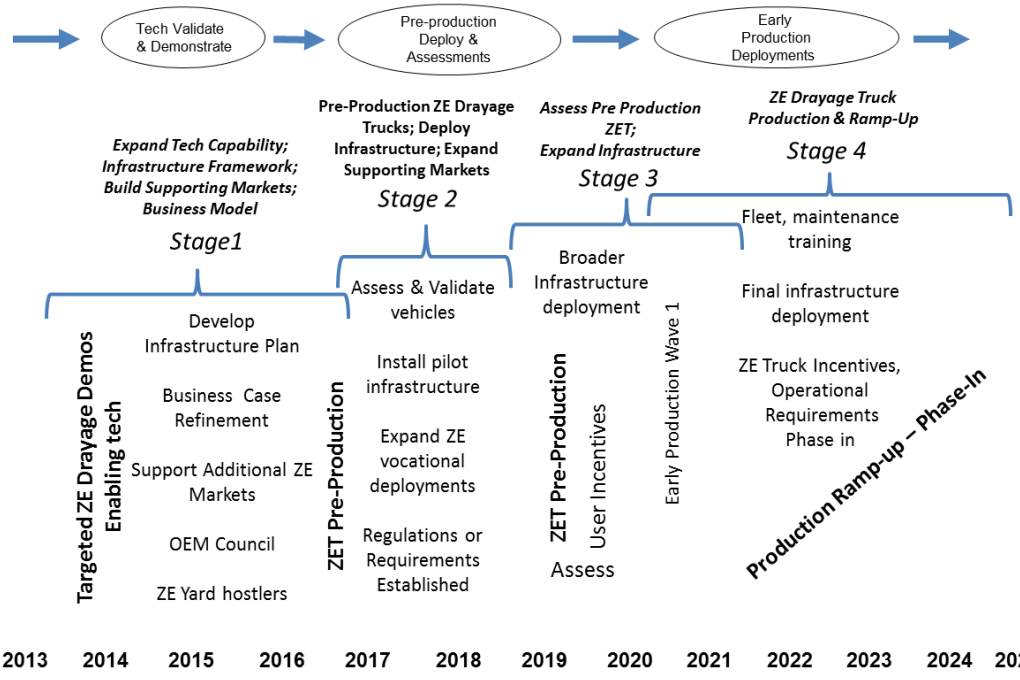
Commercialization: Phase-In Stages

The following section outlines the proposed stages to develop and deploy ZE drayage trucks and showcases the need to bring together all stakeholders in the most effective way to achieve large-scale deployment with the following principles in mind:

- Deployment steps (or stages) must be meaningful, actionable and timely;
- All relevant stakeholders need to be brought in and engaged at appropriate points in the process; and
- The plan must start but with clear, discrete steps aimed at the long-term goal.

Achieving the commercialization of the zero-emission freight truck is envisioned in a series of consecutive stages. A follow-up report is anticipated that will provide a more in-depth roadmap for the next five years of commercialization activity. However, at the high level, the following stages encompass the commercialization activities outlined above and provide a first estimate of potential and anticipated vehicle volumes and their timing. The following outline provides a high level view of the stages and their associated activities. A more detailed five-year action plan will be completed as a separate report.

Figure 5.2 ZE Drayage Truck Commercialization and Phase-In Process



Source CALSTART.

Stage 1. Expand the Technology Capability, Establish the Infrastructure Framework, Build Supporting Markets and Design the Business and Operational Model, 2014-2016

Given the accelerated timeline for ZE truck deployment, it is critical that this first stage of activity launch quickly and push multiple activities forward. First and foremost, technology demonstrations of the architectures discussed in this report must be funded, fielded and evaluated. Concurrently, a comprehensive infrastructure plan, based on the most promising technologies, must be developed at this stage. Most electric infrastructure today is geared more to passenger car needs and energy storage. Trucks will demand higher power and faster charging systems. Additionally, building of supporting and additional markets for ZE trucks needs to begin, as does work to refine the specific business case, develop supporting incentives, and frame the regulatory and operational structure for using ZE trucks.

Expand Technology Capability Beyond Prototype

Building off the CalHEAT Roadmap (see Appendix F), establish a multi-year development plan with goals for technology stages and pre-production, production intent, and early production.

This would include ZE drayage demonstrations of multiple vehicles, not just single vehicle prototypes. In Stage 1, specific promising architectures identified in this report would be demonstrated in different energy storage/range configurations, such as those listed below:

- Extended range electric (multiple architectures, both natural gas and hydrogen fuel cell; DME may also be a promising fuel);
- All electric with high efficiency or fast charge schemes; and
- Dual-mode and plug-in hybrid (important pathway architectures for truck OEMs).

ZE Yard Hostlers should be developed and demonstrated concurrently. (This is a core part of creating infrastructure nodes for goods movement. It also supports building volumes for the future components and truck architectures needed for drayage).

Technology that supports zero-emission trucks should also be expanded during Stage 1, including

- Electrified accessories;
- Optimized alt fuel and low NO_x engines;
- Alt fuel hybrids;
- Battery pack modularity;

- Lower cost hydrogen and natural gas storage; and
- Operation and maintenance strategies.

Plan and Develop Infrastructure Framework

In order to ensure that the new refueling systems, particularly electric and hydrogen, are ready to deploy in advance of the first wave of trucks, significant work is needed to assess specific infrastructure capacity, distribution, costs and siting issues, as well as developing and demonstrating multi-vehicle fast-charge and fast-fuel systems.

Stage 1 will be the time for development and demonstration projects of needed infrastructure systems listed below:

- High-power fast charge;
- Opportunity and road power charging at truck dwell points; and
- Gaseous fuel fast fueling (H2) demonstrations.

The impact of specific ZE infrastructure to be deployed should be studied in detail. Siting locations will need to be determined. Fuel availability will need to be evaluated as well as infrastructure cost, development, transmission, and distribution needs.

Once initial assessment and demonstration projects are completed, initial infrastructure should be deployed in the region to support expanded vocational electric truck use.

Validate the Business Case and Operational Model

Validate the business case using the estimates identified in this report to perform detailed analyses of operational costs, residual value, and secondary markets for ZE vehicles. Also during Stage 1, it will be important to analyze the business case for non-traditional ownership models. After performing these various analyses, it should be possible to develop a framework business case for successful ZE truck operations.

To develop an operational model, it will be important to perform detailed analysis to determine operating and maintenance costs for the duty-life of each type of zero-emission truck that is evaluated or considered. The potential for used truck sale or reuse, and residual value for each type of zero emission truck should be a part of duty-life analysis. In addition, analysis needs to determine return on investment for operators and owners.

At this point, the project should begin development of after-markets for zero emission trucks and/or their technology (e.g., batteries) and develop a business plan to determine best ownership models, methods, and strategies.

To guide the process, the project will establish a truck OEM Advisory Council to provide feedback for the business case assessment and development process. The project should also establish an ongoing "user advisory" process; including regular reporting and sharing of information with fleets and stakeholders in annual technical interchange meetings.

Build Supporting Markets and Market Structure to Build ZE Volumes, Supply Chain, and Infrastructure

One of the requirements for a successful ZE truck deployment will be the development of parallel and supporting markets for the vehicles and their components. **These can be markets in other classes of vehicle using similar components (ZE vocational trucks and buses) and markets using the same trucks in other geographical regions (East Coast, Gulf Coast, Europe, Asia).** Immediate opportunities exist to support early users of ZE technology, such as transit buses and vocational trucks. This helps to build experience with infrastructure, heightens visibility, increases the volumes of energy storage and drivelines produced, and builds out the early "ecosystem" for drayage.

The first step in building markets and volumes is to deploy a significant number (many thousands) of ZE trucks and buses along I-710 at the ports, Gateway Cities, marine terminals, rail terminals, and distribution centers. Key private fleets are potential partners. The Gateway Cities can serve as the focus of this commitment for use and deployment. Regional and state partners should create additional incentives for expanded and accelerated deployment of these vehicles and their infrastructure.

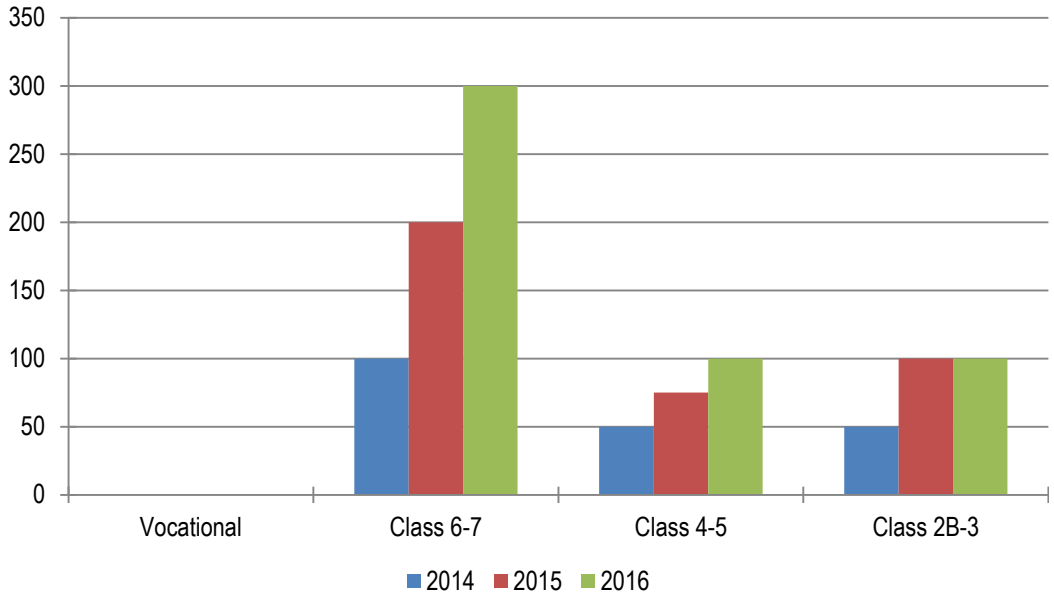
Potential vehicles are yard hostlers, municipal, and private trucks (Classes 2B and 4 to 6), such as cargo, food, beverage, and freight delivery. Multiple low volume manufacturers are already active, several with California manufacturing sites.

Funding partners who may be willing to participate in the Zero Emission Goods Movement zone include SCAQMD, ARB (HVIP, Prop 1B, Cap and Trade), CEC, TAP, EPA, utilities, infrastructure providers, vehicle makers, suppliers and fleets.

To achieve economies of scale, it will be important to determine and evaluate additional markets for a wider deployment of zero-emission trucks and increased volumes. In addition to lowering costs, wide deployment will improve the business case for OEMs. New approaches for funding, plus innovative programs for operations and ownership will also offset costs. These activities will include developing incentive and subsidy commitments from public agencies.

In addition, it will be necessary to work with regulators to develop regulations and rules to assist in deployment of zero-emission trucks.

Figure 5.3 Possible Zero Emission Vocational Truck Early Deployments in I-710 Region



Source CALSTART.

Stage 1 Goals: Deployment of several thousand ZE trucks in targeted region. Demonstrations of the technology outlined in Stage 2 of the CalHEAT Roadmap.[27] Development of future fleet regulation for ZE drayage trucks by the appropriate government agency.

Stage 2. Deploy Pre-Production ZE Drayage Trucks and Infrastructure, Expand Supporting Markets, 2017-18

In this second stage of activity, the focus for ZE drayage trucks will turn from technology demonstration to product development and evaluation. Additional parallel markets, such as ZE yard hostlers, will be expanded. The first major infrastructure, as established in Stage 1 studies, will be deployed with the pre-commercial pilot projects. Continued expansion of ZE vocational truck and bus deployments will take place to help build component volumes.

[27]See Appendix F, Silver, Fred, and Brotherton, Tom (CalHEAT), Research and Market Transformation Roadmap to 2020 for Medium- and Heavy-Duty Trucks, California Energy Commission.

Pre-Commercial Pilot Projects

Stage 2 will start with 20 to 50 truck pre-commercial pilot projects aiming for production intent designs in 2019.

Zero-Emission Vocational Trucks

ZE truck deployments will increase with the goal of saturating the ZE zone and region with non-drayage ZE trucks that are already in the market. Vocational trucks, parcel delivery trucks, and other vehicles in Class 3 to Class 6 are in production today and can be deployed immediately across many companies and uses.

ZE Yard Hostlers

Stage 2 will begin the process of phasing in electric yard hostlers at all terminals, rail yards, and distribution centers. This technology can help establish the framework for recharging at locations supportive to future zero-emission drayage trucks.

Drayage to Near-Dock Rail

Drayage to Near-Dock Rail will begin the process of transitioning to either low NO_x vehicles or full ZE vehicles for the near-dock rail. A transition goal for this period will be established. (Financial support for this phase is yet to be determined. Possibilities include operator fees, contract requirements, incentives, AQMD rules or a combination thereof.)

Develop ZE Training Curriculum

During this period curriculum will be developed for workforce training on ZE technologies and their maintenance.

Begin Development of Backbone Infrastructure for ZE Trucks

This development will be based on Stage 1 study results and on the infrastructure plan that will be developed to address "range" anxiety. This deployment should include sufficient infrastructure needs to satisfy full ZE drayage truck operation in the I-710 region. Depending on research findings, this could include a circle of charging and refueling stations and fuel distribution facilities for ZE trucks at potential "hubs" in the region. Partnerships need to be formed with others to implement and develop this infrastructure plan, which could include:

- Hydrogen fuel generating entities and refueling providers;
- Electric utility companies and recharging system providers;
- Natural gas utility companies and natural gas refueling providers;

- Trucking associations;
- Government agencies; and
- Small and large vehicle manufacturers.

Stage 2 Goals: Deployment of more than 2,500 ZE trucks in targeted region. Begin deployment of ZE yard hostlers in I-710 region terminals and distribution centers. Begin transition to ZE drayage for near-dock activities based on demonstration fleets. Begin pre-commercial volume validation deployments of the most promising ZE drayage trucks (multiple designs).

Stage 3. Down-Select: Pre-Commercial ZE Drayage Assessment and Validation; Infrastructure Deployments Expand, 2019-22

At this stage over 100 to 200 pre-commercial ZE drayage trucks will be actively evaluated in pilot projects with tens of fleets in the I-710 region. These projects will allow fleets to assess functionality and performance, and enable manufacturers to make design and engineering changes for the production vehicles that will start rolling out in Stage 4. In addition to the infrastructure that will be installed to support the pilot fleets and trucks of this stage, an expanded installation of infrastructure will begin to support the thousands of trucks to be introduced during Stage 4.

Multiple Parallel Assessments of Pre-Commercial ZE Drayage Trucks

This phase finalizes the data collection, user assessment, and validation of the pre-commercial vehicles from roughly 2 to 4 manufacturers at 20 to 50 trucks per manufacturer – deployed with multiple fleets throughout the I-710 zone. Data gathered at this stage provides final design information to seed the early commercial production and deployments of Stage 4.

Expand Installation of Infrastructure for Stage 4 Truck Rollout

Infrastructure will be refined and installed at additional sites based on feedback from operators and fleets during Stage 2, as well as manufacturer recommendations and information about emerging truck use patterns.

Deployment of ZE Trucks, Yard Hostlers, and Drayage Near-Dock Rail

The deployment and ongoing replacement of vocational ZE trucks in the region would continue at a supporting rate, rather than a ramp-up rate. Similarly, deployments of ZE yard hostlers and ZE drayage for near-dock rail operations would reach final stages and move into support/replacement stages.

ZE Technology Maintenance Training

During this period new workforce training for ZE technology maintenance will be launched as well as programs for continuing training of personnel.

Stage 3 Goals: Complete deployment and assessment of more ZET trucks (roughly 100 to 300 ZE drayage trucks or more) with leader fleets in I-710 zone. Complete deployment of ZE yard hostlers and near-dock ZE drayage vehicles. Establish infrastructure deployment sites for Stage 4. Train current maintenance personnel, launch workforce training for new workers.

Stage 4. Commercial ZE Drayage Production, Deployment Ramp-Up, 2020-25

Overlapping with Stage 3 and beginning as early as 2020 for early-adopter fleets with special incentives, Stage 4 ramps up the production and deployment of commercial ZE drayage trucks to fleets in the I-710 zone. It would start with delivery of several hundred trucks per year from the first manufacturers ready to produce, targeting those first-mover fleets that would qualify for special early action incentives. By 2023, production and deployment would increase to the 1,000 to 2,000 truck-per-year range with build-out at roughly 10,000 ZE trucks, including mostly production vehicles as well as some of the late Stage 3 pre-production vehicles still in service.

Infrastructure Siting and Construction

Infrastructure siting and construction would continue to take place both at truck domicile points and at locations identified in earlier stages as conducive to supporting ZE drayage truck usage. Specific deployment numbers will depend in part on the truck technology mix selected from the assessment project and the amount of fueling needed away from domicile sites.

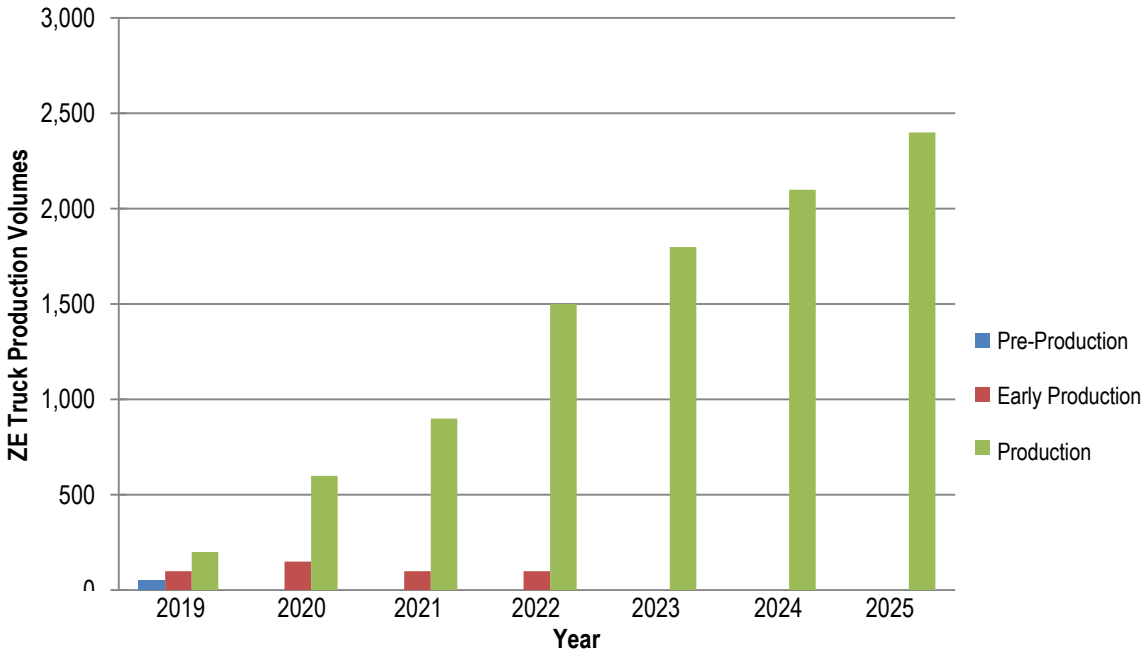
The full build-out of infrastructure probably will include high power, rapid charging locations at some terminal, rail and transshipment points; "hands free" opportunity charging that could be co-located at some of these same points (ideally at sites with some small amount of truck dwell or slow speed driving); and hydrogen fueling stations.

Additional Training

Training in this stage would include: Fleet user best practices sessions; incentive and business case assistance training, maintenance training, and region-wide infrastructure training. Existing truck and fleet associations, shippers' organizations, leasing entities and others could lead or assist in this training.

Stage 4 Goals: Phase up production over a 5-year period for a cumulative number of roughly 10,000 zero-emission drayage trucks by 2025. Deploy sufficient infrastructure to support those trucks in daily operations in the ZE zone. Stage ongoing training and support for impacted fleets. Have in operation an incentive-based purchase or lease system for fleets to obtain ZE trucks for their operations (with additional incentives provided for early mover fleets in the first few years of the ramp-up).

Figure 5.4 ZE Truck Phase-In Timeline



Source CALSTART.

6.0 Conclusions and Recommendations

6.1 CONCLUSIONS

All the technologies presented here could be developed into viable zero-emission capable trucks, but not all will meet the needs of the I-710 corridor project, and all have challenges to overcome regarding their business cases.

- There are five fundamental truck architectures providing at least some ZE capability, which could be utilized for Class 8 drayage trucks. Those are:
  - Dual-Mode Hybrid Electric Vehicle (HEV);
  - Dual-Mode Plug-in Hybrid Electric Vehicle (PHEV);
  - Range Extended Electric Vehicle (REEV) with Engine;
  - Range Extended Electric Vehicle (REEV) with Fuel Cell; and
  - Battery Electric Vehicle (BEV).
- There are only two fuel options that are inherently zero tailpipe-emission:
  - Electricity (via batteries in EV or PHEV); and
  - Hydrogen (via fuel cells in REEV with fuel cell).
- The **zero-emission range requirement is critical** in defining the optimal technologies for I-710 drayage trucks. Logical categories for this "one-tank range" are:
  - 20 miles ZE range: Any of the five architectures can be developed;
  - 50 miles ZE range: Both REEV and BEV designs can be developed;
  - 100 miles ZE range: Both REEV and BEV designs can be developed; and
  - Over 100 miles ZE range: REEV with fuel cell is the primary viable option.
- If we presume a **50-mile zero-emission range** requirement, then only BEV and REEV designs can meet the criteria, which also includes at least 100 miles daily range (preferably 200) and performance equivalent to a current diesel truck.

  - BEV designs can deliver 100+ miles of range but based on this analysis have a challenging business case.
  - REEV with Fuel Cell designs can deliver more than 100 miles of ZE range, and based on this analysis have reasonable business cases when utilization is high. Electrical infrastructure needs are lower than BEVs, and H2 infrastructure needs should be manageable in the I-710 region.
  - REEV with Engine (CNG) can deliver 50 miles of ZE range and up to 250 more miles of "very low emissions" range. Based on this analysis they have the best business case of the examined alternatives, provided CNG costs are low and utilization is high. Electrical infrastructure needs are lower than BEVs, and CNG infrastructure is already under development.

- **Infrastructure must be considered in parallel with truck development**. The demands of the I-710 Corridor Project may preclude options that work well elsewhere.
  - Backbone infrastructure must be evaluated and developed simultaneously with the deployment of zero-emission trucks to provide the needed fuel, recharging, and refueling stations. Further studies are needed, as separate project efforts.
  - The corridor will have very high truck traffic, potentially one truck every 4 or 5 seconds. ITS may enable platooning, further increasing the density of truck traffic. With peak vehicle volumes this high, roadway power systems must be designed to deliver extremely high power, significantly higher than the transit systems upon which they are based. While not impossible to achieve, the costs and technical challenges are definitely barriers.
  - Many drayage truck trips do not use the actual I-710 freeway for any significant duration. The variety of truck activity and routes is greater than previously thought, and more study is needed to better understand drayage truck operations in the I-710 region.

Needs that Have Been Identified

Zero-emission capable drayage trucks can be developed, demonstrated, validated and moved into production by a 2025 target timeline. These trucks can be designed to meet the key performance requirements for port drayage operations, including range, power, and duty cycle. They can also show a positive business case, assuming appropriate and targeted incentive support. Anticipated economic changes should help. Conventional vehicle costs are expected to increase over the next decade, in part to meet federal efficiency and regional emissions requirements, specifically in the South Coast Basin, while at the same time, costs for core zero-emission technologies are expected to decrease.

6.2 RECOMMENDATIONS

To achieve the desired outcome (commercialized ZE drayage trucks in the I-710 region) over the next decade plus will require following an aggressive and highly focused commercialization and phase-in plan. This report recommends a four stage, phased commercialization approach to enable launching and deploying a replacement fleet of zero-emission drayage trucks by 2025. Each successive stage builds off the previous to develop the capability and establish the framework for zero-emission trucks and steer a highly focused product development process that mirrors the process used by the major manufacturers.

The following section outlines the proposed stages to develop and deploy ZE drayage trucks and showcases the need to bring together all stakeholders in the most effective way to achieve large-scale deployment with the following principles in mind:

- Deployment steps (or stages) must be meaningful, actionable and timely;
- All relevant stakeholders need to be brought in and engaged at appropriate points in the process; and
- The plan must start immediately, but with clear discrete steps aimed at the long-term goal.

Stage 1. Expand the Technology Capability, Establish the Infrastructure Framework, Build Supporting Markets and Design the Business and Operational Model - 2014-2016

- Expand tech capability beyond prototype with targeted demonstration projects in full vehicle and enabling technology.
- Plan and develop infrastructure framework including development and demonstration projects of needed infrastructure systems.
- Validate the business case and operational model, by performing detailed analyses of operational costs, residual value, and secondary markets for ZE vehicles, non-traditional ownership models (e.g., PPPs), and O&M costs.
- Build supporting markets and market structure to build ZE volumes, supply chain and infrastructure, remembering these markets can be for other classes of vehicles using similar components (ZE vocational trucks and buses) and markets using the same trucks in other geographical regions (East Coast, Gulf Coast, Europe, Asia).

Stage 1 Goals. Deployment of several thousand ZE trucks in targeted region. Achievement of "Stage 2 technology" from CalHEAT Roadmap (see Appendix F) in demonstration actions. Development of future fleet regulations for ZE drayage trucks by the appropriate government agency.

Stage 2. Deploy Pre-Production ZE Drayage Trucks and Infrastructure, Expand Supporting Markets, 2017-18

- Pre-Commercial Pilot Projects start with 20 to 50 truck pre-commercial pilot projects aiming for production intent designs in 2019.
- ZE yard hostlers will begin with phasing in electric yard hostlers at all terminals, rail yards, and distribution centers.
- Drayage to near-dock rail should begin transitioning to either low NO_x vehicles or full ZE vehicles for the near-dock rail.
- Develop ZE training curriculum for workforce training on ZE technologies and maintenance personnel training to support ZE technology.
- Begin development of backbone infrastructure for ZE trucks. This deployment should include sufficient infrastructure to satisfy full ZE drayage truck operation in the I-710 region.
- Further develop the business case and operational models for ZE trucks. In Stage 1 the ZE Truck manufacturers and drayage operators explore truck technology and capability, along with pricing models. As the technology matures, the key players should develop an understanding of how the vehicles can be contribute to a compelling business case.
- Finalize the incentive funding scenarios to support a wide-scale ZE truck roll-out. To-date many regional and state organizations (POLA/POLB TAP, CEC HVIP) have provided support for ZE truck purchases. In the timeframe of Stage 2, funding sources should be finalized in a way that allows the key players to plan further deployments.

  Further develop the regulatory framework to support a zero-emission corridor or zone in the I-710 region. Interest in the I-710 ZEFC is driven partly by proposed or potential changes to criteria pollutant standards at the regional and federal level. As these changes become better-defined, the planning for key parties will become more focused.

Stage 2 Goals: Deployment of more than 2,500 ZE trucks in targeted region. Begin deployment of ZE yard hostlers in the I-710 region terminals and distribution centers. Begin transition to ZE drayage for near-dock activities based on demonstration fleets. Begin pre-commercial volume validation deployments of the most promising ZE drayage trucks (multiple designs).

Stage 3. Down-Select: Pre-Commercial ZE Drayage Assessment and Validation; Infrastructure Deployments Expand, 2019-22

- Multiple parallel assessments of pre-commercial drayage trucks with fleets throughout port region. This phase finalizes the data collection, user assessment, and validation of the pre-commercial vehicles.

- Expand installation of needed infrastructure for the full rollout of trucks in Stage 4, concurrent with the fleet use of the ZE drayage trucks and the specific infrastructure deployed for their support.
- Deployment of ZE trucks, yard hostlers, and drayage near-dock rail and ongoing replacement of vocational ZE trucks in the region would continue at a supporting rate.
- ZE technology maintenance training will be launched for the workforce.
- Finalize the regulatory framework based on the developments in the deployment phase (Stage 2). Once the AQ drivers are finalized (both for the near term and locked in for future years), key players can finalize plans for incentive structures, expansion plans, and drivers for the business case.

Stage 3 Goals. Complete deployment and assessment of roughly 100 to 300 ZE drayage trucks with leader fleets in I-710 zone. Complete deployment of ZE yard hostlers and near-dock ZE drayage vehicles. Establish infrastructure deployment sites for Stage 4. Train current maintenance personnel, launch workforce training for new workers.

Stage 4. Commercial ZE Drayage Production, Deployment Ramp-Up, 2020-25

Overlapping with Stage 3 and beginning as early as 2020 for early-adopter fleets with special incentives, Stage 4 ramps up the production and deployment of commercial ZE drayage trucks to fleets in the I-710 zone.

- Infrastructure siting and construction would continue to take place both at truck domicile points and at locations identified in earlier stages as conducive to supporting ZE drayage truck usage.
- Additional training in this stage would include fleet user best practices sessions; incentive and business case assistance training; maintenance training; and region-wide infrastructure training.

Stage 4 Goals. Phase up production over five-year period for roughly 10,000 cumulative zero-emission drayage trucks by 2025. Deploy sufficient infrastructure to support those trucks as needed in their daily operation in the ZE zone. Stage ongoing training and support for impacted fleets. Have in operation an incentives-based purchase or lease system for fleets to obtain ZE trucks for their operations (with additional incentives provided for early mover fleets in the first few years of the ramp-up).

Over the next decade, achieving the ZE truck deployment will necessitate following an aggressive and highly focused commercialization and phase-in plan. It will require regional, state and federal government support in providing multi-year funding, and the necessary regulatory framework and operational requirements. This effort must begin immediately by initiating, several multi-

truck demonstration projects in 2014 to assess the architectures and ZE range options outlined in this report.

The plan will also need to build on the expected truck turnover timeline already set in motion by the San Pedro Bay Ports Clean Truck Program. The initial investment that was made to facilitate a rapid transition to trucks compliant with EPA 2007 and later emissions standards has resulted in a significant quantify of trucks ready for replacement by 2020 and later.

Achieving ZE truck deployment success will also require the involvement of the major truck OEMs. Each has its own current strategy on ZE-enabling technology based on their product mix, plans for fuel economy, and global market considerations. Full ZE technology is not central to their current product plans – though several have intriguing internal development efforts. In general, they are not so much skeptical of the feasibility of the technology as they are of the reality of the market for its use. OEMs need to be active participants in the commercialization process. At a minimum this would require the formation of an OEM Advisory Council.

The core issues that need to be addressed for commercialization of ZE freight vehicles to be successful include:

- **Flexibility.** Vehicles must be able to perform full drayage duties, including a range of up to 200 total miles per day and power to handle up to 80,000-pound loads and regional grades.
- **Operations.** Trucks must have the ability to go a minimum distance (possibly 20 and up to 50 miles) in zero-emission mode and then potentially continue to operate in a reduced emission mode outside the core port region.
- **Manufacturability.** To be successful, the manufacturing process would be based on a core, high-volume truck platform of which the ZE version is a producible variant.
- **Infrastructure.** Given the level of "new" fuel that may be required to meet the needs of up to 10,000 ZE trucks, particularly for electricity and hydrogen, planning for capacity, distribution, and siting of ZE truck infrastructure needs to start immediately and include utilities and fuel providers.
- **Regulations/Inducements/Incentives/Business Case.** Given the rapid timing for the rollout of an entirely new category of vehicle, it is unlikely market forces alone will be sufficient motivation. Therefore, regional and state air quality and transportation agencies need to quickly develop a regulatory framework in which ZE trucks will be both required and rewarded.
- **Define Clear Requirement: Fixed Corridor or Broader "Zone"?** OEMs and suppliers need to know clear requirements to successfully design a product. This needs to be determined soon to engage manufacturers.

3C trucks cannot operate in a vacuum. They need an ecosystem with an established framework for their operations. Therefore, several paths of parallel activity are required. They are:

- A focused vehicle development, demonstration, validation, and deployment process;
- Early action deployments of ZE vehicles in the Gateway Cities and port communities;
- A regulatory framework for ZE drayage trucks;
- Enhanced operational and business case assessment; and
- Fleet training, maintenance training, and decision support.

The critical actions to be taken over the next few years are summarized in Table 6.1

Table 6.1 Needed Next Step Activities to Support ZE Truck Commercialization

Category	Action	Outcome
Expand Technology	ZET Demonstration Projects	Focused demonstrations of various architectures and versions are required: REEV, BEV, plus dual-mode and PHEV to validate performance. 5-10 demonstration projects to evaluate performance will help lead to 25-50 truck pre-commercial pilot projects by 2017.
	Supporting Technologies Demonstrations	Development of electrified auxiliaries, modular energy storage, optimized alt fuel/low NO_x engines are some of the required enabling technology and component development needed to support ZET.
	Advanced Infrastructure Demonstrations	To meet the refueling needs of up to 10-thousand trucks will require advanced infrastructure development, including fast-charge optimized for truck size systems; opportunity charging schemes; gaseous fuel fast-fueling.
	ZE Yard Hostler Demonstrations	Demonstrations of ZE technology in potential early application that can support drayage sized systems
Plan and Develop Infrastructure	Fuel Infrastructure Availability & Impact Study	Report to identify constraints and potential system/grid impacts of core fuels, including production, distribution, transmission and dispensing
	Infrastructure Deployment Plan	Based on Fuel Infrastructure report, develop an infrastructure deployment plan identifying siting, costs and timeline to support the most likely fuels and vehicle volumes expected in 2025
Business Case & Operational Model	Analysis of ZET Operation and Maintenance Costs	Perform a detailed analysis of the expected costs to operate and maintain ZE trucks, pulling from bus and truck data, to feed into detailed business case
	Assessment Report of Secondary Use Markets and Residual Value of ZET	A key factor needed in the business case is determining the value of trucks at end of first life; this will include evaluating secondary uses of the full vehicles and f core components (batteries)

Category	Action	Outcome
	Refine Specific ZET Operational Cycle from Origin-Destination Data	OEMs require a more refined description of the ZET operational cycle – how drayage trucks are actually used. This information needs to draw from duty cycle studies, new origin-destination information, and additional data collection of in-use drayage trucks.
	Detailed Business Case Development for ZET	Using the above information, development of a more detailed business case will inform ownership models and incentives required.
	Assessment of Ownership Models Supporting ZET Use	Based on the business case structure, an assessment of how best to support ZET purchase and use will be performed, including evaluations of alternative and new ownership models (public or facility ownership/lease) and potential public-private partnership structures.
	Organize and operate a Truck OEM Advisory Council	The Truck OEM Council is a critical element in successful commercialization, and will provide on-going feedback on business case development and the product development process
	Organize and Stage Regular Fleet Workshops on ZET Tech and Operations	End users must be involved from the beginning to ensure market success, and in the early years regular technical interchanges can share the latest information on ZE technology, operations, business case and use.
Build Supporting Markets	Accelerate early deployment of existing ZE trucks in Gateway Cities and Ports region	Accelerating the deployment of 1000+ currently available ZE vocational trucks and buses in the Gateway Cities region will: 1) help build volumes and supply chains for core components; 2) expand infrastructure availability; 3) raise ZET profile and show regional leadership.
	Coordinate targeted incentive funding from regional, state and federal partners for early deployment	Negotiate with regional and other funding agencies to develop a significant increased level of incentive funding for ZET placed in the Gateway Cities and Ports region, potentially by combining multiple sources.
	Research, Determine and Evaluate Markets for Wider ZET Use and Deployment	Evaluation of other potential direct or supporting markets for ZET or ZE buses or their core components, from other port locations or other applications nationally and globally. Such markets help build the investment case for OEMs. Consider forming an international monitoring committee to share best practices with interested regions.
	Collaborate with regional and state regulators to guide and establish policy for use of ZET	Regulatory or legal framework supporting and/or inducing ZET use, including possible backstop regulations.

A. Glossary of Acronyms

3C	Clean corridor capable trucks
AFV	Alternative fuel vehicle
AIAG	Automotive Industry Action Group
APQP	Advanced product quality planning
APU	Auxiliary power unit
AQMD	Air Quality Management District
ARB	Air Resource Board
ARS	Balance of plant
BEV	Battery electric vehicle
BoP	Balance of plant
CCW	Creative Coach Works
CEC	California Energy Commission
CMAQ	Los Angeles Metro Congestion Mitigation Air Quality
CNG	Compressed natural gas
COBRA	Continuous on-board recharging applications
CTA	California Trucking Association
DC	Direct current
DGEs	Diesel gallon equivalents
DME	Di-Methyl Ether
DOE	U.S. Department of Energy
DTNA	Daimler Truck North America
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
E-Trucks	Electric trucks
EU	European Union
EV	Electric vehicle

FC	Fuel cell
STP	Strategic Transportation Plan
GCCOG or COG	Gateway Cities Council of Governments
GHG	Greenhouse gas
H2	Hydrogen
H2E	Hydrogen to electricity
HEV	Hybrid electric vehicle
HOS	Federal hours of service
HP	Horsepower
HTA	Harbor Trucking Association
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
ICE	Internal combustion engine
ITS	Intelligent transportation systems
Km	Kilometer
KPP	Key Performance Parameters.
kW	Kilowatt
kWh	Kilowatt per hour
Li-Air	Lithium-air (battery)
LNG	Liquid natural gas
Metro	Los Angeles County Metropolitan Transportation Authority
NO_x	Oxides of nitrogen
MPG	Miles per gallon
MPH	Miles per hour
NAFA	National Association of Fleet Administrators
NG	Natural gas
NPV	Negative payback value
NREL	National Renewable Energy Lab
O&M	Operating and maintenance
OEM	Original equipment manufacturer
PDD	Product Development Document

PHEV	Plug-in hybrid electric vehicle
POLA/POLB	Port of Los Angeles/Port of Long Beach
PPP	Public-private partnership
REEV	Range extended electric vehicle
RNG	Renewable natural gas
SCAQMD	South Coast Air Quality Management District
SOC	State of charge
STP	Strategic Transportation Plan
TAP	Truck Advancement Program
TCO	Total costs of ownership
TTSI	Total Transportation Services Inc.
VOC	Volatile organic compound
ZE	Zero-emission
ZEV	Zero-emission vehicle

B. Business Case Analysis Assumptions

Vehicle Life

The vehicle life represents the number of years the vehicle will be kept in service. Vehicle life was set at 10 years. This value was selected based on input from the user survey and interviews with trucking companies. As a further conservative factor, it was also presumed the truck would have no resale value at the end of the 10 years. Actual resale values, and the value of battery packs for alternative uses, is highly speculative and beyond the scope of this report.

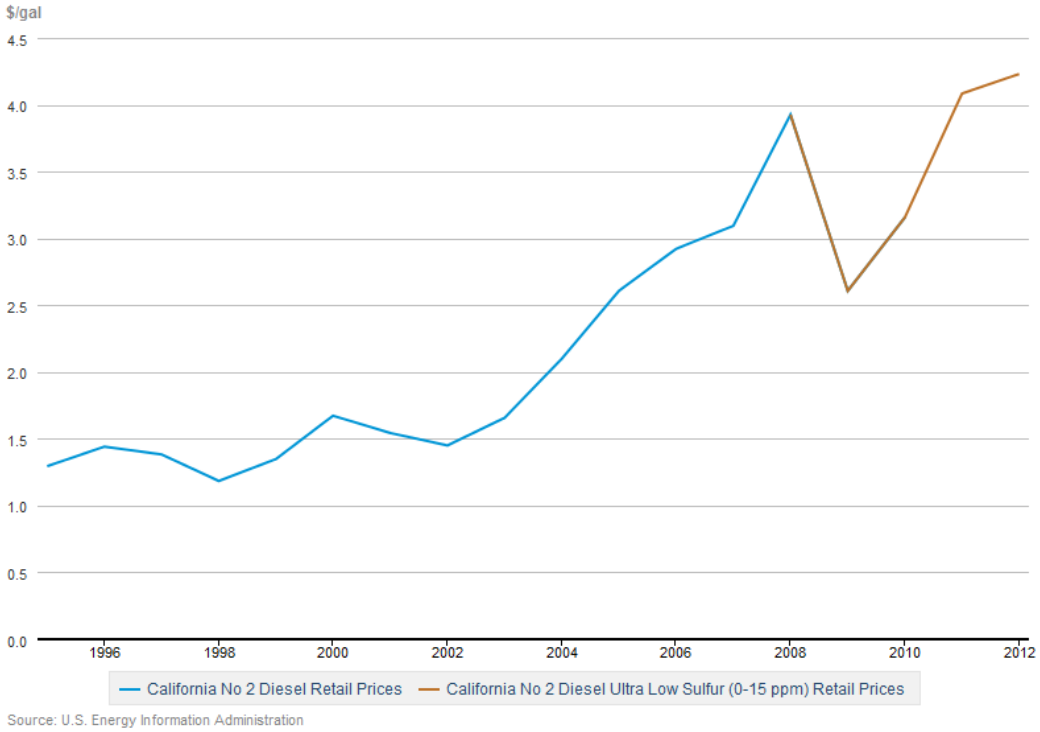
Days in Operation per Year

We assumed trucks are operated 5 days per week and 50 weeks per year.

Diesel Fuel Price

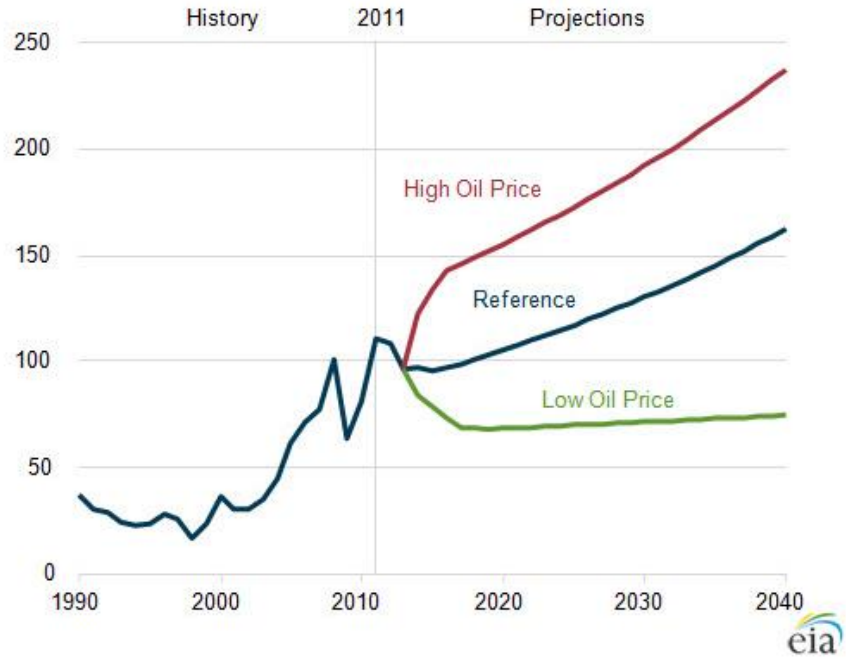
Diesel fuel price in 2020 came from 2012 California No. 2 diesel retail sales by all sellers (**Error! Reference source not found.**) and projected to 2020 following the IA Reference Case for Brent crude oil spot prices from the Annual Energy Outlook 2013 (**Error! Reference source not found.**).

Figure B.1 California No. 2 Diesel Retail Prices[a]



Source: U.S. Energy Information Administration, Weekly Retail Gasoline and Diesel Prices, http://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_sca_a.htm (accessed 2013-10-15).

Figure B.2 Brent Crude Oil Spot Prices in Three Cases, 1990 to 2040[a]
2011 Dollars per Barrel



Source U.S. Energy Information Administration, Annual Energy Outlook 2013, http://www.eia.gov/forecasts/aeo/topic_prices.cfm (accessed 2013-10-15.)

Error! Reference source not found. below summarizes the diesel prices used for his study.

Table B.1 California Diesel Prices in 2012, 2020, and 2030

Year	CA Diesel Price
2012	$4.23/gal. (actual)
2020	$4.52/gal. (projection)
2030	$5.58/gal. (projection)

Source CALSTART.

Diesel Fuel Escalation Rate

We included a 2-percent fuel escalation rate based on the EIA Reference Case for Brent crude oil spot prices from the Annual Energy Outlook 2013.[28] The fuel escalation rate is a percentage number representing the average percentage that

[28] U.S. Energy Information Administration, Annual Energy Outlook 2013, http://www.eia.gov/forecasts/aeo/topic_prices.cfm (accessed 2013-10-15).

diesel prices will increase every year and accounts for the probability that the cost of diesel in the future will be higher than it is today.

Electricity Fuel Price

Electricity price was derived from the 2012 average retail price of electricity to ultimate customers[29] and projected to 2020 following the EIA Reference Case and "Greenhouse Gas $25" scenario from the Annual Energy Outlook 2013.[30] **Error! eference source not found.** below summarizes the electricity prices used for this study.

Table B.2 California Commercial Average Retail Price of Electricity

Year	CA Commercial Average Retail Electricity Price
2012	$0.136/kWh (actual)
2020	$0.148/kWh (projection)
2030	$0.147/kWh (projection)

Source CALSTART.

Electricity Fuel Escalation Rate

We assumed no electricity fuel escalation rate.

CNG Fuel Price

CNG fuel price was derived from July 2013 CNG prices on the West Coast[31] and projected to 2020 following the EIA Reference Case for annual average Henry Hub spot prices for natural gas from the Annual Energy Outlook 2013.[32]

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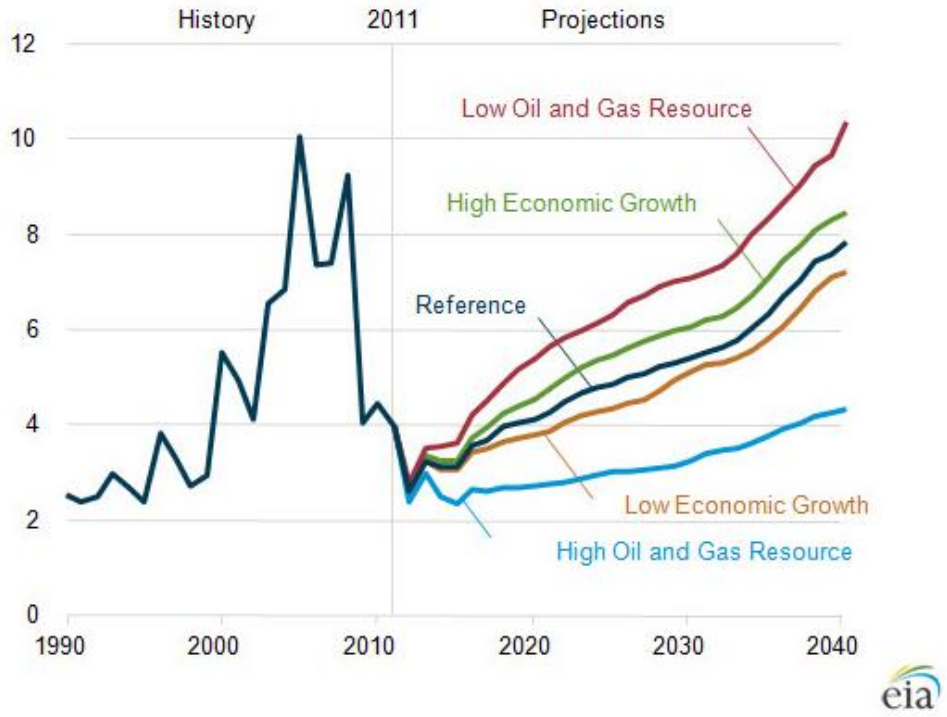
[29] U.S. Energy Information Administration, Electric Power Monthly, February 2013, http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a (accessed 2013-10-15).

[30] U.S. Energy Information Administration, Annual Energy Outlook 2013, http://www.eia.gov/oiaf/aeo/tablebrowser/#release=AEO2013&subject=0-AEO2013&table=3-AEO2013&region=1-9&cases=co2fee25-d021413a,ref2013-d102312a (accessed 2013-10-15).

[31] U.S. Department of Energy, Clean Cities Alternative Fuel Price Report, July 2013, http://www.afdc.energy.gov/uploads/publication/afpr_jul_13.pdf (accessed 2013-10-15).

[32] U.S. Energy Information Administration, Annual Energy Outlook 2013, http://www.eia.gov/forecasts/aeo/MT_naturalgas.cfm#natgas_prices?src=Natural-b5 (accessed 2013-10-15).

Figure B.3 Annual Average Henry Hub Spot Prices for Natural Gas in Five Cases, 1990 to 2040[a]
2011 Dollars per Million BTU



Source U.S. Energy Information Administration, Annual Energy Outlook 2013, http://www.eia.gov/forecasts/aeo/MT_naturalgas.cfm#natgas_prices?src=Natural-b5 (accessed 2013-10-15).

Error! Reference source not found. below summarizes the CNG prices used for his study.

Table B.3 West Coast CNG Prices in 2012, 2020, and 2030

Year	West Coast CNG Prices
2012	$2.71/DGE (July 2013)
2020	$3.45/DGE (projection)
2030	$4.50/DGE (projection)

Source CALSTART.

CNG Fuel Escalation Rate

We included a 3-percent fuel escalation rate based on the EIA Reference Case for annual average Henry Hub spot prices for natural gas from the Annual Energy

Outlook 2013.[33] The fuel escalation rate is a percentage number representing the average percentage that CNG prices will increase every year and accounts for the probability that the cost of CNG in the future will be higher than it is today.

H_2 Fuel Price

H_2 fuel price was derived from U.S. Department of Energy future prices[34] and from personal communications with industry experts.[35] **Error! Reference source ot found.** below summarizes the H_2 price used for this study.

Table B.4 South Coast H_2 Price in 2020

Year	South Coast H2 Price
2020	$3.50/kg H_2 (projection)

H_2 Fuel Escalation Rate

We included a 3-percent fuel escalation rate based on the EIA Reference Case for annual average Henry Hub spot prices for natural gas from the Annual Energy Outlook 2013.[36] The fuel escalation rate is a percentage number representing the average percentage that H_2 prices will increase every year and accounts for the probability that the cost of H_2 in the future will be higher than it is today.

Demand Charges

Electric utilities generally charge their commercial and industrial customers a monthly demand charge based on the highest amount of power drawn by the facility.[37] A quick review of electric rate schedules for the 5 largest investor-

[33] U.S. Energy Information Administration, Annual Energy Outlook 2013, http://www.eia.gov/forecasts/aeo/MT_naturalgas.cfm#natgas_prices?src=Natural-b5, accessed on 2013-10-15.

[34] U.S. Department of Energy, Overview of DOE-Supported Infrastructure Analyses, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/webinarslides_doe_analysis_h2usa_072413.pdf, accessed on 2013-10-15.

[35] Paul Scott (Transpower), personal communication, August 2013, Vic LaRosa (TTSI), personal communication, August 2013, Larry Wnuk (CALSTART), personal communication, August 2013.

[36] U.S. Energy Information Administration, Annual Energy Outlook 2013, http://www.eia.gov/forecasts/aeo/MT_naturalgas.cfm#natgas_prices?src=Natural-b5. Accessed on 2013-10-15.

[37] Masters, Gilbert, Renewable and Efficient Electric Power Systems, ISBN 0-471-28060-7, Hoboken, New Jersey: John Wiley & Sons, Inc., 2004.

owned utilities in California shows that demand charges vary between $10 and $20 per kW.[38] For some facilities, demand charges can represent a large part of the electricity bill. For this analysis, we assumed demand charges at $15 per kW. We assumed no demand charges escalation rate.

Diesel Vehicle Fuel Efficiency

For this analysis, we assumed diesel vehicle fuel efficiency at 6 MPG.

CNG Vehicle Fuel Efficiency

For this analysis, we assumed CNG vehicle fuel efficiency at 6 MPG.

Electric Vehicle Energy Consumption

For this analysis, we assumed electric vehicle fuel efficiency at 2.5 AC kWh/mile.

Fuel Cell Vehicle Efficiency

Fuel cell vehicle efficiency was derived from personal communications with industry experts.[39] For this analysis, we assumed a zero-emission fuel cell range extender electric drayage truck would drive 5 miles per kg of H_2.

Charging Infrastructure Cost

Charging infrastructure cost was based on current estimate for electric vehicle fast chargers and discussions with CALSTART staff:

- Nissan DC Quick Charger (480V, 44kW) is starting at $15,500 (does not include tax, shipping, administration or processing fee)[40] and Nissan suggests total cost of $40,000 (charging unit + material + labor).[41]

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[38] Southern California Edison. *Schedule TOU-GS-2 / Time-Of-Use – General Service – Demand Metered.* https://www.sce.com/NR/sc3/tm2/pdf/ce329.pdf. Accessed on 2013-07-16. Pacific Gas & Electric. *Tariff Book, Electric Schedules.* http://www.pge.com/tariffs/ERS.SHTML#ERS. Accessed on 2013-07-18. Sacramento Municipal Utility District. *Rates, Requirements and Interconnection Information.* https://www.smud.org/en/business/customer-service/rates-requirements-interconnection/your-rates.htm. Accessed on 2013-07-18. Los Angeles Department of Water and Power. *Electric Rates.* https://www.ladwp.com/ladwp/faces/ladwp/aboutus/a-financesandreports. Accessed on 2013-07-18. San Diego Gas & Electric. *Current and effective tariffs, Electric tariff book.* http://www.sdge.com/rates-regulations/current-and-effective-tariffs/current-and-effective-tariffs. Accessed on 2013-07-18.

[39] Mike Simon (Transpower), personal communication, August 2013. Larry Wnuk (CALSTART), personal communication, August 2013.

[40] http://www.nissanqc.com/. Accessed on 2013-10-16.

- Current Level 3 charging costs are reported between $30,000 and $160,000.[42]
- Foothill Transit/Proterra Fast Charge System recharges a 35-foot bus with a 74 kWh battery in about 10 minutes. The Fast Charge System recharges at a charging rate of about 500 kW and costs around $1,000,000.[43]

Error! Reference source not found. below summarizes the charging nfrastructure costs used for this study.

Table B.5 Estimated Recharging Infrastructure Costs

Charging Rate	*Estimated Costs (Hardware + Installation)*
150 kW	$150,000
63 kW	$50,000
25 kW	$20,000

Source CALSTART.

Zero-Emission Fuel Cell Range Extender Electric Drayage Truck Components Sizing

Fuel cell stack and battery size were derived from discussions with CALSTART staff. [44]

Discount Rate

The *discount rate* is an interest rate used to adjust a future cash flow to its present value: its value to the organization today. As the starting point for the discount rate, most organizations use their cost of capital, the rate of return that must be

[41] Green Car Report. Nissan Offers $15,000 For New Electric-Car Quick Chargers by December 31, http://www.greencarreports.com/news/1087580_nissan-offers-15000-for-new-electric-car-quick-chargers-by-dec-31. Accessed on 2013-10-16.

[42] Yilmaz, Murat and Philip T. Frein. Review of Charging Power Levels and Infrastructure for Plug-in Electric and Hybrid Vehicles and Commentary on Unidirectional Charging. 2012 IEEE International Electrical Vehicle Conference, http://ceme.ece.illinois.edu/seminars/CEME412_2KreinPlugIn_HybridVehicles.pptx, accessed on 2013-10-16.

[43] Karbowski, George. Foothill Transit Electric Bus Project. Z-TUG Meeting, Pomona, California, June 2011.

[44] Larry Wnuk (CALSTART), personal communication, August 2013.

earned in order to pay interest on debt (loans and/or bonds) used to finance investments and, where applicable, to attract equity (stock) investors.[45]

As a rule of thumb, the user can define the cost of capital for a for-profit commercial entity at 7 percent and for a government agency or municipal utility at 4 percent.[46]

Simple Payback Period

The *simple payback period* (SPP) gives the number of years an energy efficiency improvement or production system will take to pay for its initial capital cost based on its energy and economic savings. It holds true for short time periods and/or low discount rates because it ignores the time-value of money and for minor operation and maintenance costs because it usually ignores them as well. Despite these limitations, SPP is one of the most intuitive and useful measures of cost-effectiveness.[47]

The simple payback period without incentives is the number of years it takes to recoup the incremental investment if no incentives (state, federal and infrastructure) were available.

Net Present Value

Net present value (NPV) is a measure of the investment's financial worth to the organization, taking into account the preference for receiving cash flows sooner rather than later. An investment is financially worthwhile if its NPV is greater than zero, because the present value of future cash flows is greater than the outlay. In the rare case of an opportunity with a zero NPV, the organization should theoretically be indifferent between making and not making the investment. A positive NPV is the net gain to the organization from making the investment – assuming that the discount rate properly adjusts for the timing of the cash flows.

Besides helping to decide whether an investment is worthwhile, the NPV can be used to choose among alternative investments. If an organization has two or

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[45] From *Energy Star® Building Upgrade Manual,* US EPA, Office of Air and Radiation, 2008 Edition, Chapter 3: Investment Analysis, http://www.energystar.gov/ia/business/epa_bum_full.pdf, accessed on 2012-01-24

[46] For more information, Aswath Damodaran, Professor of Finance at the Stern School of Business at New York University has compiled data for 5,891 firms in various sectors. Data can be accessed at http://w4.stern.nyu.edu/~adamodar/New_Home_Page/datafile/wacc.htm (accessed on 2012-02-14).

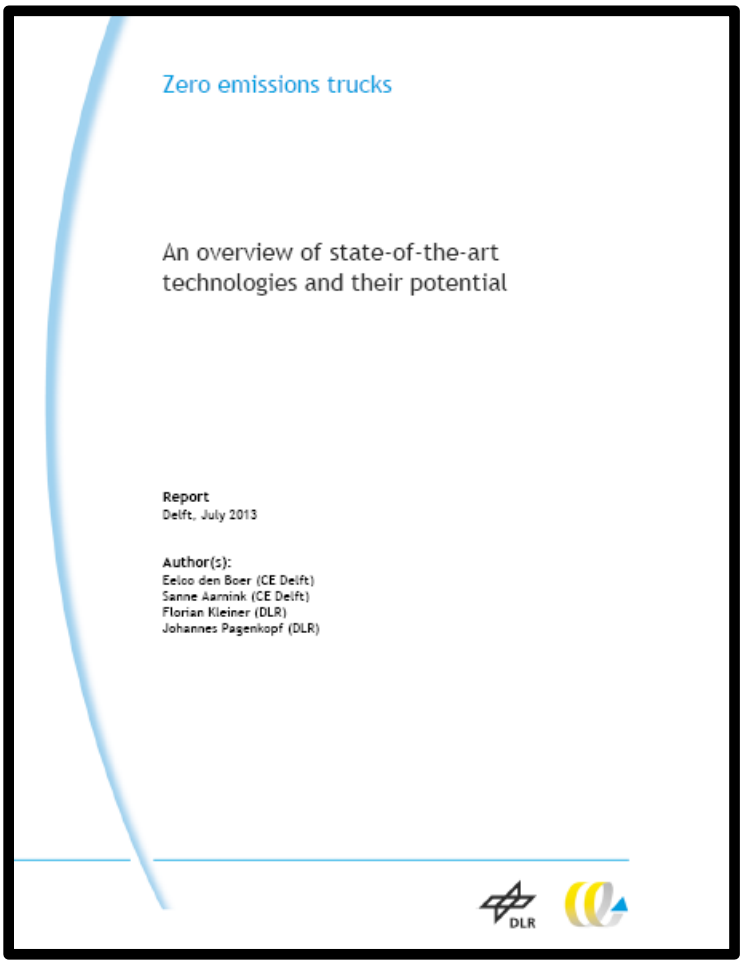
[47] From J. Randolph and G. Masters, Energy for sustainability: technology, planning, policy, ISBN 1-59726-103-3, Washington, Island Press, 2008.

more investment opportunities but can only pick one, the financially sound decision is to pick the one with the greatest NPV.[48]

[48] From Energy Star® Building Upgrade Manual, US EPA, Office of Air and Radiation, 2008 Edition, Chapter 3: Investment Analysis, http://www.energystar.gov/ia/business/epa_bum_full.pdf, accessed on 2012-01-24.

C. CE Delft Report

Due to the size of this Appendix file, a link is provided here: http://www.theicct.org/zero-emission-trucks



Zero emissions trucks

An overview of state-of-the-art technologies and their potential

Report
Delft, July 2013

Author(s):
Eelco den Boer (CE Delft)
Sanne Aarnink (CE Delft)
Florian Kleiner (DLR)
Johannes Pagenkopf (DLR)

DLR

D. CALSTART TCO Report

CALSTART Updated TCO Report

Due to the size of this Appendix file, a link is provided here: http://www.calstart.org/Libraries/I-710_Project/Technologies_Challenges_and_Opportunities_I-710_Zero-Emission_Freight_Corridor_Vehicle_Systems.sflb.ashx

TECHNOLOGIES, CHALLENGES & OPPORTUNITIES
I-710 ZERO-EMISSION FREIGHT CORRIDOR
VEHICLE SYSTEMS

REVISED VERSION
FINAL V1
NOVEMBER 2013

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E. CALSTART KPP Report

CALSTART KPP REPORT

Due to the size of this Appendix file, a link is provided here:
http://www.calstart.org/Libraries/I-710_Project/Key_Performance_Parameters_for_Drayage_Trucks_Operating_at_the_Ports_of_Los_Angeles_and_Long_Beach.sflb.ashx

Drayage Truck Key Performance Parameters: I-170 Zero Emission Freight Corridor

Completed for LA Metro and GCCOG

DRAFT

CALSTART

6/31/2013

Prepared by:
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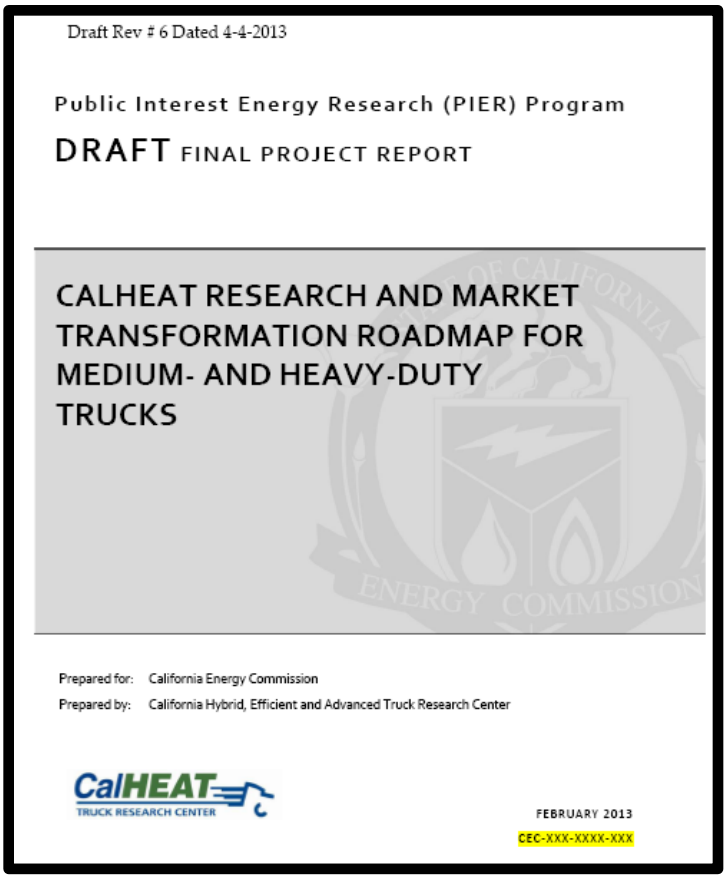
F. CALHEAT Research and Market Transformation Roadmap For Medium- and Heavy-Duty Trucks Report

Due to the size of this Appendix file, a link is provided here:

http://www.calstart.org/Libraries/CalHEAT_2013_Documents_Presentations/CalHEAT_Roadmap_Final_Draft_Publication_Rev_6.sflb.ashx



Draft Rev # 6 Dated 4-4-2013

Public Interest Energy Research (PIER) Program

DRAFT FINAL PROJECT REPORT

CALHEAT RESEARCH AND MARKET TRANSFORMATION ROADMAP FOR MEDIUM- AND HEAVY-DUTY TRUCKS

Prepared for: California Energy Commission

Prepared by: California Hybrid, Efficient and Advanced Truck Research Center

CalHEAT TRUCK RESEARCH CENTER

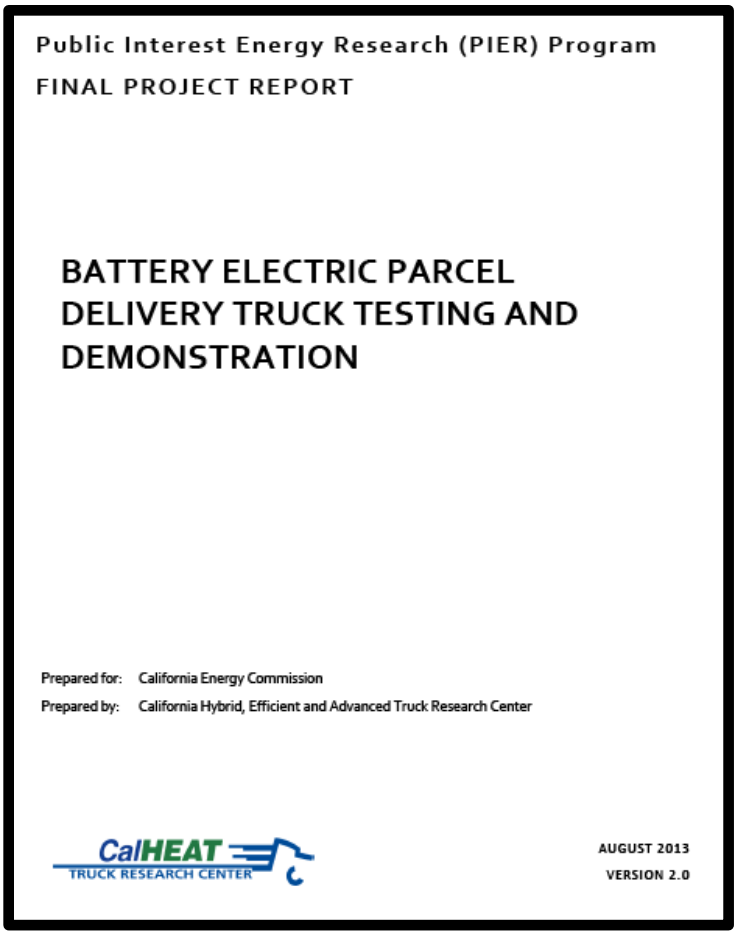
FEBRUARY 2013

CEC-XXX-XXXX-XXX

G. CalHEAT Battery Electric Parcel Delivery Truck Testing and Demonstration Report

Due to the size of this Appendix file, a link is provided here:

http://www.calstart.org/Libraries/CalHEAT_2013_Documents_Presentations/Battery_Electric_Parcel_Delivery_Truck_Testing_and_Demonstration.sflb.ashx



Public Interest Energy Research (PIER) Program

FINAL PROJECT REPORT

BATTERY ELECTRIC PARCEL DELIVERY TRUCK TESTING AND DEMONSTRATION

Prepared for: California Energy Commission

Prepared by: California Hybrid, Efficient and Advanced Truck Research Center

CalHEAT TRUCK RESEARCH CENTER

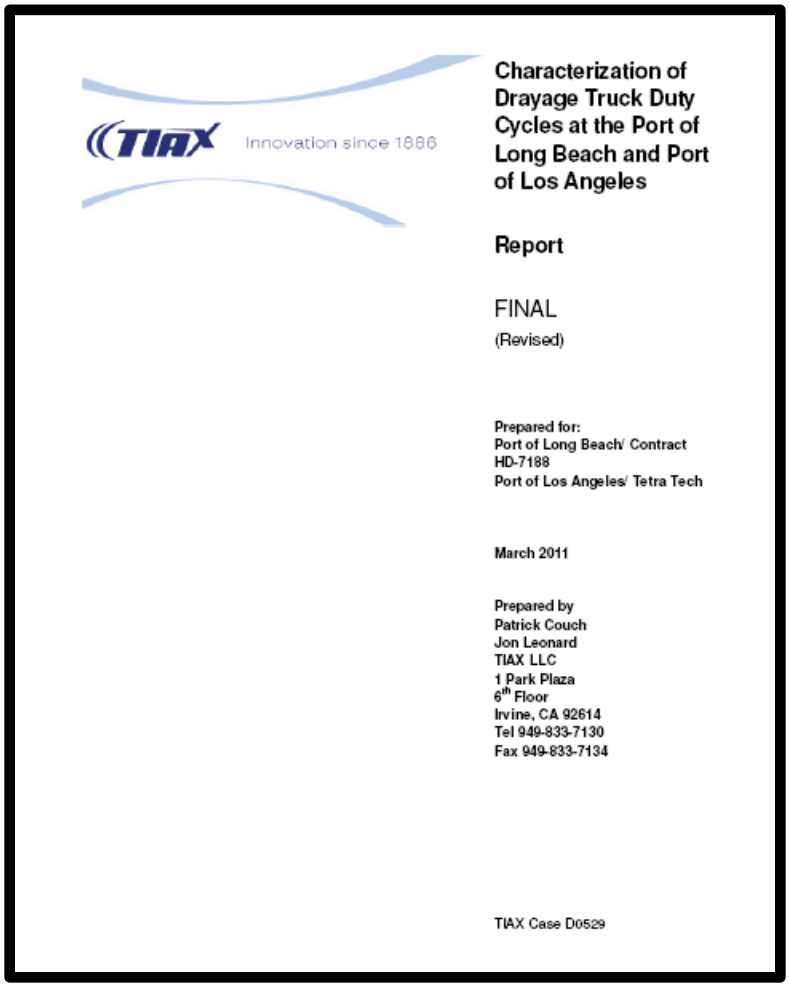
AUGUST 2013

VERSION 2.0

H. TIAX Drayage Duty Cycle Report

Due to the size of this Appendix file, a link is provided here:

http://www.cleanairactionplan.org/civica/filebank/blobdload.asp?BlobID=2515



TIAX Innovation since 1886

Characterization of Drayage Truck Duty Cycles at the Port of Long Beach and Port of Los Angeles

Report

FINAL
(Revised)

Prepared for:
Port of Long Beach/ Contract HD-7188
Port of Los Angeles/ Tetra Tech

March 2011

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TIAX Case D0529

I. The Gateway Cities Air Quality Action Plan

Task 7 New Measures Analysis

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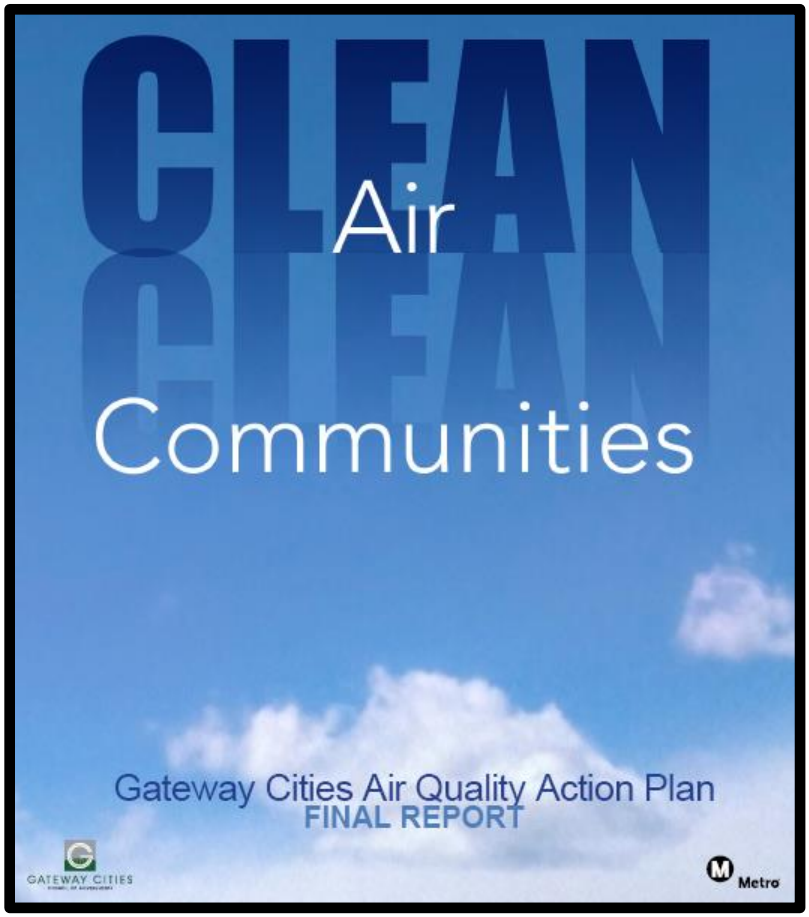
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