



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

**REVISED VERSION
FINAL V1
NOVEMBER 2013**



©CALSTART 2013



FUNDING FOR THE ORIGINAL RESEARCH PROVIDED BY:

Los Angeles County Metropolitan Transit Authority (Metro)

Douglas R. Failing - Executive Director Highway Programs

South Coast Air Quality Management District

Matt Miyasato, Ph.D. - Assistant Deputy Executive Officer, Technology Advancement Office

The original report was prepared as a result of work sponsored, paid for, in whole or in part, by the South Coast Air Quality Management District (AQMD). The opinions, findings, conclusions, and recommendations are those of the author and do not necessarily represent the views of AQMD. AQMD, its officers, employees, contractors, and subcontractors make no warranty, expressed or implied, and assume no legal liability for the information in this report. AQMD has not approved or disapproved this report, nor has AQMD passed upon the accuracy or adequacy of the information contained herein.

FUNDING FOR THIS UPDATED REVISION PROVIDED BY:

Los Angeles County Metropolitan Transit Authority (Metro) as part of the Gateway Cities Strategic Transportation Plan

Douglas R. Failing - Executive Director Highway Programs

Jerry Wood – Highway Engineer, Gateway Cities Council of Governments



Table of Contents

Executive Summary	1
1.0 Issue and Study Scope	6
2.0 Approach.....	7
2.1 Industry Expert Interview Findings	8
2.1.1 Technologies Under Development	8
2.1.2 Challenges Identified	9
2.1.3 Opportunities Under Development	11
Key Industry Players.....	12
2.2 CalHEAT Findings	14
3.0 Technologies.....	20
3.1 Dual Mode Hybrid Electric Vehicle (HEV)	20
3.2 Dual Mode Plug-in Hybrid Electric Vehicle (PHEV)	23
3.3 Range Extended Electric Vehicle (REEV) with Engine.....	23
3.4 Range Extended Electric Vehicle (REEV) with Fuel Cell	26
3.5 Battery Electric Vehicle (BEV)	28
3.6 Fuels and Energy Storage Options.....	30
3.6.1 Fuel Options.....	31
3.6.2 Energy Storage Options	33
3.7 Infrastructure Options	35
4.0 Challenges.....	41
4.1 Design / Development.....	41
4.2 Costs.....	42
4.3 Economic/Business Case	44
5.0 Opportunities.....	47
5.1 Feasible System Designs.....	48
6.0 Conclusions & Recommendations	50
6.1 Technology Opportunities	51
6.2 Concerns and Challenges.....	52
6.3 Recommendations.....	53
7.0 Appendices.....	56



Appendix A: Survey Instrument (Moderator Interview Guide).....	56
Appendix B: Acronym List.....	59
Appendix C: Developments in Near-Zero Emission Technologies.....	60
Appendix D: CalHEAT Roadmap Recommended Actions on Top Strategies to Support Zero Emission Drayage Technologies.....	63



EXECUTIVE SUMMARY

ISSUE & SCOPE

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. 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.

CALSTART was tasked with investigating the potential technologies that could achieve this goal their feasibility, and the barriers to their commercialization within the project’s horizon year of 2035, and with a planned opening in 2025.

Specifically, the scope of this report was to examine whether a Class 8 truck could be developed that would meet the zero-emissions requirements of the I-710 Project Alternatives that include ZE goods movement. The operating definition of “zero-emissions” used in the I-710 Corridor Project EIR/EIS is zero tailpipe emissions. Infrastructure options related to trucks were listed, but only in brief. The task was to ascertain technologies that could enable a Class 8 truck to move freight in the I-710 corridor (roughly 17 miles) with zero emissions.



APPROACH

In addition to standard technical research methods, CALSTART conducted interviews with industry experts across vehicle OEMs, Technology Suppliers, and Truck Operators. The responses were analyzed to assess the most likely technologies to achieve the goal of a zero-emission truck for the I-710 Corridor. Confidential interviews, in combination with CALSTART's industry knowledge and expertise, provided the basis for one part of the report findings. The data was analyzed to determine feasibility, barriers, and timeframe for potential solutions.

The findings of the CalHEAT study were also incorporated; that document can be downloaded at (http://www.calstart.org/Libraries/CalHEAT_2013_Documents_Presentations/CalHEAT_Roadmap_Final_Draft_Publication_Rev_6.sflb.ashx). Many of the Action Steps identified by that independent program, funded by the CEC, are applicable to zero-emission corridor development.

KEY FINDINGS AND CONCLUSIONS

The development of a vehicle or vehicle system (truck and infrastructure power source) that can move freight through the I-710 Corridor with zero emissions has no major technological barriers. In fact, there are several technical approaches that can achieve the desired outcome. Solutions can be developed based on existing designs and technical knowledge, and require no fundamental research or technology breakthroughs. Small-scale demonstrations have already begun or will start within a couple years, and commercialization of proven designs can be achieved within the project timeline.

The feedback from interviews conducted for this report indicates the major challenge to commercialization of zero-emissions (ZE) drayage trucks is assuring a viable market exists (in volume and demand) which could support the purchase and operation ZE trucks.

The I-710 Corridor must develop a set of market mechanisms to incorporate ZE trucks into the business models of the end users and key corridor stakeholders. Once a market model can be demonstrated, the other steps in the process will be easier to achieve: partnership funding to support vehicle development and validation, original equipment manufacturer (OEM) development and commercialization, user acceptance and adoption.

Therefore, in addition to a strong technology demonstration and validation track, the I-710 ZE truck development effort must define a complete economic model ("market mechanisms" or "economic ecosystem") that will support the advanced trucks and the operation of a zero-emissions corridor. It must show sufficient volumes of trucks –ideally trucks that are not single-use, limited operation designs – such that the OEMs and suppliers are willing to immediately invest the time and resources required, in expectation of future returns. Current product plans are not focused on ZE trucks in the near term, largely due to the missing economic and regulatory case. However, such trucks can emerge from the basic designs already in development at truck and system makers.



According to the analyses of interviews and industry data collected for this assessment, there were several possible technical approaches, a number of challenges to implementing those approaches, and some key opportunities that were seen as most feasible given the current state of the market:

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

- 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
- 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.
- Over 100 miles ZE range: REEV with Fuel Cell is the primary viable option.

A multi-variable sensitivity analysis is necessary as a future project, to evaluate the multiple options across technologies, costs, infrastructure requirements, and ZE ranges.

Defining the required ZE Range is a necessary step and critical criterion. The other core challenges 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.

RECOMMENDATIONS

The following needs have been identified:

- Conduct additional analysis of drayage truck operations and better define the daily operations and requirements for dray trucks.
- Pursue multiple technology solutions, with some focus on REEV designs – with both fuel cell and with engines as range extenders. Conduct a thorough multi-variable sensitivity analysis.
- Determine electrical infrastructure status and more accurately assess demands on the grid from various combinations of ZE truck designs in the I-710 region.
- Determine hydrogen fuel infrastructure status and determine locations for production and distribution facilities.
- Determine if roadway power infrastructure systems (e.g. catenary or in-road) can be deployed in a “convenience charging” manner, to support REEV designs that are not infrastructure dependent. Investigate specific routes or applications for these technologies.
- Fund demonstration programs for prototypes of BEV, and REEV trucks, and determine if future PHEV designs can meet the project requirements.



- Work with public agencies to develop appropriate legislation and funding mechanisms for incentives/subsidies.

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.

Several paths of parallel activity are required. They are to conduct:

- 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 development for ZE drayage trucks
- Enhanced operational and business case assessment
- Fleet training, maintenance training, and decision support

1.0 ISSUE AND STUDY SCOPE

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 (VOCs) and several air toxins can also be classed as pollutants, including carbon dioxide and other greenhouse gases. Emissions from power generation

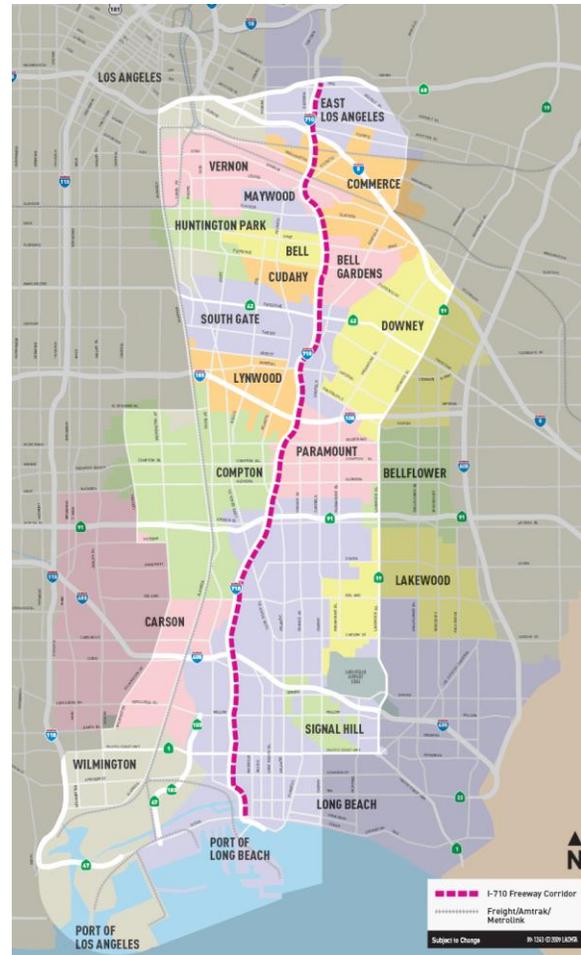


Figure 1 I-710 EIR/EIS Corridor Study Area



and distribution, fuel generation and distribution, and manufacturing process (or the ultimate disposal of the used vehicles) are ignored in this report.

Metro retained CALSTART to assess the commercial viability and development requirements for truck-based technologies that would fulfill the commitment embodied by the Project Alternatives that involve zero-emission goods movement. This report assesses the technologies needed for trucks with zero emissions, the feasibility of creating and synthesizing that technology, and identifying the barriers to commercialization. The recommendations of the report will identify the next steps that should serve as a preliminary roadmap for ultimately commercializing zero emission (ZE) trucks.

This report will outline the stages and work efforts needed to address the barriers identified, and set in motion the process to achieve a zero-emission freight corridor.

SCOPE

The task undertaken by CALSTART in partnership with Cambridge Systematics, as part of the Gateway Cities Strategic Transportation Plan (STP), was to examine the technologies and approaches that could enable a truck to move cargo containers with zero-emissions within the I-710 Corridor (see Figure 1 above). **For this revision of the original report, a review of any potential new technologies was conducted, along with updates to the previously outlined technologies, as may have occurred in the period between the last report and the writing of this one.**

The I-710 Corridor Project is making consideration for electrical power in the infrastructure of the roadway, and other options for fueling infrastructure must be considered in the overall design. CALSTART was therefore also tasked with conducting a high-level initial examination of infrastructure options and design elements as they would pertain to supporting the zero-emission truck technologies.

This report builds on practical industry knowledge of zero-emission and advanced vehicle technology, as well as commercialization processes implemented by CALSTART. This framework outlines a multi-year process for commercializing zero-emission goods movement vehicles using the I-710 Corridor.

2.0 APPROACH

For this work, CALSTART combined our broad knowledge of technologies with the findings from more than 8 interviews of truck industry experts within manufacturers and technology suppliers. In addition, we are incorporating the extensive CalHEAT program findings and roadmap, which explicitly defined 66 Actions to accelerate market transformation for medium- and heavy-duty trucks.



CALSTART contacted key individuals, usually engineering or research and development (R&D) executives, from technology developers, suppliers, and truck. The actual interview questions (interviewer guide) used is provided in Appendix A.

The CalHEAT report is available here

(http://www.calstart.org/Libraries/CalHEAT_2013_Documents_Presentations/CalHEAT_Roadmap_Final_Draft_Publication_Rev_6.sflb.ashx) and was based on a 3 year long process involving multiple industry stakeholders, technology experts, manufacturers, users, and regulators. The in-depth analysis led to a list of very specific steps on a well-defined timeline, with funding estimates – all focused on changing the market for medium- and heavy-duty trucks. The sections relevant for zero-emission drayage are included in section 2.2 below.

2.1 INDUSTRY EXPERT INTERVIEW FINDINGS

CALSTART analyzed the information from all the interview responses, compared this to our understanding of current industry conditions, and then developed key findings. Below is the summary of findings uncovered through this research effort:

2.1.1 TECHNOLOGIES UNDER DEVELOPMENT

The industry experts and their respective companies have examined many of the potential technologies in this report. Each company had different product plans, and saw the development roadmaps slightly differently. In general, the following themes were common to the interviews:

- Electricity (with batteries) and Hydrogen are the drivers of zero-emission operation. These two fuels are the only approaches to 100% zero-emissions operation that can be considered within the timeframe of this report.
- Battery technology development is well understood. In the timeframes of this work (up to 2025) no one saw major deviations from the well-defined path for battery technology development. As with any field of technology application, there is always the chance for a disruptive technology. None of the experts denied this potential, but none were planning for such breakthroughs. There is a clear path forward in battery refinement, with improvements in energy density, and more significant improvements in manufacturing and packaging. The ICCT Report (<http://www.theicct.org/zero-emission-trucks>) has a good summary of this pathway. Reliability will go up, costs will come down, but those changes are already incorporated into company plans and product development decisions.
- Similarly, fuel cell technology development is well understood, and developments are will be in the areas of increased reliability and value-engineering. No disruptive



leaps in technology are foreseen. Costs are trending downward, but will remain high. As with batteries, gradual improvements will lead to somewhat lower costs, improved field operations/reliability, and slightly smaller packages, as outlined in the ICCT report (<http://www.theicct.org/zero-emission-trucks>).

- Vehicles with electric drive (meaning all hydrogen and most electric hybrids) are standardizing on a 600V operating bus. Basic electro-physics requires this given the amounts of power that are being utilized. Some technologists have lower-voltage systems, which require larger conductors to deliver the required current. Although there is still some engineering dispute and variations do exist, the trend is clear and hence efforts to improve subsystems and components operating on 600V are an important area for future development.
- Catenary (or In-Road) infrastructure is felt to be possible but problematic. All experts could see the benefits of providing roadside power, but most questioned the cost of such a system, and how it could cover the necessary travel routes. Many suggested having roadway power at on-ramps or hills, to provide an energy source when it was most needed for acceleration or high loads. Some felt technology developments would render the catenary unnecessary by the end of the project timeframe (2025 or later), and many felt that other alternatives for charging were more economical.
- Natural Gas is a major focus for all truck makers in 2013. While not a ZE technology, the regulatory push in California for Low NOx engines, plus the current low cost and large supply of natural gas, is driving everyone to develop NG solutions. More on this topic in the “Developments in Near Zero Emission Technologies” Appendix D.

2.1.2 CHALLENGES IDENTIFIED

The cost of components, and hence the final truck (capital) costs remain a significant challenge. As outlined in the ICCT report (<http://www.theicct.org/zero-emission-trucks>) the trends in battery technology and fuel cell technology imply costs will come down but remain well above existing diesel costs (even with advanced emissions controls). The most important challenge to accelerating ZE Truck development is not costs, however, but marketplace demands. How each manufacturer sees the market dictates their product planning, and therefore their allocation of resources.

- No major truck OEMs are developing zero-emission Class 8 trucks. Nearly all have trucks under development that enable some operation in ZE mode, but all are designed to maximize fuel economy. The OEM bias to Fuel Savings (or Engine-Off Time) is driven by what the companies see as the broad market demands – they see a push for fuel economy, not zero-emissions. Hence, most products under development will not meet a target of 20 miles ZE operation. The OEMs would have



to be convinced there is a demand, requirement, regulation, or other significant market push that only ZE operation can satisfy, in order to change the focus of their development.

- Several OEMs are working on REEV designs, but as mentioned, are designing those systems to maximize fuel economy, not to operate in ZE mode. Battery sizing, and driveline system controls are focused on fuel economy, not emissions reduction, not ZE operation. Costs are lower with this focus, which adds to their belief such an approach is the most broadly viable.
- Smaller manufacturers and specialty technology suppliers are working on fully ZE truck designs – BEV and Fuel Cell REEV trucks. These companies currently do not have the capacity to build sufficient trucks to meet the 2025 plans, but could partner with larger OEMs if the market demand were to materialize.
- Low NOx and Natural Gas are occupying much of the OEMs engineering and product planning resources currently, as that is seen as the current broad market direction. This is an opportunity for near-zero emissions developments, or for REEV applications, but will displace ZE development unless all aspects of market demand for ZE Trucks are clearly defined and communicated.
- The development of modular architectures with a REEV chassis design would enable significant innovation. Many experts ideally envision an ability to swap out modular battery packs (from any maker) or to add a fuel cell pack with H2 storage, or to increase or decrease onboard energy storage as needed. The electric drivetrain and power electronics would remain the same and adapt to the energy storage/delivery mix. However, no single entity could effectively design such modularity – it will require standards and engineering effort from a broad coalition or industry group (e.g. the SAE and/or IEEE).
- Sales volume potentials are a critical parameter. Some OEMs do not even define a specific “drayage” segment of the Class 8 market. Many see a Class 8 truck as one that could do drayage, but could also travel across the country with no changes (except for the day cab of a dray truck, of course). For attention to be placed on drayage specific trucks, and then on zero-emission drayage trucks, the total market for drayage trucks has to be defined. Other parts of this project will define the Key Performance Parameters for a ZE Drayage Truck. But what of sales potential? What is the I-710 corridor sales volume opportunity (per year)? What is the National demand? What is the worldwide demand? How many trucks per year can each company expect to sell, over a 10 year period (say 2020-2030?). Such data is necessary before any OEM will commit development resources.
- The number of trucks that would constitute “sufficient potential” varies, but around 1000/year (for each manufacturer) is felt to be enough of a market to be interesting, presuming that market would exist for 5 or 10 years. Extrapolation can result in an estimate of 30,000 trucks over 10 years (say 2020-2030). That is three times the

number of port drayage trucks in the I-710 area, so evidence of demand in other regions is necessary.

- Costs for a full BEV (fully zero-emission) truck are not expected to go below \$250,000 even past the 2025 time frame of this report. (<http://www.theicct.org/zero-emission-trucks>) The ICCT findings are supported by our much broader expert interviews. The same is true for fuel cells.

2.1.3 OPPORTUNITIES UNDER DEVELOPMENT

As mentioned, virtually all the truck OEMs, and many smaller technology suppliers, are working on designs that include electric drive and the ability to operate in a zero-emission mode. Some are PHEV designs, most are REEV designs, and just a few are BEV or Fuel Cell. BEVs and Fuel Cell REEVs are under development in the US and Europe.

- The major OEMs are focused on PHEV and REEV platforms. These truck designs could potentially be adapted to greater zero-emission operation. Additional energy storage (battery) capacity, and control system changes would enable increased ZE range. In order to undertake these efforts, however, the OEMs would have to be convinced of the demand for and potential sales of such a truck.
- Catenary systems are planned for demonstration in the Southern California SCAQMD basin. Trucks that are Battery-Electric Hybrid (under 20 miles ZE range) design and also a full BEV, are being prepared to accept a “conversion kit” to enable catenary power pickup. Concerns have been expressed that the conversion kit costs could be over \$100K per truck – an incremental cost that would not provide benefits over other ZE methods since the trucks already have to be advanced hybrids. Actual costs are not known at this time, so as the project moves forward more information will be available.
- There is general agreement ZE Trucks can be ready for commercialization by 2015 to 2018. Larger OEMs are more conservative, smaller firms feel the earlier dates are possible. All agree the critical steps include more demonstrations, and validation of reliability and serviceability.

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 2010.¹ 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.

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



Table 2-1 Truck Makers New Technology

Company	Activities
Kenworth	Focusing on Class 6/7 trucks. Includes REEV truck. Technologies may transfer well to Class 8.
Navistar	Investigating parallel hybrid trucks using Meritor drivetrains. Developed Class 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.

Table 2-2 New Technology and Truck Makers Source: CALSTART

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 Class 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 Class 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 (Class 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.

2.2 CALHEAT FINDINGS

The CalHEAT program is a major effort funded by the California Energy Commission (CEC) to define the roadmap for hybrid, efficient and advanced trucks. The Final Project Report (Draft Feb 2013 – available at this link:

http://www.calstart.org/Libraries/CalHEAT_2013_Documents_Presentations/CalHEAT_Roadmap_Final_Draft_Publication_Rev_6.sflb.ashx) lists 66 Actions to accelerate market transformation of medium- and heavy-duty trucks. Several of these actions directly relate to Zero Emission Drayage Trucks. An integration of the CalHEAT Roadmap and Implications for Zero Emissions Goods Movement is provided below.

One of the most important new developments impacting the commercialization of zero emission goods movement vehicles in California was the development and publication in 2013 of a technology and market roadmap for trucks by the California Hybrid Efficient and Advanced truck (CalHEAT) Research Center. The CalHEAT Center was funded by the California Energy Commission (CEC) and did substantial research and modeling to understand the makeup of the current truck and goods movement market in California, its climate and criteria emissions impact, what technologies are becoming or can become commercially available to reduce those impacts, and what specific technology strategies



will have the most impact on the long term issue. A blue ribbon Advisory and Steering Committee and Technology Advisory Group supported the Center's work.²

Electrification

- Hybrid Electric
- Electrified Auxiliaries
- E-Trucks
- Electrified Power Take-off (EPTO)
- Plug-in Hybrid Electric
- Electrified Corridors
- Alternative Fuel Hybrids

Engine and Driveline Efficiency

- Hydraulic Hybrid
- Optimized Engines for Alternative Fuel
- Waste Heat Recovery
- Engine Optimization
- Alternative Power Plants and Combustion Cycles
- Transmission and Driveline Improvements

Chassis, Body, and Roadway Systems

- Light-weighting
- Aerodynamics
- Lower Rolling Resistance
- Intelligent Vehicle Technologies, e.g. Forecasting, Adapting
- Corridors and Platooning
- Longer, heavier single trucks

CalHEAT's "Research and Market Transformation Roadmap for Medium- and Heavy-Duty Vehicles" (Roadmap)³ quantifies what is required for the state to meet its carbon and criteria emission reduction goals, identified the core technologies needed to achieve those goals in trucks and buses, and then developed a series of specific actions and investments needed over the next ten years to move low emission and low carbon truck technology that can meet California's multiple policy goals into commercial production.

The Roadmap characterized three major technology pathways that California needed to pursue, consisting of 19 different technology strategies needing to

move forward in commercialization to achieve the state's goals. Of those 19, CalHEAT developed detailed action steps for 13 of the strategies where it was felt the state could use its assets best. All three pathways contain elements that are important to commercializing the zero emission drayage capability, but the most critical early actions stem most from the Electrification and Engine and Driveline Efficiency pathways.

It's important to note that no one entity or agency must alone try to accomplish or perform all the actions identified in the Roadmap. Indeed, it is critical to leverage and build on projects and investments being made by several agencies to drive new technologies; but it is equally critical to include attempt to build out all or most of the projects and technology stages as outlined in the roadmap to assure that all the supporting capabilities are being developed in line with core functions. An example would be electrified accessories: it will make little sense to try and develop fully electric drivelines for trucks without also developing commercially available accessories for electric steering, braking and other accessories – otherwise the vehicles will remain too expensive and have higher maintenance costs.

² CalHEAT Advisory Committees <http://www.calstart.org/Projects/CalHEAT/Research-and-Market-Transformation-Roadmap/CalHEAT-Committees.aspx>

³ Research and Market transformation Roadmap for Medium- and Heavy-Duty Vehicles", CALSTART, February 2013, <http://www.calstart.org/Projects/CalHEAT/Research-and-Market-Transformation-Roadmap.aspx>



CalHEAT identified technology strategies that are of value to specific ways trucks are used, with drayage trucks falling under the Class 7-8 Urban category. Those strategy impacts are highlighted in the following chart.

Promising Technology Pathways by Truck Category (from CalHEAT Roadmap)

Pathway	Technology	Class 7-8 Urban	Class 8 OTR	C 3 – 8 Work Site	Class 3 – 8 Urban	Class 3 – 8 Rural	Class 2b – 3 Vans/trucks
Electrification	Hybrid Electric	●	◐	●	●	●	●
	Electrified Auxiliaries	●	●	●	●	◐	●
	E-Trucks	●	○	◐	●	◐	◐
	Electric Power Take-off	○	○	●	○	○	○
	Plug-in Hybrids	●	○	●	●	●	●
	Electrified Corridor	●	○	○	◐	○	○
	AF Hybrid	●	◐	◐	●	●	◐
Engine and Driveline	Hydraulic Hybrid	◐	○	○	●	●	●
	Optimized AF Engine	●	●	●	●	●	●
	Waste Heat Recovery	●	●	○	●	◐	◐
	Engine Optimization	●	●	●	●	●	●
	Alternative Power Plants & Combustion Cycles	●	●	◐	◐	◐	◐
	Transmission and Driveline	●	●	●	●	●	●

The 13 technology strategies deemed most feasible by the CalHEAT research are shown in this chart. Solid circles represent the technologies in the Roadmap that are expected to contribute to noticeable CO₂e reductions by 2020. Half circles represent technologies expected to be implementable after 2020 with noticeable results. The empty circles indicate technologies not expected to offer significant results in that truck category.

Pathway	Technology	Class 7-8 Urban
Electrification	Hybrid Electric	●
	Electrified Auxiliaries	●
	E-Trucks	●
	Electric Power Take-off	○
	Plug-in Hybrids	●
	Electrified Corridor	●
	AF Hybrid	●
Engine and Driveline	Hydraulic Hybrid	◐
	Optimized AF Engine	●
	Waste Heat Recovery	●
	Engine Optimization	●
	Alternative Power Plants & Combustion Cycles	●
	Transmission and Driveline	●

Now, looked at specifically for drayage and down-selecting categories that are the most salient (and therefore the commercialization actions and stages most needed) for zero-emission goods movement are:

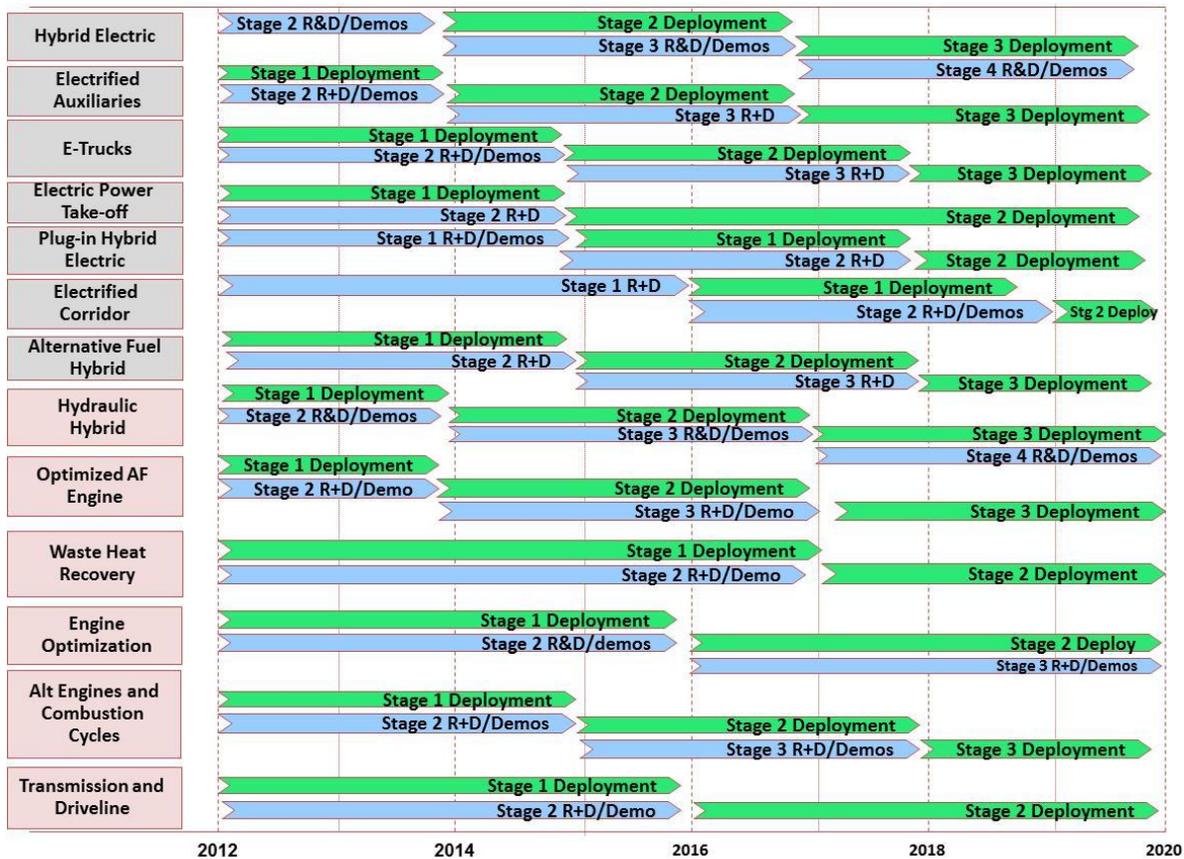
- Hybrid electric
- E-trucks
- Plug in hybrid
- Electrified corridor
- Alt fuel hybrid

In a supporting role:



- Electrified auxiliaries
- Optimized alt fuel engine
- Alternative power plants and combustion cycles (such as fuel cells and turbines)
- Engine optimization.

The CalHEAT Roadmap has developed in-depth technology and market stages for each of these categories, outlining specific demonstration projects, performance expectations and needed investments for each of these categories. To guide the needed next stages over the next five to ten years for achieving a zero emission goods movement capability by 2025, the Roadmap shows the clear actions needed immediately and is a strong foundation upon which to build a commercialization plan. Viewed in its highest level, this is the overview:



Source: CalHEAT

The Roadmap lays out a series of “stepping stones” for all its technology categories, and these steps – taking the form of focused, fast-paced actions over time that move technology through several increasing stages of capability – are highly instructive for guiding the next ten years of work to achieve a commercial zero emission drayage truck. Commercialization is a complex process: it normally involves a series of overlapping

activities and stages to achieve a specific product. In the case of zero emission goods movement, specifically looking at a zero emission drayage vehicle, it will likely involve moving the commercialization process through several different stages of capabilities to reach the final desired goal. Stated another way, the first investment is not always in a demonstration of what the final product must be, but rather in the next stage through which the technology must progress to reach the final product. For each “stage” CalHEAT’s Roadmap lays out different actions that can be used to drive technology to the deployment phase.



As raw material for a future zero emission drayage truck commercialization plan, the following table summarizes the “rolled up” CalHEAT actions for those specific technology strategies that can assist in driving a zero emission drayage truck capability.

Top Priority CalHEAT Actions Salient to Zero Emission Goods Movement Truck Commercialization Source: CalHEAT

Tech	Action	2014	2015	2016	2017	2018	2019	2020
HEV	<i>Develop and Pilot</i>		Down-sized engines integrated for hybrids					
HEV	<i>Pre-Comm Demo and Deploy</i>	Stage 2 hybrid (OBD, lower costs) demo	Deploy 1000 stage 2 hybrids			Demo more-electric OTR hybrid truck		
E-Trucks	<i>Pilot</i>	Smart Charging systems						
E-Trucks	<i>Pre-Comm Demos</i>	Stage 2 E-Trucks, improved integration, for goods movement	Lower cost Stage 3 E-trucks, longer ranges & fast charging					
E-Trucks	<i>Deployment</i>		1000 Stage 2 E-trucks on road					



PHEVs and Electric Corridor	Pre-Comm Demos and Deployment	Demos of PHEV goods movement and drayage trucks; also 2B; corridor power connection device	Demos of dual-mode hybrid & range extended electric drayage	Support for first 500 PHEVs when available; Stage 2 Class 7/8 PHEV dray trucks		Support for dual-mode hybrid and range extended electric dray trucks		
AF Hybrid	Develop & Pilot	Develop lighter CNG tanks	Pilot evaluations of alt fuel hybrid vocational trucks	Pilot demos of alt fuel hybrids with down-sized or low NOx engines				
AF Hybrid	Pre-Comm Demos & Deployment	Demo of two new platforms of NG/hybrid drayage truck meeting ZEV Corridor requirements	Support 200 NG hybrid vocational trucks			Support for 100 NG hybrid drayage trucks		
Elec Accessories	Develop & Pilot	Develop purpose-designed electronics, systems for vehicle integration	Validate e-auxiliaries in Class 7-8 tractors, and other trucks					
Optimized AF Engine	Develop	Develop small AF engines	Develop higher efficiency AF engine strategies					
Optimized AF Engine	Pilot & Pre-Comm Demos	Pilot light weight NG tanks on vehicles		Demo 80% decreased NOx engines;				
Optimized AF Engine	Deployment		Support for 1000 Stage 2 engines (high efficiency)	Incentives for 200 low NOx line haul trucks	Incentives for 200 80% low NOx dray trucks			
Alt Power & Combustion	Develop & Pre-Comm Demos	Leverage transit investments in fuel cell that have truck uses	Develop new combustion engines, purpose-designed turbine	Pilots and demos of new combustion engines/turbines				
Alt Power & Combustion	Deployment			Incentives for 100 Stage 2 tech drayage trucks		Incentives for 100 stage 3 drayage trucks and 200 line haul		



Engine Optimization	<i>Develop & Pilot & Pre-Comm Demos</i>	50% reduced NOx engine		Pilot 50% brake thermal efficiency engine	Incentives for 200 50% Nox reduction, 1.5X efficiency engine	Pilot 55% brake thermal efficiency engine	Demo 55% efficient engine, double vehicle efficiency, 50% NOx reduction	
---------------------	---	------------------------	--	---	--	---	---	--

In the above table, items in green are already being funded in some early stage projects; items in blue are good candidates for California Energy Commission, Port TAP or air district funding. Items in yellow could represent ARB incentive funding, or funds from Prop 1B or cap and trade revenues.

The actions outlined above were developed at a higher level than for a specific truck – they were assembled to drive a higher level capability across several classes of trucks. To develop a more specific commercialization and roll-out plan specifically for zero emission drayage trucks will require an additional level of evaluation and customizing of the actions, and assembling details on a slightly revised (extended) timeline. Nonetheless, CalHEAT’s Roadmap will be one of the primary guides in the development of the commercialization plan for the zero emission goods movement trucks for the I-710 and South Coast region.

3.0 TECHNOLOGIES

The key findings in this section describe which technologies are available, what developments are coming, how far a technology is from demonstration, and how far from production and commercialization a final design may be. The findings indicate that zero-emission trucks can be powered by a variety of energy sources. Each technology presents certain opportunities, but each faces hurdles to commercial success, particularly given the long-standing and entrenched status of the incumbent technology – diesel trucks.

3.1 DUAL MODE HYBRID ELECTRIC VEHICLE (HEV)

A Hybrid Electric Vehicle (HEV) has a diesel, CNG, or other conventional engine as the primary driver of the vehicle. Dual Mode indicates the ability to operate in a zero-emission mode as well as conventional mode (engine running, creating emissions).

Dual-Mode, in this document, means a Hybrid Electric Vehicle (HEV) that can run as an EV-only for a limited period, such as the 17 miles of the I-710 corridor. Speed limitations were often mentioned as a challenge – in EV-only mode the same issues as with a full battery-electric vehicle (BEV) apply – large electric storage capacity and large electric motor size are needed. The advantage to a dual-mode HEV is that the costly and heavy batteries do not

need to be as large as for full BEV. Battery size is also adjustable based on whether catenary or in-road power was available.

- Zero Emission Capability - Can be Zero-Emissions in the corridor (mix of zero and non-zero outside the corridor) depending on design. Natural Gas hybrids would be lower emissions than diesel hybrids when outside of corridor and running on engine power.
- Definition - A type of hybrid truck, usually a parallel hybrid, where there is sufficient battery energy storage and electric motor power to run in EV-only mode for some distance and/or up to a certain speed. Then the engine (usually a conventional diesel, or natural gas in an NG hybrid) would come on to move the truck and recharge the batteries.
- Can be combined with Infrastructure Power (Catenary, In-Road) to minimize the need for engine use, depending on design.
- Pros
 - Early stage demos have begun; based on technology ready today; zero-emissions mode available;
 - Pathway aspect of designs makes them appealing to OEMs, less costly, and potentially easier to adopt . Such trucks may have multiple uses outside corridor
 - Natural gas internal combustion engine (ICE) would be additive to hybrid technologies identified; builds on existing, known NG engines and fueling systems; can be ultra-low emissions; lowest GHG system when using renewable natural gas (RNG).
- Cons
 - Costs are greater than conventional truck, depending on battery loads, packaging, and performance needs; integration of power sources can be an issue; may require infrastructure for battery charging depending on design.
 - If engine is natural gas, NG adds to cost; limited operations outside of NG infrastructure build-out zones – but NG infrastructure growing quickly and well ahead of other alternative fuels.

EXAMPLES



*ArvinMeritor dual-mode hybrid electric truck prototype Gen 1
(Navistar Pro-Star chassis)*



Peterbilt hybrid electric Class 8 truck prototype (Eaton system)



Volvo/Mack "Granite" HEV Class 8 Tractor (in demo testing)

3.2 DUAL MODE PLUG-IN HYBRID ELECTRIC VEHICLE (PHEV)

A Plug-in Hybrid Electric Vehicle (PHEV) is similar to the Dual Mode Hybrid, but with the ability to plug into an electrical supply (the grid) to charge the batteries without the engine running. The engine is the primary driver for the vehicle, and usually a PHEV has larger batteries than a conventional HEV, theoretically enabling longer ZE-mode operation.

- Zero Emission Capability - Can be Zero-Emissions in the corridor (mix of zero and non-zero outside the corridor) depending on design. Natural Gas hybrids would be lower emissions than diesel hybrids when outside of corridor and running on engine power.
- Definition - A type of hybrid truck, usually a parallel hybrid, where there is sufficient battery energy storage and electric motor power to run in EV-only mode for some distance and/or up to a certain speed. Then the engine (usually a conventional diesel, or natural gas in an NG hybrid) would come on to move the truck and recharge the batteries. In the PHEV, the batteries can also be charged when parked and the engine is off, by connecting to the electrical grid using a cord and plug.
- Pros
 - A Plug-In HEV (PHEV) would enable engine-off use in the corridor if infrastructure power were available, and would eliminate the need to stop for recharging.
 - Use of grid electricity lowers fuel costs, and strategies to maximize battery power use would be developed to take advantage
- Cons
 - Still may have limitations on speed, power or range in EV-only mode.
 - Larger battery pack means higher initial costs

3.3 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) 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 micro-turbine burning CNG as a range extender. Alternatives under consideration include low-NOx 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

EXAMPLES



*Turbine Range-Extender Electric Truck
(Artisan/Capstone/Parker on a Freightliner chassis)*



*Turbine Range-Extender Electric Truck
(Artisan/Capstone/Parker on a Freightliner chassis)*



Eaton Diesel Electric PHEV Hybrid (Peterbilt chassis)



Seattle dual mode diesel-electric hybrid Transit Bus (Allison)

3.4 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 trade-off 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 trade-off).
- 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

EXAMPLE



Vision Fuel Cell Electric Hybrid truck

3.5 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.

Definition

- A truck with sufficient batteries on board, and a sufficiently large electric motor, to run on only battery power for some period. The truck would then have to stop and recharge (plug in) at some intervals.
- Can be combined with Infrastructure Power (Catenary or In-Road) to minimize or eliminate need for recharging.

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.

EXAMPLES



Balqon BEV Drayage Truck



Transpower BEV Drayage Truck

3.6 FUELS AND ENERGY STORAGE OPTIONS

All vehicles need a fuel, whether liquid (gasoline, diesel); gaseous (natural gas, hydrogen) or electronic (electricity). In addition, all vehicles that are required to move on their own, without connection to infrastructure, need to have some way of storing fuel onboard.

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 trade-offs 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 compressed natural gas (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.

3.6.1 FUEL OPTIONS

This section will only briefly discuss fuels that produce emissions, since those fuels are part of a pathway to fully zero-emissions trucks. They are usually the incumbent fuel, and have well established production and delivery. Please see Appendix D for more discussion of near-zero emissions developments.

Pros and cons will be presented here for fuels that can deliver 100% 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)
- Hydrogen (via fuel cells in REEV with Fuel Cell)

Diesel

The incumbent fuel has reached this position due to very high energy density. A given quantity (volume or weight) of diesel fuel carries a large amount of energy relative to other fuel options. Technologies to mitigate the emissions from diesel are advancing, but are raising costs simultaneously. Diesel could very well serve as a pathway fuel for hybrid designs moving to cleaner alternatives or full zero-emissions fuels.

Natural Gas

In both compressed (CNG) and liquid (LNG) form, natural gas is currently the fuel receiving the most development focus and funding. In particular, efforts to produce low NOx engines using natural gas are highly active. Such an engine would be an ideal range extender in a REEV design, and can serve as a pathway vehicle for moving to zero-emissions designs with greater ZE range. Distribution, delivery, and dispensing of CNG and LNG are well



understood, however larger use of the fuel in the I-710 region would require build-out of the NG infrastructure.

Hydrogen (H₂) Fuel Facts

As a vehicle 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 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.

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 (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 re-charging locations.

3.6.2 ENERGY STORAGE OPTIONS

Fuels other than electricity rely on tanks for onboard storage. Electricity can be stored in batteries or capacitors.

Fuel Tanks

- For liquid fuels such as gasoline or diesel, ambient pressure tanks can be used. These are the simplest and most familiar fuel tank systems. Neither the tank nor the dispenser use pressures above normal atmosphere.
- For gaseous fuels such as CNG or Propane, pressurized tanks are used. The pressure varies depending on the fuel and system design. Typical pressure tanks are metal with valves to control insertion and removal of fuels, and are heavier than ambient tanks. The use of such tanks in vehicles is well understood and presents minimal risk. The focus for tank designs today is weight reduction, while maintaining the necessary strength. Companies such as Quantum Technologies in southern California are leading the development of carbon fiber wound tanks and other innovations.
- For gaseous fuels such as Hydrogen and for getting greater amounts of natural gas

onboard a truck, cryogenic pressure tanks are used. These systems highly compress the gas, and the temperature of the fuel is also lowered (to about -260 degrees F for LNG), resulting in a liquid form that can be stored and dispensed with specialized equipment. For hydrogen, the current state-of-the-art is 700 bar (about 10,000 pounds per square inch or PSI). Many systems operate at half that (350 bar). Again, the challenges are reducing weight and volume.

For gaseous fuels like hydrogen and natural gas, 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. These fuels can be compressed, cryogenically compressed (low temperature and high pressure, respectively) or can be physically or chemically adsorbed into a specially designed material. Hydrogen and LNG are “off-gassing fuels”, meaning that as fuel in the tank warms up, the pressure increases and fuel must be vented at a certain point to ensure safe operation. This will 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.

Batteries and Capacitors

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, although designs vary in their focus on energy or power. Ultra-capacitors are primarily power (storage) devices. Both use similar chemical structures but due to unique design characteristics, ultra-capacitors are designed to quickly store and discharge energy.

For the applications under discussion here (large vehicle energy storage) ultra-capacitors are not being used in the designs 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 policymakers. 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.

3.7 INFRASTRUCTURE OPTIONS

Infrastructure options related to I-710 corridor ZEV truck operation include:

- Electric
 - Overhead Catenary
 - In-Road Power (contact- e.g. Volvo Slot, or wireless pad)
 - Fast Chargers (contacts overhead, roadway, or plug)
 - Battery Swapping
- H2 Fueling
- CNG/LNG Fueling

INFRASTRUCTURE TECHNOLOGY	<ul style="list-style-type: none"> ▪ Catenary Power Source
DESCRIPTION	<ul style="list-style-type: none"> ▪ Overhead wires are charged, and a pantograph device on the truck slides along it to deliver power from the overhead wires to the vehicle. The pantograph could be lowered when no operating in the corridor (dual-mode hybrid).
PROS	<ul style="list-style-type: none"> ▪ Well known technology from transit and mining operations; reduces per-vehicle costs by eliminating need for larger battery loads; could support extension of corridor benefits to other regions that add this infrastructure.
CONS	<ul style="list-style-type: none"> ▪ Additional infrastructure costs must be built into design of corridor; business structure needed for payment/use; vehicle connection system adds cost and integration to vehicle; some consider overhead wires nuisance or visually unattractive (others feel new designs are attractive).

EXAMPLES



Catenary-Powered Mining Trucks (Siemens drive system)

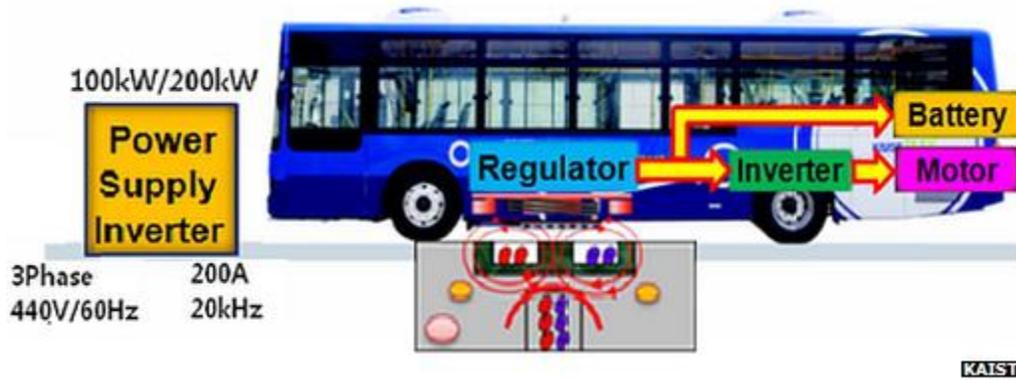


Siemens eHighways Concept (in prototype form now with diesel-electric hybrid truck)

INFRASTRUCTURE TECHNOLOGY	<ul style="list-style-type: none"> ▪ In-Road Power Source.
DESCRIPTION	<ul style="list-style-type: none"> ▪ A system of embedded wires or cables would carry electric power within the roadway. Trucks would have pick-up devices that receive power from road. Designs include “inductive” where there is no physical contact (wireless), and “conductive” where a pickup touches a conductor.
PROS	<ul style="list-style-type: none"> ▪ No “visual pollution”; technology known but less well developed than overhead power; System in Bordeaux France is highly sophisticated. Truck-based system(s) are currently under development in Europe.
CONS	<ul style="list-style-type: none"> ▪ Infrastructure costs may be higher than overhead; must be built into design of corridor; business structure needed for payment/use; vehicle connection system adds cost and integration to vehicle.

EXAMPLES





The Korean Advanced Institute of Science and Technology (KAIST) Buses. KAIST deploys these buses on a 7.5-mile route with in-road wireless charging while in motion



Bordeaux France - Alimentation par Sol (APS) is a modern method of third-rail electrical pick-up for street trams.

INFRASTRUCTURE TECHNOLOGY	<ul style="list-style-type: none"> ▪ Fast Chargers.
DESCRIPTION	<ul style="list-style-type: none"> ▪ High Current chargers that accelerate the battery recharging process. Likely located at ends of corridor for convenience and cost limitation.
PROS	<ul style="list-style-type: none"> ▪ Known basic technology; some lower power installations going in for passenger EVs; at demonstration phase.
CONS	<ul style="list-style-type: none"> ▪ Unproven infrastructure systems; unknown operational timing of use, how many chargers required; high pulse power demand on grid; possible reduction in life cycle of batteries; need additional development and validation.

EXAMPLE:



Proterra BEV Transit Bus Overhead Ultra-Fast Charger, Stockton, CA

<p>INFRASTRUCTURE TECHNOLOGY</p>	<ul style="list-style-type: none"> ▪ Battery Swapping
<p>DESCRIPTION</p>	<ul style="list-style-type: none"> ▪ 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..
<p>PROS</p>	<ul style="list-style-type: none"> ▪ 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.
<p>CONS</p>	<ul style="list-style-type: none"> ▪ 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.

EXAMPLE:



H2 Fueling

- 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.

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. The physical layout and space required for truck processing must be considered in future projects on infrastructure.

It is possible a business model similar to CNG could be used, where the station cost is absorbed by the distributor based on a promised level of fuel throughput and hence profitability. Location and access to hydrogen fuel have to be assessed, determined and analyzed. 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.



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



**Typical Onsite Compression, Dispensing,
and Storage Equipment for H₂**



CNG/LNG Fueling

Some ZE-Capable truck architectures will create emissions some of the time, using fuels that are not 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. A need exists for greater build-out of CNG/LNG infrastructure for both distribution and dispensing, but we do not believe CNG infrastructure costs will impact the I-710 ZE Truck Commercialization project and more detailed evaluation can be left to other entities and future analyses.

4.0 CHALLENGES

A majority of the experts in the Delphi interview group said more Research and Development (R&D) was needed. A significant minority, however (about 1/3) felt there was no need for more basic R&D in zero-emission trucks. This minority felt design and product engineering are now the main focus. Recognizing the makeup of the Delphi expert group, with a predominance of engineering managers, adds insight to these findings. Engineers generally prefer additional R&D, and are reluctant to say a technology is “ready” unless it truly is set for commercialization. The large minority who felt ZE technology needed no further R&D supports the conclusion that many zero-emissions truck technologies have moved into Product Development (e.g. on the path to commercialization).

A number of challenges to be overcome were identified. These can be grouped into 3 primary categories, discussed here in order of increasing importance – Design Factors, Costs, and Economic/Business Case:

4.1 DESIGN / DEVELOPMENT

- Battery Weight/Volume.
- Infrastructure (fuel/energy storage and distribution).



- Specifics of User Needs.
- Durability testing.
- Internal Resources/Manpower.
- Development Costs

These barriers are all factors that have to be considered in the design of the truck and/or the system in which the truck operates. In some cases (battery weight) there are technological issues that force trade-offs (full EV operation means large batteries, potentially cutting into payload – a classic engineering balancing act). In other cases they limit the speed with which deployment and commercialization can occur (durability testing cannot be accelerated; H2 infrastructure roll-out is not under the control of fuel cell truck makers). Others are simply normal development factors that have not yet been addressed in this application (specifics of user needs) and therefore are a “barrier” to deployment. Similarly, internal resources in a company are allocated to projects based on the views of company executives, which will change over time.

The most important of these is the Infrastructure issue, as a chicken-and-egg situation must be avoided for successful development of ZE trucks. In terms of truck development, infrastructure development would be a key signal to the OEMs that serious demand is being created and that would support their allocation of resources.

To some interviewees, development cost was not a problem. Others felt it was the biggest single barrier. In general, the challenges of battery technology and fuel cell technology were the drivers of development costs. Advanced drivetrain engineering is still a young profession, and there is a shortage of skilled and experienced engineers. Separate from the costs of the materials themselves, there is a development learning curve and each company is at a different point on the curve and hence has a different view of the costs.

4.2 COSTS

Costs can be broken down into four categories. Three apply to the trucks themselves, the fourth is infrastructure.

- Materials/Component cost.
- Capital (Up-Front) cost
- Operating Costs
- Infrastructure Costs

Materials/Component Cost

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 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.

The costs for fuel cells are still quite high, but are also expected to fall significantly. 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

There are also supply chain issues for all advanced truck components, due to low production volumes and capacity. There is a ramp-up period to expanding and growing this supply chain, and is the basis for those who feel that selling more hybrid trucks is an essential precursor to a full BEV truck.

Capital (Up-Front) Costs

The combined materials and development costs impact the selling price of the trucks, and hence the up-front costs. The Commercialization Report will conduct some very simplistic analyses to examine incentive amounts necessary to compensate for increased capital costs. In some cases, with the BEV being the most expensive, the trucks can cost 3 to 4 times as much as a conventional diesel. Greater ZE truck volumes, and greater volumes of component parts, would lower costs.

Operating 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. An essential element of ongoing demonstration projects should be to collect Operating and Maintenance costs so these factors can be better estimated.

Infrastructure Costs

The Final Commercialization Report will include a very simplistic analysis of infrastructure costs. The split of costs between the infrastructure and the truck itself must be further investigated (beyond the scope of this report, but an important area for further work). A catenary system could slightly lower the cost of the truck (by allowing somewhat smaller batteries for full EV zero-emissions operation) but would raise the infrastructure costs and the overall system costs significantly.

4.3 ECONOMIC/BUSINESS CASE

While additional product and engineering development is vitally important, the broad area of defining a sustainable Economic/Business Case was, without question, the single biggest challenge to be addressed for moving ahead in truck development.

A majority of concerns and challenges voiced by interviewees, and by the research investigation, were centered on defining the business case for 3C trucks, and the economic and operational framework for the operation of a “ZE Corridor” itself. Developing the economic framework, market mechanisms, and business cases are one of the key next steps to ensure progress will be made on the technologies, and on vehicles using those technologies.

The economic/business case issues identified can be separated into the following categories:

- Market Demand (Customer Pull, Affordability, Need).
- Potential Volumes over Time.
- Corridor Market Mechanisms.
- Potential Regulation and Legislation.
- Petroleum/Diesel Fuel Prices.

The above categories will be covered individually. However they do work together as a combined set of parameters that need to be addressed in a unified way – as an “ecosystem” for the successful production and use of these vehicles. For example, fuel prices are a contributing factor in determining what customers will pay for a hybrid truck, which affects demand and favors certain technologies. Regulations may force some users to adopt certain technologies but regulations alone may not create a large enough market base to support an OEM program. Current goods movement economics are “lowest cost possible” and do not apply any monetary value to zero-emissions, limiting demand for a more costly ZE truck (or even a 2010 emissions diesel truck).

MARKET DEMAND

Ultimately, a truck is produced, sold, warranted, and maintained by an OEM. While technology developers and suppliers were more certain of the need for their products, the OEMs remain focused on customer demand. All the OEMs, and some suppliers, are saying there has to be a match between the costs of these vehicles and a sufficient number of customers willing to pay that price. No OEM will move past prototype stage unless they can see a match between their costs, market demand, and potential profitability.



In particular, OEMs are not focused on developing zero-emission trucks. Even those who have designs that could achieve zero-emissions, the development focus is on fuel economy. Low-NOx natural gas is another driveline being aggressively pursued by the OEMs. For any of them to shift to ZE truck development, clear demand and an ongoing market will have to be proven.

Based on current prototype designs, and estimating the retail prices were those designs to enter production at existing volume projections, the OEMs see prices from \$150,000 to \$300,000 (50% to 200% greater than current conventional trucks). All the interviewed experts questioned how many buyers there would be at such high prices. This question then led to discussion of incentives (state or federal) as a way to reduce the incremental costs until volumes increased to a level where costs came down.

For costs to fall sufficiently, it is likely the volumes needed would have to be higher than current projections for the I-710 corridor market alone, even in 2035 sales forecasts (note this is not the same as truck traffic forecasts or container volume forecasts). Therefore, incentives can be only one part of the solution. Another key need is a clear identification of how many trucks would be purchased, and over what period – in the I-710 corridor and in all other possible use areas – other ports, other short-haul operations, potentially nationwide and globally.

POTENTIAL VOLUMES OVER TIME

All the interviewed experts were looking past this specific project to the larger potential market for a ZE-capable Class 8 truck. Even if the eventual market is larger, the I-710 project would be the first deployment of ZE drayage trucks, and requires a valid stand-alone business case. Therefore, the current and future vehicle sales volumes in the corridor are critical. A few interviewees felt the sales volumes in the corridor were simply too small, while others felt a few hundred trucks per year were enough to justify moving ahead. A better definition of the potential purchase volumes and buying patterns was desired by all respondents. After the I-710 market itself, a further expansion of the potential market to other corridors and other uses was another needed step to build the business case.

In addition to the basic volumes, an estimate of the turnover rates in the potential buyer fleets is critical. If the total new ZE truck sales potential in the I-710 region is, for example, 9000 vehicles, but drayage companies have a 12 year replacement cycle, that means fleets only buy 750 trucks/year. Will that be enough sales/profits to support moving ahead? Other estimates have the potential sales volume significantly higher. The upshot is that well-supported sales forecasts are essential to the project. On top of the volumes, the timing of the purchases needs to be discussed with trucking companies, who need to plan their regular turnover of vehicles, and the impact of recent Clean Truck purchases. Theoretically there is a good alignment for when those trucks will be nearing the end of their lifespan and the arrival of ZE trucks from this project effort.



CORRIDOR ECONOMIC MARKET MECHANISMS

Linked to the behavior of the potential buyer fleets is the economic market mechanisms in which they operate. Many respondents were concerned that the current drayage market, including the I-710 corridor, is a “lowest cost possible” operation, with estimates of \$100/container for the trip from the ports to the rail yards. As was seen in the Clean Trucks Program implemented by the ports, there is a decentralized set of players who express great resistance to change and focus on minimal costs, rapid turns, and market-driven freedom of choice (even if that choice carries negative social and environmental impacts – economic externalities). In addition, would the ZE Corridor change the market dynamics for the San Pedro ports, making them more costly than other west coast ports (a bad outcome) or improving their speed and efficiency (a good outcome)?

Before the above two barriers (market demand and sales volumes) can be addressed, the larger economic market mechanisms must be addressed. There have to well defined mechanisms that can monetize for users and manufacturers the benefits of zero-emissions goods movement; and/or monetize the costs or consequences of not implementing the technology. The market stakeholders include the ports, shippers, railroads, truck drivers, truck owner-operators, and warehouse operators, consolidators, trucking fleets, unions, business associations, communities, regional governments and other entities in the regional goods movement value chain.

The drayage market ecosystem, particularly in the San Pedro Ports and I-710 Corridor, is very complex. The Port’s Clean Air Action Plan and Clean Truck Program have begun a shift in the types of trucks used and in the economic ecosystem. Previously, the drayage market was defined by owner-operators driving \$3000 very old used trucks for \$100/container-trip. Those old and dirty trucks are no longer allowed in the ports, but may still be used elsewhere in the I-710 Corridor. The shift from clean trucks (MY2007 and newer) for port access, to Zero-Emission trucks for the entire I-710 Corridor, will be an even greater change in market dynamics. Major revisions of the existing economic ecosystem will be required for zero-emissions trucks at \$200,000+ to become the primary means of moving goods in the corridor. All Delphi experts interviewed, in some fashion, defined this challenge as a significant barrier to accelerated progress on ZE trucks. Put another way, as a key finding of the work summarized here: ZE goods movement can be successful and can be implemented in the I-710 corridor, but only if the “economic ecosystem” issues are addressed and new economic/market structures developed as part of the truck commercialization process.

POTENTIAL REGULATION AND LEGISLATION

As with the Clean Trucks initiative, it could be that a regulatory process would partially drive the adoption of ZE trucks. Emissions requirements set down by CARB or the South Coast AQMD could mandate changes. “Backstop” regulations could be used, where a future date is set for regulatory action, encouraging development in advance of the forced deadline. Legislation such as the Low Carbon Fuel Standard could create economic



incentives for moving to advanced trucks. Federal action, such as carbon trading markets, which put a price on carbon emissions, has the potential to drive change. Additionally, a Federal or State gas tax change would impact fuel pricing. Several respondents saw the avenue of regulation/legislation as the most likely route to change. The preliminary nature of the corridor, combined with unknown regulatory drivers, pre-commercialization technologies, and fuzzy long-term forecasts for oil prices all result in great uncertainty - inhibiting decisions. While some see regulation/legislation as a solution to some barriers, the uncertainty of that avenue is a challenge in itself.

PETROLEUM/DIESEL FUEL PRICES

Some interviewees saw fuel prices as a major concern, while others were equally clear that fuel savings did not always drive the decisions of this market. Most agreed that as diesel rose above \$5.00/gallon, the demand for alternatives would increase. How that factor will impact a business case for deciding to develop ZE trucks was less clear. The Final Commercialization Report will make some assumptions on petroleum prices based on the best available data, but those are still estimates in an uncertain market.

Those in the “major impact” camp say that low fuel prices hurt the business case because it is much harder to make up the incremental cost via fuel savings. In most instances, fuel savings is a critical reason to adopt advanced technology. Emissions are a concern only as it relates to fuel savings, and that choice is usually driven by regulation/legislation. The expectation is that fuel prices will rise, as they are now, but predicting the speed and timing of fuel price changes is a well-known challenge, making it hard to build into a valid business case 5 or 10 years out. Furthermore, no one knows the point at which drayage fleets will decide diesel costs too much and look for alternatives.

Those who feel fuel price is not a factor cite the larger economic market mechanisms. It is the truck driver (or truck fleet, or potentially the shipping company) who have to absorb fluctuations in fuel costs. Even as prices pass \$4.00/gallon, the \$100/container price remains constant and other means are found to compensate – using older, cheaper trucks; paying drivers less; skimping on maintenance. These respondents feel the drayage economics are bigger than the price of fuel alone. Hence, the demand for ZE trucks in the I-710 corridor will be driven by the market mechanisms and regulation/legislation, not fuel cost

5.0 OPPORTUNITIES

While achieving the outcomes desired 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. The business case has to be fully developed to prove the advantages to the various stakeholders. The 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.

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.

5.1 FEASIBLE SYSTEM DESIGNS

All products, including heavy duty trucks, go through a development process with defined steps. As has been discussed elsewhere, skipping steps is not possible if a product is to be successful (although steps can be combined or shortened). CALSTART uses the following stages to define the required steps for truck technology advances:

- Research & Development
- Prototype
- Demonstration
- Production Intent
- Pre-Production
- Commercial Production

The ultimate goal is commercialization, or full commercial production. OEMs move methodically through each development phase, conducting engineering and financial analyses before proceeding to the next phase.

All of the advanced truck technologies discussed in this report, if provided with focused support and funding, would be able to reach Demonstration phase within 5 years. Some are already in Prototype form, some are approaching Demonstration phase, while others have yet to reach a Prototype. Commercial Production is further away, but again, with the right actions and funding, all could reach commercial production within the project timeframes.

The interaction of technologies and infrastructure is also a factor to consider. As mentioned previously, this report does not attempt to examine infrastructure options, timing, specific costs, or challenges. A thorough multi-variable sensitivity analysis is an important future



project element, to examine the many possible combinations.

An additional issue to be considered in assessing technology feasibility is cost, and the rapidly changing cost structures of some technologies being considered. We did not specifically evaluate cost comparisons between the technologies, as all are in development and all need of business case evaluation. Business cases and decisions should not be based on current costs, especially for systems with batteries. The same can be said, to a greater or lesser extent, for electric machines, fuel cells, power electronics, and allied telematics and ITS tools. How all of these technology elements combine into a business case for vehicles, and for the infrastructure in the corridor, is a highly complex analysis.

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. :

- 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
- Battery Electric Vehicle (BEV)

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

- Electricity (via batteries in EV or PHEV)
- 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
- 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.

Ultimately, the technology options, including infrastructure interactions, are to be defined by the amount of zero-emission range required by the overall project. Scenarios can be developed with a variety of technology options based on a variety of ZE Range requirements. The timing, costs, emissions impact, and infrastructure needs all vary based on the ZE requirements.

An important future step would be a multi-variable sensitivity analysis, where the impact of ZE Range and the resulting technological options can be compared and overall costs estimated. For example, a Plug-In Hybrid truck with 25 miles of ZE range could use catenary in certain areas to maintain a charge, reducing the need to stop and plug-in. Alternatively, the costs of the catenary infrastructure could be converted into larger batteries on the trucks and the resulting range compared to other options. Such an analysis is beyond the scope of this report, but some version of that kind of analysis, across all 5 technology architectures and the various infrastructure options, is necessary as a future step.

6.0 CONCLUSIONS & RECOMMENDATIONS

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.

6.1 TECHNOLOGY OPPORTUNITIES

A ZE capable truck to serve the I-710 freight corridor (what could be called a Clean Corridor Capable or 3C truck) is fully technically feasible and can be based on vehicle architectures and designs already in prototype status. Several manufacturers and suppliers have existing systems and prototype trucks which represent steps on a “pathway” to 100% zero-emissions trucks. These include dual-mode hybrids; plug-in hybrids; range-extender battery electrics; and battery electric.

A zero-emissions capable freight truck can be developed for potential production well within the proposed timing of the corridor project. Indeed, such a truck could be developed in advance of the corridor’s actual construction.

There is a high degree of agreement on the near-term technical approaches that are most promising for a zero emissions truck. 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:

- 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
- Battery Electric Vehicle (BEV)

The critical deciding criterion is the amount of zero-tailpipe-emissions range required. Expert interviewees felt a dual-mode hybrid or range-extended hybrid (possibly using a natural gas engine) with some engine-off driving capability (hence zero tailpipe emissions) coupled with corridor-supplied electrical power (lowest risk is believed to be a catenary system) was the most feasible system at the time of this report. Those anecdotal views will have to be verified by a thorough multi-variable analyses of the technology options and costs.

A single-purpose truck is considered less likely to be successful, while a multiple purpose truck is considered much more likely. Manufacturers in particular believe a successful system must be useful beyond the corridor or its production cannot be justified or sustained.

Based on interview responses, technology is not considered a barrier to a zero emission freight truck. Fundamental research and development is not required. Additional development of systems and system integration, and on fielding and validating prototype vehicles, would be valuable.

6.2 CONCERNS AND CHALLENGES

The core challenges 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.

Clean Corridor Capable (3C) trucks cannot operate in a vacuum; they must be part of a full ecosystem that has an established framework for their operations. The industry experts and executives were clear that there are no “show stoppers” in producing a zero emissions truck that can work in the I-710 Corridor. There were issues that had to be focused upon, defined, addressed, and resolved. Such issues are a normal part of the product development process.

Driving down costs is seen as a critical challenge. Moving more designs into production, and building more “pathway trucks” (current technology, non-zero emissions) is an important step. For example, a Full EV is prohibitively expensive, but if more Diesel Electric Hybrids were sold, the costs would come down and a Full EV would become more viable.

Hence, there is a need to not only promote full zero-emissions trucks, but also other near-zero emission variants that advance the technology and systems that can lead to a zero emissions truck. It is not considered viable to skip directly to a “final outcome” either technologically or economically.

The industry (truck makers, technology developers, and component suppliers) are very interested in managing the cost of the vehicles they produce. Approaches that result in a truck that costs more than 100% above the current vehicle cost are pushed back in time and seen as needing further development or technological advancement to lower costs. Such industry behavior is rational, and another argument for pathway trucks and an incremental, step-wise approach to solving the I-710 challenges.

Limiting the battery needs (size, capacity and weight) is still a focus of the industry, largely because of current battery costs. Batteries are the leading example of the need for gradual advancement based on near-zero emissions vehicles. Managing the cost and weight of the vehicle is a critical factor in decision-making by truck producers. Important advancements in battery technology and reductions in cost are happening, but would be sped up by introducing pathway trucks, and moving toward greater use of batteries in heavy duty trucks.

Making these trucks suitable for applications beyond the I-710 corridor is also seen as critical challenge. Making the business case for production is highly volume-dependent, and the expected sales within the I-710 corridor do not support a development program of the scale needed. The vehicles planned for the I-710 should have application outside of the corridor, nationally and globally. That requirement places constraints on the potential design solutions. A vehicle with multiple uses and potentially built on a standardized global platform - as opposed to an I-710 specific solution - is necessary for sufficient industry players to see a business case, and to invest their own time and resources into developing a zero-emissions vehicle. It may turn out that such a truck will end up having more in common with a port yard tractor or other port equipment, than a Class-8 over the road tractor.

6.3 RECOMMENDATIONS

The following needs have been identified:

- Conduct additional analysis of drayage truck operations and better define the daily operations and requirements for dray trucks.
- Pursue multiple technology solutions, with some focus on REEV designs – with both fuel cell and with engines as range extenders. Conduct a thorough multi-variable sensitivity analysis.



- Determine electrical infrastructure status and more accurately assess demands on the grid from various combinations of ZE truck designs in the I-710 region.
- Determine hydrogen fuel infrastructure status and determine locations for production and distribution facilities.
- Determine if roadway power infrastructure systems (e.g. catenary or in-road) can be deployed in a “convenience charging” manner, to support REEV designs that are not infrastructure dependent. Investigate specific routes or applications for these technologies.
- Fund demonstration programs for prototypes of BEV, and REEV trucks, and determine if future PHEV designs can meet the project requirements.
- Work with public agencies to develop appropriate legislation and funding mechanisms for incentives/subsides.

Zero-emissions goods movement vehicles can be successfully developed and produced for the I-710 corridor if a consistent, focused and multi-year process is engaged that addresses key engineering, commercialization, market and regulatory issues outlined in this report, and to be further detailed in the Final ZE Truck Commercialization Report.

This outline highlights the need for a multi-year process to:

- Engage the truck and system technology developers on phased vehicle demonstration and commercialization stages to move along a product pathway from near-zero to zero emission designs.
- Bring together potential users to validate functionality and performance and confirm vehicle operational needs.
- Develop an economic and business case for the successful operation of a zero-emission corridor and its vehicles, including incentives, inducements and potential regulations.

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
- 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. The Final ZE Truck Commercialization Report will expand on these recommended next steps.



7.0 Appendices

Appendix A: Survey Instrument (Moderator Interview Guide)

Zero Emission Truck OEM and Technology Supplier SURVEY INTERVIEW GUIDE

The Gateway Cities Council of Governments, through Cambridge Systematics and LA County Metropolitan Transportation Authority (“Metro”) has engaged CALSTART to examine the commercial viability of zero-emission trucks in the I-710 corridor, and to define a process for commercializing zero-emission freight movement vehicles and infrastructure. **The target year for the Zero Emission (ZE) Corridor to open is 2025.**

The program will be a multi-year effort involving stakeholders who are serving, using, and living along the I-710 corridor. The goal is to define, develop, validate, and commercialize vehicles and infrastructure that will support market-sustainable, zero-emission goods movement for the I-710 freight corridor, and potentially for similar uses worldwide, starting on or before 2025.

The program focuses on Class 8 drayage/day-cab trucks (GVWR: 60,000 to 88,000 pounds). The minimum goal is for the vehicles to **travel the length of the corridor (20 miles) fully loaded, at freeway speeds (55 mph) without refueling and with zero tailpipe emissions.** The preferred goal is for the vehicles to travel at full load for at least one “turn” (approximately 40 miles)

CALSTART is working with the CalHEAT program, which you may be familiar with, to **build upon the existing body of knowledge around Zero Emission Class 8 trucks.** Previous studies have pointed to particular technologies as the most viable. We want to remain open to new innovations while recognizing the lengthy R&D process and the target date of commercialization (2025).

Some of the technologies under consideration are:



- Dual-Mode Hybrid Diesel Electric (including plug-in hybrids)
- Range-Extended Series Hybrid using Diesel/CNG/Turbine/Fuel Cell extender
- Full Battery Electric

And for vehicles who require it, the following infrastructure support

- In-road electric power (on the corridor)
- Catenary electric power (on corridor)
- Fast chargers or Wireless Chargers (locations TBD)
- H2 Stations and infrastructure (the San Pedro ports have a pipeline nearby)

Retrofit and Refurbishing are viable options, as are diesel reformers for H2 supply, catenary conversions of diesel-electric hybrids, and other potential truck and infrastructure technologies that would enable the ZE goal (20 miles travel loaded to 80,000 lbs at 55 mph) in commercial volumes by 2025.

We would like to talk with you today about the technologies you are working with, and your views on readiness for commercialization.

We will be disguising your input so it cannot be attributed to you or your company. We will not be disclosing any confidential information, and not be naming you or your company in any reporting.

Mr./Ms. _____, I understand your work is focused on the _____ technology. Can we discuss that in particular?

1. Given the parameters described above:

- a. Do you have systems that could achieve this performance now? IF NOT
- b. How close are you to achieving these performance goals? (Miles @ ZEV, etc.)
- c. Do you have any vehicles running that could demonstrate this technology?

2. How far away (years) from production intent designs are your technologies?

- a. Could your programs be accelerated if the right conditions were present?
 - i. What is needed to accelerate?



3. What are the barriers to your technology that prevents it from being ready “now”?

- a. Is there further R&D needed?
- b. Cost for development
- c. Available engineering talent
- d. Cost of materials/components
- e. Market demand
- f. Fuel prices
- g. Other?

4. Does your technology have infrastructure dependencies (fueling or corridor power?)

- a. In an ideal world, what infrastructure/ technology would you prefer?
- b. Would that infrastructure/technology help your company’s development of a commercialized vehicle?

5. What sales volume would you need in order to justify development on an accelerated timeframe? To achieve Commercial Production in 10 years?

- a. Do you feel a pathway or interim truck is necessary?
- b. How would you see that pathway truck relating to infrastructure dependencies (if any)?



Appendix B: Acronym List

APCD – (San Joaquin) Air Pollution Control District
CalHEAT – California High Efficiency and Advanced Truck (Research Center)
CARB (or ARB) – California Air Resources Board
CARGO – Clean Air Rapid Goods Movement (proposal to MTA from CALSTART)
BEV – Battery Electric Vehicle
DME – Di-Methyl Ether
EIR/EIS – Environmental Impact Report/Environmental Impact Statement
EV – Electric Vehicle
HEV – Hybrid Electric Vehicle
HTUF – Hybrid Truck Users Forum
ICE – Internal Combustion Engine
ICTF – Intermodal Container Transfer Facility
ITS – Intelligent Transportation Systems
KPP – Key Performance Parameter(s)
kW – Kilowatt, a measure of energy
kWh – Kilowatt/hour, a measure of power
LACMTA – Los Angeles County Metropolitan Transit Authority
MTA – Metropolitan Transit Authority
NG – Natural Gas
NO_x – Nitrogen Oxides
OEM – Original Equipment Manufacturer
PHEV – Plug-in Hybrid Electric Vehicle
PM – (Diesel) Particulate Matter
POLA – Port of Los Angeles
POLB – Port of Long Beach
REEV – Range Extended Electric Vehicle (or Range Extended Vehicle - REV)
RFP – Request for Proposal
RNG – Renewable Natural Gas (Biomethane)
SCAQMD (or AQMD) – South Coast Air Quality Management District
SCIG – Southern California International Gateway
SO_x – Sulfur Oxides
WG – working group
ZE – Zero Emissions
ZEV – Zero Emissions Vehicle

Appendix C: Developments in Near-Zero Emission Technologies

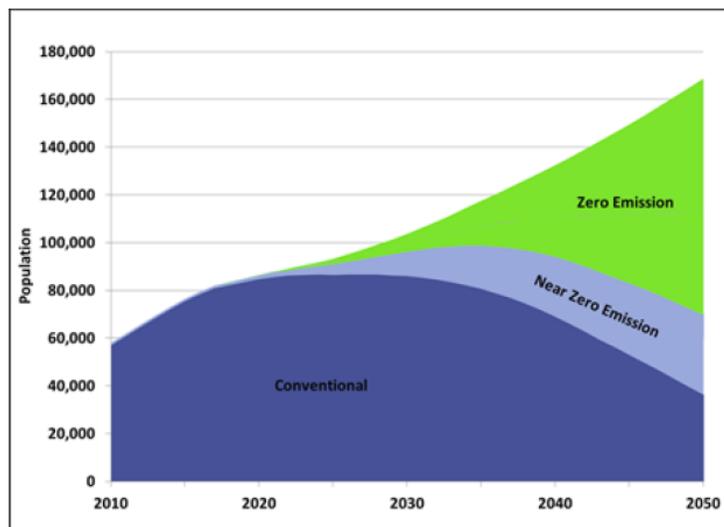
There have been very important new developments in the category of near zero emission trucks over the period of the past year and a half. Most notably, the capability to achieve significantly reduced nitrogen oxide (NOx) levels from heavy duty truck engines was identified because of research performed by the California Hybrid Efficient and Advanced Truck (CalHEAT) Research Center.

Based on the technical capability it found, CalHEAT’s Technology and Market Transformation Roadmap (Roadmap)⁴ recommended that California agencies seriously consider establishing a “near-zero” or low NOx standard for trucks that could be between 50 and 80 percent below the NOx emission levels in the national 2010 EPA standards. The Roadmap also identified specific stages of development and demonstration and projects that could lead to production capability of such engines.

The technologies identified included optimized natural gas engines, turbines, camless engine schemes and other low emission engine designs as possible approaches. CalHEAT documented that the level could be achieved, but that engine manufacturers had no market pull for developing the capability, and no certification level to develop to.

Concurrently, the California Air Resources Board (ARB), in coordination with the South Coast Air Quality management District (SCAQMD) and the San Joaquin Valley Unified Air Pollution Control District (SJVAPCD) developed in 2012 a Vision for Clean Air⁵ for California and specifically outlined the emissions reductions needed from medium- and heavy-duty vehicles in the state. ARB highlighted a potential scenario to meet the state’s dual needs to both reduce greenhouse gas (GHG) emissions by 80 percent by 2050, and the need to reduce NOx (a key pre-cursor to ozone formation) by nearly that much in the South Coast and San Joaquin airsheds by 2032.

South Coast Heavy Duty Truck Population
(advanced technology scenario)



⁴ CalHEAT Research and Market Transformation Roadmap for Medium- and Heavy-Duty Trucks, CALSTART, April 4, 2013

⁵ Vision for Clean Air: A Framework for Air Quality and Climate Planning; California Air Resources Board; June 27, 2012

The scenario was predicated on both a heavy implementation of full zero emission trucks as well as a significant portion that were “near zero”: emitting 80 percent lower NO_x than a 2010 certified engine.

Partly from this Vision plan and the CalHEAT findings, the ARB is exploring the establishment of a “voluntary low NO_x” engine certification standard to encourage industry to develop an engine with lower emissions than currently required under national EPA rules. The proposed standard would give industry up to three new voluntary levels of NO_x emissions at which to certify, at 50 percent, 75 percent and 90 percent below EPA 2010 (0.1, 0.05 and 0.02 g/bhp-hr).⁶ Achieving this certification could conceivably then be rewarded with additional incentives or other assistance for sales and use. This voluntary certification will be considered at the ARB December 2013 Board meeting.

In support of this development, in the summer of 2013 several agencies led by the SCAQMD pooled funding resources on a joint \$9-million solicitation for a low NO_x natural gas engine. Supporting agencies include SJVAPCD, the California Energy Commission (CEC) and the Southern California Gas Company (SoCalGas). The agencies hope to drive forward several engine projects that could demonstrate this low emission capability. The projects would directly support recommended actions in the CalHEAT Roadmap and the ARB Vision Plan.

In addition to natural gas-based engines there exist other engine schemes and approaches that could both reduce NO_x emissions and increase or maintain current diesel fuel economy. One of the newest alternative fuel entrants that may provide such a low NO_x pathway is Dimethyl Ether



(DME), which Volvo announced it would support as a vehicle fuel and engine technology starting in the 2015 model year.⁷ DME is widely used around the world already as a substitute for liquefied petroleum gas (LPG), more commonly called propane in the U.S.

DME has many of the properties of propane, including low pressure storage and therefore the ability to use less expensive storage tanks and fuel systems. However, it is able to combust in a diesel engine using compression (diesel) ignition, as

opposed to a spark-ignited combustion needed by natural gas or propane. Therefore it serves as

⁶ Proposed Regulation Order, Appendix A, California Air Resources Board, August 2013

⁷ Volvo Trucks to Commercialize DME-Powered Vehicles for North America, press release June 6, 2013 - See more at: http://www.volvotrucks.com/trucks/na/en-us/_layouts/CWP.Internet.VolvoCom/NewsItem.aspx?News.ItemId=143305&News.Language=en-gb#sthash.qChJk JrB.dpuf



a highly efficient fuel for a diesel engine with nominal changes to the engine. Given that DME can be produced from multiple feedstocks, it also has the potential to be a low carbon fuel (in first tests in California, fuel-maker Oberon is using natural gas as its feedstock, but plans to build mini-refineries that derive the DME from a mixture of natural gas and renewable feedstocks⁸). Finally, DME also produces no or little soot, and therefore requires no diesel particulate filter to meet current engine standards, and contains little to no sulfur, which extends after-treatment system life.

These last factors are important considerations when looking at the ability to meet lower NO_x outputs. Current diesel engines actually test at levels as much as half the current NO_x standard levels, but need that margin to account over time for reduced effectiveness of DPFs and overall degradation (often from sulfur) of the remainder of the after treatment system. Theoretically, a DME engine might be less prone to such degradation; it might be able to maintain its test standard levels (at half current levels) for a meaningful length of time. While in no way assured, DME's potential provides an additional potential pathway to achieving low NO_x engine.

⁸ Notes from Oberon briefing, June 6, 2013



Appendix D: CalHEAT Roadmap Recommended Actions on Top Strategies to Support Zero Emission Drayage Technologies

Development				
Development of a component, subsystem or complex drivetrain system				
Technology	2013	2014	2015	2016
Hybrid-Electric		23. Develop prototypes for optimized and downsized engines to be used in hybrid systems		
Electrified Accessories	7. Develop more purposely-designed electronics (but ideally shared architecture, DC-DC converters, auxiliary drives, power steering, pumps) that can be integrated into vehicles.			
	8. Develop a power distribution box/supplier to allow for commonality across OEMs. (This is an enabler to further cost reduction.)			
AF Hybrid	9. Develop smaller & lighter CNG tanks designed for HE trucks			
Optimized AF Engine	11. Develop additional smaller engine sizes for efficiency and performance improvements (especially low-end torque)	24. Develop advanced engine efficiency strategies and improved methane catalysts		
	12. Develop a lower cost HHD NG solutions (Heavy – Heavy 15 liter engines)			
Engine Optimization	14. Develop an engine and system to provide 50% reduced NOx			
Alternative Power Plants and Combustion Cycles	15. FTA providing development funding for fuel cell transit buses, to reduce fuel cell cost, reducing footprint, increasing reliability			
		16. Develop one or two new advanced engine designs such as camless, Opposed Piston and HCCI Engine		
		17. Develop a purposely-devised turbine for vehicles		



Pilot Demonstrations						
A pilot demonstration is the full integration of a component, subsystem or complex drivetrain into 1 to 5 trucks to evaluate performance.						
Technology	2013	2014	2015	2016	2017	2018
Hybrid Electric			42. Pilot demo of optimized and downsized engine/s to be used in hybrid systems			
Electrified Auxiliaries			43. Pilot demo validation of electrified auxiliaries in Class 7-8 (non-hybrid) tractors, line haul trucks and other trucks			
E-Trucks	18. Pilot demo of smart charging systems					
AF Hybrid		25. Pilot demos to evaluate/benchmark various NG/hybrid refuse trucks		53. Pilot demos of NG/hybrid refuse trucks with downsized engines and/or 80% less NOx		
Optimized Alternative Fuel Engines	20. Pilot demos of special CNG tanks with newer lighter materials					
Engine Optimization			44. Pilot demos of 50% break thermal efficiency engines leveraging DOE program and also incorporating all relevant technologies to achieve up to 1.5x truck efficiency improvement		58. Pilot demos of 55% break thermal efficiency engines also incorporating all relevant technologies to achieve 2x truck efficiency improvement and 50% lower NOx	
Alt Power Plants and Combustion Cycles			27. Pilot demos of Camless, Opposed Piston or HCCI engines in trucks			



Pre-Commercial Demonstrations								
Pre-commercial demonstrations involve 1 to 50 trucks to evaluate performance in the field. Further refinement precedes commercial production.								
Technology	2013	2014	2015	2016	2017	2018	2019	2020
Hybrid Electric	21. Demo of next Stage 2 hybrid drivelines with improved design and integration, and ARB OBD compliance and electrified accessories					62. Demo of the more electric OTR hybrid truck		
E-Trucks	28. Demos of improved integration- lower cost Stage 2 E-Trucks, for ZEV Corridor applications & goods movement							
	45. Demos of lower cost Stage 3 E-Trucks, including longer ranges & fast charging							
Plug-in Hybrid Electric	30. Demos of goods movement and drayage trucks							
	31. DOE SCAQMD utility trucks (ARRA Funded)							
	32. Demos of Stage 1 in Class 2b trucks							
Electric Corridor	33. Demo of preferred on-road connection device for electric or PHET yard hostlers			54. Demos of dual-mode hybrid and range-extended electric drayage trucks to broaden mfrs offerings and truck types				
AF Hybrid	34. Demo of two new platforms of NG/hybrid drayage truck meeting ZEV Corridor requirements							
Optimized AF Engine	36. Demos of lower engine sizes and new lower cost 1.5 liter engine to broaden number of platforms			55. Demo of 80% decreased NOx (NZEV)				
Engine Optimization						66. Demo of 55% brake thermal efficiency engine with technologies to achieve 2x truck efficiency improvement and 50% lower NOx		
Alt Power Plant/ Combustion			48. Demos of camless, Opposed Piston, HCCI engines in trucks					



Deployment Support and Incentives								
Policy and Regulatory Support and Financial Incentives for early deployment of commercial products in the marketplace								
Technology	2013	2014	2015	2016	2017	2018	2019	2020
Hybrid Electric		37. Support for 1000 Stage 2 hybrids starting when they become commercially available						
E-Trucks			49. Support for 1000 Stage 2 trucks to reduce ROI to 5 years (assuming daily driving of 80% of energy storage capacity)					
Plug-in Hybrid			51. Support for the first 500 Stage one PHETs when they become commercially available					
Electric Corridor				56. Support for Stage 2 PHET Class 7 & 8 drayage trucks (focus on Electric Corridor)	63. Support for dual-mode hybrid and range-extended electric drayage			
AF Hybrid			52. Support for 200 NG hybrid refuse trucks			64. Support for 100 NG hybrid drayage trucks for ZEV Corridor		
Optimized AF Engine		39. Support for 1000 Stage 2 trucks			60. Introduce performance-based incentives for 200 NZEV/higher-efficiency trucks			
Engine Optimization					61. Introduce performance-based incentives for early fleet deployments in California (1.5X efficiency conventional and 50% lower NOx) for first 200 OTR trucks			
Alternative Engines and Combustion Cycles				57. Stage 2 tech support for 100 drayage truck buy-downs and introduce performance-based incentives for 200 low NOx higher efficiency line-haul trucks				
						65. Stage 3 tech support of 100 drayage truck buy-downs and 200 OTR trucks using performance-based incentives		

Summary:

- Pre-commercial demonstration of improved integration, lower-cost stage 2E-trucks for ZEV Corridor applications and goods movement (2014-2015)
- Demos of dual-mode hybrid and range-extended electric drayage trucks to broaden manufacturers offerings and truck types (2016-2017)
- Deployment support for stage 2 PHET Class 7 & 8 drayage trucks (focus on Electric Corridor) (2016-2017)
- Deployment Support and Incentives - Support for dual mode hybrid and range-extended electric drayage (2018-2020)