

PRELIMINARY ASSESSMENT



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

FINAL – PUBLIC RELEASE
JUNE 2012



©CALSTART 2012



FUNDING FOR THIS RESEARCH PROVIDED BY:

Los Angeles County Metropolitan Transit Authority (Metro)

Douglas R. Failing - Executive Director, Highway Program

South Coast Air Quality Management District

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

This 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.



TABLE OF CONTENTS

Executive Summary	1
1.0 Issue and Study Scope	5
2.0 Approach.....	6
3.0 Key Findings	7
3.1 Technologies	7
3.2 Feasibility.....	22
3.3 Challenges.....	24
4.0 Conclusions.....	30
5.0 Recommendations.....	32
6.0 Appendices.....	35
Appendix A: Survey Instrument (Moderator Interview Guide).....	35
Appendix B: Matrix of Interview Subjects	37
Appendix C: Anonymous Quotes from Delphi Experts.....	38
Appendix D: Acronym List.....	41
Appendix E: Original “CARGO” program proposal	42



EXECUTIVE SUMMARY

ISSUE & SCOPE

The Los Angeles County Metropolitan Transportation Authority (Metro), in cooperation with the California Department of Transportation (Caltrans), the Gateway Cities Council of Governments (GCCOG), the Southern California Association of Governments (SCAG), the Ports of Los Angeles (POLA) and Long Beach (POLB) (collectively known as the Ports), and the Interstate 5 Joint Powers Authority (I-5 JPA) (collectively referred to as the I-710 Funding Partners), are investigating alternatives that will improve Interstate 710 (I-710, also known as the Long Beach Freeway) in Los Angeles County between Ocean Blvd. and State Route 60 (SR-60). The current endeavor is referred to as the I-710 Corridor Project EIR/EIS (Environmental Impact Report/Environmental Impact Statement).

I-710 is a major north-south interstate freeway connecting the city of Long Beach to central Los Angeles. Within the I-710 Corridor Project study area, I-710 serves as the principal transportation connection for goods movement between POLA and POLB, located at the southern terminus of I-710, and the Burlington Northern Santa Fe (BNSF)/Union Pacific Railroad (UPRR) railyards in the cities of Commerce and Vernon.

The existing I-710 Corridor has high levels of health risks related to high levels of diesel particulate emissions, traffic congestion, high truck volumes, high accident rates, and many design features in need of modernization (the original freeway was built in the 1950s and 1960s). The I-710 Major Corridor Study (MCS), undertaken to address the I-710 Corridor's mobility and safety needs and to explore possible solutions for transportation improvements, was completed in March 2005 and identified a community-based Locally Preferred Strategy (LPS) consisting of ten general-purpose (GP) lanes plus a separate four-lane freight corridor (e.g. truck-only lanes).

In addition to proposing separated freight movement lanes (freight corridor), two of the project alternatives being studied in the I-710 EIR/EIS goes a step further by qualifying the freight corridor as a zero tail-pipe emission freight corridor (zero-emission corridor). Via this corridor, trucks would travel from the Ports of Los Angeles and Long Beach to the Vernon/Commerce rail yards via a separate facility from the general purpose lanes, generating no local emissions.

CALSTART was tasked with investigating the potential technologies that could achieve this goal, their feasibility, and the challenges to their commercialization within the project's horizon year of 2035.

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 I-710 Project Alternatives 6B and 6C. 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

A modified “single-round Delphi Interview” technique was used, targeting a representative collection of leading manufacturers, suppliers, and technology developers. 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 the report findings. The data was analyzed to determine feasibility, challenges, and timeframe for potential solutions.

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 can begin immediately and commercialization of proven designs can certainly be achieved by 2035, the horizon year of the I-710 Corridor Project. Provided there is a strong focus on the commercialization process, this assessment finds commercial viability could occur well before 2035, indeed within the next decade.

The feedback from interviews conducted for this report indicates the major challenge to commercialization of zero-emissions (ZE) drayage trucks is in assuring a viable market exists (in volume and demand) which could support the purchase and operation of 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. As outlined in Section 5, CALSTART has defined the requirements of a multi-year and multi-phase process, including developing the corridor economic, regulatory and economic structures, which can address these challenges and enable a sustainable zero emission corridor.



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:

- The technology approaches identified were:
 - Dual Mode Hybrid Diesel-Electric Vehicle (HEV).
 - Range Extender Electric Vehicle (REEV) or Plug-In HEV (PHEV).
 - Full electric vehicle (EV).
 - Fuel Cell (EV/REEV).
 - Natural Gas (NG) Hybrid.
 - Advanced combustion NG engine with next gen after-treatment.
 - Hydrogen Internal Combustion Engine (ICE).
 - Exotic Fuel advanced engines.
- The infrastructure approaches identified were:
 - Catenary Power Source
 - In-Road Power Source
 - Fast Chargers (electric) at corridor ends
 - Hydrogen Fuel
 - ITS – Intelligent Transportation Systems - mode control, platooning, driverless operation (not an emissions technology, but can be combined with those technologies to increase efficiency)
- The key challenges identified were:
 - Economic Case.
 - Market Demand (including Customer Pull, Affordability, and Needs).
 - Potential Volumes over Time.
 - Corridor Market Mechanisms.
 - Policy/Regulatory Actions (or lack thereof, on Emissions or Carbon).
 - Petroleum/Diesel Fuel Prices.
 - Costs.
 - Development cost.
 - Materials/Component cost.
 - Infrastructure cost.
 - Initial Incremental Vehicle Cost.
 - Capital Costs.
 - Potential Rebates (Incentives, Policies, Taxes).
 - Design Factors.
 - Battery Weight/Volume.
 - Infrastructure (fuel storage and distribution).
 - Grade Capability, Specifics of User Needs.
 - Durability testing.
 - Internal Resources/Manpower
- The key conclusions are:



- A “dual mode” or “range extender” Hybrid Electric Vehicle (HEV) with some EV-only capability was seen as the most feasible solution, particularly if combined with an infrastructure power source such as catenary or in-road, which would allow for smaller battery packs aboard the vehicles. Clarification and development of a sustainable overall economic and business case and corridor market mechanisms were seen as the most significant challenges to be overcome.

RECOMMENDATIONS

- Recognize the project as a “commercialization process” that must go through a series of critical stages. It is not advisable to jump directly to the desired outcome because competing technologies must be evaluated, tested, proven, and commercialized. The commercialization process for a complex product like a Class 8 truck includes significant engineering and development work, including demonstration and validation of early prototypes, building a small number of pre-production vehicles, and constructing a business case for moving to full production – over the course of several years. Similarly, the other stakeholders in the Corridor must work through the steps of transitioning from their current business processes and approaches into a new structure that incorporates zero-emissions as a critical component – a new set of market mechanisms must be developed and adopted or the goal of a ZE Corridor may not be achieved.
- Recognize and develop plans for funding that covers not only advancing and demonstrating technologies, but also shaping and creating the frameworks, market mechanisms and marketplace for an I-710 zero-emissions freight corridor and ZE trucks. In concert with this, investigate and develop the market mechanisms for an overall economic case, including regulatory requirements and financial support required to make the corridor function.
- Launch a Vehicle Development (industry) Working Group to address issues raised in this study on vehicle performance needs, market size, alternative vehicle markets and uses.
- Launch a User Needs Working Group to identify end user needs and vehicle design parameters. The performance needs identified will drive design criteria, and ideally would be communicated within 12 months to the Vehicle Development (industry) group.
- Initiate a Corridor Market Mechanisms Study and Process to assess the best models for financially supporting and enabling ZE trucks. Such a study needs to assess and outline alternative ownership and business models (such as amortizing truck costs with corridor construction costs), and possible regulatory structures to enforce the model.

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, with connections to Interstate 405, State Route 91, Interstate 105, Interstate 5, State Route 60, and Interstate 10. I-710 is a 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 generate 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 effects of diesel emissions are felt keenly among the communities through which I-710 passes, whose residents are immediately subject to the health risks and quality of life impacts imposed by truck operations and emissions. The projected growth in population and employment in the study area (see Figure 1 above), and in economic activities related to goods movement, prompted residents to question how congestion and air pollution in the area will change over time.

In response to these concerns, the Los Angeles County Metropolitan Transportation Authority (Metro) and its partner agencies are studying alternatives to improve the I-710 with respect to public health, safety, and quality of life issues (of local residents), while providing the capacity needed to accommodate forecast passenger travel and goods movement.

Two alternatives in the I-710 Draft EIR/EIS, Alternative 6B and Alternative 6C, contain a unique component. These two Alternatives contain a variation on the options that utilize a

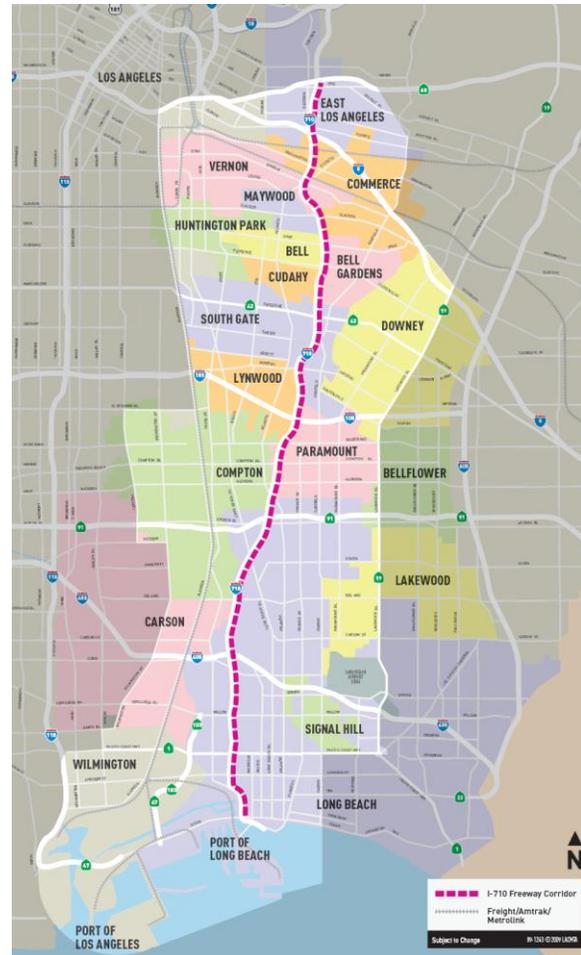


Figure 1 I-710 EIR/EIS Corridor Study Area



dedicated Freight Corridor, whereby the freight corridor has zero tailpipe emissions. These “zero-emissions” (ZE) alternatives reflect a commitment by the I-710 Funding Partners to the communities – to define and study alternatives that will improve air quality.

Metro retained CALSTART to assess the commercial viability and development requirements for truck-based technologies that would fulfill the commitment embodied by Alternatives 6B & 6C. This report assesses the technologies needed for trucks with zero emissions, the feasibility of creating and synthesizing that technology, and identifying the challenges 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 challenges identified, and set in motion the process to achieve a zero-emission freight corridor.

SCOPE

The task undertaken by CALSTART in partnership with Metro and the South Coast Air Quality Management District (SCAQMD) was to examine the technologies and approaches that could enable a truck to move cargo containers with zero-emissions within the I-710 Study Area (see Figure 1 above).

While the I-710 Corridor Project is making consideration for electrical power in the infrastructure of the roadway, CALSTART was not tasked with any specific examination of infrastructure options or design elements. Therefore this report focused its efforts only on zero-emission (at the tailpipe) truck technologies and the timeframes, challenges, and opportunities therewith.

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. This outline is included in Appendix E.

2.0 APPROACH

For this work, CALSTART is combining our broad knowledge of technologies and the state of the industry, with a single-pass Delphi Interview approach. The Delphi approach is a structured communication technique, originally developed as an interactive forecasting method which utilizes a panel of experts. The approach is well known and frequently used in market research and technology forecasting (among other fields), when the objective is to predict future developments in an uncertain and changing environment. The views of a broad set of experts in the field are solicited in a structured manner, using a skilled facilitator.

In this project, a set of experts in zero-emission vehicle technology and truck engineering were contacted and interviewed. The collected “Delphi” knowledge was condensed and combined with CALSTART staff knowledge and expertise to develop the conclusions and



recommendations in this report.

CALSTART contacted key individuals, usually engineering or research and development (R&D) executives, from technology developers, suppliers, and truck. As is typical of Delphi research, not every possible company and contact could be interviewed. Efforts were made to ensure a broad cross section of interviewees, to provide a variety of inputs. This breadth of expertise and viewpoints is the key to Delphi forecasting, by incorporating a wide range of ideas and potential developments. The scope of this project, including resources, timing, and difficulty in scheduling high-level executives, made it impossible to reach everyone desired, or every company working in the market. The Delphi group used is representative of the ZE truck market and provided a very solid set of inputs. Any development of ZE trucks would include the people interviewed, and the existing heavy truck industry is the only resource that could successfully commercialize ZE trucks.

The actual interview questions used are provided in Appendix A. The analysis process removed identification of companies or individuals (again a key element of the Delphi method). Much of the information given to CALSTART was proprietary or competitive trade secrets. Our role as industry confidant and ombudsman enabled this depth of disclosure but also required we fully obscure the information we were provided. A matrix of the interview subjects (with identifying data removed) is included here as Appendix B.

CALSTART analyzed the information from responses, compared this to our understanding of current industry conditions, and then developed the key findings, which supported the development of conclusions and recommendations. CALSTART staff experts were consulted to add information not brought up in the interviews, or to provide context for statements.

3.0 KEY FINDINGS

The key findings look at what 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 TECHNOLOGIES

Below is the summary of technologies covered during the “Delphi Interviews”, plus those known to the experts on CALSTART’s staff.

What was particularly striking during the interview process was the unprompted degree of consensus around the “most promising and commercially viable” approaches. While this consensus is not an absolute signal of the most feasible technology, it does indicate a strong belief that the approaches described are seen as promising and feasible by experts.



After each technology listing are comments from experts (Delphi interviewees, quotes from other sources, or CALSTART experts), and photographs of trucks demonstrating the technology, if any are available. Not all of these technologies have reached the stage of prototype or demonstration at this point, but all of the trucks shown have reached at least the prototype stage of development. The current existence of this many “pathway trucks” – vehicles close to meeting the I-710 Alternative 6B requirements – is another indication that there are no major or fundamental technological barriers to having zero-emission trucks operating on the I-710 freight corridor.

TECHNOLOGIES DISCUSSED

TECHNOLOGY	<ul style="list-style-type: none"> ▪ Dual-Mode Diesel-Electric Hybrid (HEV). (aka the “Toyota Prius of trucks”) ▪ Dual-Mode NG Hybrid (HEV).(Natural Gas – Electric Hybrid).
ZERO EMISSION CAPABILITY	<ul style="list-style-type: none"> ▪ 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	<ul style="list-style-type: none"> ▪ 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	<ul style="list-style-type: none"> ▪ Early stage demos have begun; based on technology ready today; zero-emissions mode available; strong pathway to increased zero emissions operation; can have multiple uses outside corridor. ▪ Natural gas internal combustion engine (ICE) is 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	<ul style="list-style-type: none"> ▪ Can be expensive (up to 2x regular 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. ▪ NG adds to cost (0.25 more than regular truck); limited operations outside of NG infrastructure build-out zones – but NG infrastructure growing quickly and well ahead of other alternative fuels.

COMMENTS

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.

EXAMPLES



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



Peterbilt hybrid electric HEV Class 8 truck prototype (Eaton system)



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

TECHNOLOGY	<ul style="list-style-type: none"> Range Extender EV (REEV) or Plug-In HEV (PHEV) (Gasoline, Diesel, Turbine, or other Range Extender engine). (aka “The Chevy Volt of trucks”)
ZERO EMISSION CAPABILITY	<ul style="list-style-type: none"> Can be Zero-Emissions or Near-Zero Emissions in the corridor depending on design.
DEFINITION	<ul style="list-style-type: none"> A type of hybrid truck, usually a series hybrid, where the batteries enabling an EV-only mode are re-charged by an engine running a generator, and/or the ability to plug into a fast charger. May require a larger electric motor and/or greater EV capacity than a Dual-Mode hybrid.
PROS	<ul style="list-style-type: none"> Early stage demos have begun; based on known technology; zero-emissions mode available. Fuel-cell versions are fully zero-emissions; solid pathway to increased zero-emissions operation; turbines or fuel cells can be ultra-low or zero emissions
CONS	<ul style="list-style-type: none"> Can be expensive (up to 2x regular 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

COMMENTS

Range extenders, or on-board electricity generation in a REEV, could be used instead of catenary or in-road power, with similar effect. If there is charging availability in the corridor (In-Road, Catenary, or Fast Chargers), the engine would only need to run outside the corridor. 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.

EXAMPLES



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



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



Eaton Diesel Electric PHEV Hybrid (Peterbilt chassis)



*Seattle dual mode diesel-electric hybrid (HEV+Catenary) Transit Bus
(Allison)*



TECHNOLOGY	<ul style="list-style-type: none"> Full EV (BEV – Battery Electric Vehicle).
ZERO EMISSION CAPABILITY	<ul style="list-style-type: none"> Fully Zero-Emissions (from tailpipe).
DEFINITION	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Some demos today; based on known technology; full zero emissions today; no petroleum use; good for fixed route and circulator operations.
CONS	<ul style="list-style-type: none"> Currently very expensive depending on battery load and performance requirements (up to 4x regular truck), limited range and uses; limited speed in some designs; battery weight and size/volume are a challenge; does not build on existing commercial offerings (which are currently focused on delivery/class 5-6).

COMMENTS

A large (250 to 400Kw) motor would be needed to pull the required load (80K lb.) up a standard grade (5%). It is expected a truck viable in uses other than the I-710 would have to meet these requirements (even if I-710 needs could be met with less performance). The resulting energy storage needs means high cost, driven by battery costs.

Some Delphi experts said that even if battery costs came down, battery weight and volume/size may not. The amount of batteries needed for full-EV operation would cut into payload capacity.

Most experts said a full BEV Class 8 truck would be expensive and/or hard to engineer; with no payback or business case – a few said it was not currently feasible for Class 8 over-the-road trucks. A few said catenary or in-road could supply power in corridor, enabling full BEV operation outside of the corridor with limited range.

EXAMPLES



Balqon full BEV drayage truck



BEV Delivery trucks – Class 5-6 (Modec, Smith)

TECHNOLOGY	<ul style="list-style-type: none"> Fuel Cell (EV/REEV) truck.
ZERO EMISSION CAPABILITY	<ul style="list-style-type: none"> Fully Zero-Emissions (from tailpipe). Fuel Cell byproducts usually just water.
DEFINITION	<ul style="list-style-type: none"> A battery-electric vehicle with onboard electric generation capability via a fuel cell. Battery storage can be quite small (covering fuel cell startup/shutdown) depending on electric generation capacity of fuel cell.
PROS	<ul style="list-style-type: none"> Early stage demos begun; based on known technology; can achieve full zero emissions today.
CONS	<ul style="list-style-type: none"> Expensive packaging of batteries and fuel cell (2x to 3x more than regular trucks) integration challenges; reliability and life cycle of fuel cells unclear; availability of hydrogen limited; limited use vehicle beyond corridor/ports where H2 fueling is most readily available.

COMMENTS

The interviewees who worked with Fuel Cell trucks were the only ones who could comment extensively on fuel cell truck status. There is general awareness of fuel cells as a way to generate electricity for vehicles, probably as a result of light-duty press from the auto companies, but truck development lags behind.. Buses and cars are further along the development curve than trucks.

One interviewee felt fuel cells were not feasible in trucks; others said the fuel (H2) production, distribution and storage were difficult roadblocks.

EXAMPLE



Vision Fuel Cell Electric Hybrid truck



TECHNOLOGIES NOT YET IN CLASS 8 TRUCK PROTOTYPES OR DEMONSTRATIONS

TECHNOLOGY	<ul style="list-style-type: none"> ▪ Advanced combustion NG engine with next gen after-treatment.
ZERO EMISSION CAPABILITY	<ul style="list-style-type: none"> ▪ Moving beyond current NG engine technology has the potential to substantially reduce NOx and PM emissions – the most critical pollutants – to levels potentially significantly below the EPA 2010 engine standards.
DEFINITION	<ul style="list-style-type: none"> ▪ The combustion and emissions properties of advanced (in development) NG engines can enable exhaust after-treatment systems with the potential to substantially reduce NOx and PM. Some other emissions remain, however. Further testing/verification is required. ▪ Could be combined with Hybrid designs.
PROS	<ul style="list-style-type: none"> ▪ Builds on known fuel and engine structures; reported potential to achieve near “zero PM and NOx” emissions; expands on Clean Truck Program goals.
CONS	<ul style="list-style-type: none"> ▪ Higher cost than existing NG engines (but cost not yet fully known); still in development stages and may require several years of work; needs advanced controls; not yet clear full emissions profile - not truly full zero tailpipe emissions; operation limited to NG infrastructure build-out zones but NG infrastructure growing rapidly.

TECHNOLOGY	<ul style="list-style-type: none"> ▪ Hydrogen internal combustion engine (ICE).
ZERO EMISSION CAPABILITY	<ul style="list-style-type: none"> ▪ H2ICE has the potential to substantially reduce-emissions; no PM or carbon-related pollutants – no carbon in the fuel, few byproducts.
DEFINITION	<ul style="list-style-type: none"> ▪ An internal combustion engine (ICE) designed to run on Hydrogen. Same H2 storage and refueling issues/systems as a fuel cell truck.
PROS	<ul style="list-style-type: none"> ▪ Some demos underway; may achieve far lower emissions; lower cost than fuel cells; known, existing technology. Further testing and verification is needed.
CONS	<ul style="list-style-type: none"> ▪ Still mostly in development stage; not truly full zero tailpipe emissions; added weight and integration of fuel storage; potential engine performance deficit; limited operation based on H2 fuel availability and infrastructure.



TECHNOLOGY	▪ Ammonia and Exotic Fuel advanced engines.
ZERO EMISSION CAPABILITY	▪ Exotic fuels have the potential to be drastically lower in emissions; no PM or carbon-related pollutants – no carbon in the fuel, few byproducts. Further development and verification is needed.
DEFINITION	▪ Ammonia has no carbon, so is inherently cleaner. Other fuels such as Di-Methyl-Ether (DME) offer significant emissions benefits at potentially lower costs than battery/electric systems.
PROS	▪ May achieve drastically lower emissions; can create a new marketplace for fuel in transportation.
CONS	▪ Only design and bench stage technology; no prototypes; no existing infrastructure; requires full development and are notably further from readiness due to need for both fuel and truck development.

INFRASTRUCTURE OPTIONS

As discussed in Section 1.0, infrastructure was not part of the scope for this project, and thus no infrastructure experts were consulted in this study. No examination of the H2 or Natural Gas infrastructure was conducted. Therefore, no conclusions regarding infrastructure can be drawn from this report. However, since infrastructure is an important factor, a brief outline of potential options is provided here.

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

- Catenary power supply (electric).
- In-Road power supply (electric).
- Exotic and Advanced Fuel (Ammonia, Hydrogen) production, distribution and storage.
- Fast Chargers at ends of corridor (for PHEVs or BEVs).
- ITS – mode control, platooning, driverless operation (not an emissions technology, but can be combined with those technologies to increase efficiency or enable zero-emissions operation).

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 not 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, 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.

EXAMPLE



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"> ▪ Limited experience with 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.



INFRASTRUCTURE TECHNOLOGY	<ul style="list-style-type: none"> ▪ Exotic Fuels.
DESCRIPTION	<ul style="list-style-type: none"> ▪ It is possible to run vehicles on ammonia (NH₃). Ammonia can be generated in ways similar to Hydrogen. Di-Methyl Ether (DME) is another new fuel being promoted and produced in small amounts.
PROS	<ul style="list-style-type: none"> ▪ Could support a “closed loop” bio-generated fueling infrastructure; known substances with existing handling requirements, but some are dangerous or complex. May be viable options near the end of the time frame (2035).
CONS	<ul style="list-style-type: none"> ▪ No fueling infrastructure exists today; ammonia is hazardous material to handle and safety concerns; engines only in conceptual stages.

INFRASTRUCTURE TECHNOLOGY	<ul style="list-style-type: none"> ▪ Hydrogen Fuel.
DESCRIPTION	<ul style="list-style-type: none"> ▪ H₂ as a fuel has been in development for years. No carbon, no GHGs from use; appropriate for ICE or Fuel Cells. Various methods of generation, transport and storage are being worked on.
PROS	<ul style="list-style-type: none"> ▪ Can achieve zero emissions in fuel cell use and near zero in ICE; matches some state future fuel goals; in LA Basin can be sourced from refineries and can use some distribution infrastructure.
CONS	<ul style="list-style-type: none"> ▪ High fuel volumes needed for truck use; limited infrastructure capacity today; fuel cost not well documented at present; very limited infrastructure at the moment.

INFRASTRUCTURE TECHNOLOGY	<ul style="list-style-type: none"> ▪ ITS and Control Technologies.
DESCRIPTION	<ul style="list-style-type: none"> ▪ Computerized location and vehicle guidance systems combine to allow multiple trucks to form a train, without human intervention. The same system can turn on or off a Zero Emissions Mode in the corridor. ▪ Technically not an emissions technology; can be combined with other technology to increase efficiency.
PROS	<ul style="list-style-type: none"> ▪ Could control emissions/drivetrain mode and take over driving in the corridor. ▪ Enables the flexibility of individual trucks with drivers, while gaining most of the throughput efficiency of fixed guideway or rail systems.
CONS	<ul style="list-style-type: none"> ▪ Complexity, driver resistance. Legal situation (e.g. liability) undefined. No standardized systems. Costs and infrastructure needs currently not defined.



3.2 FEASIBILITY

All products, including heavy duty trucks, go through a development process with defined steps. As has been discussed elsewhere, skipping steps is not advisable 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. The trucks shown range from Prototypes to Demonstration phase, with a few in late R&D development stage. However, in all cases, Commercial Production is further away, some up to 12 or more years, but still within the time frame of the I-710 project, where the infrastructure for a zero-emission freight corridor would be complete and ready to support the vehicles, if Alternative 6B or 6C should be selected as the Preferred Alternative.

This spread of “technology readiness” is indicative of both the technologies themselves, and of the companies developing the technologies. Each company sees different futures and is allocating internal resources in different ways. In general, the technologies closest to demonstration were Range-Extender REEV (Fuel Cell or Turbine powered) trucks, and Diesel-Electric HEV trucks (dual-mode). Adding technology elements to these baselines pushed out the readiness window – adding catenary or in-road power, or CNG instead of Diesel, moved the designs further from demonstration-ready status.

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.

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 following diagram depicts some of the technology factors.



Figure 2 Technology Capability, Timing and Complexity

A number of technologies were proposed by the OEMs, Suppliers and Technology Providers interviewed. Figure 2 above captures the consensus with respect to zero-emission capabilities, timing and overall feasibility.

Several Delphi experts raised alternative approaches that they believed could be called “near-zero” emissions options, such as natural gas (NG) trucks fueled with Renewable Natural Gas (RNG or biomethane). These technologies are 100% feasible today, less costly, and more easily integrated into the market ecosystem. However they are only reduced



emissions options, and do not fully meet the requirement of a freight corridor with zero tailpipe emissions.

A valid point raised was the need to define the zero-emissions freight corridor so there is no ambiguity with how it is characterized in the I-710 EIR/EIS, in air quality regulations (e.g. regional and federal definitions) and within the goods movement industry. Some experts felt a larger discussion was needed around improving goods movement efficiency along with reductions in emissions.

Indeed, the definition of “zero-emissions” is a critical issue that drives the technologies. Significantly different technological approaches could be taken if “zero-emission” is defined to mean zero tailpipe emissions, zero emissions in the “well-to-wheels” energy chain, zero GHG emissions, zero criteria pollutant emissions, or if zero can be defined as un-measurable or extremely low relative to today. In the EIR/EIS, and in this report, it is presumed zero-emissions meant zero tailpipe emissions. But a number of questions are appropriate to ask as the project moves forward: Is displacing emissions acceptable (moving them to the location of the electricity generation plant, for example)? If a technology delivers engine emissions below the level of emissions created by tire and brake dust, is that equivalent to zero?

Related to the emissions reduction objective, it must be remembered that any change in the I-710 corridor will have ripple effects and externalities that need to be considered. It could push conventional truck traffic to alternative highways. An examination of the effects of the San Pedro Ports PierPass program, for example, could be enlightening. The overall I-710 project is working to address the larger traffic flow issues, and tolling options are being investigated along with their propensity to shift traffic.

3.3 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:

DESIGN FACTORS

- Battery Weight/Volume.



- Infrastructure (fuel/energy storage and distribution).
- Grade Capability, Specifics of User Needs.
- Durability testing.
- Internal Resources/Manpower.

This group of challenges was seen as less critical to the overall goal of achieving a zero-emissions truck. While each could be discussed individually, none is a show-stopper, and are best taken as a group. These challenges 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.

COSTS

Costs can be broken down into three categories. Each will be discussed in turn; these are listed in rough decreasing priority, however, infrastructure costs are not a focus of this study and so are much more ambiguous. One recommendation of this work is to further examine infrastructure costs specifically, as they relate to the vehicles.

- Development cost.
- Materials/Component cost.
- Infrastructure cost.

DEVELOPMENT COST

To some interviewees, development cost was not a problem. Others felt it was the biggest single challenge. 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.

MATERIALS/COMPONENT COST

Fuel cells and batteries are both on rapidly falling price curves, but at the moment their costs are quite high. Battery suppliers are often quoted as saying the cost of batteries has now fallen to \$750/kWh. Truck OEMs are saying the real cost of an integrated battery pack is \$2000/kWh. There is a significant difference between the costs for a single battery cell (the battery-maker viewpoint) and the costs for an entire battery pack with the required



control software and equipment (the truck-maker viewpoint). These costs are coming down, and will surely be lower in the future, but the speed of that drop is a subject of much debate.

Similarly, the costs for electric motors (electric machines) are currently high, but falling. Motors of the size required for a truck pulling an 80,000 pound container up a 5% grade are not common, and hence are more expensive – this is one area of significant difference between light-duty EVs and heavy-duty EVs. A dual mode hybrid still faces this cost challenge, as it must operate on EV power alone for at least short periods, and the performance of the truck in that mode cannot be significantly degraded.

These are 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.

INFRASTRUCTURE COST

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. In accordance with direction from Metro, the scope of this report did not include any attempt to examine infrastructure cost issues and no infrastructure experts were consulted. Because the trucks developed must operate outside of the corridor and have broad applicability globally, a study of infrastructure designs and costs (and their impact on truck designs), is a recommended step for future phases of work.

ECONOMIC/BUSINESS CASE

While additional product and engineering development was vitally important, the broad area of 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 hurdles were centered on defining the business case for these vehicles, and the economic and operational framework for the corridor itself. Developing this economic framework, market mechanisms, and business case is one of the key next steps to ensure progress will be made on the technologies, or vehicles using those technologies.

The economic/business case issues identified can be separated into the following categories, listed in rough order of decreasing importance:

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



The above categories are listed roughly in order of priority, and 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.

Based on current prototype designs, and estimating the retail prices to enter production at existing volume projections, the OEMs see prices from \$150,000 to \$300,000 (50% to 100% greater than current conventional trucks). This interviewee conclusion did not include any future savings, but represents the “sticker shock” that a new truck buyer would face, and that initial cost is a significant current challenge to adoption. All the Delphi 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 Delphi 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. Presuming the current estimate for total new ZE truck sales potential (in the corridor) is 9000 vehicles, but drayage companies have a 12 year replacement cycle, that means fleets may only buy 750 trucks/year. Will that be enough sales/profits to support moving ahead? Other estimates have the potential sales volume significantly higher. One approach to estimating vehicle sales would be to take forecast truck trips (90,000 to 95,000 on the I-710 Corridor in 2035) and calculate backward to determine the number of trucks needed, reducing that count by a ZE truck market penetration factor. Regardless, the upshot here is that well-supported sales forecasts are essential to the project, and to successful commercialization of any new technology.

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 challenges (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 challenge 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. 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 challenges, 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.

Those in the first 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.



4.0 CONCLUSIONS

The conclusions presented here are based on extensive interviews with a representative cross section of key manufacturers and suppliers capable of producing advanced Class 8 freight trucks. These individuals are the key decision makers and influencers in any attempt at commercializing ZE trucks. In addition, CALSTART (as the leading medium- and heavy-duty advanced truck consultancy) has added its own knowledge of industry capabilities, status and development projects.

Below are the main conclusions regarding feasibility and challenges to Zero-Emission trucks serving the I-710 corridor, should Alternative 6B or 6C be selected as the Preferred Alternative.

TECHNICAL FEASIBILITY

- A ZE truck to serve the I-710 freight corridor (in Alternatives 6B or 6C) 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 ranging from near-zero- to full zero-emissions. These include dual-mode hybrids; plug-in hybrids; range-extender battery electrics; hydrogen fuel cell EVs, and battery electric trucks.
- A zero-emissions 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 over the next five years to meet the stated requirements of the I-710 freight corridor alternatives 6B & 6C.
 - 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 overwhelmingly identified as the most feasible system in the 5-year time frame.
- Other possible less likely near-term solutions included in-road power, all-battery trucks with fast charge or battery swap, zero-emission equivalent engines (virtually zero NOx and PM) and exotic fuel engines.
- 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 and demonstration of systems and system integration, and on fielding and validating prototype vehicles, would be valuable.



- Development timelines run from near term demonstrations within eighteen months to three years, to the potential for production in as few as five years, assuming market demand was sufficient to justify moving to production. Funding assistance will be needed to speed development, validation and deployment. It will also be likely needed to support purchase. Longer-term solutions were not examined here, as the 5-year time frame best fit the I-710 project.

CONCERNS AND CHALLENGES TO ADDRESS

- While technology was not considered a barrier, the key challenges identified were customer/market demand, potential production volumes, and defining the economic business case.
- A main concern for the economic/business case is the higher added cost of the zero-emission trucks and what mechanism would pay for this cost. The current business case is lowest-cost cargo haul, and projected diesel price increases may not deliver enough savings in drayage applications to cover the ZE truck costs within a time frame acceptable to truck operators.
- Manufacturers in particular, but also suppliers, want to know the more specific performance needs of the system (such as weight, routes, grades and required speeds). They need to know exactly what the definition of zero-emissions would be for the project (zero tailpipe, near-zero, etc.).
- Market participants have concerns over lack of clear (forecast) sales/production volumes, additional uses for this kind of vehicle (as part of total market volume) and the business case for purchase and operation of these ZE trucks.
- Suppliers and manufacturers believe the issue will not be technical capability but regulatory and financial support issues. Said one OEM: “We need to see strong evidence of market demand and regulatory support [before we can enter production].”
- There are serious questions raised by manufacturers and suppliers about whether a market exists for the kinds of vehicles they could produce to meet this expressed need in the San Pedro Port region. Additionally, there is a concern whether there is any demand elsewhere in the US or globally, for such a vehicle capability.

ADDITIONAL CONCLUSIONS

The industry experts and executives were clear that there are no “show stoppers” in producing a zero-emission truck that can work in the I-710 Corridor. There are issues that need 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 issue. Moving more designs into production, and building more “pathway trucks” (current technology, non-zero-emissions) is an important step. For example, a Full BEV is currently very expensive, but if more Diesel Electric Hybrids were sold, the costs would come down and a Full BEV would become more viable. Hence, there is a need to not only develop and promote full zero-emission trucks, but also



develop and promote other near-zero-emission variants that advance the technology and systems which can *lead to* a zero-emission truck.

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.

A vehicle that has application beyond the I-710 study area is also seen as critical. 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.

5.0 RECOMMENDATIONS

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 the key engineering, commercialization, market and regulatory issues outlined in this report.

These findings confirm and provide additional detail to the approach outlined by CALSTART for Metro and SCAQMD in 2009 – See Appendix E. This outline highlighted the need for a multi-year process to:

- Engage the truck and system technology developers on vehicle demonstration and commercialization stages to develop, test, and commercialize both near-zero- and fully-zero-emission truck 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.

This report's findings have confirmed the validity of this approach, and also shown the need to further accelerate some of the recommended phases. In particular, developing the economic/business case and functional structure for a zero-emission freight corridor should be conducted in parallel with technology demonstration as soon as practicable. The economic framework for ZE trucks has emerged as an important enabler. The structure of this corridor "ecosystem" will lend confidence to technology developers as well as provide guidance to vehicle design. As a result, the recommendations below call for an immediate, parallel track to shape the corridor and vehicle economic and regulatory framework.

Based on the findings made in this study, we have developed the following recommendations. Many of them echo and build upon the I-710 program plan initially developed, while others call for an earlier than anticipated tackling of key issues, namely market demand, user acceptance and the corridor use and financial design (the total "market mechanisms" business case for the vehicle).

- Recognize that the development of a successful volume-production (profitable, widely-adopted, sustainable) zero-emissions truck, for the 710 corridor or any other application, is a "commercialization process" that must go through a series of steps. A number of technologies are possible, and the industry responsible for developing them needs to work through the process of commercialization. That process includes demonstrations of early prototypes, building a small number of pre-production vehicles, and then defining a business case for moving to full production – over the course of several years. Similarly, the other stakeholders (e.g. shippers, truck owners and operators) must work through the steps of rapidly transitioning from their current technologies and ways of doing business, to new ones that incorporate the zero-emissions element as a critical component.
- Recognize and develop plans for funding that covers not only advancing and demonstrating technologies, but also shaping and creating the policies and regulations, operational rules, market mechanisms and marketplace for I-710 zero-emissions goods movement. Investigate regulatory and financial supports required to make the corridor function, and develop the market mechanisms and economic/business case.
- Launch the Vehicle Commercialization (Industry) Working Group as planned but target addressing issues raised in this study on vehicle performance needs, market size, alternative vehicle markets and uses.
- Launch a User Needs Working Group to identify the core end user needs and vehicle design parameters. The performance needs identified will drive design criteria, and ideally would be signaled within 12 months to the Vehicle Commercialization (industry) group.
- Initiate a Corridor Market Mechanisms Study Process to assess the best models for financially supporting and enabling the advanced capability vehicles. Such a study



needs to assess and outline alternative ownership and business models (such as amortizing truck costs with corridor construction costs), and possible regulatory structures to enforce the model.

PARALLEL AND SUPPORTING PROJECTS

Several existing programs were identified by industry or CALSTART as possible parallel supporting activities that could be linked to and/or leveraged by the I-710 freight corridor. These include:

- Activities in Europe around vehicle platooning (SARTRE) and powered roadways.
- Department of Energy “SuperTruck” development program.
- The Hybrid Truck Users Forum (HTUF) program with the Department of Defense/U.S. Army.
- The California Hybrid Efficient and Advanced Truck (CalHEAT) research center with the California Energy Commission.
- The Four Agency Agreement between the ARB, EPA Region IX, San Joaquin APCD and the South Coast AQMD targeting zero emissions goods movement.
- Projects linking to the proposed ICTF (Intermodal Container Transfer Facility) and SCIG (Southern California International Gateway).

There was general agreement that the goal can be met, and trucks can be produced that will operate with zero-emissions on the I-710 corridor. However, to ensure success, the economic business case needs to be defined before, or at least in parallel with, the technology/product development.



6.0 Appendices

Appendix A: Survey Instrument (Moderator Interview Guide)

I. INTRODUCTION:

The Los Angeles County Metropolitan Transportation Authority (“Metro”) has engaged CALSTART to examine the commercial viability of zero-emission freight movement and to launch a process to commercialize zero-emission freight movement vehicles and infrastructure. The program will be a multi-year public-private partnership involving stakeholders who are serving, using, and living along the I-710 corridor. The goal is to develop, validate, and commercialize vehicles and infrastructure that support a market-sustainable, zero-emission goods movement for the I-710 freight corridor (and additional uses).

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 (17 miles) fully loaded, without stopping to charge/refuel, and with zero tailpipe emissions. The preferred goal is for the vehicles to travel at full load for at least one “turn” (approximately 35 miles) without refueling at freeway speeds and with zero tailpipe emissions.

We are considering the following technologies:

- In-road electric power (on corridor)
- Catenary electric power (on corridor)
- Fast chargers (at corridor ends?)
- Fuel cells (H2 infrastructure?)

Dual-Mode operation is an acceptable option, including the use of ZEVs in the corridor and PZEVs elsewhere. This would expand operational capabilities beyond the I-710 corridor.

II. QUESTIONS TO ANSWER:

1. Given the parameters described above:

- a. Do you have technologies that could achieve this performance now?
- b. Do you have any vehicles running that could demonstrate this technology?
- c. How close are you to achieving these performance goals? (Miles @ ZEV, etc.)
- d. What technologies do you believe could achieve this performance?
- e. Which of those are the best options?

2. How far away (years) from production intent designs are:

- a. The technologies you have in development now that can achieve the goals
- b. The possible technologies you suggest from the previous question
- c. Could your programs be accelerated if the right conditions were present?

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

- a. Is there further R&D needed?
- b. Cost for development



- c. Cost of materials/components
- d. Market demand
- e. Fuel prices
- f. Other?

4. If corridor/highway infrastructure could support a technology, what infrastructure/technology would be the best choice 10 years out?

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

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

- a. Do you feel a pathway or interim truck is necessary (e.g. CNG Hybrid before full electric)?
- b. How would you see that pathway truck relating to infrastructure support?

6. Would a pathway truck help define and build the market for a ZEV truck?

- a. Is it a requirement for the market?
- b. Would you like to participate in the working group who will help create this corridor, truck, and market? Note: there will be a funding request (approximately \$25K).

III. OTHER TRUCK SPECS: CLASS 8 TRACTOR (TYPICAL PER HTUF)

- GVWR: 60,000-88,000 pounds
- GCWR: 105,000 pounds
- Approx. 350HP equivalent
- Approx. 1250 lb/ft of torque

Maximum speed

- 55 – 65 mph @ GCWR
- Controllable via software calibration parameter
- The vehicle should be capable of 65 mph but should be governable to 55 mph as necessary

Gradeability

- 8% @ \geq 15 mph @ GCWR

Acceleration

- 0 – 12 – 0 mph in 100 ft. @ 75% GCWR;
- 0 – 60 mph in 65 sec @ GCWR
- 12 mph => peak house-to-house speed; 60 mph => peak highway speed

Range

- Minimum 17 miles @ GCWR @ speed. Ideally at least one full turn at zero-emissions before refuel – 35-40 Miles @ GCWR @ speed

Startability

- \geq 20% grade



Appendix B: Matrix of Interview Subjects

Supplier 1	OEM 1	OEM 2	Technology 1
Business Development Manager	Senior Manager, Hybrid Engineering	Head of Advanced Engineering	Founder; Marketing Director

Technology 2	Supplier 2	OEM 3	Technology 3
Founder/Inventor	Head of Engineering; Marketing Leader	VP of Business Development; VP Powertrains; US Marketing;	Founder; Head of Marketing

OEM 4	Technology/Supplier 1	Supplier 3	Technology 5
Senior Product Engineer	North American Marketing Mgr.	Product Development Engineer	Truck Program Manager

OEM 5	Technology 6	Technology/Supplier 2
Senior Project Engineer	Senior Principal Systems Engineer	Head of R&D



Appendix C: Anonymous Quotes from Delphi Experts

OEM

“If the port doesn’t invest, we won’t either. It’s that simple. The average trucker can’t afford to invest another \$80,000 per truck. It helps a lot to have a concentrated single buyer.”

OEM

“At one point, the ports were going to switch to NG, and said 8-16,000 trucks, but then that disappeared. There’s another part of the question: credibility.”

OEM

“It’s still apples and oranges here to get people to buy b/c you don’t have all the costs laid out. You’d have to do two demos: the pathway, and then the ZEV.”

OEM

“There’s still a lot of engineering to do, but the real feasibility issues are with infrastructure”

OEM

“What assurance do we have that there will be enough sales volume to provide profits?”

OEM

“We have a [power delivery] system that is cheaper than catenary.”

OEM

“Everyone says there’s no H2 infrastructure, but compare it to LNG. LNG is seen as mainstream, but there’s only one LNG fueling station at the ports. There are H2 pipelines near refineries. H2 could be done in just the same way as LNG, with a fueling station at each end of the corridor.”

OEM

“The guys who are moving freight now are doing it for \$100 a can, and they’re buying old trucks for \$3,000, so this stuff won’t work with them. The port will have to pay a lot more than \$100 a pop.”



OEM

“This is not a simple question: you can throw a lot of batteries, etc. at the problem, but in the end, you’ll need the grid.”

OEM

“The problem is that in general, people aren’t designing [electric] motors that large. “

OEM

“Industry has invested a lot and wants to build out the current technology before funding the next one.”

Supplier

“Hypothetically speaking, if a ZEV truck was allowed to cut to the front of the [container pick-up] line, it would be a HUGE incentive to the truck operator, and it doesn’t cost anything.”

Supplier

“Customers don’t really care about the environment. They care about fuel costs. What sells this are the savings in fuel.

Supplier

“Fuel prices aren’t driving this; the logistics are. By “logistics”, I mean what they can get paid for doing the job. Even if fuel were to cost \$8/gallon, these drivers would just charge more and use crappy trucks.”

Supplier

“Market demand is the biggest hurdle right now. We started looking at the 710 project because it seemed interesting but we stopped looking due to the lack of demand.”

Supplier

“We’re building these components to ensure the truck will perform for 1 million miles. They have to do as well as current diesel trucks.”

Supplier

“Even if battery costs come down, the weight penalty will not go away”



Supplier

“We have between 40,000 to 60,000 trucks that drive that stretch each day. You’d have a better impact [on air quality] if you had half of them being hybrid, than if [just] 10% were ZEV.”

Supplier

“It keeps coming back to the question of whether the industry is willing to do this. If it’s not, then it comes back to how many vehicles the State is willing to fund. The rest will be dirty vehicles.”

Supplier

“We’ve forecast to the year 2050 and have seen urbanization as one of the biggest challenges in the future. We believe there will be a very strong demand in the out years.”

Technology Provider

“We’d be really interested in learning more about the market opportunity here.”

Technology Provider

“One area where we could get a lot of help is setting up a leasing program for Lithium batteries. You can take LI-ion batteries and run them for 3 years and then refurbish them and use them for utility type applications.”

Technology Provider

“If you were to reinvent the IC engine today, what would you do? We’ve done it. We’ve developed smart engine technology that allows the engine to be improved.”



Appendix D: Acronym List

APCD – (San Joaquin) Air Pollution Control District
CalHEAT – California Hybrid Efficient and Advanced Truck (Research Center)
CARB (or ARB) – California Air Resources Board
CARGO – Clean Air Rapid Goods Movement (proposal to Metro)
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 (Metro)
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
REV – Range Extender Vehicle (or Range Extended Electric Vehicle)
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 E: Original “CARGO” program proposal

Please contact CALSTART if you would like a copy of this appendix.

A BRIEF SUMMARY:

The original **Clean Air Rapid Goods Movement** (CARGO) program was outlined by CALSTART to METRO in mid-2009. It has been refined and adapted as the I-710 project developed.

The fundamental premise of the commercialization process was to simultaneously develop the infrastructure, the vehicles, and the economic ecosystem for a zero-emission I-710 corridor.

SELECT PARAGRAPHS FROM THE CARGO PROPOSAL:

The outlined I-710 CARGO program is a process to combine the development of zero-emissions goods movement vehicles coordinated with the development of the I-710 Freight Corridor. The CARGO Program can break the logjams preventing implementation of zero-emission vehicles, and thereby deliver dramatic benefits to the Ports, the surrounding communities, and the Nation.

CALSTART recommends a focused multi-year regional process built around the technical needs and business-case needs of the vehicle, and the parallel development of a robust market for its commercial success and use. The ultimate goal will not be prototypes nor technology development: the goal will be creating a viable new class of commercial vehicle, available from multiple manufacturers and supported by several suppliers, within 5-8 years. This strategy fits the timeframe for the opening of the first phases of the improved 710. Increasing truck volumes will follow a staged introduction process to steadily expand until all goods movement vehicles using the corridor will meet the new requirements.