



California Energy Commission Clean Transportation Program

FINAL PROJECT REPORT

Kenworth Class 8 Alternative Fuel Vehicle Natural Gas Micro-Turbine Hybrid Electric Vehicle

Prepared for: California Energy Commission Prepared by: Kenworth Research and Development Center



A PACCAR COMPANY

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PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program, formerly known as the Alternative and Renewable Fuel and Vehicle Technology Program (ARFVTP). The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to \$20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about \$100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued PON-09-004 to provide funding opportunities under the Clean Transportation Program for developing the commercialization of advanced medium-duty and heavy-duty vehicle technologies. In response to PON-09-004, the recipient submitted an application which was proposed for funding in the CEC's notice of proposed awards June 10, 2010, and the agreement was executed as ARV-09-012 on January 3, 2012.

ABSTRACT

There is growing interest in hybrid electric vehicles using alternative fuels in heavy truck applications. This project developed and demonstrated a Class 8 hybrid electric heavy truck tractor powered by a natural gas-fueled, intercooled-recuperated microturbine engine. The research project used forward-looking simulation models and acquired field data to determine hybrid type and commercial heavy haul applications.

Research was conducted to identify suppliers with heavy truck and hybrid vehicle applications, leverage technology developed to date, and integrate the components onto a chassis with the shortest possible wheelbase. The short wheelbase was selected as it was the most challenging to package, thus allowing the component layout to be applicable to a broad range of heavy truck chassis designs of various wheelbases and applications.

The type of hybrid selected is a series hybrid in which the engine is mechanically decoupled from the drive train. The microturbine engine is directly coupled to a generator, which then supplies electric power either directly to the power train or indirectly through an energy storage and retrieval system. The microturbine output was designed to compete with similarly-sized diesel engines used in this same application. A hybrid drive assembly was powered by the energy storage system and power was managed by a programmable power distribution box and a vehicle control system.

Once assembled and site tested, the Class 8 natural gas intercooled microturbine serial hybrid electric vehicle, through simulation, is predicted to have a better fuel economy in pickup and delivery applications and should compete will in short haul/regional applications. Further testing is required to validate simulation results.

Keywords: hybrid, heavy truck, microturbine, alternative fuel, electric, Class 8.

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EXECUTIVE SUMMARY

The goal of this project was to determine the technical and economic feasibility of replacing current diesel engine technology for Class 8 truck tractors with a microturbine engine fueled by natural gas in a hybrid electric vehicle.

A simulation model was developed to emulate real-world conditions. Data was gathered from customer routes in Southern California, including a pick-up and delivery route in Poway, and a Regional Haul from Poway to Whittier and back. These data were used as the input source for the model, enabling the model to predict the performance of various hybrid configurations and components.

Based on these predictions, a serial hybrid electric vehicle was designed, components were sourced and the vehicle was constructed and tested.

The completed vehicle was tested on a dynamometer measuring power and torque at the wheels. Using these dynamometer data in the simulation model, the vehicle achieved nearly 30 percent fuel economy improvement in pick-up and delivery applications, but only very small gains in regional haul applications. These results closely match initial predictions made from simulation.

The simulation model created for this project proved to be quite accurate. This tool can be used for choosing hybrid designs and components in future truck designs. It also showed that hybrid design must be optimized to the specific applications and route profiles in order to achieve desired operational and fuel economy gains.

The microturbine engine and hybrid system was technically feasible in these applications, although not yet reliable enough for mass production. Efficiency and environmental gains were nearly as predicted.

Additional testing is recommended to further evaluate the environmental benefits of this truck design. Development of the microturbine and the hybrid vehicle design should continue, with a focus on improving reliability, reducing complexity and lowering cost.

CHAPTER 1: Turbine Serial Hybrid Development

1.1 Introduction

The serial hybrid electric vehicle project demonstrates an engine technology that is fuel flexible and produces fewer greenhouse gas (GHG) emissions. Two key technologies were employed to accomplish this project: the advanced hybrid electric system designed for Class 8 applications and the intercooled recuperated microturbine (Figure 1).



Figure 1: High-level View of Serial Hybrid Electric Vehicle System

Source: Kenworth Truck Company and Brayton Energy

Hybrid electric systems have been in development for several years with limited success in over-the-road Class 8 truck applications. The intercooled recuperated microturbine will be a second generation engine developed for this program and is based on successful stationary applications. Natural gas is the selected near-term fuel for this project because of its low GHG potential, low cost, and emerging distribution infrastructure.

The target market will be a regional/short haul and pickup and delivery application. These applications offer the greatest market opportunity with respect to the goals and objectives of this solicitation, and makes use of existing refueling infrastructure in California with potentially the best efficiency improvements in duty-cycle. The potential high efficiency of an intercooled recuperated microturbine was tested and compared against a conventional internal combustion engine.

The proposed intercooled recuperated microturbine combines the attributes and advancements of modern microturbines and high-volume automotive turbochargers. A compelling feature of the engine technology is multifuel capability, permitting use of either gaseous or liquid fuels including ethanol, biodiesel, liquefied natural gas (LNG), compressed natural gas (CNG), and hydrogen. Furthermore, existing microturbine designs have been certified to California Air Resources Board (ARB) 2007 standards without an after-treatment

system for natural gas or diesel fuels. This feature, unique among transportation engines, has the potential to reduce cost and enable wider use of renewable and low GHG-emitting fuels in the transportation sector.

1.2 Problem Statement

Current heavy-duty natural gas vehicle conversions add an \$80,000—\$90,000 cost penalty over a diesel equivalent (Figures 2 and 3). A detailed cost analysis of the intercooled recuperated microturbine engine and hybrid system will add an estimated incremental cost of about \$50,000. A key component in this lower incremental cost is the elimination of the diesel engine and the associated after-treatment systems for emissions control. These after-treatment systems cost \$35,000—\$45,000. Eliminating after-treatment systems will offset some of the cost of the added technology. The overall cost when compared to yearly savings translates into a three- to four-year payback. A lower payback period and competitive operation costs are key components to drive market adoption.



Figure 2: Kenworth LNG Chassis

Photo credit: Kenworth Truck Company

Figure 3: Kenworth CNG Chassis



Photo credit: Kenworth Truck Company

1.3 Objectives

Develop and demonstrate a commercially viable Class 8 alternative fuel vehicle using microturbine and hybrid technologies. The proposed tasks for this project are:

- Development of a 350 kilowatt (kW) high efficiency, low emissions, multifuel intercooled recuperated microturbine and powertrain.
- Six-month demonstration program in California.
- Meet emissions standard without after-treatment.
- Successfully demonstrate in excess of 20 percent fuel economy improvement in "real world" operation using natural gas.
- Develop business plan for production rollout.

Develop engine technology that reduces emissions including GHGs:

- 15—26 million metric tons of carbon dioxide (CO2) annually will be reduced by 2050.
- Reduce criteria pollutants to meet December 2007 State Alternative Fuels Plan.

Reduce petroleum fuel consumption:

• 3.8—9.6 billion gallons of diesel fuel eliminated by 2050, which is about 15 percent of the Energy Commission goals.

Create jobs in California:

• In excess of 6,000 high-tech and green tech jobs on a sustainable basis in California by the 2025 to 2030 time frames.

CHAPTER 2: Conclusion

The project produced a microturbine-powered serial hybrid electric vehicle that runs on natural gas and performs in a manner similar to a standard Class 8 truck with an internal combustion diesel engine. At the time of this report, the truck had accumulated about 300 miles of testing on site, on the dyno, and on over-the-road trips to the CNG filling station (Figure 4). The chassis is operational and ready for additional functional and track testing. Further testing would be possible only with significant effort from a team of engineers and skilled technicians.



Figure 4: Test Truck Out for Fuel (Left) and in Dyno Test Bay (Right)

Initial simulations showed that a serial hybrid electric vehicle configuration has the potential to achieve the 20 percent fuel economy goal (Table 1). A parallel hybrid configuration could have provided marginally better fuel economy but was deemed too complex from a controls standpoint, and too risky due to unknown transient response of the microturbine.

Preliminary results from dynamometer and road test data suggest the vehicle performs 10 percent more efficiently in Electric Vehicle (EV) mode than initial simulations showed. The data also suggest that the system performance can be improved through better torque balance between the motors and control algorithm tuning.

Brayton analysis of bench test data concludes that the microturbine achieved a 38 percent operating efficiency versus the predicted 44 percent. Additional in-vehicle tuning could improve this efficiency (Table 1). The microturbine produced sufficient power to achieve peak torque from the electric motors while also providing power to charge the battery in full-vehicle hybrid mode testing.

Photo credit: Kenworth Truck Company

	Distance	Fuel Used		Diesel	Max Road	Min Road	Change in Fuel Economy
Cycle (HEV Mode)	(Miles)	(kWh)	kWh/Mile	MPG (Calc)	Grade (%)	Grade (%)	Against the Baseline
High Speed Cruise	26.69				NA	NA	°
Baseline Data	1	159.33	5.97	6.35			
Initial Model Estimate	1	151.79	5.69	6.67			4.74% Improvement
Final Model Estimate	1	132.35	4.96	7.65	1		16.94% Improvement
Pick Up and Delivery Cycle	33.16				NA	NA	
Baseline Data		286.38	8.64	4.40			
Initial Model Estimate		202.89	6.12	6.20			29.16% Improvement
Final Model Estimate		188.09	5.67	6.69			34.32% Improvement
					_		
Regional Haul	232.82				3.83	-4.68	
Baseline Data		1304.5	5.60	6.78			
Initial Model Estimate		1331.4	5.72	6.64			-2.06% Reduction
Final Model Estimate		1303.0	5.60	6.78			0.11% Improvement
High Speed Cruise				Fuel	Fuel		
Estimated Gain/Penalty Managing				Consumed	Economy		Change in Fuel Economy
State of Charge	SoC Init%	SoC Target%	SoC Final%	(Kg)	(Km/Kg)		Against Proportional
Proportional Power Discharge Mode	100	30	25	4.57	9.4		
Rated Power Discharge Mode	100	50	- 35	4.17	10.29		9% Improvement
Proportional Power Recharge Mode	25	80	85	15.36	2.80		
Rated Power Recharge Mode	25		35	9.52	4.51		38% Improvement

Table 1: Simulation Results

Source: Kenworth Truck Company

The simulation indicates that for a serial hybrid electric vehicle in applications where stop-andgo traffic is prevalent, this chassis should perform better than initial estimates. In applications where much time is spent traveling at or near a constant speed, the model suggests initial performance estimates were reasonable. The final comparison to note from the data is battery state of change (bottom section of Table 1). The tests suggest fuel economy is improved by charging the batteries quickly and shutting the turbine off.

However, after several internal reviews and significant effort to keep the truck operational, Kenworth has determined that the chassis must remain a prototype, as it is not sufficiently reliable for field testing and cannot be released for use in an uncontrolled environment. Significant improvements in reliability will require another iteration of design and simplification of systems and components. Therefore, field-testing was not conducted.

The project results do suggest that Class 8 microturbine hybrids may be capable of competing with a stock diesel chassis in pickup and delivery and regional haul applications. However, additional road and track tests under varying load and driving conditions are required to substantiate the capability.

One of the principal benefits from this project is the tractor itself (Figure 5). The existence of a physical vehicle provides a test bed for future development. The experience building and operating the vehicle along with the rapid control prototype simulation/model was invaluable. The project yielded a team of designers and developers with a fundamental understanding of hybrid systems and the experience to direct improvement.



Figure 5: Vehicle Layout

Source: Kenworth Truck Company

The results confirm industry estimates and strongly suggest that a commercial natural gas hybrid Class 8 truck in targeted applications can be expected to produce a 10—30 percent improvement in fuel economy. This equates to about 147—227 gallons of diesel displaced and a reduction of about 384—1,265 tons of CO2 for every truck every one thousand miles of service.

3.1 CEC Benefits

This project successfully demonstrated the technical feasibility of a high-efficiency, lowemissions, low-GHG powertrain for use in Class 8 applications. The component configuration and layout of the chassis meet the needs of a broad spectrum of customer applications. The vehicle performance – in terms of acceleration, top speed, and gradeability – compare favorably with vehicles currently in use in regional haul and pickup and delivery applications. Further, this project demonstrated that the powertrain could, with further development, be economically viable in the intended market.

The principal benefits, however, are an original equipment manufacturer better prepared to develop a chassis that can be built in volume, and a team ready to address, react to, and support a customer base. Kenworth will leverage this experience, apply it to future hybrid projects, and continue to develop competitive, reliable hybrid trucks for pickup and delivery and regional haul applications. This application will support the CEC's demand for trucks to be used in port facilities, drayage truck, and other utility district markets.

3.2 List of Commission Benefits

- System control design kept within Kenworth, enabling engineers to share information with the hybrid component suppliers. This knowledge-sharing will allow suppliers to improve their product for all customers.
- Demonstrated the possibility of building a hybrid vehicle for use as a very short wheelbase tractor typically specified for double trailer applications. This design layout can be easily applied to multiple longer wheelbases.
- Demonstrated the possibility of building a hybrid vehicle in which driver instrumentation and controls remain identical to current production trucks (it looks and acts like a standard truck). This minimizes the need for specialized driver training and greatly increases the available driver pool.
- Demonstrated the possibility of building a hybrid vehicle that is completely interchangeable with existing fleet trucks.
- The design and specification of the battery pack was found to be unique for Class 8 applications. Specifically, the high charge and discharge rates for acceleration and regenerative braking with heavy loads required specific battery design.
- Developed a robust specification for a high-voltage interlock loop that can be used on future hybrid vehicle design.

These benefits, when fully developed, will directly support specifications needed to ensure products in this market will perform in a robust and reliable manner.

3.3 Kenworth Truck Company Benefits

Kenworth benefits from the experience of developing and building future hybrid chassis. Kenworth utilizes a fact-based decision process within a standardized product creation process based on Six Sigma design principles. In addition to creating a working hybrid chassis, the team gained experience designing, developing, and controlling electric accessories (Table 2). The costs to convert these accessories have been prohibitive in the past; funding opportunities such as this enable companies to build and test electric versions that will perform and survive in a heavy truck environment.

Table 2: Vehicle Electrification

Accessories				
Coolant and Lubrication Pumps	Fuel Delivery and Storage System			
Cooling Module Fan Assembly	Chassis Air Systems			
Power Steering System	Heating, Ventilation and Air Conditioning Systems			

Source: Kenworth Truck Company

Once the systems were installed, they had to be mapped and tethered to a supervisory control system. This control system managed all sub-level control systems, central area network (CAN) bus traffic, and human-machine interactions. The project also demonstrated the need for a quick and efficient rapid controls model to support prototype vehicle development. Every electrical subcomponent on a hybrid electric vehicle (HEV) has to be managed; CAN and power control become synonymous, and system control becomes the priority for chassis operations. The hierarchy and timing protocol process for multiple closed loop controls had to be developed to ensure systems functioned as designed and when they were needed (Figure 6). As the sophistication of the supervisory control system grew in complexity and completeness, the control system incrementally began to manage the vehicle systems and command subsystems to perform as predicted and react to operator inputs as designed.



Figure 6: Communication and Controls Architecture

Source: Kenworth Truck Company

These benefits, with continued growth and application, will directly support product design specifications needed to ensure a quality and durable product is released to the market.

3.4 List of Kenworth Benefits:

- Kenworth assembled an HEV development team that acquired a level of expertise enabling reliability improvements in hybrid trucks.
- Developed an HEV simulation model that can be used for future iterations.
- Developed an HEV control system that can be used for future iterations.
- Acquired knowledge to handle HEV products and components safely.
- Learned that customer infrastructure must include nearby availability of natural gas and on-site overnight shore power supply.
- Developed a hybrid architecture that can accommodate a variety of power-generating systems.
- Developed specifications for hybrid components that can be used for future iterations.

CHAPTER 4: Lessons Learned

4.1 Serial versus Parallel HEV

Early in the project, the simulation model suggested that a parallel hybrid electric vehicle would be more efficient than a serial hybrid electric vehicle. Simulation models were developed to compare performance estimates between serial and parallel hybrid electric vehicle systems. The results of the analysis suggested that parallel hybrid electric vehicles would average a 6 percent higher fuel economy benefit. However, the analysis also showed that the parallel hybrid electric vehicle was a more complex system. Little data was available on the transient torque response of the selected microturbine. Additionally, the clutch design and the electronic control of the clutch that would mechanically connect the turbine to the transmission would have significantly increased the complexity of the chassis.

The decision was made to take the route of least risk, which was to build a serial hybrid electric vehicle and gain additional experience with this type of technology. The lesson learned is that using simulation models in the planning stage of the project allows the team to make informed decisions earlier and reduce risk.

4.2 Vehicle Electrification and Controls

The level of vehicle electrification is significantly greater than a standard truck and the controls to manage all of these systems forced a change in the vehicle control strategy. The controls architecture was revised and a controls hierarchy was developed to mitigate subsystem conflicts. The result of this development was a supervisory control system.

The supervisory control system is used to manage vehicle operations and is the primary integrator for all supporting subsystems. The supervisory control system manages power and communications, and settles conflicts at the vehicle level. Although not ready for production, it is a robust and stable rapid control prototyping software package.

Figure 7, below, shows the 2013 control system as designed through Task 2 of this project. The highly detailed 2015 system shows the level of complexity and detail required to ensure the truck was operational in EV and HEV modes. The level of complexity significantly exceeded initial estimates.

The supervisory control software managing the vehicle ended up being one of the most significant advancements of this project. The ability to iterate through the changes quickly and efficiently permitted the team to test specific components individually and as a system. The team could take the results from minor tests and feed the results back to improve the controls.



Figure 7: Complexity Growth of Vehicle Model

Source: Kenworth Truck Company

A MotoHawk controller was used as the base control module for the vehicle hybrid control and turbine engine. Woodward, the controller supplier, discontinued direct support for small or new customers midway through the project period. Woodward selected New Eagle as their sole contractor for code development and primary support to such organizations. Kenworth found New Eagle to be too expensive and slow to respond for the budget and schedule of this project. To meet the cost and schedule requirements of this project, the team decided to bring this expertise in-house and develop an internal control strategy.

During the development of the control system, the team found the MotoHawk software and hardware documentation insufficient for inexperienced users. Subtle undocumented features produced unexpected results that required significant effort to understand and resolve. For

example, copying and pasting blocks of code worked well for most of the feature development, but produced failures in the resulting code when used in the development of CAN communication messages.

4.3 High Voltage Architecture

Interference and isolation was an issue, as some subcomponents procured were not built to the specifications developed by the team and provided as part of the purchase order. The commissioning process identified multiple opportunities for improvement, and input from the performance data acquired will be incorporated in future projects.

Included in this improvement is the understanding that power cable routings for high voltage systems will have a significant role. The lines and their minimum bend radii are too large to merely expect them to route around other components. The lines carrying power, connections, and routings must be designed to dedicated and fixed paths.

The analysis also suggested that the electrical architecture of this system had to be a minimum of 600 volts direct current and a maximum of 1,000 volts direct current. The principle drivers for this direction are related to necessary torque to keep vehicle performance similar to a stock truck, to minimize the wire diameter in the high voltage harness and hence minimum bend radii, and to minimize power loss through the cables (I²R losses).

Additional time and effort will be required to better define and specify isolation resistance for components and connectors called out in high-voltage applications.

4.4 Fluid Loops

As development of the microturbine progressed, Brayton found that the temperature of the cooling oil needed to be kept within a very narrow range. Heaters had to be added to increase the minimum oil temperature to 120°F (48.9°C) for turbine start. To protect the low pressure turbine bearing, the maximum oil temperature could not exceed 135°F (57.2°C). This forced a design change to locate the cooling module back of cab and over the fuel tanks. A Brayton analysis suggested that a second auxiliary cooling module would be required to transfer sufficient heat away from the system and protect rotating components. Due to schedule and packaging constraints and a change in requirements, the second cooling module was not installed.

Routing of coolant lines on this short wheelbase chassis was a significant challenge. In addition to the oil coolant lines for the microturbine with a heat exchanger and heaters, two additional oil cooling loops were required: one for the generator and one for the traction motors and transmission. An ethylene-glycol/water cooling system with several parallel loops was required to maintain temperature in the high-voltage power distribution box, the two invertors for the traction motors, the three invertors for the microturbine systems, the battery management controller, and the battery packs. Two refrigerant cooling loops were used: one to provide air conditioning in the truck's cabin, and one to chill the battery packs.

Future project tests should include a phase to instrument the existing systems and acquire data. This information can be used to redesign and simulate the coolant loops to match the thermal load conditions.

4.5 Energy Storage Systems

Late in the design and assembly process, the battery supplier, EnerDel, suggested that the battery systems could not be on a single loop and had to have a separate loop or an auxiliary battery chiller in addition to the glycol/water coolant to ensure the battery pack was sufficiently protected. The thermal capacity of the battery will require optimization in future projects.

An early design criterion was to keep the battery packs away from the fuel source and install the two packs on one side of the vehicle. This was not the best option from a weight distribution specification but it did minimize safety risk with the fuel system. It also minimized the length of the routings used to power the high voltage components. Balancing the battery weight evenly to the tires will have to be reconsidered for future installations.

4.6 Engine Air Intake

The air intake system became a significant design project, as it had to be packaged within a very tight design envelope and had to have a particulate filter of sufficient size to prolong maintenance intervals and prevent premature turbine issues. The resulting design draws air through the sides of the hood and includes features to remove rainwater before reaching the filter mounted at the low-pressure compressor.

4.7 Electrical Steering

RH Sheppard suggested that the steering assembly is not ready for use in uncontrolled environments. The increased starting load from the engine may create a condition where steering response could be compromised. A complete study with shared results is required to ensure starting systems match engine demands. This may require a larger accumulator in future design iterations. Additionally, the prototype controller used in this assembly cannot be maintained or supported for field use as the supplier has since closed business operations.

4.8 Resource Management

Truck manufacturers and their suppliers are lean operations. Team turnover is a difficult obstacle and the loss of an entire team and multiple controls engineers had a direct impact on project schedule and forced the incoming team to push product design to the supply base. This activity had a negative effect on project development costs and increased integration complexity.

Team depth and experience with HEVs at the original equipment manufacturer and suppliers were not sufficient to manage turnover of resources involved. This inexperience tended to produce overly conservative parts and assemblies. In some cases, these components severely limited the ability to tune them down for application within this system.

4.9 Build and Integration

With any vehicle, packaging becomes a significant challenge. Most heavy truck components are large, bulky, and very heavy. The chassis selected has one of the shortest wheelbases Kenworth makes (Figure 8). Appearance is not as strong a consideration as it is in the passenger car industry, but a truck must appear ready for customer use.

The project identified a constraint for heavy truck subcomponents and the existence of a performance and reliability gap between preproduction and production-ready hybrid parts. After many hours of repair, rework, and system modifications, the vehicle met operational conditions and completed dynamometer test runs; and although the prototype, from a distance, has the appearance of a standard truck, it is not.



Figure 8: Target Short/Regional Haul and Pickup-and-Delivery

Source: Kenworth Truck Company

Auxiliary cooling modules, oil flow and preheating, and converter and connector reliability all contributed to the delays and problem solving exercises that are inherent with prototype builds. The complications for the routing were not helped by the need for two separate and parallel oil coolant loops and a glycol/water coolant loop. The accessories cooled were not optimally located, which then required several of these lines to pass across the chassis and cross over each other to access all thermal loads and to complete the coolant loops. Tucking these parts into available space while keeping the appearance clean truly challenged designers (Figure 9).



Figure 9: Auxiliary Engine Coolant System above Fuel Tank Assembly

Source: Kenworth Truck Company

Custom engineering was not limited to appearance. For example, the high voltage battery box frame not only held the battery assemblies, but also had to efficiently transfer loads back

through the chassis. This frame also had to support the motor controller, generator controller, shore power, and high-voltage power distribution box components. Once all the large components were added, the assembly was further tasked to carry the heating, ventilation, and air conditioning compressor controllers and the passenger side access steps. Finite element analysis of the stresses in the structure and the chassis rails resulted in design changes, creating a large and heavy battery carrier frame.

The commissioning phase of the chassis and engine was an iterative process at best. The intents of the commissioning and test phase were to resolve engine issues before installation and EV mode issues before combining the two assemblies.

An oversight in planning left the project with an inability to dissipate enough energy from the generator to permit the engine to run up to the designed temperature before installation into the chassis. The only method to discharge the batteries was through powering the wheels. Therefore, full vehicle systems could not be validated until the major subcomponents were installed on the chassis, wired for power, and communication and plumbed for oil, coolant, and fuel. The project simply ran out of time to further refine operations. Significant effort will be required to achieve an optimal generator charge and battery depletion rates. An optimized blend between generator, battery, and motors will simplify and standardize energy generation parameters and drive the battery type and capacity.

In summary, more work is required to keep the vehicle performing above a minimum threshold. Specifically, vehicle speed as a function of battery state of change was not an issue until state of change dropped below 20 percent. However, even at a low state of change, the chassis was able to climb more than 10 percent grades, albeit below the speed limit (Figure 10). Additional time and effort will be required to efficiently blend engine recharge conditions with battery state of change, and depletion rate with vehicle power demands.



Figure 10: Impact Battery State of Change Has on Vehicle Speed

Source: Kenworth Truck Company

CHAPTER 5: Recommendations

The goal was to build a short-wheelbased HEV powered by a natural gas microturbine that will offer improved fuel economy and compete with a standard diesel engine. In building this truck it was important to balance performance, reliability, and schedule to minimize project risk. However, performance and schedule became the driving factors and reliability was compromised to ensure the project was completed in time and with favorable results. Future projects will emphasize vehicle reliability to meet corporate quality guidelines and product design specifications.

The recommendations for this chassis are:

- Continuing vehicle tests and acquiring performance data.
- Increasing cold engine startup process.
- Updating and adding controls modules to support performance improvements.

The recommendations for future hybrid projects are:

- Designing a modular vehicle that is energy agnostic.
- Incorporating a production part approval process.
- Redesigning vehicle layout for even weight distribution.
- Designing dedicated high voltage wire routings.

Without a broad market acceptance and a reasonable recurring/replacement market, production development costs will not be recovered. Additional development projects and customer technology acceptance is required before expanding into other applications or markets. Growth strategies are outlined in the CALSTART report (Appendix A) and increased economies of scale are required before cost reductions are possible. Typical payback for the truck industry is two years or less and the vehicle must operate reliably through the first customer life cycle.

It is recommended that Kenworth continue to participate in similar development projects, explore cost reduction opportunities, optimize vehicle layout to align with manufacturing standards, and interview existing and new customers to test technology acceptance in the industry.

CHAPTER 6: Background Information

6.1 T680 Model Selection

The single rear axle T680 Day Cab was selected as the base model for this project (Figure 11 and Table 3). The 2.1-meter-wide cab is the most aerodynamic truck in Kenworth's 90-year history. This highly configurable model established a new standard of excellence since the production launch in 2013. It is available with dual or single rear axles, was available as a glider (without a drivetrain), and in this configuration can be applied to a reasonably sized market.



Figure 11: T680 Single-drive Axle Day Cab

Source: Kenworth Truck Company

Item	Specification	Comments	
GVWR	>33,000 lbs.	GVWR for Class 8 trucks	
GCWR	80,000 lbs. max	61,000 lbs. average	
Engine type/Rating	350 kW intercooled recuperated microturbine	Brayton-Remy Generator Set	
Engine fuel	CNG		
Fuel tank capacity	150–200 US DGE	Agility Fuel Tank Assembly	
Hybrid motor rating	300 kW	Remy HVH 410-75 (2)	
Transmission Type	Automated Manual EATON Transmis		
Power assist Steering	Electric over hydraulic RH Sheppard Asse		
Tire specs	Smart Way Certified		
Acceleration	Equal to or better than conventional vehicle		
Interior noise	Per FMCSA Part 393.94		
Exterior noise	Must comply with federal, state and local noise ordinances (FMCSA Part 325.7)		
Fuel economy	20% or greater reduction in duty cycle dependent fuel use		

Table 3: Chassis Specifications

Chassis specification selected for pickup and delivery and regional haul applications. Selection of the single axle chassis, hybrid type, and application were the results of a model-based design process and a detailed digital layout.

Source: Kenworth Truck Company

6.2 Major Sub-Components

6.2.1 Brayton Energy Microturbine

Brayton Energy's intercooled-recuperated gas turbine will achieve fuel-to-electric conversion efficiency over 40 percent (44 percent shaft efficiency), emissions compliance with ARB 2010 requirements, and will be manufactured at a competitive price for the Class 8 truck market. The engine is also operable on multiple fuels, including standard diesel fuel, bio-diesel, bio-oils, and natural gas (Figure 12).

Figure 12: Brayton Turbine Engine and Remy Generator



Sources: Kenworth Truck Company and Brayton Energy LLC

6.2.2 Remy Generator

Remy developed the HVH-210 generator for heavy-duty hybrid applications. The generator is directly coupled to the end of the turbine assembly and is the primary power source for the vehicle during normal operations. The generator completes the gen-set (motor and generator assembly) that was installed into the front of the chassis and provides power to the vehicle during normal operations.

6.2.3 RH Sheppard Electric Steering System and Engine Starter

Engine start was accomplished by pumping high pressure oil onto the Pelton wheel of the turbine assembly. The RH Sheppard electric steering system serves double duty as an engine starter and power steering system (Figure 13). The accumulator, pump, and smart valve are controlled by the engine controller with a parallel input from the chassis controller. Priority is given to steering, then to starting the engine.

Figure 53: RH Sheppard Hybrid Electric Power Steering Assembly



Sources: Kenworth Truck Company and RH Sheppard Inc.

The steering gear is common between standard and electric steering systems; the rest of the system is unique to hybrid applications. What makes this system unique is the integration of an accumulator that allowed this fluid loop to double as a hydraulic capacitor for starting the main engine.

6.2.4 EATON High Voltage Distribution Box

The EATON high voltage power distribution system manages and distributes all high voltage demands (Figure 14). It is controlled by the vehicle supervisory control system and distributes power automatically either by CAN communication or by direct power requests from connected devices. However, the high voltage power distribution system was designed for a 400-volt system and has struggled to perform reliably at the 600 volts required for this truck. Additional modifications were required to accommodate all high voltage accessories. Future models will require additional design considerations.



Figure 64: EATON High Voltage Power Distribution Center

Sources: Kenworth Truck Company and EATON Corporation

6.2.5 Phoenix Motor/Generator Controllers

The Phoenix Drives Family is a series of Class B Power Inverters designed to provide advanced control for AC motor applications. They bi-directionally convert high-voltage direct current (DC) power to three-phase AC power to drive a variety of machines in a compact, rugged,

environmentally sealed package (Figure 15). The drives are built upon a common hardware platform accommodating a wide range of possible drive schemes with standard, configurable software modules that determine specific family members. The drives were designed primarily for use on medium-to-large vehicles and can be used on an electrified vehicle as an engine assistant to reduce peak loading and provide brake energy recapture and further improve fuel economy.



Figure 15: The Phoenix Motor Controller

Sources: Kenworth Truck Company and Phoenix International

6.2.6 Remy Drive Motors and EATON Transmission

Remy developed the HVH410-75 motors for heavy-duty hybrid applications. Their proposal was the dual motors mechanically coupled with independent high voltage connection boxes. The technology enables industry leading power and torque densities with high and broad efficiency windows (Figure 16).

6.2.7 EATON Transmission

The EATON Fuller four speed auxiliary transmission was designed for high reduction and heavy truck applications (Figure 16). It is mechanically coupled to the dual Remy motors and directly drives the rear axles via a mechanical drive shaft. The AMT transmission prototype is CAN-capable and will be driven through the transmission control unit. The transmission control unit communicates desired motor torque, output speed and gear selected.

Figure 16: Inline Dual Remy Motors and EATON 4-Speed Transmission



Sources: Kenworth Truck Company, Remy Inc., and EATON Corporation

6.2.8 EnerDel Energy Storage System

The EnerDel 613V (nom) HEV battery pack is a high-voltage, high-current energy storage system with a built-in battery management system (BMS) and CAN communications capability (Figure 17). The battery pack system will provide data and operating limits via a CAN communication connection. Operating limits are expressed in the form of current limits and data provided includes pack voltage, cell voltage, state of charge, and pack temperature. The EnerDel HEV battery pack is intended to be used as a development evaluation pack used across multiple user applications.





Sources: Kenworth Truck Company and Enerdel Inc.

6.2.9 EMP Chassis Coolant Loops

The nonengine components are cooled by parallel chassis oil and glycol coolant loops. The two isolated systems required redundant and parallel systems which were incredibly difficult to package into an already overloaded chassis assembly. The Engineered Machine Products electric glycol and water system (TK2) and electric oil system (OK2) were packaged on separate sides of the chassis and near thermal loads to keep routings and fluid volumes to a minimum (Figures 18 and 19).

Figure 78: EMP TK2 Air-to-Glycol/Water Cooling Module



Sources: Kenworth Truck Company and EMP Corporation

Figure 19: EMP OK2 Air-to-Oil Cooling Module



Sources: Kenworth Truck Company and EMP Corporation

6.2.10 Bendix Electric Air Charger System

The Bendix Electric Air Charger System was designed specifically for heavy truck hybrid applications and worked without significant issue (Figure 20). It is a modular electric air charging system installed on the side of the chassis. The Bendix electric air charger system, when paired with a tank assembly, maintains vehicle air pressure for air brakes and other pneumatic systems.
Figure 80: Bendix Electric Air Charger System and Air Tank Assembly



Sources: Kenworth Truck Company and Bendix Corporation

6.2.11 Agility CNG Fuel Delivery System

The Agility CNG fuel system is a three-tank installation carrying 150 diesel gallon equivalents (DGE). One tank is mounted on the side of the chassis (Figure 21) and two additional tanks are mounted back of cab above the frame rail (Figure 22). The system is passive but has the ability to manually isolate each tank without compromising fuel delivery.

Figure 21: Primary Natural Gas Fuel Tank Installed on Side of Chassis



Sources: Kenworth Truck Company and Agility Fuel Systems

Figure 92: Secondary Natural Gas Tanks Installed Behind Cab on Top of Chassis Rail



Sources: Kenworth Truck Company and Agility Fuel Systems

GLOSSARY

ALTERNATING CURRENT (AC) - Flow of electricity that constantly changes direction between positive and negative sides. Almost all power produced by electric utilities in the United States moves in current that shifts direction at a rate of 60 times per second.

ALTERNATIVE-FUEL VEHICLE (AFV) - A vehicle designed to operate on an alternative fuel (e.g., compressed natural gas, methane blend, electricity). The vehicle could be either a dedicated vehicle designed to operate exclusively on alternative fuel or a nondedicated vehicle designed to operate on alternative fuel and/or a traditional fuel.

BATTERY MANAGEMENT SYSTEM (BMS) - Systems encompassing not only the monitoring and protection of the battery but also methods for keeping it ready to deliver full power when called upon and methods for prolonging its life. This includes everything from controlling the charging regime to planned maintenance.

BRAKE THERMAL ENERGY (BTE) - The ratio of brake power output to power input, the product of indicated thermal efficiency and mechanical efficiency.1

CALIFORNIA AIR RESOURCES BOARD (ARB) - The "clean air agency" in the government of California, whose main goals include attaining and maintaining healthy air quality; protecting the public from exposure to toxic air contaminants; and providing innovative approaches for complying with air pollution rules and regulations.

CALIFORNIA ENERGY COMMISSION (CEC) - The state agency established by the Warren-Alquist State Energy Resources Conservation and Development Act in 1974 (Public Resources Code, Sections 25000 et seq.) responsible for energy policy. The Energy Commission's five major areas of responsibilities are:

- Forecasting future statewide energy needs
- Licensing power plants sufficient to meet those needs
- Promoting energy conservation and efficiency measures
- Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels
- Planning for and directing state response to energy emergencies.

CARBON DIOXIDE (CO₂) - A colorless, odorless, non-poisonous gas that is a normal part of the air. Carbon dioxide is exhaled by humans and animals and is absorbed by green growing things and by the sea. CO2 is the greenhouse gas whose concentration is being most affected directly by human activities. CO2 also serves as the reference to compare all other greenhouse gases (see carbon dioxide equivalent).

CARBON MONOXIDE (CO) - A colorless, odorless, highly poisonous gas made up of carbon and

^{1 &}lt;u>The National Academies Press</u> (https://www.nap.edu)

oxygen molecules formed by the incomplete combustion of carbon or carbonaceous material, including gasoline. It is a major air pollutant on the basis of weight.

CENTRAL AREA NETWORK (CAN) - A robust vehicle bus standard designed to allow microcontrollers and devices to communicate with each other in applications without a host computer.**Error! Bookmark not defined**.

COMPRESSED NATURAL GAS (CNG) - Natural gas that has been compressed under high pressure, typically between 2,000 and 3,600 pounds per square inch, held in a container. The gas expands when released for use as a fuel.

DIESEL GALLON-EQUIVALENT (DGE) - The amount of alternative fuel it takes to equal the energy content of one liquid gallon of diesel gasoline.

DIRECT CURRENT (DC) - A charge of electricity that flows in one direction and is the type of power that comes from a battery.

ELECTRIC VEHICLE (EV) – A motor vehicle that uses an electric motor as the basis of its operation. Such vehicles emit virtually no air pollutants.**Error! Bookmark not defined.**

FAHRENHEIT (F) -- A temperature scale in which the boiling point of water is 212 degrees and its freezing point is 32 degrees. To convert Fahrenheit to Celsius, subtract 32, multiply by 5, and divide the product by 9. For example: 100 degrees Fahrenheit - 32 = 68; $68 \times 5 = 340$; 340 / 9 = 37.77 degrees Celsius.

FREE POWER TURBINE (FPT) - An arrangement in which a turbine, or stage of turbines, in a gas turbine engine does not drive the compressor. Free turbines are used to drive the reduction gears for the propeller in a turboprop engine or the transmission and rotor of a helicopter. Also known as a power turbine or a free turbine. In a turbine engine, a turbine wheel drives the output shaft and is not connected to the shaft driving the compressor.

GREENHOUSE GASES (GHG) – Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), halogenated fluorocarbons (HCFCs), ozone (O3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

HIGH EFFICIENCY TRUCK USERS FORUM (HTUF) - A national program based in Michigan that works with the U.S. Army to improve the efficiency of military and commercial trucks. CALSTART connects high-efficiency vehicle technology suppliers with commercial fleets, as well as military planners at the U.S. Army's Tank Automotive Research Development and Engineering Center (TARDEC) and military customers such as U.S. Army Tank-automotive and Armaments Command (TACOM) on projects that develop and demonstrate dual-use technologies in the following areas: vehicle electrification and efficiency, connected and automated vehicle technologies and vehicle cybersecurity.2

² CALSTART (https://calstart.org/)

KILOWATT (kW) -- One thousand (1,000) watts. A unit of measure of the amount of electricity needed to operate given equipment. On a hot summer afternoon a typical home, with central air conditioning and other equipment in use, might have a demand of four kW each hour.

LIQUEFIED NATURAL GAS (LNG) – Natural gas that has been condensed to a liquid, typically by cryogenically cooling the gas to minus 260 degrees Fahrenheit (below zero).

NITROGEN OXIDES (NOx) - Oxides of nitrogen that are a chief component of air pollution that can be produced by the burning of fossil fuels.

ORIGINAL EQUIPMENT MANUFACTURER (OEM) - makes equipment or components that are then marketed by its client, another manufacturer or a reseller, usually under that reseller's own name.

PARTICULATE MATTER (PM) - Unburned fuel particles that form smoke or soot and stick to lung tissue when inhaled. A chief component of exhaust emissions from heavy-duty diesel engines.

REVOLUTIONS PER MINUTE (RPM) - The number of turns in one minute. It is a unit of rotational speed or the frequency of rotation around a fixed axis.

U.S. ENERGY INFORMATION ADMINISTRATION (U.S. EIA) - An independent agency within the U.S. Department of Energy that develops surveys, collects energy data, and does analytical and modeling analyses of energy issues. The Agency must satisfy the requests of Congress, other elements within the Department of Energy, Federal Energy Regulatory Commission, the Executive Branch, its own independent needs, and assist the general public, or other interest groups, without taking a policy position.**Error! Bookmark not defined**.

VOLT (V) - A unit of electromotive force. It is the amount of force required to drive a steady current of one ampere through a resistance of one ohm. Electrical systems of most homes and office have 120 volts.



REPORT

Deployment of a Next Generation Alternative Fuel Powered Truck

In response to:

California Energy Commission

Alternative and Renewable Fuel and Vehicle Technology Program Solicitation (PON-09-004)

Provided to the California Energy Commission and Kenworth

February 20, 2015

Project:	CEC-ARV-09-012
Control Number:	
Subject:	Kenworth Class 8 Alternative Fuel Vehicle
Date:	March 28, 2015
To:	Kenworth Truck Company
From:	Brayton Energy LLC
Copies:	

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CHAPTER 1: Introduction

The ICR350 is an advanced prototype gas turbine engine, designed for automotive and stationary power applications. The 350 kilowatt (kW) equivalent power was selected to match the needs of a Class 8 truck. The ICR350 is distinguished from other microturbines and small gas turbines as an intercooled-recuperated gas turbine with an advanced ceramic hot section and free power turbine, designed for Class 8 vehicles. At a 14:1 pressure ratio, it has a significantly higher working pressure than other microturbines, while using turbomachinery similar to automotive turbochargers. The high-pressure ratio, elevated firing temperature, and intercooling increase specific power (power/unit mass flow), driving down the size and cost of expensive hot-section components. Most importantly, the ceramic turbine, recuperator, and combustor. The intercooled-recuperated and high firing temperature also have a positive impact on efficiency. In its mature form,3 the engine will achieve a peak efficiency of 44 percent, with a flat efficiency over a wide power range. For a number of reasons described in this report, the current efficiency is compromised, reaching a peak of roughly 38 percent under test.

This program also highlights the ICR350's low emissions. In qualification tests, nitrogen oxide and carbon monoxide emissions were significantly below the ARB limits, with no aftertreatment. While the engine for this project is configured for only CNGs, laboratory testing indicates that the future product will also meet ARB standards using diesel or gasoline fuels, taking advantage of this engine's dual fuel switch-on-the-fly features.

This project allowed ICRTec, Brayton, and PACCAR to deploy the first generation of an ICR350 engine in a Class 8 truck. Engine packaging and vehicle integration represented a major investment for both companies. To lessen the development costs and early risks, it was decided to proceed with a series-electric hybrid, thereby leveraging Kenworth's past work on electric vehicles, and decoupling the unknown transient performance of the engine from the drive train. However, this engine is designed to be a mechanical drive, suitable as a primary power source, with optional consideration for parallel hybrid features. The engine's free power turbine is suited to meet the drivability features of the Class 8 vehicle, providing max torque at low speed, superior acceleration, and part-load efficiency better than a conventional diesel engine. Properly integrated, the engine is smaller and lighter than the diesel engine, potentially enabling aerodynamic improvements to the future vehicle.

³ Advanced Gas Turbine Truck, *SAE 2014 Commercial Vehicle Engineering Congress*, October 7-9, 2014, Rosemont, Illinois, USA

CHAPTER 2: Technical Description of ICR350 Gas Turbine Engine

2.1 Physical Description

The ICR350 engine is a Brayton cycle gas turbine that is represented schematically in Figure 1, below. The engine has a low-pressure spool, high-pressure spool, and a free power turbine. An intercooler, recuperator, and combustor are also part of the core engine. The free power turbine is coupled through a gearbox to either a transmission or generator.



Figure 1: ICR350 Schematic

Source: Brayton Energy LLC

The low-pressure spool (Figure 2) is a radial turbine and compressor on a rotating shaft. The expansion work through the low-pressure turbine functions entirely to drive the low-pressure compressor.



Figure 2: Low-pressure Spool

Source: Brayton Energy LLC

The low-pressure compressor discharges at a 2.7:1 pressure ratio into the intercooler, which rejects the low-pressure heat of compression. The intercooler is a crossflow air-to-air heat exchanger with a fan, as shown in Figure 3, below.



Source: Brayton Energy LLC

Downstream of the intercooler, the high-pressure compressor receives air and compresses it to a 14:1 overall pressure ratio. The high-pressure spool (Figure 4) is a radial compressor and turbine on the same rotating shaft as is the low-pressure spool. The cool air received from the intercooler improves the high-pressure compressor efficiency, and the overall cycle efficiency of the engine.

Figure 4: High-pressure Spool



Source: Brayton Energy LLC

Discharged air from the high-pressure compressor then enters the recuperator, where it absorbs exhaust heat that would otherwise be lost to the cycle. The recuperator is a counterflow heat exchanger (Figure 5) composed of 107 individual cells welded into a core assembly.

Figure 5: Recuperator Core



Photo credit: Brayton Energy LLC

Preheated and pressurized air leaves the recuperator and enters the combustor (Figure 6), where fuel is burned to further elevate the temperature to high-pressure turbine inlet temperature. This area contains the hottest and highest pressure gas in the engine.

Figure 6: Combustor Fuel Canister, Liner, and Swirler Head



Photo credit: Brayton Energy LLC

The combustion products expand through the high-pressure turbine, low-pressure turbine, and then the free power turbine. The high-pressure and low-pressure turbines function only to drive their respective compressors. The free power turbine functions to extract power from the engine; it produces shaft power, rather than coupling to a compressor. The free power turbine has a variable area nozzle that allows it to operate efficiently, with varying levels of power output from the engine and varying speeds (Figure 7).



Figure 7: Free Power Turbine Variable Area Nozzle

Photo credit: Brayton Energy LLC

The free power turbine is geared down and coupled to a generator, as shown in Figure 8, below. The generator is a Remy 250 model and the gearbox is a custom, parallel-shaft, single stage gearbox with a 6.7:1 ratio.



Figure 8: Free Power Turbine, Gearbox, and Generator Assembly

Photo credit: Brayton Energy LLC

Gases leaving the free power turbine are ducted through the low-pressure side of the recuperator and then exhausted to atmosphere. The recuperator absorbs otherwise rejected heat from the cycle, allowing the engine to operate more efficiently.

2.2 Specifications

Following Kenworth's detailed mission analysis, its direction to Brayton was to configure the ICR350 as a series hybrid. Though the performance studies showed benefits for the parallel drive, the series was selected to reduce early program risks. The series mode narrowed the operating range of the engine and avoided the requirement for rapid transients for this new engine. It should be mentioned that the ICR350 is designed as a mechanical drive, and is expected to meet or exceed all acceleration and general drivability standards. Moreover, as a mechanical drive, possibly with limited parallel features, the overall product cost targets are more approachable.

Based on these long-range cost and performance studies, we hope to evolve the product toward a mechanical drive configuration.

The specifications for the hybrid series drive are summarized in Table 1, below.

Specification	Series M2	Product
Output power form	420 to 700 volts direct current (VDC)	Mechanical shaft output, with rated power at 2,200 revolutions per minute (RPM)
Max power	150 kW equivalent	350 kW mechanical
Transient ramp rate: idle to 150 kW equivalent	10 minutes	10 seconds
Transient response: time to idle	30 seconds	30 seconds
Transient ramp-down form 150 kW equivalent to idle	30 seconds	2 seconds
Life: hours of operation	20,000	20,000
Life: miles of operation	1,000,000	1,000,000
Life: cold start cycles	5,000	10,000
Life: full power excursions	20,000	10,000
Life: hot restarts	10,000	10,000
Controls: automation protocol	Central area network (CAN) bus protocol	CAN bus psrotocol
Low-voltage accessory power supply	12 VDC	12 VDC
Fuel system	Compressed natural gas (CNG), 3600 psi	CNG and Diesel

Table 1: Design Specifications

CHAPTER 3: Vehicle Integration

3.1 Engine Mechanical

The mechanical layout of the ICR350, within the confines of an existing Kenworth T680 chassis, proved to be challenging. While a gas turbine engine has better power-to-weight and power-to-volume ratios than a traditional diesel drivetrain, packaging issues did present themselves. There were several requirements for the turbine engine that could not be violated. First, each radial turbine and centrifugal compressor have a 90 degree turn between the inlet and outlet (Figure 9).



Figure 9: Inlet and Outlet of Radial Turbomachinery

The spools also required horizontal rotating shafts due to bearing and seal requirements. Lastly, the gearbox and/or generator centerline was required to be lined up with the rear differential for possible direct drive or parallel hybrid drive configurations. One of the biggest challenges was plumbing and ducting to each of the discrete subassemblies of the engine.

The ideal layout would have the hot section components directly coupled to minimize parasitic losses in high energy pipe runs. The combustor and all three turbines would be directly bolted in series. These components are hot and pressured, so minimizing length between them is ideal from a mechanical standpoint. However, it was physically impossible for all three turbines to be horizontal, close coupled, and for the free power turbine to be in the rear of the engine lined up with the differential. A compromise solution was arrived at to allow packaging within the truck chassis. The high-pressure and low-pressure spools were located in the engine compartment close coupled to the recuperator and combustor. A long pipe from the low-pressure to free power turbine was then routed to the back of the engine (Figure 10).



Figure 10: Low-pressure to Free Power Turbine Pipe

Source: Brayton Energy LLC

The long, low-pressure to free power turbine pipe was the least penalizing place in the hot section to add length, as most of the energy is absorbed by the high-pressure and low-pressure turbines. However, this pipe had to be long, custom, double walled, internally insulated pipe with multiple bends; a tight clearance between the firewall and the recuperator was also necessary. The pipe also added pressure drop to the system. The elbow directly in front of the power turbine inlet likely led to some maldistribution, and had an impact on turbine efficiency, as well. However, the layout of the engine fit with the given space constraints and requirements, and Brayton made efforts to keep these losses to a minimum.

The air intake system to the truck was another challenging aspect of the engine packaging. The turbine engine uses substantially more air than a diesel engine of equivalent power rating, requiring larger ducting. The air intake ducting to the ICR350 used the same location of the diesel truck on either side of the hood (Figure 11). A custom sheet metal plenum directing the flow to the low-pressure compressor inlet was fabricated (Figure 12). Prior to entering the low-pressure compressor, the flow went through a filtering box. The ductwork was undersized for necessary airflow, resulting in a higher pressure drop, and reducing engine efficiency.



Figure 11: Air Intake Location

Figure 12: Air Intake Plenum



Photo credit: Brayton Energy LLC

The exhaust of the engine exits out of the top of the recuperator, but must also exit under the cab. An exhaust plenum was fabricated to get the exhaust under the frame, to the side of the free power turbine, then towards the back of the vehicle (Figure 13). The plenum is also somewhat undersized for the amount of flow, and has several bends resulting in a pressure drop and thus an engine efficiency reduction.



Figure 13: Exhaust

Source: Brayton Energy LLC

The lubrication system providing oil to the spools and gearbox also had some packaging challenges that resulted in a more complicated system than would otherwise be required in a

stationary power application. The main oil skid assembly with the pumps, tank, valves, and other equipment (Figure 15) was placed under the high-pressure and low-pressure turbines, and above the front axle of the truck. The free power turbine and gearbox were lower in the vehicle than the main lube system–unfortunately they need to be gravity drained. An auxiliary sump with a dedicated scavenge pump – to send oil to the main sump – was placed under them (Figure 14).



Figure 14: Lube Skid and Free Power Turbine/Gearbox Sump

Figure 15: Main Oil Skid



Source: Brayton Energy LLC

The oil cooler, placed above the cab of the truck, presented another issue. The volume in the oil cooler and associated plumbing was more than the main sump volume. Measures were required to avoid oil draining back into the free power turbine while the engine was off, or oil overflowing the main sump. Filling the system adequately also required running the pumps to fill the cooling unit completely, before topping off the main sump. The oil system performed well, but it was more complicated than a typical stationary power oil system that would not have the same packaging constraints.

The Remy HVH 250 was the selected generator for the truck for several reasons. It was a commonly used automotive generator/motor that was rated for 300 kW, a good fit for the engine's power output. Phoenix PD550S inverters were readily available and were designed to be used in conjunction with the Remy generator and high-voltage direct current (DC) buses. Also appealing was that it could run to the relatively high speed of 11,000 RPM. The power turbine operates at 75,000 nominally, and the gear reduction to the Remy speed could be done with a parallel shaft, single stage gearbox. The power turbine, gearbox, and Remy generator were packaged into a subassembly that sits well between the frame rails of the truck chassis (Figure 16).



Figure 16: Bottom View of Engine Layout

Source: Brayton Energy LLC

3.2 Engine Accessories

3.2.1 Lubrication, Starting, and Cooling System

The lubrication system provides cooling and lubricant throughout the engine. In its simplest form, the lubrication system would consist of an oil sump, oil pump, feed lines, and drain lines. The schematic below (Figure 17) shows that it isn't so simple. The heart of the system is a Viking pump circulating turbine oil at 30 gallons per minute.

From the main lubrication pump, oil flows up to the roof-mounted oil cooler. There, the oil is cooled to 130°F (54.4°C) by an array of fans. Oil then flows down to the three spools and the gearbox. Flow distribution among the lines was fixed by needle valves during testing. After lubricating the bearings in the high-pressure and low-pressure spools, gravity drains the oil back to the sump. Due to packaging constraints, the free power turbine and gearbox drains are below the oil level of the main sump. They have a small sump with a scavenge pump pulling oil up to the main sump.

Starting this engine is also part of the lubrication system. There is a pelton wheel (impulse liquid turbine) starter on the high-pressure rotor. A high-pressure jet of oil sprays onto buckets of the pelton wheel, spinning the rotor to approximately 15,000 RPM.

The pressure and flow requirements for the pelton wheel jet were close to the performance specifications of a typical truck's power steering pump. Brayton and Kenworth made modifications to allow the power steering pump to perform as a starter as well. An electronic ball valve separates the pelton wheel supply from the power steering loop.



Figure 17: Lubrication System Schematic

3.2.2 Intercooler Module

The intercooler is a crossflow air-to-air heat exchanger that significantly improves efficiency of the high-pressure compressor. The intercooler occupies most of the space behind the grill in the vehicle, where a radiator would typically be located. Ambient air is forced through the larger faces of the heat exchanger by ram air (when the vehicle is moving forward) and a multiwing fan. The fan is driven by an 8 kW alternating current (AC) motor. Under normal operating conditions, the 90 percent effective heat exchanger reduces the temperature of air entering the high-pressure compressor by 135°F (57.2°C).



Figure 18: Intercooler Module

Source: Brayton Energy LLC

3.2.3 Fuel System

The fuel system is responsible for safe and accurate delivery of CNG from vehicle-mounted tanks to the combustor. For fast response in E-stop situations or electrical failures, normally closed solenoid valves are located on the fuel supply tubes close to the combustor. During regular operation of the engine, fuel is metered by an electrically actuated needle valve and the mass flow is directly measured by a Coriolis flowmeter. A thermocouple measures the fuel temperature just before entering the combustor for precise calculation of the energy exiting the combustor. The fuel system schematic is shown in Figure 19, below.





Source: Brayton Energy LLC

Figures 20 and 21, below, depict the combustor's fuel system and swirler head.



Figure 20: Fuel System on Combustor Canister



Figure 21: Combustor Fuel System and Swirler Head

Photo credit: Brayton Energy LLC

3.3 Electrical Integration

The engine integrates with the vehicle electrically via a small number of carefully controlled interfaces. These interfaces are low-voltage power, high-voltage power, and central area network communications. All communication between the engine system and vehicle follows the Society of Automotive Engineers standard J1939 CAN protocol for message formatting, diagnostics, and operating parameters.

Communications connection: The engine system includes a standard 10-pin Delhi GT 150 S port. This connector includes signal ground (pin B), CAN high (pin C), CAN low (pin D), and Wakeup (pin F). The wakeup signal is used to turn the engine controller on and off, in lieu of a typical key switch.

Low-voltage grounding: The engine system includes 4X 10 American wire gauge black wires connected to vehicle ground via a large bus bar. The bus bar runs with high current connection to the low-voltage battery ground.

12-volt (V) Power: The engine system includes 4X 10 American wire gauge red wires connected, unfused, to the vehicle 12V battery.

24V Power: The engine system includes 1X 10 American wire gauge white wire connected to a fused 600 to 24V DC-to-DC converter.

High-voltage Connection: The engine system connects to the vehicle high-voltage bus at a power distribution unit provided by Kenworth. There are a total of four high-voltage, positive and four high-voltage, negative, unterminated wires from the engine to the power distribution unit. The connections consist of main high current connections for the output from the engine inverter, and a pair of connections for each of the three auxiliary pumps or fans in the engine.

CHAPTER 4: Controls and Power Electronics

The ICR350 has three primary degrees of freedom for control: fuel flow, variable area nozzle opening, and power turbine speed. Exercising these degrees of freedom allows optimization of engine efficiency for a wide range of ambient conditions and power demand. Each degree of freedom is coupled to a physical property of the engine, with some cross coupling among the three. Independent software loops control the degrees of freedom with different time constants to avoid resonance.

Fuel flow, controlled by a servo-actuated needle valve, sets the turbine inlet temperature or recuperator inlet temperature. For maximum efficiency, turbine inlet temperature and recuperator inlet temperature are controlled to the maximum allowable temperatures that meet the life requirement of the engine. In most of the operating range the high-pressure turbine inlet temperature is the limiting factor, and is set to a limit of 1,700°F (926.7°C). At lower power levels, low-pressure turbine inlet temperature, and therefore must be limited to ensure long life of the components. Low-pressure turbine inlet temperature and recuperator inlet temperator inlet temperator is to be limited to ensure long life of the components. Low-pressure turbine inlet temperature and recuperator inlet temperator inlet temperature is too hot to measure directly with inexpensive thermocouples for 80,000 hours. High-pressure turbine inlet temperature. The calculations used to infer high-pressure turbine inlet temperature were validated in testing against directly measured data.

The variable area nozzle opening directly affects the air flow through the power turbine, which affects the power extracted from the flow, therefore the shaft power available for export. The nozzle vanes of the variable area nozzle are actuated by a series of linkages connected to a linear actuator typically used for throttle applications in on- and off-road vehicles. Electrical power output is measured directly by the Phoenix PD550S inverter. The control software simply adjusts the variable area nozzle position until the requested amount of power is being exported.

The final degrees of freedom is power turbine speed. In a parallel hybrid or mechanical drive implementation of the ICR350, this variable would be tied to the wheel speed through the transmission. In this series hybrid implementation, however, power turbine speed may be optimized for the operating conditions. In this case, the speed of the power turbine is set to maximize efficiency by setting the mach number of air flowing into the turbine to its optimum value. To make this calculation, temperatures and pressures into and out of the power turbine are continuously measured. The calculated optimal speed is then controlled by the inverter.

At a higher level, the engine communicates with the vehicle controller through a number of states and control variables. Typical flow through the states would be "Off" to "Startup" to "Run" to "Cool down" to "Off". The complete state flow is shown in Figure 22, below. The "Run" state controls the three degrees of freedom described above, while also monitoring various temperatures and pressures throughout the engine and maintaining oil pressure. The

"Startup" state is unique to this engine due to the pelton wheel starter on the high-pressure rotor. An electronic ball valve allows high-pressure oil to jet into the pelton wheel, spinning the rotor to approximately 15,000 RPM. This starts the flow of air through the engine before adding fuel and lighting the combustor. A diagram of the complete "Startup" routine is shown in Figure 23, below.



Figure 23: Startup Routine



The control system was built around automotive grade electronics where possible with ruggedized laboratory grade components making up the remainder. The following pages show the interconnections of the active components with their signal names. Most of the electronics were packaged around the intercooler behind the grill of the truck for protection from high temperatures. Figure 24, below, shows the physical layout of the low-voltage wiring around the engine.

Figure 24: Physical Layout of Low-voltage Wiring and Each Electrical Component






	Mod_ECU_1	
	Primary Control Unit	
ECU Fused Power 	BATT 1 ECM-5554-112-0904 XDRP 1 XDRP 2 CUP (KEY SWITCH)	C-D4
(ECU1_E-Stop) B-H3-	STOP MPRD CNK+ (VR) DVRP 1	
Reserved_CNK- Reserved_CNK (DG)	CNK- (VR) DVRP 2 CNK (DG) CAM (DG) FUEL 1	
Pa_Ambient_Air_0 Pd_LPcomplN_Air_T1 Pg_trClrlN_Air_T2a Pg_HPcmplN_Air_T2b PettonValveFeedback1 PettonValveFeedback2 Reserved_AN7M C-F2-	AN1M (51.1K PD) FUEL 2 AN2M (51.1K PD) FUEL 3 AN2M (51.1K PD) FUEL 5 AN3M (51.1K PD) FUEL 5 AN4M (220K PD) FUEL 6 AN5M (1K PU) FUEL 7 AN5M (1K PU) FUEL 8 AN7M (1K PU) FUEL 8	$\begin{array}{c} -A + H2 \longrightarrow \\ -A - G3 \longrightarrow \\ -A - G4 \longrightarrow \\ -A - G1 \longrightarrow \\ -A - G2 \longrightarrow \\ -A - F3 \longrightarrow \\$
Reserved_ANISM	ANBM (1K PU) EST 1 AN9M (1K PU) EST 2 AN10M (1K PU) EST 3 AN11M (1K PU) EST 4 AN12M (1K PU) EST 5 AN13M (1K PU) EST 5 AN13M (1K PU) EST 7	$ \begin{array}{c} -A - A4 \longrightarrow \\ -A - A3 \longrightarrow \\ -A - A2 \longrightarrow \\ -A - A1 \longrightarrow \\ -A - B4 \longrightarrow \\ -A - B2 \longrightarrow \\ -A - B2 \longrightarrow \\ -A - B2 \longrightarrow \\ \end{array} $
←	KNK1+ EST 8 KNK2+ KNK2- TACH	$ \xrightarrow{A \to 1} $
← B-K1 ← B-L1 ← B-L2 ← B-L2 ← B-L2 ← B-L3 ← B-J3 ← B-J4 ← B-J4	O2A+ FUELPR O2A- (CCD) LSO1 O2B+ LSO2 O2B- LSO3 O2C+ LSO4 O2C- LSO5 O2D+ LSO5 O2D- LSO7	A-D2 A-F2 A-E1 A-F1 B-M3 B-M4 Viv_Pelton1_LSD B-M1 B-M2 Reserved_LSO7
d HPcmpIN_Air_T2b_S2b Pg_HPcompOUT_Air_T3 Reserved_AN16M Pg_HPturbIN_Air_S5 Reserved_AN18M Reserved_AN18M Reserved_AN19M	AN14M (51.1K PD) AN15M (220K PD) XDRG 1 AN16M (183 PU) XDRG 2 AN17M (220K PD) AN18M (183 PU) DVRG 1 AN19M (183 PU) DVRG 2 AN19M (185 PU) DVRG 2	A-E2
Reserved_AN2III ————————————————————————————————————	AN21M (10K PU) AN21M (10K PU) AN22M (220K PD) AN23M (220K PD) HBRIDGE1B HBRIDGE2B SPEED1 (DG) SPEED3 (DG) LSO9	C-H4
Pd_recup_Air_SS C-D1- (Pg_HPfeed_Oi) C-F1- Pg_CNG	AN24M (220K PD) LSO10 AN25M (220K PD) LSO11 AN25M (220K PD) LSO12 AN26M (51.1K PD) (CCD) LSO13 AN27M (51.1K PD) AN28M (51.1K PD) AN28M (51.1K PD) CAN1+ AN29M (1K PU) CAN1-	$ \begin{array}{c} -A - E4 \longrightarrow \\ -A - H3 \longrightarrow \\ -A - H3 \longrightarrow \\ -A - D1 \longrightarrow \\ \hline B - A2 \longrightarrow \\ \hline \end{array} $
Pg_GearBox_Oil	AN30M (220K PD) AN31M (1K PU) CAN2+ AN32M (1K PU) CAN2- AN33M (150K PU) CAN2SHIELD	B-C1 Can2EcuHi B-C2 Can2EcuLo B-C3 B-C3 Can2EcuLo
	A CANS+ CANS- CANSSHIELD	B-B1 CanSEculo
	(RS-485A) RS485+ (RS-485B) RS485-	A-C2 R5485+_F_MssFlwRt_CNG A-C2 R5485F_MssFlwRt_CNG











SenseActor12W	12V GND CAN2+ CAN2- STOP WAKE CAN3- CAN1+ CAN1- 12V GND CAN2+ CAN2- STOP	Mod_JBox_1 6-WAY SMARTCRAFT JUNCTION BOX CON-JBOX-002	12V GND CAN2+ CAN2- STOP WAKE CAN3+ CAN3+ CAN3+ CAN1+ CAN1- 12V GND CAN2+ CAN2- STOP	$\begin{array}{cccccccccccccccccccccccccccccccccccc$
ECU1_WakeUp	CAN3+ CAN3- CAN1+ CAN1-		WAKE CAN3+ CAN3- CAN1+ CAN1- 12V	-C?-F→→-(HVCM_WakeUp) -C?-G→→- -C?-H→→- -C?-I→→- -C?-K→→- -C3-A→→-(JB2-12V)
120 OHM CAN1 & CAN3 TERMINATOR CON-TERMOSCOO TERMINATOR CON-TERMOSCOO CONTO CON-TERMOSCOO CON-TERMOSCOO CONTO CON-TERMOSCOO CONTO CON-TERMOSCOO CONTO CON-TERMOSCOO CONTO	GND CAN2+ CAN2- STOP WAKE CAN3+ CAN3- CAN1+ CAN1-		GND CAN2+ CAN2- STOP WAKE CAN3+ CAN3- CAN1+ CAN1-	C3-R→→ JB2-Ground C3-C→→ JB2-CAN2+ C3-D→→ JB2-CAN2- C3-F→→ C3-F→→ C3-F→→ C3-G→ JB2-CAN3+ JB2-CAN3+ JB2-CAN1+ JB2-CAN1+ JB2-CAN1-
Ground_VAN	12V GND		12V GND CAN2+-	—C1-A→>- —C1-B→>- —C1-C→>-
	CAN2- STOP WAKE CAN3+ CAN3- CAN1+ CAN1-	Mod_JBox_2 6-WAY SMARTCRAFT JUNCTION BOX CON-JBOX-002	CAN2 STOP- WAKE CAN3+- CAN3 CAN1+- CAN1	
	CAN2- CAN2- STOP WAKE CAN3- CAN3- CAN1- 12V GND CAN2- STOP WAKE CAN3- CA	Mod_JBox_2 6-WAY SMARTCRAFT JUNCTION BOX CON-JBOX-002	CAN2 STOP - WAKE - CAN3+- CAN3+- CAN3 CAN1 CAN2+- CAN2+- CAN2+- CAN2+- CAN2+- CAN2+- CAN3-	

Source: Brayton Energy LLCs

GLOSSARY

ALTERNATING CURRENT (AC) - Flow of electricity that constantly changes direction between positive and negative sides. Almost all power produced by electric utilities in the United States moves in current that shifts direction at a rate of 60 times per second.

CENTRAL AREA NETWORK (CAN) - A robust vehicle bus standard designed to allow microcontrollers and devices to communicate with each other in applications without a host computer.4

COMPRESSED NATURAL GAS (CNG) - Natural gas that has been compressed under high pressure, typically between 2,000 and 3,600 pounds per square inch, held in a container. The gas expands when released for use as a fuel.

DIRECT CURRENT (DC) - A charge of electricity that flows in one direction, also the type of power that comes from a battery.

KILOWATT (kW) - One thousand (1,000) watts. A unit of measure of the amount of electricity needed to operate given equipment. On a hot summer afternoon a typical home, with central air conditioning and other equipment in use, might have a demand of four kW each hour.

REVOLUTIONS PER MINUTE (RPM) - The number of turns in one minute. It is a unit of rotational speed or the frequency of rotation around a fixed axis.

VOLT (V) - A unit of electromotive force. It is the amount of force required to drive a steady current of one ampere through a resistance of one ohm. Electrical systems of most homes and office have 120 volts.

VOLTS DIRECT CURRENT (VDC) – Measurement of the unidirectional flow of an electrical charge.4

^{4 &}lt;u>Wikipedia</u> (https://www.wikipedia.org/)



Near-Zero-Emission Heavy-Duty Truck Commercialization Study

Final Report

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CHAPTER 1: Introduction

Medium and heavy-duty vehicles are critical to the economy, yet remain a real and growing challenge for fuel use, greenhouse gases (GHG) and criteria emissions. Medium and heavy-duty on-road truck traffic serving urban and goods movement needs, combined with heavy-duty off-road vehicle use at distribution centers and ports, contribute significantly to fuel use, poor regional air quality, and are a sizable source of GHG emissions. Heavy-duty Class 8 truck tractors are a very important category of trucks contributing to the challenge. In 2011, only one quarter of registered medium and heavy-duty commercial trucks were Class 8 truck tractors, but these same vehicles consumed two-thirds of overall fuel use.⁵

To support the development and demonstration of a commercially viable near-zero-emission heavy-duty truck manufactured by Kenworth, CALSTART carried out a comprehensive commercialization study. Using a wide variety of resources (internet and literature research, internal expertise and knowledge, California Hybrid, Efficient and Advanced Truck inventory, market surveys of industry stakeholders, etc.) this study will guide the successful introduction into key markets of advanced truck technologies capable of providing criteria and GHG emission reductions needed at the state and federal level.

Chapter 1 is the present introduction and Chapter 2 reviews the primary drivers of change that make near-zero-emission heavy-duty trucks an interesting truck technology. Chapter 3 looks at the heavy-duty truck applications most likely to first adopt near-zero-emission technology and provides an overview of the market trends that make each application a good market for the technology. Chapter 4 reviews general truck specifications and key performance parameters for a preproduction hybrid drive system integrated into a standard Class 8 truck tractor chassis and presents in further detail an example of near-zero-emission heavy-duty truck technology. Chapter 5 presents and analyzes the results of the market survey, which took the pulse of various industry stakeholders, shed a light on purchasing intent for a near-zero-emission heavy-duty truck and helped refine truck design. It also performs a market analysis for near-zero-emission heavy-duty trucks, identifying primary and ultimate markets for both port drayage and local/regional delivery, estimating market penetration projections and analyzing the business case for near-zero-emission heavy-duty trucks. Lastly, Chapter 6 puts everything together to develop commercialization approaches and phase-in stages for near-zero-emission heavy-duty trucks.

⁵ Davis, S., S. Diegel and R. Boundy. *Transportation Energy Data Book*: Edition 33. ONRL-6990.

CHAPTER 2: Drivers of Change

In this chapter, the primary drivers of change that make near-zero-emission technology interesting for heavy-duty trucks are summarized. Focus was given on the following three topics of interest for the California and US truck market:

- Continuation of low natural gas prices
- Increase of regulatory pressure on lowering nitrogen oxide (NOx) emissions
- Increase of regulatory pressure on GHG and truck efficiency

2.1 Continuation of Low Natural Gas Prices

The recent developments of domestic shale gas resources have greatly impacted the US natural gas market. As Figure 1, below, shows, while oil prices have been steadily increasing since the early 2000s, natural gas prices – measured in millions of British thermal units (Btu) – have only moderately increased until about 2008 and have dropped since then.



Figure 1: Historical Oil and Natural Gas Prices

Sources: U.S. Energy Information Administration and ycharts.com

On-highway diesel and compressed natural gas (CNG) fuel prices have followed a similar evolution, leading to a significant price gap in favor of CNG – measured in diesel gallon-equivalents (DGE) – as shown in Table 1.

Region	Diesel Average Price (\$/gallon)	CNG Average Price (\$/DGE)
U.S.	3.922	2.35
East Coast	3.947	N/A
Midwest	3.903	2.07
Gulf Coast	3.835	2.30
Rocky Mountain	3.876	1.96
West Coast	4.051	2.67
California	4.126	N/A

Table 1: 2013 U.S. On-highway Diesel and CNG Fuel Prices

Source: U.S. Energy Information Administration and U.S. Department of Energy Report

Although recent market events in the end of 2014 have led to steep declines in diesel prices, projections of future prices indicate that this price gap will remain, but may widen or narrow depending on many factors. Based on the U.S. Energy Information Administration (U.S. EIA) Annual Energy Outlook 2014, the average percentage that diesel prices will increase every year for three different scenarios was calculated (Table 2).

Table 2: Diesel Fuel Escalation Rate for the U.S. EIA Scenarios in the Pacific Region

U.S. EIA Scenarios	Diesel Fuel Escalation Rate (average/year from 2014 to 2030)
Low Oil Price	-0.4%
Reference	+0.9%
High Oil Price	+2.5%

Source: U.S. Energy Information Administration

Applying these three different fuel escalation rates to the price of diesel in California in 2013, the price of diesel in California in 2020 and 2030 for the three different scenarios was calculated (Table 3).

Table 3: California Diesel Prices in 2013, 2020, and 2030

	CA Diesel Prices		
Year	Low Oil Price	Reference	High Oil Price
2013		\$4.126/gal.	
2020	\$4.012/gal.	\$4.393/gal.	\$4.905/gal.
2030	\$3.854/gal.	\$4.805/gal.	\$6.278/gal.

Source: U.S. Energy Information Administration

Based on the U.S. EIA Annual Energy Outlook 2013, the average percentage that CNG prices will increase every year for the same three different scenarios was calculated (Table 4).⁶ Since the natural gas commodity price component of CNG is only a fraction of the total price of CNG, the fuel escalation rate of CNG was calculated using projected prices of commercial natural gas and assuming a constant \$0.39 per DGE retail mark-up, and a constant \$1.01/DGE for taxes, distribution and compression.⁶

Table 4: Natural Gas and CNG Fuel Escalation Rate for U.S. EIA Scenarios in PacificRegion

U.S. EIA Scenarios	Commercial Natural Gas Fuel Escalation Rate (average/yr. from 2014 to 2030)	CNG Fuel Escalation Rate (average/yr. from 2014 to 2030)
Low Oil Price	+1.8%	+0.9%
Reference	+2.0%	+1.0%
High Oil Price	+2.2%	+1.1%

Source: U.S. Energy Information Administration

Applying these three different fuel escalation rates to the price of CNG in the West Coast region in 2013, the price of CNG on the West Coast region in 2020 and 2030 for the three different scenarios was calculated (Table 5).

⁶ American Clean Skies Foundation. Driving on Natural Gas: Fuel Price and Demand Scenarios for Natural Gas Vehicles to 2025, April 2013.

	Table 5	: West	Coast	CNG	Retail	Prices	in	2013,	2020,	and	2030
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	West Coast CNG Retail Prices				
Year	Low Oil Price	Reference	High Oil Price		
2013		\$2.67/DGE			
2020	\$2.84/DGE	\$2.86/DGE	\$2.88/DGE		
2030	\$3.12/DGE	\$3.18/DGE	\$3.24/DGE		

Source: U.S. Energy Information Administration

CNG prices will remain fairly stable in the three selected scenarios. Comparing Table 3 and Table 5 confirms that, although CNG prices will be increasing, the price gap between CNG and diesel will remain and could even widen. Low and stable natural gas prices (compared to higher and more volatile diesel prices) are projected to continue in the near term, keeping natural gas an economically viable option to diesel for powering medium and heavy-duty vehicles.

2.2 Increasing Regulatory Pressure on Lowering NOx Emissions

Despite significant progress, the San Joaquin Valley and South Coast air basins in California remain the most polluted areas in the country. Both are "nonattainment areas" for eight-hour ozone pollution, meaning that they do not meet the national primary or secondary air quality standard for the pollutant. In addition, the U.S. Environmental Protection Agency (U.S. EPA) has ranked both air basins in the "extreme" category for eight-hour ozone classification (Figure 2).

Figure 2: Eight-hour Ozone Nonattainment Areas (2008 Standard)



Source: U.S. Department of Energy

Federal ozone regulations will require the San Joaquin Valley and South Coast air basins to reduce NOx emissions beyond current projections (Figure 3):

- The San Joaquin Valley air basin must reduce NOx emissions from 257 tons/day to 160 tons/day in 2023 (a 38 percent reduction).
- The South Coast air basin must reduce NOx emissions from 319 tons/day to 115 tons/day in 2023 (a 64 percent reduction) and to 80 tons/day in 2033 (a 75 percent reduction).





Source: SoCalGas

In November 2014, the U.S. EPA announced new ozone rules that would lower the current threshold for ozone pollution to an even stricter standard of 65—70 parts per billion, requiring a greater reduction in NOx emissions.7

As Figure 4, below, shows, heavy-duty trucks will be the largest contributor of NOx in both the San Joaquin Valley and South Coast air basins in 2023 but will also represent a high potential target for additional emission reductions necessary to meet the ozone National Ambient Air Quality Standards.

⁷ The New York Times. E.P.A. Ozone Rules Divide Industry and Environmentalists.

⁽https://www.nytimes.com/2014/11/27/us/epa-ozone-limits-divide-industry-and-environmentalists.html?_)



Figure 4: Top-15 NOx Source Categories in 2023 in the SCAQMD and SJVAPCD

1. Heavy-Duty Trucks include Light-Heavy Duty, Medium-Heavy Duty, Heavy-Heavy Duty Trucks

2. Emissions for on-road mobile sources are based on EMFAC2011 output for San Joaquin Valley Air Basin

3. Emissions for off-road equipment are based on 2011 CARB inventory models

4. Emissions for stationary sources, area sources, and other off-road mobile sources are based on CARB Staff Report, Analysis of the 2007 8-hour Ozone SIP

Source: SoCalGas

Near-zero and zero-emission truck technologies offer significant reduction in NOx emissions beyond the measures that are already planned in current emission projections and these advanced technologies will benefit from this regulatory pressure on lowering NOx emissions in California and in the rest of the country.

2.3 Increasing Regulatory Pressure on GHG and Truck Efficiency

2.3.1 GHG Emissions

With the Global Warming Solutions Act of 2006 (Assembly Bill 32) and Executive Order S-03-2005, the State of California has adopted ambitious GHG emission reduction targets:

- By 2010,8 reduce GHG emissions to 2000 levels.
- By 2020, reduce GHG emissions to 1990 levels.
- By 2050, reduce GHG emissions to 80 percent below 1990 levels.

⁸ Office of Governor Edmund G. Brown Jr. Executive Order S-3-05. (http://gov.ca.gov/news.php?id=1861)

Figure 5, below, illustrates the impact that the enacted regulation would have on California GHG emissions.



Figure 5: California GHG Emissions Program

Source: Lawrence Berkeley National Laboratory

To meet the reduction targets, the California Air Resources Board (ARB), the lead agency responsible for implementing the act, is following a blueprint known as Assembly Bill 32: Climate Change Scoping Plan. The plan lays out the strategy and a comprehensive set of actions including establishing targets for transportation-related GHG for regions throughout California, and pursuing policies and incentives to achieve those targets.

Recognizing the impact of the transportation sector on California's GHG emissions, Executive Order B-16-2012 adopted a similar emission reduction target. This was to reduce GHG emissions from the transportation sector by 80 percent below 1990 levels by 2050.9

Beyond California, 19 other states – plus the District of Columbia – have adopted statewide GHG emissions targets.10

2.3.2 Medium- and Heavy-duty Truck Efficiency

At the federal level, the U.S. EPA and the National Highway Traffic Safety Administration (NHTSA) have adopted the first ever GHG and fuel consumption standards for medium- and

^{9 &}lt;u>"Berkeley Scientists at AAAS Highlight Challenges of Meeting State Energy Goals by 2050"</u> (http://newscenter.lbl.gov/2011/03/01/berkeley-scientists-at-aaas-state-energy-2050/)

^{10 &}lt;u>Center for Climate and Energy Solutions</u>. *Greenhouse Gas Emissions Targets*. (http://www.c2es.org/document/greenhouse-gas-emissions-targets/)

heavy-duty standards.¹¹ The U.S. EPA GHG standards are mandatory for model year 2014, while the NHTSA fuel efficiency standards are mandatory for model year 2016 (voluntary early compliance is possible with model year 2014 and model year 2015).¹²

In Phase 1, the standards are applicable to three categories of vehicles:

- **Combination tractors (semi-trucks that typically pull trailers):** Adopted engine and vehicle standards begin in model year 2014 and achieve 7 to 20 percent reduction in carbon dioxide (CO2) emissions and fuel consumption by model year 2017 over the 2010 baselines. While tractors are a key component of this regulation, trailers are not included in the program.
- **Heavy-duty pickup trucks and vans:** Standards phase in beginning model year 2014 and achieve up to a 10 percent reduction in CO2 emissions and fuel consumption for gasoline vehicles, and a 15 percent reduction for diesel vehicles by model year 2018.
- **Vocational vehicles:** Engine and vehicle standards start model year 2014 and achieve up to a 10 percent reduction in fuel consumption and CO2 emissions by model year 2017.

The Phase 2 of the standards is under development and should be announced in 2015. Standards will apply to medium- and heavy-duty trucks beyond model year 2018 and are expected to require more aggressive GHG emission and fuel economy targets.

These federal efficiency standards, as well as ambitious GHG emission reduction targets in California and other states, will encourage medium- and heavy-duty truck manufacturers to develop highly efficient advanced trucks.

11 The U.S. EPA regulates CO₂, N₂O, CH₄ and HFC emissions. The NHTSA regulates fuel economy.

12 <u>TransportPolicy.net</u>. *US Heavy-duty Fuel Consumption and GHG*. (http://transportpolicy.net/index.php?title=US:_Heavy)

CHAPTER 3: Near-Zero-Emission Heavy-Duty Truck Applications

In this section, the heavy-duty truck applications most likely to first adopt near-zero-emission technology are identified and an overview of the market trends that make each application a good market for the technology is provided.

The California Hybrid, Efficient, and Advanced Truck research center identified six truck categories (Figure 6).13

Figure 6: 2010 California Hybrid, Efficient, and Advanced Truck Inventory Categories

Class 7/8 Tractors

0-0-

Over the Road	 Younger Trucks; High Annual VMT Mostly higher average speed, highway driving
Short Haul/ Regional	 Between cities; Drayage; Day Cabs Includes second use trucks; trucks with smaller engines

Class 3-8 Vocational Work Trucks

	Urban	 Cargo, freight, delivery collection Lower VMT; Lower Average speed; Lots of stop start
	Rural/ Intracity	 Cargo, freight, delivery collection Higher VMT; Higher Avg speed; Combined urban/ highway
	Work site support	 Utility trucks, construction, etc. Lots of idle time; Lots of PTO use
Class 2B/3		
	Pickups/	

Commercial use; Automotive OEMs & volumes

Source: California Hybrid, Efficient, and Advanced Truck

Vans

While Class 8 heavy-duty trucks are present in five of the six truck categories, near-zero-

¹³ Brotherton, T. & F. Silver. *CalHEAT Technology Roadmap.* CalHEAT Forum 2013.

emission heavy-duty trucks would find their best applications in the Short Haul/Regional truck category. In this truck category, two specific applications, port drayage and local and regional delivery, are most likely to first adopt near-zero-emission technology and were looked at as such.

3.1 Port Drayage

3.1.1 Description

Port drayage operation consists of moving containerized goods between a port and a variety of businesses, terminals, warehouses, trans-loading facilities, and container yards.14 Figure 7, below, shows an example of a truck involved in port drayage operation. Truck original equipment manufacturers (OEMs) generally do not define a specific "port drayage" segment of the Class 8 truck market. Class 8 truck tractors are specified to be versatile and meet various operating requirements.15



Figure 7: Class 8 Truck Tractor Involved in Port Drayage Operation

Photo credit: Kenworth Truck Company

14 Couch,P. & J,Leonard. Development of a Drayage Truck Chassis Dynamometer Test Cycle. August 2011.
15 CALSTART Inc. Technologies, Challenges & Opportunities. I-710 Zero-emission Freight Corridor Vehicle Systems. Revised Version Final V1. November 2013. (http://www.calstart.org/Libraries/I-710_Project/Technologies_Challenges_and_Opportunities_I-710_Zero-Emission_Freight_Corridor_Vehicle_Systems.sflb.ashx.) While operating characteristics vary by locations, the port drayage drive cycle can generally be described by the following three types of operation:16

- Near dock operation (less than six miles)
- Local operation (between six and 20 miles)
- Regional operation (between 20 and 120 miles)

Table 6, below, summarizes the characteristics of the previous three types of operation.

Table 6: Characteristics of the Three Types of Port Drayage Operation

	Near Dock	Local	Regional
Average speed	6.6 MPH	6.8 MPH	28.6 MPH
Maximum speed	40.6 MPH	46.5 MPH	58.5 MPH
Distance	5.6 miles	8.7 miles	49.0 miles
Stops per mile	5.4	4.6	0.7
% at idle	50%	60%	22%

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

Sources: Couch, P. & J. Leonard

In 2013, CALSTART surveyed several drayage operators serving the Ports of Long Beach and Los Angeles to determine the key performance parameters for drayage trucks operating at the two ports. The report identified three key performance parameters that port drayage trucks must have: ²²

- Sufficient power for operation (400 horsepower [HP], 1,200-1,800 ft.-lbs. of torque).
- Ability to drive at least 200 miles without refueling.
- Capability to be used on various delivery routes.

While these characteristics were developed out of interviews and surveys with drayage operation in Southern California, the findings are believed to be applicable to port drayage trucks in general.

3.1.2 Truck Population Estimate

To estimate the number of drayage trucks in North America, six major North American port complexes which together handled over 66 percent of the total twenty-foot equivalent units handled by the United States and Canada for the year 2013 were considered (Table 7).

¹⁶ Couch, P. & J. Leonard. *Characterization of Drayage Truck Duty Cycles at the Port of Long Beach and Port of Los Angeles. March 2011.*

Table 7: Number of Port Drayage Trucks for Major North American Port Complexes

	Twenty-foot Equivalent Units Handled in 2013	Number of Trucks Transporting Cargo
Port of Long Beach/Los Angeles 17,18	14,599,155	12,893
Northwest Ports 19,20 (Seattle – Tacoma – Vancouver)	6,309.796	~9,000
Port of New York and New Jersey 21,22	5,467,347	4,544
Port of Oakland 23,24	2,346,564	~6,500
Port of Houston 25,26	1,950,071	3,042
South Carolina Ports Authority 27,28	>1,600,000	2,617

Source: The World Bank

Approximately 38,600 trucks transport cargo to and from the six port complexes. The total

20 Northwest Ports Clean Air Strategy. 2013 Update/December 2013.

(http://www.portseattle.org/Environmental/Air/Seaport-Air-Quality/Documents/NWCleanAirUpdate_2013_FINAL.PDF)

21 2013 Trade Statistics – The Port of New York And New Jersey. (http://www.panynj.gov/port/pdf/historical stats 2003-2013 trade-stats.pdf)

22 <u>A Clean Air Strategy for The Port of New York & New Jersey. Final – October 21, 2009.</u> (http://www.panynj.gov/about/pdf/cas-final.pdf)

23 Port of Oakland - Container Statistics. (http://www.portofoakland.com/maritime/containerstats.aspx)

24 Port of Oakland 2012 Seaport Air Emissions Inventory.

(http://www.portofoakland.com/pdf/environment/maqip_emissions_inventory.pdf)

25 <u>Port of Houston Authority TEUs.</u> (http://www.portofhouston.com/business-development/trade-developmentand-marketing/trade-statistics/)

26 2007 Goods Movement Air Emissions Inventory at the Port of Houston.

(http://www.portofhouston.com/static/gen/inside-the-port/Environment/PHA-GM-AirEmissions-07.pdf)

27 SC Ports Volume up Nearly 6 Percent in 2013.

28 <u>SCSPA Truck Survey Summary Report. December 10, 2010.</u> (http://www.scspa.com/SCSPA Truck Study Dec 2010.pdf)

^{17 &}lt;u>The Port of Los Angeles Container Statistics – 2013.</u> (http://www.portoflosangeles.org/Stats/stats_2013.html). <u>Port of Long Beach Yearly TEUs.</u> (http://www.polb.com/economics/stats/yearly_teus.asp).

¹⁸ Port of Long Beach – Clean Trucks Program. May 2014.

^{19 &}lt;u>Port of Seattle 10-Year History.</u> (http://www.portseattle.org/About/Publications/Statistics/Seaport/Pages/10-Year-History.aspx) <u>Port of Tacoma – Monthly cargo stats.</u> (http://portoftacoma.com/monthly-cargo-stats/2014-01-22/tacoma-containers-end-2013-near-2-million-teu-mark). <u>Port Metro Vancouver – Statistics Overview 2013.</u> (https://www.portvancouver.com/docs/default-source/about-facts-stats/2013-statistic-overview-(new).pdf?sfvrsn=0).

⁽http://www.scspa.com/About/News/pressroom/pressroom.asp?PressRelease=401)

port drayage truck population in North America was estimated to be about 58,500 trucks. With three major ports, California represents a large part of the North American market for port drayage trucks, as shown in Figure 8, below.



Figure 8: North American Port Drayage Truck Market

Source: CALSTART

3.1.3 Market Trends

In this section, three major trends that are impacting or will impact the port drayage truck market are analyzed.

3.1.3.1 Phase-out of Older Trucks

Although the port drayage truck market is relatively small compared to the total market for Class 8 trucks, a strong regulatory push throughout the nation for reducing emissions in

heavily polluted corridors make it a favorable market for clean technologies. Examples of major emission reduction initiatives at the six port complexes previously identified are listed below.

California Ports

In 2007, the ARB approved a new regulation to reduce emissions from drayage trucks transporting cargo to and from California's ports and intermodal rail yard. For Class 8 trucks, the regulation mandates a phase out of trucks built before 2007 according to the following schedule:29

- Truck engine model years 1993 and older are prohibited.
- Truck engine model years 1994 to 2004 must reduce particulate matter emissions by 85 percent and after December 31, 2013 must meet 2007 engine emission standards.
- Truck engine model years 2005 and 2006 must reduce particulate matter emissions by 85 percent after December 31, 2012 and after December 31, 2013 must meet 2007 engine emission standards.
- Truck engine model years 2007 to 2009 must meet 2010 engine emission standards by December 31, 2022.

Beyond the phase-out of older port drayage trucks, federal and state funding promotes several projects to develop and deploy advanced port drayage trucks. The list below gives examples of companies and advanced technologies that have been funded in the past:

- Artisan Vehicle Systems: two drayage tractors (one turbine electric tractor and one battery electric tractor).
- BAE Systems: two drayage tractors (one CNG powered series hybrid and one range extender fuel cell).
- Balqon: three battery electric drayage tractors.
- International Rectifier: one plug-in hybrid drayage tractor.
- Transpower: seven battery electric drayage tractors.
- US Hybrid: three drayage tractors (two battery electric and one fuel cell).
- Vision Motor: four fuel cell hybrid drayage tractors.
- Volvo Trucks: two plug-in hybrid drayage tractors.

In addition, the State of California is about to fund more projects with \$25 million from the CEC for medium- and heavy-duty advanced vehicle technology demonstration projects and \$25 million from the ARB GHG Reduction Fund for zero-emission drayage demonstration projects.

Northwest Ports

In 2007, the Port of Seattle, Port of Tacoma, and Port Metro Vancouver have adopted the

²⁹ California Air Resources Board. *California's Drayage Truck Regulation, California Code of Regulations, Title 13, Section 2027, Summarized Version for Truck Owners.*

Northwest Ports Clean Air Strategy to reduce diesel particulate matter and GHG emissions.20 Specifically for trucks, the strategy adopted the following goals:

- By 2017, 100 percent of trucks will meet or surpass U.S. EPA emission standards or equivalent for model year 2007.
- By 2020, 50 percent of trucks have fuel-efficiency plans in place that promote continuous improvement.

Port of Houston

In 2011, the Port of Houston adopted the Clean Air Strategy Plan to reduce emissions from maritime and associated maritime transportation sources:30

- Short term (one to three years) goal is to reduce by 10 percent the number of pre-1994 trucks.
- Long term (10 years) goal is to increase the number of 2007 or newer trucks.

Port of New York and New Jersey

In 2009, the Port of New York and New Jersey adopted a Clean Air Strategy to reduce criteria air pollutants and GHG emissions. One example of committed action for trucks is the implementation of a program to phase out older trucks.²²

South Carolina Ports Authority

In 2011, the Port of Charleston launched the Seaport Truck Air Cleanup Southeast, a voluntary truck replacement program to help truckers replace pre-1994 tractors with less-polluting ones.³¹

While port drayage trucks have traditionally been older second-hand trucks, new market trends, such as the clean ports initiatives presented above, are pushing new business models toward greater consolidation of drayage operation, from independent owner-operators to larger companies, able to purchase newer and cleaner trucks. This is reflected in Figure 9, below, which shows the average truck age at the six port complexes.

^{30 &}lt;u>Port of Houston Authority. 2011 Clean Air Strategy Plan.</u> (http://www.portofhouston.com/inside-the-port-authority/environmental-stewardship/air-quality/)

^{31 &}lt;u>South Carolina Ports. Port of Charleston Increases Incentive for Truck Replacement.</u> (http://www.scspa.com/About/News/pressroom/pressroom.asp?PressRelease=349)



Figure 9: Average Truck Age at Six Major North American Port Complexes

The average age of port drayage trucks is generally between eight and 12 years. However, Figure 9 clearly shows how truck phase-out programs in California have been successful at renewing port drayage truck fleets. While this has led to important reduction in emissions of criteria pollutants, a younger truck fleet also means that some key port drayage truck markets may already be saturated with newer and cleaner trucks and thus, are less likely to adopt new technologies in the short term.

3.1.3.2 Expansion of Natural Gas-powered Trucks

As was demonstrated in Section 2.1, market and regulatory conditions have created the opportunity for a market growth of natural gas powered Class 8 trucks. As shown in Figure 10, below, Class 8 natural gas penetration in the near term will remain limited: from 2 percent in 2012 to between 4 percent and 15 percent in 2017.

Source: CALSTART



Figure 10: Near-term Class 8 Natural Gas Penetration Forecasts

Source: Citi GPS

While previous studies have forecasted a sharp increase to over 50 percent of the Class 8 truck market by 2025, falling diesel prices, limited refueling infrastructure and concerns about payback have led to revisions for the market growth of natural gas powered vehicles.³² The current most optimistic studies forecast natural gas Class 8 truck/transit bus market to total 23 percent of the units sold in 2025.³³

Much of the market growth is expected to come from dense freight corridors near major population centers and will depend on the availability of fueling infrastructure and cheaper technology for CNG tanks for instance. Short haul/regional delivery Class 8 tractors are forecasted to be key growth markets.

³² Dominguez-Faus, Rosa. *Natural Gas Market Update*. December 10, 2013 NextSTEPS Symposium. ITS – UC Davis.

^{33 &}lt;u>FleetOwner. *Will natural gas stall out as heavy-duty alternative?* (http://fleetowner.com/running-green/will-natural-gas-stall-out-heavy-duty-alternative)</u>

Pushed by strong regulation and favorable market conditions, natural gas penetration at the Port of Long Beach and Port of Los Angeles is currently above the average for Class 8 trucks, as shown in Figure 11, below.



Figure 11: Natural Gas Penetration at the Ports of Long Beach and Los Angeles

Source: Port of Los Angeles – Clean Truck Program

The expansion of natural gas in the Class 8 truck market will pave the way for the successful introduction of near-zero-emission heavy-duty trucks for the following reasons:

- Natural gas fueling infrastructure will be developed to support the growing number of natural gas powered trucks.
- Municipal and commercial fleets will have gained experience with operation of natural gas powered trucks.
- Some fleets will already be on their way to transitioning to natural gas powered trucks.

3.1.3.2 Growing Port Activity

As population and trade increases in North America, goods movement activity is expected to grow and with it port drayage truck activity. For instance, container forecast at the San Pedro Bay ports (Port of Long Beach and Port of Los Angeles) is expected to increase by 50 percent by 2020 and by 137 percent by 2030 (Figure 12).



Figure 12: San Pedro Bay Ports Container Forecast

Source: Collaborative Planning for Goods Movement

Assuming that port-related truck activity will follow the same growth pattern, the number of port drayage trucks serving the Ports of Long Beach and Los Angeles will increase to 19,300 by 2020 and 30,500 by 2030. If port-related truck activity grows at half the growth rate as trade volumes, the number of port drayage trucks will still increase to 16,100 by 2020 and 20,500 by 2030 (Table 8).

Table 8: Estimated Projection for Number of Trucks Serving the San Pedro BayPorts

Number of port drayage trucks	2013	2020	2025	2030	2035
Assuming same growth as trade volumes	12,893	19,300	24,500	30,500	33,700
Assuming 50% growth as trade volumes	12,893	16,100	18,200	20,500	21,600

Source: Collaborative Planning for Goods Movements

In comparison, more limited growth is forecasted for the Port of Oakland.4734 And outside of California, several trends will impact North American port activity and ultimately port-related truck activity:35

- Shifting trade volumes among various ports of entry.
- Panama Canal widening may redistribute Asian trade.
- Growth in trade with Europe and Latin America may favor east and gulf coast ports.

Port trade volumes are expected to grow, and despite redistribution of activity between various ports, California will remain an important trade gateway and ultimately a major market for port drayage trucks.

3.2 Local and Regional

3.2.1 Delivery Description

Local/regional delivery consists of moving freight between manufacturers, distributors, retailers and other businesses. Local/regional delivery fleets are generally private fleets who own or lease a fleet in support of their primary business and for-hire fleets who offer freight transportation services to the public.³⁶ Local/regional delivery operation involves truck tractors usually based at one specific location and returning to the same location at the end of the work shift. Trucks operate in a mix of urban and over-the-road operations, using highways to access several delivery/pick-up points in urban areas.³⁷

Figure 13, below, shows an example of a truck involved in local/regional delivery operation. There is no specific configuration for local/regional delivery trucks but they usually are day cab truck tractors since they return to the same location at the end of the work shift and can be single axle depending on weight requirement.

36 American Trucking Associations, Inc., American Trucking Trends 2011.

³⁴ Jacob, Mike. *Restoring Growth in California's Maritime Economy.* "*State of the State"*. California Maritime Leadership Symposium. Sacramento, CA.

³⁵ Ikhrata, Hasan. *Collaborative Planning for Goods Movement. Southern California's Experience.* Presented to Joint Informational Meeting of the California Transportation Commission and the Washington State Transportation Commission.

⁽http://portal.trucking.org/Federation/Councils/ITLC/Documents/2011%20Conference/ATA%20American%20Trucking%20Trends%202011.pdf)

³⁷ Gallo, J., "*Development of Representative Regional Delivery Drive Cycles for Heavy duty Truck Tractors,*" SAE Int. J. Commer. Veh. 7(1):2014, doi:10.4271/2014-01-9024.

Figure 13: Class 8 Truck Tractor Involved in Regional Delivery Operation



Photo credit: Kenworth Truck Company

From September 2011 to May 2012, CALSTART collected real-life data on six Class 8 truck tractors involved in local/regional delivery operation. These six trucks collectively drove more than 60,000 miles across five U.S. states and one Canadian province, recording more than 1,700 hours of engine operation over 180 working shifts. These vehicles were selected among four major North American private and for-hire carriers' fleets, driving from 30—510 miles per shift, sometimes two shifts per day, across a representative range of private and for-hire carrier operation.³⁸ From the data collected, two representative drive cycles were developed for chassis dynamometer testing of advanced technology vehicles (Table 9 and Figure 14).

	High Efficiency Truck Users Forum (HTUF) RD1	HTUF RD2
Average driving speed (MPH)	37.5	17.1
Maximum speed (MPH)	62.4	45.3
Distance (mi.)	15.7	4.9
Stops per mile	0.83	3.44
% at idle	21.2	31.7

Table 9: Characteristics of Two Regional Delivery Drive Cycles

Source: HTUF Class 8b Working Group

38 Parish, R., J.-B. Gallo. HTUF Class 8b Working Group. Project Definition Document. September 4, 2012.



Figure 14: The HTUF Regional Delivery Number 1 (Left) and 2 (Right) Drive-cycles

Source: HTUF Class 8b Working Group

The HTUF Regional Delivery number 1 drive-cycle starts with several short maneuvers in the yard where the vehicle is based or at a customer site. Next, the truck drives at highway speeds on a medium to long distance to a delivery/pickup site or back to the terminal where the vehicle is based. Lastly, the vehicle maneuvers slowly on the terminal yard or customer site to back the vehicle into a loading dock or swap a trailer. The HTUF Regional Delivery number 2 drive-cycle starts with the truck travelling at nonhighway speeds from one delivery/pickup site to another on a medium distance. Next follows several short maneuvers at a customer site to back the vehicle into a loading dock or park the vehicle. Then, the truck travels at non-highway speeds to another delivery/pickup site on a medium distance. Lastly, the vehicle maneuvers slowly at a customer site to back the vehicle into a loading dock or swap a trailer.

3.2.2 Truck Population Estimate

In 2012, there were 2,581,245 truck tractors in the United States (Class 7 and Class 8), the top five markets being California, Texas, Indiana, Illinois, and Ohio (Figure 15).39

^{39 &}lt;u>Office of Highway Policy Information</u>. *Highway Statistics Series*. *Truck and Truck-Tractor Registrations* – 2012. (http://www.fhwa.dot.gov/policyinformation/statistics/2012/mv9.cfm)

Figure 15: United States Truck Tractor Market



Source: Office of Highway Policy Information

To estimate the number of local/regional delivery trucks in the United States, the overall truck tractor market was broken into two parts: California and the rest of the United States.

For California, the 2010 California Hybrid, Efficient, and Advanced Truck Inventory revealed that there were 286,143 Class 7 and Class 8 truck tractors registered in the state, including 175,345 Tractors – Over The Road and 110,798 Tractors – Short Haul/Regional.40 Subtracting the port drayage trucks estimated in Section 3.1.2 from the Tractors – Short Haul/Regional truck category, the California market counts 91,405 truck tractors involved in local/regional delivery.

For the rest of the United States, retail sales of Class 8 truck tractors were used, assuming that sleeper cab trucks correspond to Tractors – Over The Road and day cab trucks to Tractors

⁴⁰ Brotherton, T. & F. Silver. *CalHEAT Technology Roadmap.* CalHEAT Forum 2013.
Short Haul/Regional trucks. January to November 2012 retail sales of Class 8 truck tractors were split between sleeper and day cabs as follows:41

- Class 8 tractor sleeper cab: 119,280 (63.5 percent)
- Class 8 tractor day cab: 68,650 (36.5 percent)

Assuming that among the 2,310,650 registered truck tractors in the rest of the United States, 36.5 percent are day cab trucks, then the market for the rest of the United States counts 843,390 Tractors – Short Haul/Regional trucks. Subtracting the port drayage trucks estimated in Section 3.1.2, the market for the rest of the United States counts 804,280 truck tractors involved in local/regional delivery.

There are approximately 895,685 local/regional delivery truck tractors in the United States. California represents an important part of the U.S. market for local/regional delivery trucks, as shown in Figure 16, below.



Figure 16: U.S. Local and Regional Delivery Truck Market

3.2.3 Market Trends

^{41 &}lt;u>ACT Research</u>. *State of the Industry: Classes 5-8 Vehicles*. *November & YTD 2012 Data*. (www.actresearch.net/wp-content/uploads/2013/04/soi1212.pdf)

In this section, two major trends that are impacting or will impact the local/regional delivery truck market are analyzed.

3.2.3.1 Expansion of Natural Gas Powered Trucks

As was described in Section 3.1.3.2, Class 8 natural gas penetration is forecasted to increase and short haul/regional delivery will be one of the key growth markets. Below is a list of a few large North American fleets involved in local/regional delivery and that are currently transitioning part of their Class 8 truck tractor fleet to natural gas:

- Penske Truck Leasing has some 200 CNG-powered trucks on offer for rental or long term lease throughout all five of its U.S. regions.42
- Ryder System has over 500 liquefied natural gas (LNG) and CNG truck tractors serving over 40 customer operations across the country.43
- UPS will have the most extensive private LNG fleet in the U.S. by the end of 2014. UPS currently operates 112 LNG tractors today and is planning to purchase 700 and build an extensive network of LNG fueling stations across 10 U.S. states.44
- Frito-Lay plans to deploy 208 CNG tractors that will make up 20 percent of Frito-Lay's fleet.45
- Nuverra Environmental Solutions purchased 200 Peterbilt Model 367 LNG vehicles for its fleet.46
- Transport Robert runs 125 LNG trucks between Quebec City and Windsor, Ontario.47

Beyond these vehicle deployments, market growth for natural gas powered Class 8 trucks will depend on many factors such as the price gap between diesel and natural gas, the availability of refueling infrastructure and high horsepower natural gas engines. Advanced natural gas trucks, such as range extended hybrid electric trucks provide additional fuel consumption reduction and environmental benefits and they could see their market share grow as well.

3.2.3.2 Improving Conventional Diesel Fuel Economy

In 2011, the first fuel efficiency standards for medium and heavy vehicles were mandated by the federal government (see Section 2.3). By requiring the achievement of up to approximately 20 percent reduction in fuel consumption and GHG emissions by model year

42 Fleets and Fuels. Penske has 200 CNG Trucks on Offer.

(http://www.fleetsandfuels.com/fuels/cng/2014/01/penske-has-200-cng-trucks-on-offer/)

43 <u>Market Watch. *Ryder's Natural Gas Fleet Surpasses 20 Million Miles.*</u> (http://www.marketwatch.com/story/ryders-natural-gas-fleet-surpasses-20-million-miles-2014-03-31)

46 <u>Successful Dealer</u>. *Peterbilt Receives Order for 200 LNG Trucks*. (http://www.successfuldealer.com/peterbilt-receives-order-for-200-lng-trucks/)

47 <u>Reuters. *INSIGHT-Ride to lower costs for LNG-run trucks rockier than expected.*</u> (http://www.reuters.com/article/2014/04/09/lng-transportation-trucking-idUSL1N0MT10M20140409)

⁴⁴ UPS. LNG Fact Sheet. (http://www.pressroom.ups.com/Fact+Sheets/LNG+Fact+Sheet)

⁴⁵ Frito-Lay. Driving The Alternative Fuel Movement, Frito-Lay Unveils Investment in Compressed Natural Gas Infrastructure.

2018, this first phase of medium and heavy-duty GHG and fuel efficiency standards will accelerate the introduction to market of new and more efficient diesel engines.⁴⁸

The Administration is also supporting innovation and breakthrough research and development. In particular, the U.S. Department of Energy coordinated with truck manufacturers to develop advanced generation, highly efficient prototype Class 8 trucks under the SuperTruck program. Launched in 2009, this public-private partnership has three main goals:

- Achieve a 50 percent freight efficiency improvement
- Demonstrate 50 percent brake thermal efficiency (BTE)
- Design a pathway to 55 percent BTE

Each truck manufacturer was given the freedom to investigate and deploy any technology they wanted, only constrained in their focus by the three objectives listed above. Ultimately, teams approached the project by combining a variety of prototype and pre-production technologies on a final demonstration vehicle: engine downsizing, engine downspeeding, transmission, hybridization, organic Rankine cycle and turbocompounding. Table 10, below, summarizes the latest progress status of the SuperTruck program.

Table 10: SuperTruck Progress Status as of June 2014

	Achieve a 50% freight efficiency improvement	Demonstrate 50% BTE	Design a pathway to 55% BTE
Cummins/Peterbilt	86% improvement achieved	51% achieved	>55% BTE designed
Daimler Trucks NA	50% improvement modeled	>50% demonstrated	55% BTE expected
Volvo Group	48% demonstrated	43% demonstrated	55% BTE expected

Source: U.S. Department of Energy

During real world testing, Peterbilt achieved an impressive 10.7 miles per gallon fuel economy with the prototype developed for the SuperTruck program (Figure 17).

^{48 &}lt;u>The White House.</u> *Improving the Fuel Efficiency of American Trucks – Bolstering Energy Security, Cutting* <u>Carbon Pollution, Saving Money and Supporting Manufacturing Innovation. February 2014.</u> (http://www.whitehouse.gov/sites/default/files/docs/finaltrucksreport.pdf)



Figure 17: Peterbilt SuperTruck Prototype

Source: Cummins, Inc.

The considerable investment of the SuperTruck program promises the acceleration to market of key technologies that can make Class 8 trucks more efficient. While the SuperTruck program was targeted at long-haul trucks, local/regional delivery trucks share many of the same technical specifications. Therefore, it is expected that some of the technologies developed for the SuperTruck programs will make their way into other areas of the Class 8 truck market.

New and more efficient heavy-duty diesel trucks, capable of achieving over 10 miles per gallon in real world operation, will be a tough competition for other high-efficiency truck technologies such as natural gas and near-zero-emission truck technologies.

3.3 Barriers to Market Entry

Several barriers to market entry were identified for both the port drayage and local/regional delivery truck market.

Port Drayage

- The port drayage truck market is a small market compared to the local/regional delivery market.
- Port drayage fleets seem unlikely to widely adopt new technologies without strong regulation and should be considered as "reluctant early adopters" whose truck purchases will be influenced by local and federal regulation.
- Regulation and funding mostly from the State of California have generated significant activity in near-zero and zero-emission technology that is moving the market past the ideation stage, and into the prototype demonstration stage. To use the Technology Readiness Levels (TRL) from NASA, we are past TRL 3 and into TRL 4 and 5. Any new technologies will have to jump levels to catch up with the already demonstrated technologies – a difficult task.
- Current and expected demonstration and deployment projects may create a glut of near-zero and zero-emission heavy-duty trucks on the market.
- Corporate sustainability is not a large factor differentiating port drayage fleets.

• Proper fueling infrastructure is a key enabler of alternative fuel vehicles and will be an important aspect to achieve successful deployment of near-zero-emission heavy-duty trucks.

Local and Regional Delivery

- The local/regional delivery truck market is a much larger market compared to the port drayage market but truck purchases are less driven by local regulation.
- A new technology trying to enter the market will face competition with a wide variety of other fuel efficiency technologies such as aerodynamics, weight reduction and engine improvements.
- A new technology trying to enter the market will need to show a proven business case to move beyond early demonstration projects supported by government incentives.
- Fleets generally require evidence of where else the technology is being used, what kind of fleet has been using it, a solid overall understanding of the technology, and an indication of how the technology may affect downtime or uptime.
- Proper fueling infrastructure is a key enabler of alternative fuel vehicles and will be an important aspect to achieve successful deployment of near-zero-emission heavy-duty trucks.

CHAPTER 4: Near-Zero-Emission Heavy-Duty Truck Technology Assessment

In this chapter, general truck specifications and key performance parameters for a preproduction hybrid drive system integrated into a standard Class 8 truck tractor chassis are reviewed. Next, an example of a near-zero-emission heavy-duty truck technology is presented. This example is a range extended series hybrid electric truck and three different potential range extender options are also considered.

4.1 General Truck Specifications

In 2012, the HTUF developed a project definition document to define the process and requirements to pursue the testing and evaluation of a pre-production hybrid drive system integrated into a standard Class 8 truck tractor chassis. HTUF developed the following "highly desired" specifications presented in Table 11, below, as defined by a consensus of participating North American regional delivery and drayage fleets.49

Item	Specification	Comments
Gener		
Gross vehicle weight rating	>33,000 lbs.	Defined gross vehicle weight rating for Class 8 trucks
Gross combination weight rating	80,000 - 105,000 lbs.	
Axle configuration	4x2; single drive axle	6x4 and 6x2 options should be available on production vehicles
Cab type	Conventional Day Cab	
Engine performance rating	375 - 450 horse power 1,550 – 1,800 lbsft.	2010 emissions compliant engine
Fuel tank capacity	150 – 200 USG diesel equiv.	
Transmission	To be determined	Automatic or automated manual
Dimensions		

Table 11: Preproduction Hybrid Drive System Specifications for Class 8 True	ck
Tractor	

⁴⁹ Parish, R., J.-B. Gallo. *HTUF Class 8b Working Group Project Definition Document.* September 4, 2012.

Item	Specification	Comments	
Wheelbase	150" – 156"	This encompasses the range of wheelbase requirements of different fleets and will be specified at time of purchase.	
Chassis length	192″	Front bumper to center of fifth wheel	
Width	96″ max.	Excludes mirrors	
Fifth wheel height	48" minimum		
Brake	25		
Туре	Air	Non-belt driven auxiliary systems are acceptable	
Anti-lock Brake System	Required		
Traction control system	Required		
Air dryer	Required	Sufficient capacity to service air system	
Driveline retarder	Not required	Assumed unnecessary due to regenerative braking function in hybrid drive system	
Engine retarder	Not required	Assumed unnecessary due to regenerative braking function in hybrid drive system	
Axle	s		
Front axle rating	12,000 lbs.		
Rear axle type	Single		
Rear axle rating	23,000 lbs.		
Suspension			
Front suspension rating	12,000 lbs.	Match front axle rating	
Rear suspension rating	23,000 lbs.	Match rear axle rating	
Steering			
Power assist	Required	Non-belt driven auxiliary systems are acceptable	
Front axle turning angle	To be identified by supplier		
Curb-to-curb turning radius	To be identified by supplier		
Tires and \			
Wheel size	22.5″		

Item	Specification	Comments
Wheel mounting	Hub-piloted	Not stud-piloted
Tire specs	Compatible with local climate and operating conditions	Rated for the vehicle gross vehicle weight; low rolling resistance; SmartWay certified
Exhaust System		
Туре	Vertical	
Mounting location	Must not obstruct operator's view of vehicle front or interfere with normal maintenance activities	
Cab		
Cab interior	Must accommodate all reasonably expected body types	e.g. 100 – 350 lbs. person
Heating ventilation and air conditioning system	Heating ventilation and air conditioning required	

Item	Specification	Comments
General		
Max. speed	55 – 65 miles per hour at gross combination weight rating - 0% grade	Controllable via software. The vehicle should be capable of 65 miles per hour but should be governable to 55 mph as necessary.
Gradeability	8% at ≥15 miles per hour at gross combination weight rating	Combined powertrain capability
Startability	≥ 20% grade at gross combination weight rating	
Acceleration	Equal to or better than conventional vehicle	
Hybrid Drive Syst	em Features	
Hybrid components	Unspecified	
Hybrid motor rating	To be determined	Based on duty cycle
Energy storage	Unspecified	
Max. weight penalty of hybrid drive system	Goal is minimum weight impact	
Regenerative braking	Presumed required	Presumed necessary for fuel economy improvement and brake wear reduction

Item	Specification	Comments
Launch assist	Presumed required	Presumed necessary for fuel economy improvement
		If included, must be transparent
tic engine off during normal idling times	Highly desired	operator and allow accessory operation during engine off periods
Interior noise	Per Federal Motor Carrier Safety Administration Part 393.94	
Exterior noise	Must comply with federal, state and local noise ordinances	Ref. Federal Motor Carrier Safety Administration Part 325.7 for federal requirements
Fuel economy	<u>Goa</u> l of 20% or greater reduction in fuel use	
Miscellan	eous	
Reliability	Equal to or better than baseline vehicle	
Durability	Equal to or better than baseline vehicle	
Maintainability	Equal to or better than baseline vehicle	Routine maintenance components must be easily accessible; high- voltage equipment must be clearly marked and maintenance procedures specified where applicable
Serviceability	Equal to or better than baseline vehicle	
Safety	Must comply with all applicable federal and truck industry safety standards and best practices	
Engine certification	Must meet applicable federal and state standards	
Operating temperature	-40°F to 120°F (-40°C to 48.9°C)	

Source: HTUF Class 8b Working Group

In addition, fleets desire that production trucks be "customizable" as much as possible, in keeping with the normal order and purchase flexibility fleets enjoy. Within the weight limits specified for the overall trucks (60,000—88,000 lbs.), the fleets who participated in the creation of this project definition document express their need for flexibility for each fleet member's final order in the following items:

• External and internal cab and driver comfort elements

- Wheelbase (within limits) and chassis elements
- Axle configurations
- Fuel capacity

4.2 Key Performance Parameters

In addition to the desired chassis specifications presented in Section 4.1, HTUF also developed and ranked performance goals and enhanced capabilities for a production hybrid electric truck. Table 12 below ranks the key performance parameters by order of priority based on average rankings from the participating fleets. Tied rankings are identified by "A" or "B."

Rank	Key Performance Parameter	Description
1	Meet or exceed base vehicle startability	Achieves same or better startability vs. grade performance relative to comparable diesel vehicle
2	Operation in climate extremes (-40°F to 120°F [-40°C to 48.9°C])	Meets all requirements down to -40°F (-40°C) and up to 120°F (48.9°C) without performance degradation
3A	Goal of \ge 20% fuel use improvement	Consumes at least 20% less fuel vs. comparable diesel vehicle
3B	Meet or exceed base vehicle gradeability	Achieves same speed vs. grade performance relative to comparable diesel vehicle
5A	Meet or exceed base vehicle chassis reliability	Design intent for production version is that chassis availability or mean time between failures is as good as or better than comparable diesel vehicle chassis
5B	Life cycle costs \leq base vehicle chassis	Total cost of ownership over vehicle service life is the same or lower than comparable diesel vehicle chassis
7A	Meet or exceed base vehicle chassis durability (service life)	Useful service life is as long or longer than comparable diesel vehicle chassis
7B	Meet or exceed base vehicle chassis maintainability	Hybrid drive system does not create significant additional chassis maintenance requirements or accessibility issues vs. comparable diesel chassis
9	Meet base vehicle average acceleration	Average acceleration is as good as comparable diesel vehicle
10	Meet or exceed base vehicle chassis serviceability	Hybrid drive system does not create significant additional work associated with unscheduled chassis service vs. comparable diesel chassis
11A	Minimum weight impact from hybrid drive system	Production vehicle demonstrates minimal weight penalty vs. comparable diesel vehicle
11B	Vehicle range \geq 600 miles	Driving range of at least 600 miles

Table 12: Ranked Key Performance Parameters by Priority

Rank	Key Performance Parameter	Description
13	Meet or exceed payload capacity compared to base vehicle	Capable of carrying same or greater payload compared to diesel version of vehicle
14	Meet base vehicle top speed	Achieves same top speed as comparable diesel vehicle
15	Automatic engine off during idle	Hybrid drive system incorporates an engine shut off feature during idling
16	No increase to base vehicle turning radius	Hybrid drive system does not increase turning radius of vehicle (e.g. by necessitating an increase in wheelbase length) compared to diesel version of vehicle
17	Noticeable decrease in interior and exterior noise levels (e.g3 dBA) compared to base vehicle	Noise experienced by driver in cab and people outside of vehicle is noticeably less than comparable diesel vehicle

Source: HTUF Class 8b Working Group

4.3 Range Extended Series-Hybrid Electric Truck

Rather than looking at all the potential technologies capable of meeting the specifications and key performance parameters listed in Sections 4.1 and 4.2, a range extended series-hybrid electric truck platform was selected for this commercialization study. A range extended series-hybrid electric truck 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 CNG) which runs a generator to produce electricity when the batteries are depleted (Figure 18). 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.



Figure 18: Range-extended Series Hybrid Electric System Layout

Source: Steve Gillette, Microturbine Technology Overview

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), 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 can be a connector for charging that battery pack from the electrical grid. There is also an internal combustion engine that runs when needed to operate a generator and recharge the batteries as they are depleted.

There are many possible designs and variations in operating modes, but most often a range extended series-hybrid electric truck would work 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, therefore equipping the vehicle with a larger battery pack will result in greater zero-emission range. When the batteries are drained, the engine starts and operates a generator to run the primary electric motor 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. In the following sections, three different range extender options are presented:

- A fuel-flexible microturbine
- An internal combustion natural gas engine
- A fuel cell

4.3.1 Option 1: Fuel-flexible Microturbine

The first option uses a microturbine as the range extender, capable of burning different fuel sources (diesel or natural gas for instance) while keeping emissions well below current emission standards for criteria pollutants as shown in Figure 19, below.





Source: Steve Gillette, *Microturbine Technology Overview*

The microturbine emission levels for NOx, particulate matter, and carbon monoxide are significantly lower than the current emission standards when running either on diesel or natural gas. This is mainly due to the steady-state operation of the microturbine which runs the generator for battery charging. Steady-state operation inherently has fewer transient events, which are responsible for emission spikes, and allows for better temperature control which can limit emissions as well. Ultimately, trucks equipped with a microturbine can be cleaner than battery electric trucks charged with utility power (Figure 20).



Figure 20: Capstone Turbine C30 NOx Emissions Compared to Utility Power

Source: Steve Gillette, Microturbine Technology Overview

Depending on the size of the battery, the microturbine range extender option would be capable of operating in all-electric zero-emission mode for a short distance (generally up 30—50 miles) and then operate as a low emission series hybrid. With a large enough microturbine and adequate on-board fuel capacity, the truck could operate without plugging in to the grid, saving on hardware and charging infrastructure, though this would reduce the zero-emission capability of the vehicle.

We list below the advantages and drawbacks of a fuel-flexible microturbine range extender series-hybrid electric truck:

Pros

- Emissions from clean burning microturbine are equivalent to or lower than battery electric vehicles using utility power.
- Zero tailpipe emissions when operating in charge depleting mode.

- No exhaust after-treatment is required to meet current emission standards.
- Capable of burning diesel, natural gas and other fuels and fuel switching capability is possible during operation.
- Better fuel efficiency than conventional vehicle due to hybrid powertrain.
- Microturbine can be smaller and lighter than conventional power plant by up to 50 percent.
- Reduced maintenance costs with regenerative braking and simple microturbine design.

Cons

- Relatively unknown technology in the heavy-duty truck market.
- Life cycle and maintenance costs are presumed lower but remain unknown.
- Current designs are still in prototype stages with limited testing.
- 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.
- 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.

This technology is at the prototype or pre-commercialization stage and several early demonstration projects have begun. For instance, Capstone Turbine, with funding from the CEC, is currently building and conducting a pilot demonstration of a Class 7 delivery truck equipped with a Capstone microturbine (Figure 21).

Figure 21: Kenworth Class 7 Heavy-duty Truck with Capstone Microturbine



Photo credit: Kenworth Truck Company

4.3.2 Option 2: Dedicated Natural Gas Engine

A natural gas internal combustion engine (or dedicated natural gas engine) as the range extender option would combine some of the advantages of both conventional natural gas and battery electric heavy-duty trucks. Depending on the size of the battery, it would be capable of operating in all-electric zero-emission mode for a short distance (generally 30—50 miles) and then operate as a low emission natural gas powered series hybrid. With a large enough natural gas engine and adequate on-board fuel capacity, the truck could operate without plugging in to the grid, saving on hardware and charging infrastructure, but this would reduce the zero-emission capability of the vehicle.

Although there were almost 122,000 natural gas powered trucks in the US in 2011 (Figure 22), there is currently no series hybrid model commercially available for the Class 8 truck tractor market.⁵⁰



Figure 22: Kenworth Natural Gas-powered Conventional Class 8 Heavy-duty Truck

Source: Kenworth Truck Company

Similar to the steady-state microturbine operation, emissions are predicted to be reduced even further on a series-hybrid platform as the dedicated natural gas engine could be downsized and enabled to operate in its sweet spot of best fuel consumption and lower emissions for a given power level. We list below the advantages and drawbacks of the dedicated natural gas range extender Class 8 heavy-duty truck:

Pros

- Natural gas piston engine technology is commercially ready for heavy-duty truck applications.
- Zero tailpipe emissions when operating in charge depleting mode.

⁵⁰ U.S. Department of Energy. *Transportation Energy Data Book: Edition 33.*

- The series hybrid system allows optimized engine control capable of powering the vehicle without using the engine and operating the dedicated natural gas engine in its sweet spot of best fuel consumption and lower emissions for a given power model.
- Reduced maintenance costs with regenerative braking and zero-emission mode.
- With a large enough battery, it is possible to downsize the natural gas engine and optimize the performance and efficiency of the system.
- The number of natural gas fueling stations nationwide has been growing steadily in the past few years with CNG fueling stations located around large urban areas such as Northern and Southern California, Dallas/Fort Worth, Great Lakes and New York.

Cons

- System without plug-in capability may be more economical but will decrease environmental benefits.
- Life cycle and maintenance costs may be lower but remain unknown.
- Current designs are still in prototype stages with limited testing.
- 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.
- 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.
- The lack of fueling infrastructure remains an issue for the full-scale deployment of natural gas powered vehicles. While large commercial fleets will most likely rely on private fueling stations installed at a truck depot, port drayage and local/regional delivery fleets will also need public fueling stations if they are not large enough to justify the purchase of a private fueling station or if they use trucks for longer intercity travel.
- Not all currently available public stations have been designed to accommodate large heavy-duty vehicles. Accessibility of fueling infrastructure is an important factor in ensuring easy access to fueling for the early-adopter fleets that may depend on public stations in lieu of investing in their own infrastructure.

4.3.3 Option 3: Fuel Cell Range Extender

With a fuel cell range extender generating electricity from hydrogen stored onboard in highpressure compressed gas cylinders, this option operates with zero tailpipe emissions. The zeroemission range of this vehicle is limited only by the amount of onboard hydrogen storage. Over 320 fuel cell electric buses have been deployed worldwide since 1991, with 22 currently in active demonstration in the US.51 Currently, only one model is commercially available for the Class 8 truck tractor market: the Tyrano from Vision Motor Corp (Figure 23).



Figure 23: Vision Motor Corp's Tyrano Class 8 Heavy-duty Truck

Photo credit: Southern California Public Radio (https://www.scpr.org/)

This fuel cell option operates similarly to the other two range extender presented previously. However, the size of the fuel cell stack or the battery pack can be optimized to reduce costs while keeping zero-emission capabilities. With improvements in fuel cell reliability and costs and better availability of hydrogen, a fuel cell dominant version would make more economic sense. With improvements in battery prices and infrastructure costs, a battery dominant version would be more interesting. We list below the advantages and drawbacks of fuel cell range extender Class 8 heavy-duty truck:

Pros

- Technology is ready today in transit bus applications and is ready for transfer to heavyduty truck applications; early stage demonstrations for heavy-duty trucks have started or are planned.
- Zero tailpipe emissions at all times, which can make regulatory certifications easier.
- Reduced maintenance cost with regenerative braking and fuel cell stack and battery lifetime projections.
- Hydrogen can be accessed in large quantities via large reforming plants and pipelines, often readily available near oil refineries and other industrial sites in port complexes.

^{51 &}lt;u>California Air Resources Board. *Medium- and Heavy-Duty Fuel Cell Electric Vehicles. Technology Assessment.* (http://www.arb.ca.gov/msprog/tech/presentation/fuelcelltrucks.pdf)</u>

• Hydrogen can be produced from different sources such as refinery hydrogen pipelines, reforming commercial natural gas or electrolyzing water using electricity.

Cons

- Relatively unknown technology in the heavy-duty truck market
- Fuel cell reliability is improving but not proven in truck applications. Life cycle and maintenance costs may be lower than conventional trucks but remain unknown.
- Battery and fuel cell costs lead to very high initial costs.
- Hydrogen fueling infrastructure is not developed, which compounds the knowledge gap on fuel cell technologies, inherently challenging fleets who might be interested in this option.

CHAPTER 5: Near-Zero-Emission Heavy-Duty Truck Market Analysis

In this chapter, the results of the market survey are presented and analyzed. With responses from commercial fleets, advanced technology truck manufacturers and California regulators, this market survey takes the pulse of various industry stakeholders, sheds a light on purchasing intent for a near-zero-emission heavy-duty trucks and helps refine truck design aspects.

Using the findings of the market survey and previous chapter, a market analysis for near-zeroemission heavy-duty trucks was carried out. This market analysis identifies primary and ultimate markets for both port drayage and local/regional delivery, project market penetration and analyze the business case for near-zero-emission heavy-duty trucks.

5.1 Market Survey

In order to determine the interest of industry stakeholders in the near-zero-emission heavyduty truck technology presented in Chapter 4, surveys of key market players were conducted. Truck manufacturers, truck fleets and regulators provided valuable information to help identify attractive design aspects for future vehicles and possible market penetration of a commercial truck offering. Surveys were collected from a variety of respondents over a month-long distribution effort and were supplemented with follow-up conversations for additional detail.

5.1.1 Methodology

Surveys were sent to fleets, powertrain and hybrid drive system OEMs, and regulatory authority representatives in California via an online survey creation and hosting website. The fleet and OEM survey were nearly identical though fleet vehicle population questions were omitted in the OEM survey. The regulator survey uses slightly different language to provide appropriate context for the respondents. The survey link was emailed to individual contacts with which CALSTART has a working relationship as well as through key contacts with industry distribution lists. Respondents were given roughly one month to complete the survey. More fleets were contacted than OEMs or regulators in an effort to obtain adequate market penetration data, as depicted in Figure 24, below.

Figure 24: Survey Disbursement Groups and Their Relative Size



Source: CALSTART

The fleet survey began with questions aimed to establish a size profile of Class 8 truck tractors both within California and nationwide in three different applications, port drayage, local/regional delivery and a write-in other application. Further questioning asked about the number of these truck tractors which were natural gas powered.

The powertrain diagram (shown in Figure 18) was presented along with a specifications table of the series hybrid with different range extender engine options (fuel-flexible microturbine, dedicated natural gas engine and fuel cell). Such specifications included estimated vehicle and all-electric range, economy improvement, maintenance savings, and payback. Selecting specific design aspects that might be of interest, respondents were asked for their interest in each aspect as it related to their business operations. OEMs and regulators were presented the same information and asked to gauge their interest level based on product planning priorities and funding opportunities, respectively.

Next, respondents estimated incremental costs of the three range extender options by selecting from a drop-down list of percentage increases over the cost of a conventional truck. For fleets and OEMs these questions led to an estimation of the annual sales potential in California of each platform. Regulators were asked these questions, though worded as the required market penetration of such vehicles in order for the state to achieve future clean air regulations.

Each respondent group has a different willingness to fund fuel economy improvement technologies and understanding of likelihood for market successes. Fleets estimated incremental cost of segmented fuel economy improvements from 10—50 percent, and indicated their preferred option to help quantify this willingness. For OEMs and regulators this question probed which fuel economy improvement option they thought would obtain the most market success, which often aligned with fleet responses.

Finally, current and future trends of natural gas infrastructure were identified and fleets were asked if their similarly-sized competition would be more or less conservative in survey response estimations. The latter question enables further extrapolations of data to project possible market penetration on a more national scene.

5.1.2 Findings

The fleet-specific survey was sent to 14 local/regional delivery contacts from large nationwide companies to small companies operating only in California, as well as two additional fleet and Class 8 trucking fleet experts. The small core of individuals contacted that comprised the OEM group were highly specialized in their field of work, focusing on advanced vehicle technologies and therefore intimately familiar with many of the design aspects of the proposed vehicle. All 11 regulators contacted about the survey were part of California state or regional institutions, and focused their answers accordingly.

Overall, six complete surveys were received from each group, along with information gathered from follow-up conversations. The aggregated fleet vehicle numbers reported by the six fleet respondents present an interesting picture of California presence, early-adopter status, and predominance of the local/regional delivery duty cycle. Figure 25, below, details the extent of California-domiciled vehicles reported by the surveyed fleets.



Figure 25: California Presence of Surveyed Fleets

Source: NGV America

When asked to report numbers of fleet vehicles nationwide and in California, over 20 percent of all vehicles were domiciled in California, showing the strong presence of these fleets throughout the state. This group of fleets also had significant experience with natural gas vehicles (Figure 26).

Figure 26: National Heavy-duty Port Drayage and Regional Haul Natural Gas Vehicles



Source: NGV America

The aggregated natural gas truck population numbers of the surveyed fleets comprise 17 percent of the nationwide heavy-duty port drayage and regional haul natural gas vehicle numbers.⁵² This demonstrates an impressive penetration of natural gas amongst these six surveyed fleets, underscoring their status as early adopters of advanced technology vehicles. Additionally, fleet respondents were generally very closely connected with CALSTART and have a historical record as early adopters of other advanced technologies; their knowledge of design aspects of the proposed vehicle gives credence to their answers.

A port drayage contact forwarded the fleet survey to over 100 port drayage fleets, but survey response in this sector was still limited, with only two fleet respondents. The proportion of port drayage compared to local/regional delivery trucks is reported in Figure 27, below.

⁵² NGV America. (https://www.ngvamerica.org/vehicles/for-fleets/)



Source: CALSTART

An overwhelming majority of fleet vehicles were classified as local/regional delivery, even though more than ten times as many port drayage fleets received the survey link. These fleets represent food delivery services, national package and freight delivery, and large rental companies.

Estimates for average vehicle lifetime for both fleet types were calculated from survey responses and validated in follow-up conversations (Table 13).

Fleet Type	Average Vehicle Lifetime
Port Drayage	8-12 years
Local/Regional Delivery	8-12 years

Source: CALSTART

The response of the single port-drayage fleet was within the range of aggregate vehicle lifetime estimations made by the other local/regional delivery fleets. Since all fleets responded with respect to their Class 8 vehicles we estimated that both applications have the same lifetime.

The market penetration rate for a commercial near-zero-emission heavy-duty truck technology for local/regional delivery applications was then estimated (Table 14).

Table 14: Market Penetration Data for Local and Regional Delivery Application

Class 8 Local/Regional Delivery		
Total National Truck Population of Fleets Surveyed	48,233	
Average Vehicle Lifetime	10 years	
Total Estimated Annual Vehicle Purchases	4,823	
Prospective Annual Purchases for Near-zero-Emission HD Truck	557	
Estimated Market Penetration	11%	

Source: CALSTART

The total national truck population of all surveyed fleets was divided by the average vehicle lifetime (10 years), giving the total estimated annual vehicle purchases. Prospective annual sales figures for near-zero-emission heavy-duty truck technology estimated by the fleets were then compared to this total sales value. The market penetration rate was calculated at 11 percent of annual sales. This means that the fleets surveyed estimate that for 100 Class 8 trucks purchased for local/regional delivery operation, they would purchase 11 near-zero-emission heavy-duty trucks.

There was not sufficient data to establish similar market penetration data for port drayage fleets.

Fleets, regulators, and OEMs were all given the opportunity to rate their interest level on a variety of design aspects associated with the near-zero-emission heavy-duty truck technology. This aimed to capture a general idea of funding interests and state goals for emissions and petroleum reduction amongst California regulators, feasibility and challenges of the proposed technologies from OEMs, as well as technical interest and purchasing intent from fleets. Figure 28, below, shows the overall and range of average ratings for each of the eight design aspects.



Figure 28: Average Interest Level for Advanced Class 8 Truck Design Aspects

Source: CALSTART

Both California regulators and fleets were extremely interested in the all-electric range and near-zero-emission aspects of the vehicle, while the OEM rating was the lowest among the three groups for both of these. There were nearly equivalent ratings between all three groups for the 20—30 percent fuel economy improvement and natural gas fuel capability, though the latter generated somewhat less interest. Similarly, the dedicated natural gas engine received the lowest overall interest rating among the eight design aspects, both regulators and fleets rated it lower than did the OEMs. As expected, the fleets were more interested than the other two groups in the possible maintenance savings of the technology; strong reliability remains a major tenet of fleet purchasing intent.

Incremental costs were investigated for the two most well-known range-extender options, the dedicated natural gas engine and natural gas microturbine. Results for the dedicated natural gas engine range-extender are shown in Figure 29, below, wherein the number of respondents in each group that selected a specific incremental cost was aggregated.



Figure 29: Surveyed Cost of Natural Gas Engine Range-extended Hybrid

Source: CALSTART

At first glance it is clear that not all the regulators were able to complete this question, mainly due to somewhat less knowledge on technology cost data. Unsurprisingly, there is a gap between what OEMs thought this option should cost, and what the fleets were willing to pay, some of whom would not accept any increase in cost over a conventional vehicle. A similar figure was generated for the natural gas microturbine and is shown in Figure 30, below.



Figure 30: Surveyed Cost of Natural Gas Microturbine Range-extended Hybrid

Source: CALSTART

There is even less regulator input on the natural gas microturbine, indicating its relatively unknown technical status on Class 8 trucks. A few OEMs rated the microturbine cost somewhat higher than the dedicated natural gas engine, likely due to its currently low production volumes. Fleets continued to show their unwillingness for major or any incremental costs above conventional vehicles, though one outlier indicated a possible 25 percent cost increase would be acceptable if vehicle performance and reliability were as strong as promised.

Fleets indicated support for two fuel economy improvement pathways. Fleet and OEM details on these two options are shown in Table 15, below.

	Fuel Economy Improvement (over conventional)	Fleet Accepted Incremental Cost	OEM Estimated Incremental Cost
Option 1	Less than 20%	Less than \$10,000	\$5,000 to \$20,000
Option 2	30% to 50%	\$15,000 to \$35,000	\$30,000 to \$120,000

Table 15: Preferred Fleet Fuel Economy Improvement and Cost Estimates

Source: CALSTART

Half the fleet respondents preferred the 30—50 percent improvement in fuel economy at an incremental cost between \$15,000—\$35,000. The OEM group was also split, with approximately half agreeing that this major improvement in fuel economy would be most attractive but at a cost between \$30,000—\$120,000. The second option, supported by the other half of fleets and recognized by some of the OEMs, involves lesser fuel economy gains of less than 20 percent at \$10,000 or less. Interestingly, the cost gap between OEM expectations

and fleet acceptance is much lower at this range; perhaps only \$5,000—\$10,000 distinguish the two groups.

Respondents were also given the opportunity to comment on the option of offering this vehicle as a plug-in hybrid electric, which once again split the fleets evenly. For the suggestion that a plug-in option that increased all-electric range to 50 miles might cost up to \$30,000 one large, one medium, and one small-sized fleet indicated they would be interested in this measure. This is important because it not only shows that a mixed group supports vehicles that plug-in to the electric grid for their operations but also that the other half of the fleet group thinks the vehicle would be interesting without plug-in capability and the associated incremental cost and charging infrastructure. The OEMs estimated the incremental cost of this technology option, which when averaged give approximately \$35,000, validating initial estimates and putting fleet responses in a real-world context.

5.1.3 Conclusions

Eighteen surveys were received from three different respondent groups: fleets, OEMs, and state and California regulators. Follow-up conversations with a handful of respondents helped clarify questions and in some cases provided further detail on given responses. The main conclusion regarding the survey process is the fact that drayage fleets appear particularly hard to reach, possibly due to their small fleet size and current truck ownership models.

Related to respondent interest toward purchasing and individual design aspects, the following trends were identified:

- All respondents showed the same level of positive interest toward near-zero-emission heavy-duty truck technology.
- One of the fleets operates in an environment with little to no natural gas infrastructure and indicated that a diesel-powered range extender option would be much more attractive.
- Near-zero and zero-emission heavy-duty trucks are of high interest to California regulators as these advanced trucks will enable the creation of zero-emission zones or corridors.
- Regulators were least interested in the dedicated natural gas engine, though OEMs, perhaps recognizing applications outside this vehicle concept were most intrigued by this design aspect.
- The hydrogen fuel cell range-extender was interesting for the regulators as a zeroemission technology but not nearly as accepted by the fleets, mainly because it feels too new even for the early-adopters we contacted.

There were a few more conclusions related to the incremental costs and prospective infrastructure required for upcoming technologies:

- The major cost gap between what fleets are willing to pay and current technology costs underscores the work that must still be done by regulators and OEMs to enable the development of affordable advanced technologies.
- Fleets recognize benefits and see interest in both a low-cost technology option that provides small fuel economy improvement (less than 20 percent) and a high-cost technology option that provides large fuel economy improvement (up to 50 percent).

- While respondents were split, most agreed that there is not currently adequate natural gas fueling infrastructure to support expansion of natural gas powered Class 8 trucks.
- Most fleets identified themselves as equally conservative as other competitor fleets of similar size.

5.2 Market Analysis

5.2.1 Market Penetration Estimate

Using the truck population estimates calculated in Chapter 3, the average truck lifetime and the market penetration rates determined in Section 5.1, the average number of new technology trucks purchased per year was estimated. The process is detailed in Figure 31, below.



Figure 31: Market Penetration Estimation Process

In purple: data collected from market surveys. In blue: data collected from market research. In green: calculated data.

Source: CALSTART

This process was applied to both the port drayage and local/regional delivery truck market that we identified in Chapter 3. In addition, the following assumptions were made:

- A 10-year average truck lifetime was used for both truck markets.
- The 11 percent penetration rate determined in Section 5.1.2 was rounded down to 10 percent and considered a high penetration rate for the deployment of near-zero-emission heavy-duty trucks. In addition, we considered more conservative medium and low penetration rates at five percent and two percent respectively.
- The same penetration rates were used for the port drayage and the local/regional delivery truck markets.
- Each truck market was split into a primary market, where near-zero-emission heavyduty trucks would most likely see a successful deployment in the short term, and an

ultimate market, which corresponds to the total truck population estimates identified in Chapter 3.

Port Drayage

The primary market for port drayage trucks is considered to be the three major ports in California (Port of Long Beach, Port of Los Angeles and Port of Oakland). Regulatory pressure has accelerated the introduction to market of newer and cleaner port drayage trucks in California and we believe the trend will continue. In addition, recent publicly-funded development and demonstration projects (see Section 3.1.3.1, page 14) indicate that port drayage trucks will most likely be leading the adoption of near-zero and zero-emission truck technology.

Although 19,393 port drayage trucks were counted at the three major ports in California, the primary market for port drayage was rounded to 19,000 trucks for simplicity. The ultimate market for port drayage was set at 58,500 trucks. Please note that these numbers do not take into account any growth in the total truck population due to increased activity.

As the market survey showed, port drayage fleets were hard to reach and as a result there was not sufficient data to establish market penetration rates for port drayage fleets. Instead, the same penetration rates were used for the port drayage and the local/regional delivery truck markets.

Table 16, below, details the market penetration projection for the port drayage truck market.



Table 16: Market Penetration Project for Port Drayage Application

Source: CALSTART

The port drayage truck market is relatively small with sales projections ranging from 38—190 near-zero-emission heavy-duty trucks purchased per year for the primary market and from 117—585 for the ultimate market.

Local and Regional Delivery

While the local/regional delivery market is much larger, it will follow the port drayage truck market only after seeing the trucks work as advertised, or if regulations move beyond ports to cover entire regions. The primary market for local/regional delivery trucks is considered to be early adopter fleets most likely to adopt new and clean technologies and is estimated at about 100,000 trucks. These early adopters include large fleets such as Coca Cola, Frito-Lay/PepsiCo, UPS, FedEx Express, Purolator, IKEA and smaller fleets with a strong focus on sustainability such as Veritable Vegetable. The ultimate market for local/regional delivery was rounded to

900,000 trucks. Please note that these numbers do not take into account any growth in the total truck population due to increased activity.

Table 17, below, details the market penetration projection for the local/regional delivery truck market.



Table 17: Market Penetration Projection for Local and Regional DeliveryApplication

Source: CALSTART

The local/regional delivery market is a much larger market with sales projection ranging from 200—1,000 near-zero-emission heavy-duty trucks purchased per year for the primary market and from 1,800—9,000 for the ultimate market.

5.2.2 Business Case Analysis

In November 2013, CALSTART analyzed the business case for zero-emission trucks operating on the I-710 corridor in Southern California.⁵³ When compared with an all-electric drayage truck and a fuel cell range extended drayage truck, the natural gas powered range extended option was the most interesting economically and the most likely to succeed without a high level of incentives.

In this section, this previous analysis for the natural gas powered range extended option is updated using current and future (2020) market conditions. Rather than estimating an incremental cost for this particular technology, it was decided to estimate the maximum incremental costs acceptable to achieve two-year and four-year payback periods, generally widely accepted by commercial fleets when making truck purchase decisions. Table 18, below, lists the assumptions made for the baseline diesel truck for both current and future market conditions.

⁵³ CALSTART, Inc. *I-710 Project Zero-Emission Struck Commercialization Study Final Report*. Prepared for Gateway Cities Council of Governments. 2013. Page 4-17.

Baseline Diesel	Current	2020
Vehicle Life	10 years	
Days in Operation per Year	250 days/year	
Total Daily Range	200 miles	
Total Truck Cost	\$125,000	\$140,000
Fuel Economy	6.0 miles per gallon	7.5 miles per gallon
Diesel Fuel Price	\$4.00/gal.	\$4.39 /gal.
Fuel Escalation Rate	+0.9%	
Maintenance Costs	\$0.10/mile	

Table 18: Business Case Assumptions for Baseline Diesel Truck

Source: CALSTART

The current and future total truck costs for a baseline diesel were derived from available estimates.⁵⁴ The fuel economy of a diesel truck was assumed to be 6 miles per gallon. Using a fuel consumption improvement of 20 percent by 2020, the effect of the U.S. EPA and the NHTSA medium- and heavy-duty standards was included to project the fuel economy to 7.5 miles per gallon in 2020. The current and future diesel prices were calculated in Section 2.1. Please note, that a current diesel fuel price of \$4.00 per gallon (instead of \$4.13) was used to reflect lower average diesel prices in 2014. The diesel fuel escalation rate was calculated in Section 2.1, and the maintenance costs were derived from previous estimates.

Two technology options derived from the findings of Section 5.1.2 were compared to the baseline diesel:

- **Option 1:** This option is a range extended series-hybrid truck fueled by natural gas (using a microturbine or dedicated natural gas range extender). It has a 20 percent better fuel economy than a similar conventional diesel.
- **Option 2:** This option builds on the same platform as Option 1 but with a bigger battery pack, it has a 40 percent better fuel economy than a similar conventional diesel and can operate in electric mode for up to 50 miles. It also is capable of plugging in to the grid to recharge the battery pack.

Table 19, below, lists the assumptions used for the business case analysis of the two technology options.

⁵⁴ Tam, S. *Energy Use and Policy in the U.S. Trucking Sector. State of the Trucking Industry*. ACT Research. October 10, 2012.

Table 19: Case Assumptions for Two Natural Gas-powered Range Extended Options

	Option 1	Option 2
Fuel Economy Improvement	20%	40%
CNG Price	Current price: \$2.67/DGE 2020 price: \$2.86/DGE	
Fuel Escalation Rate	1%	
Maintenance Costs	\$0.08/mile	
Zero-emission Energy Consumption	N/A	2.50 kWh/mi.
Energy Charge	N/A	\$0.10/kWh
Electricity Escalation Rate	N/A	1%

Source: CALSTART

The current and future natural gas prices as well as the natural gas fuel escalation rate were calculated in Section 2.1. The zero-emission energy consumption and the maintenance costs were derived from previous estimates.⁵⁵ Electricity prices were assumed to be \$0.10 per kWh, fuel escalation rate for electricity at 1 percent (mirroring the natural gas fuel escalation rate) and demand charges and fueling/charging infrastructure costs were not considered in this analysis. Figure 32, below, shows the maximum incremental cost analysis in current and 2020 market conditions.

⁵⁵ CALSTART, Inc. *I-710 Project Zero-Emission Struck Commercialization Study Final Report*. Prepared for Gateway Cities Council of Governments. 2013.

Figure 32: Maximum Incremental Cost Analysis in Current (Left) and 2020 (Right) Market Conditions



Source: CALSTART

In order to achieve a two-year payback period in current market conditions, the analysis shows that the total truck cost for Option 1 cannot be more than the total truck cost of a comparable diesel, plus \$31,600. For Option 2, this limit cannot be more than the total truck cost of a comparable diesel, plus \$38,500. With a four-year payback period, the maximum incremental cost for both technology options increases to \$63,200 (Option 1) and \$77,200 (Option 2).

Using 2020 market conditions, both technology options will need to be more affordable to achieve both two- and four-year payback periods. This is due in large part to the better fuel economy of future diesel trucks which limits the amount of fuel an advanced technology can save.

To assess the impact of fuel prices on the business case, a sensitivity analysis was performed using two oil price scenarios from the U.S. EIA and projected to 2020 (for more information, see Section 2.1):

- Low Oil Price: Diesel \$4.01/gallon CNG \$2.84/DGE.
- High Oil Price: Diesel \$4.91/gallon CNG \$2.88/DGE.

Figure 33, below, shows the maximum incremental cost analysis in 2020 market conditions for both the U.S. EIA Low Oil and High Oil Price Scenarios.

Figure 33: Maximum Incremental Cost Analysis in 2020 Market Conditions Using U.S. EIA Low Oil Price (Left) and High Oil Price (Right) Scenarios



Source: CALSTART

As expected, oil prices do impact the business case for near-zero-emission heavy-duty trucks. Option 2, which saves more fuel, will benefit more from higher diesel prices. For instance, the analysis shows that the maximum incremental cost can be \$23,400 greater in the High Oil Price than in the Low Oil Price and still achieve a four-year payback period.

To assess the impact of truck operation on the business case, a sensitivity analysis was performed assuming the total daily range at 100 miles per day instead of 200 miles per day. Figure 34, below, shows the maximum incremental cost analysis in 2020 market conditions when driving 100 miles per day.

Figure 34: Maximum Incremental Cost Analysis in 2020 Market Conditions Driving 100 Miles per Day



Source: CALSTART

Reduced daily mileage vastly reduces maximum theoretical costs that still enable fleets to achieve two- and four-year payback. Since the vehicles travel fewer annual miles there is less opportunity to save fuel and payback the higher incremental cost.

The business case analysis identifies several findings important for the successful commercialization and deployment of near-zero-emission heavy-duty trucks:

- Both options would need to be more affordable in 2020 to compensate the increasing efficiency of diesel trucks.
- Oil prices do impact the business case for near-zero-emission heavy-duty trucks but not greatly. Option 2, which saves more fuel, will benefit more from higher diesel prices.
- Option 1 may be more economically viable when oil prices are low, while Option 2 may be more economically viable when oil prices are high.
- When trucks travel fewer miles, there is less opportunity to save fuel and pay back the higher incremental cost. Vehicles should be deployed on high utilization routes.
- The incremental costs for both options are in line with fleets and OEMs expectations presented in Table 15 in Section 5.1.2.

• Fleets willingness to pay for near-zero-emission heavy-duty trucks is not in line with their payback expectations. Their desired incremental costs can lead to payback periods inferior to two years.
CHAPTER 6: Commercialization Approaches and Phase-In Stages

6.1 Commercialization Process

Commercialization is the successful combination of market adoption and manufacturer production in response to growing demand for a new product. Both adoption and production response elements must be present for a new technology to be successful. The commercialization approaches outlined here are based on prior experience in the advanced truck industry, along with funded research and roadmap development. These approaches are not truly new-the same kind of approach is used in many different industries. However, each industry and technology has unique requirements and we specifically focus here on near-zero and zero-emission heavy-duty truck technology. Since it is felt that these trucks need to be more quickly guided to commercialization in order to address critical air pollution challenges, the intent here is to outline ways to accelerate an otherwise slow pace of adoption.

There are six core issues that need to be addressed for successful accelerated commercialization of near-zero-emission heavy-duty trucks. Figure 35, below, provides explanations for these issues and their relationships to different stakeholders.



Figure 35: Commercialization Core Issues Relationship Diagram

Source: CALSTART

Successful near-zero and zero-emission heavy-duty truck commercialization requires establishing a framework for accelerated product and technology development, infrastructure deployment, user acceptance, regulation, and business case. These trucks cannot operate in a vacuum; they need an ecosystem with an established framework for their operations. Therefore, several paths of parallel activity are required:

- A focused vehicle development, demonstration, validation, and deployment process.
- Early action deployments of near-zero and zero-emission vehicles in targeted locations.
- A regulatory framework for near-zero and zero-emission trucks.
- Enhanced operational and business case assessment.
- Fleet training, maintenance training, and decision support.

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

Achieving a rapid change in heavy-duty truck technology, as well as spurring the adoption of advanced technologies in specific application segments, will require a high degree of focus, cooperation, and consensus among public and private entities. In the near term, it will require a much higher degree of focused technology development funding and outcome setting than typically occurs for a single application. Federal, state, and regional agencies currently have several funding programs that enable such investments in advanced vehicle technology and alternative fuels to help meet climate change and emissions goals.

However, having the funds available is only one part of the issue: the various agencies ideally need to agree to follow a clear roadmap for focusing those resources on the specific technologies, vehicle architectures, and fuels that can achieve the outcomes needed. This will require an unprecedented level of agency cooperation. Furthermore, this intensive development process must leverage and include the truck OEMs.

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

It will also be critical to encourage development of the new technology's supporting systems, such as electrified auxiliary components, high-power rapid charging, lightweight natural gas and hydrogen storage systems, optimized alternative fuel engines and modular battery packs by working with OEM's and component manufacturers.

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

6.1.2 Early Action Deployments of Near-zero-Emission and Zero-emission Vehicles in Targeted Region(s)

In parallel with an aggressive advanced truck product development process, it is imperative to start establishing successful "nodes" of near-zero and zero-emission truck operation and infrastructure. These targeted areas can, in fact, be first adopters of the technology in other appropriate applications, such as battery electric medium duty trucks for food, beverage,

parcel delivery and freight movement. By focusing these deployments on a limited area, this approach can create many benefits and establish the outlines of an ecosystem for advanced vehicles.

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

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

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

6.1.3 Regulatory Framework for Near-zero-Emission and Zero-emission Trucks

While fleets and manufacturers will often not publicly call for new rules or requirements for more stringent vehicle emissions standards, privately several manufacturers have shared with CALSTART that they believe a regulation or requirement of some type will be required to propel adoption of near-zero and zero-emission truck technology on the aggressive timeline being proposed. Voluntary action and incentives alone are insufficient; a potential business case, with assistance (such as incentives), exists but is evolving and will take time to develop. To create a level playing field and to show manufacturers their investments are justified because the region is serious about near-zero and zero-emission operations, some type of fleet rule or backstop regulation on regional emissions is likely required.

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

In California, the San Joaquin Valley Air Pollution Control District, South Coast Air Quality Management District, and the ARB have published extensive data showing the need for reducing emissions from most transportation activities by 2031 in order to meet federal healthbased air standards (see Section 2.2). Near-zero and zero-emission heavy-duty trucks have been cited as one of the targeted actions in the near-term for NOx reductions, and over the longer term for GHG reductions. To meet the air standard goals on such a timeline, these agencies probably will need formal requirements. Additional critical "non-attainment" zones could be similarly addressed by federal, state, and local regulation in other parts of the country.

6.1.4 Enhanced Operational and Business Case Assessment

The medium and heavy-duty truck marketplace is complex, disaggregated, and competitive. Vehicle use is driven by daily needs, and while there appears to be general vehicle use profiles, there are often no set patterns or daily predictable routes. Better understanding the various applications and duty cycles will be critical to manufacturers and suppliers as the succeeding generations of advanced truck systems are designed and validated. Meeting the needs of users with the most optimized solution is of paramount importance to the business case.

Additional data collection, analysis and validation of truck use profiles, truck delivery distribution, trip patterns, and performance needs will be of significant value and will help refine technology selections and vehicle design architectures.

An enhanced business case assessment also needs to be performed, with additional testing of specific technology packages and more discrete identification of expected component costs and operational benefits of near-zero and zero-emission trucks.

An important consideration for advanced trucks, given their increased incremental cost, is to consider which ownership models might make it easier for fleets to make a rapid transition without incurring substantial upfront capital costs. Even with incentives, many operators find making new truck purchases difficult, even at costs on par with current conventional technology. One possible approach would be to establish a lease process for the trucks. This could be public or private with public underwriting. In such a case, fleets would not be required to purchase the trucks. Rather, they could choose to lease them from either a private lease pool or a publicly operated lease authority.

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

6.1.5 Fleet Training, Maintenance Training, and Decision Support

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

Yearly fleet workshops on near-zero and zero-emission technology will be important ground builders for the transition. Such workshops should provide good information on the value and

need for near-zero and zero-emission technology, and on the status of vehicle demonstration and deployment activities. These workshops would also showcase the emerging support programs that will assist the transition to near-zero and zero-emission trucks.

6.2 Key Issues Impacting Commercialization

The classic and frequently cited text "Diffusion of Innovations," by Everett M. Rogers, goes into great depth regarding the pathways and processes for new technologies to enter markets and become commercialized. Rogers examined many new innovations across multiple fields, with historical and current-day examples, and distilled this knowledge to a set of critical factors. Within a given social system (in this case the target market of heavy-duty truck buyers and operators) the way an innovation is perceived will affect the rate of adoption. Note that perception is the consistent pivotal factor—reality and perception may not be the same, which is a further challenge but also one path to solutions. Outreach to change mistaken perceptions is essential.⁵⁶

Regardless of the technology or the market, certain factors accelerate or impede market adoption. Those key issues can be seen in the market for near-zero and zero-emission heavyduty trucks. Each will be discussed in the following sections, and these key issues will combine with other factors such as target market size, specific vehicle classes and duty cycles, OEM development processes, and technology readiness, to set the groundwork for a commercialization pathway. The outcome will be a series of phase-in steps to be covered in Section 6.3. The five factors identified in Rogers' "Diffusion of Innovations," which have significant impact on market adoption, are displayed in Figure 36, below.

⁵⁶ Rogers, Everett M. *Diffusion of Innovations, 5th edition.* ISBN-13: 978-0-7432-2209-9. New York, NY, Free Press. 2003.

Figure 36: Rogers' Five Market Adoption Factors from "Diffusion of Innovations"



Source: Diffusion of Innovations, 5th edition

6.2.1 Relative Advantage

Relative advantage is the degree to which an innovation is perceived as better than the idea it supersedes.⁵⁶ This advantage can be economic, convenience, satisfaction or a combination of "hard" (objective) and "soft" (subjective) perceived advantages. Importantly, it is perception that matters. Greater perceived advantage means faster adoption.

In the case of advanced trucks, the actual performance of the truck is largely the same. To the user, there may appear to be no actual relative advantage because the benefits are not things highly valued by the users. The only exception is operating costs. Saving money on operations has proven to be the one reliable driver of adoption for near-zero and zero-emission heavy-duty trucks.

6.2.2 Compatibility

Compatibility is the degree to which an innovation is perceived as being consistent with the existing values, past experiences, and needs of potential adopters.²⁹ The compatibility factor can cover many different types of similarity: value systems, ways of working, familiar devices, operational standards, and current regulations or requirements.

For advanced trucks, the "high level" compatibility issue would be the trucking business model: how do truck buyers and operators view their vehicles and their business? Most are pragmatic and bottom-line focused, so lower emissions do not directly provide benefits compatible with business motivations. A new value system could slowly be adopted over time, or ways to monetize the cost of emissions reductions created by regulation or legislation.

At a lower level, compatibility can mean fueling operations (currently based on an ambient temperature and pressure liquid fuel with short refueling times). It could mean range of operations, where current trucks can go several hundred miles before refueling. The truck designs have to be compatible with fleet operations. Requiring large changes in how the truck must be used will undoubtedly slow adoption. Each of these factors can be readily examined and the constraints defined.

6.2.3 Complexity

Complexity is the degree to which an innovation is perceived as difficult to understand and use. New ideas that are simpler to understand are adopted more rapidly than innovations that require the adopter to develop new skills and understandings.

Diesel trucks, while complex, are thoroughly understood and familiar. New technologies range in complexity, where some (e.g., fuel cells) utilize entirely new processes, fuels, fueling systems, engines/motors, configurations, and infrastructure. A battery electric vehicle would likely be seen as slightly less complex than a fuel cell range extended electric truck. A natural gas range extended electric, with an internal combustion engine would be perceived as even less complex, since it has familiar elements. Especially for maintenance personnel, these factors are important. As with other factors, the challenges can be identified and addressed without significant difficulty.

6.2.4 Trialability

Trialability is the degree to which an innovation may be experimented with on a limited basis. New ideas that can be tried on the installment plan will generally be adopted more quickly. The key here is that trial or experimentation reduces the uncertainty and risk to those considering the adoption of a technology.

Many advanced truck programs are directly addressing this area, providing the opportunity for truck operators to demonstrate the prototype vehicles. While grant-funded demonstration programs are good trials, they often have associated costs for the fleet demonstrator. Higher costs create greater risks to operators, resulting in less interest and potentially less effective outcomes.

Another challenge to trials is the level of development for the prototypes. For a truly representative trial, the new vehicle should be as reliable and durable as the final production version, so those unrelated factors do not negatively impact the assessment of the actual technology innovation. Realism or "fidelity" is important in testing new designs by way of prototype trials. The fit and finish of the trucks, the interior cab equipment, and other things not necessarily related to the technology should all be at full production levels of refinement. If the trial units are not good representatives of the final produce, the trial will not succeed in encouraging adoption.

6.2.5 Observability

Observability is the degree to which the results of an innovation are visible to others.⁸⁶ The easier it is for individuals to see the results of an innovation, the more likely they are to adopt it. In effect, this is about "buzz" or word-of-mouth. Visibility creates peer discussions, and can create clusters of adoption that expand outward from the initial adopter. This is especially true if the initial adopter is an "influencer" in the target market.

For near-zero and zero-emission trucks, this factor can take a few forms, and is often overlooked. An analogy would be how early electric cars were designed to look very different than conventional cars. It was clear and obvious that this was a new kind of car, and that elicited conversations about the technology. Even if the design was disliked, the observability was important to spreading knowledge and adoption. Similarly, advanced trucks would ideally be quite clearly different than conventional trucks. Ways of creating this differentiation can be examined, and sometimes (for large battery packs on battery electric vehicles for example) are necessary to the design. The sound of a microturbine-powered truck is another observable trait.

A different view of observability for low-emission trucks is to make tangible the emissions reduction or the operational cost savings. The lack of an exhaust stack and clouds of diesel smoke are probably the most direct examples. Cost savings are hard to make visible. Other ways to make the benefits more obvious can be examined. One area could be the desire of users to have unique designs – early adopters may want to "show off" their advanced trucks by having them look quite different. Others may not. It could be that as the trucks move further toward full commercialization, the need for distinctive design will decrease.

6.3 Phase-in Stages

This report recommends a four stage, phased commercialization approach to enable developing, launching and deploying near-zero-emission heavy-duty trucks by 2025. Each successive stage builds off the previous to develop the capability and establish the framework for advanced trucks and steer a highly focused product development process that mirrors the process used by the major manufacturers. The following section outlines the proposed stages to commercialize near-zero-emission trucks, with a target year of 2025. These stages highlight the need to bring together all stakeholders in the most effective way to achieve large-scale deployment with the following principles in mind:

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

Figure 38, below, illustrates the four stages and commercialization phases, along with their respective timeframes, action items, and outcomes.

Figure 38: Phase-in Stages for Near-zero-emission Heavy-duty Truck Commercialization

Stage I:	Stage 2:	Stage 3:	Stage 4:
Intro Phase	Developing Phase	Growth Phase	Mature Phase
Timeframe	Timeframe	Timeframe	Timeframe
2014 – 2016	2017 – 2018	2019 – 2022	2020 – 2025
Action Items - Technology expansion - Plan and develop infrastructure framework - Build new markets - Validate business and operational models Dutcomes - I to 5 pre-commercial trucks deployed in first market - Advanced development of future fleet emissions regulations	 Action Items Expand pilot projects Develop training for ZE technologies Begin backbone ZE infrastructure Advance business and operational models Finalize incentives Enhance regulations to spur adoption Outcomes 5 to 20 pre-commercial trucks deployed in first market I to 5 deployed in next market 	 Action Items Multiple fleet vehicle assessments Expand infrastructure for full roll-out Continue deployment in ancillary markets Launch ZE training Finalize regulations Outcomes Complete assessment of 20 to 50 pre-commercial trucks in first market Deploy 5 to 20 pre- commercial trucks in next market Deploy 1 – 5 in other market Establish infrastructure and begin training programs 	 Action Items Ramp up deployment by 2025 Continue infrastructure expansion Expand training and support Finalize regulations Dutcomes Annual production of up to 1,600 near-ZE heavy duty trucks Deploy sufficient infrastructure in target markets Ongoing fleet training Incentives for purchasing and leasing

Source: CALSTART

6.3.1 Stage 1: Introduction Phase

Introduction phase goals are as follows (Table 20):

- Expand technology capability beyond prototypes with targeted demonstration projects for both entire vehicle systems and enabling technology components (such as electrified steering pump, auxiliary power unit, and battery-powered heating, cooling, and ventilation).
- Plan and develop infrastructure framework including development and demonstration projects of needed infrastructure systems.
- Validate the business case and operational model, by performing detailed analyses of operational costs, residual value, and ancillary markets for near-zero-emission vehicles, non-traditional ownership models, and operations and maintenance costs.
- Build supporting markets and market structure to build near-zero-emission volumes, supply chain and infrastructure, remembering these markets can be for many classes of vehicles using similar components (vocational trucks and buses) and markets using the same trucks in other geographical regions.

Table 20: Stage 1

Timeframe	2014 to 2016
Goals	 Deployment of one to five precommercial trucks in Southern California ports or early adopter local/regional delivery fleets.
	• Development of future fleet regulations for emissions requirements by the appropriate government agency.

Source: CALSTART

6.3.2 Stage 2: Developing Phase

Development phase goals for this project are as follows (Table 21):

- Expand technology validation activities with pre-commercial pilot projects to achieve a production intent design by 2019.
- Develop advanced truck training curriculum for workforce training on zero-emission technologies and maintenance personnel training to support zero-emission technology.
- Begin development of backbone infrastructure for near-zero and zero-emission trucks. This deployment should include sufficient infrastructure to satisfy full truck operation in the targeted market(s).
- Further develop the business case and operational models for near-zero-emission trucks. In Stage 1, truck technology and capability was explored, along with pricing models. As the technology matures, the key players should develop an understanding of how the vehicles can contribute to a compelling business case.
- Finalize the incentive funding scenarios to support a wide-scale truck roll-out. To date many regional and state organizations have provided support for advanced truck purchases. In the timeframe of Stage 2, funding sources should be finalized in a way that allows the key players to plan further deployments.
- Further develop the regulatory framework to support the adoption of low-emission trucks Interest can be motivated partly by proposed or potential changes to criteria pollutant standards at the regional and federal level. As these changes become better-defined, the planning for key parties will become more focused.

Table 21: Stage 2

Timeframe	2017 to 2018
Goals	 Deployment of five to 20 precommercial trucks in Southern California ports and/or "first" early adopter local/regional delivery fleets.
	 Deployment of one to five precommercial trucks in Pacific Northwest, New York/New Jersey and/or Houston ports and/or "next" early adopter local/regional delivery fleets.

Source: CALSTART

6.3.3 Stage 3: Growth Phase

Growth phase goals for this project are as follows (Table 22):

- Multiple parallel assessments of pre-commercial near-zero-emission trucks with fleets throughout targeted market(s). This phase finalizes the data collection, user assessment, and validation of the pre-commercial vehicles.
- Begin the definition of production intent design to release commercial product offering.
- Expand installation of needed infrastructure for the full rollout of trucks in Stage 4, concurrent with the fleet use of the advanced trucks and the specific infrastructure deployed for their support.
- Deployment of additional near-zero-emission trucks in ancillary markets would continue at a supporting rate.
- Zero-emission technology maintenance training will be launched for the workforce.
- Finalize the regulatory framework based on the developments in the deployment phase (Stage 2). Once the air quality and emissions criteria drivers are finalized (both for the near term and locked in for future years), key players can finalize plans for incentive structures, expansion plans, and drivers for the business case.

Timeframe	2019 to 2022
Goals	 Complete deployment and assessment of 20—50 pre-commercial trucks in Southern California ports and/or "first" early adopter local/regional delivery fleets.
	 Deployment of five to 20 pre-commercial trucks in Pacific Northwest, New York/New Jersey and/or Houston ports and/or "next" early adopter local/regional delivery fleets.
	 Deployment of one to five pre-commercial trucks in other ports and/or additional early adopter local/regional delivery fleets.
	 Establish infrastructure deployment sites for Stage 4.
	 Train current maintenance personnel, launch workforce training for new workers.

Table 22: Stage 3

Source: CALSTART

6.3.4 Stage 4: Mature Phase

Overlapping with Stage 3 and beginning as early as 2020 for early-adopter fleets with special incentives, Stage 4 ramps up the production and deployment of commercial truck offering to fleets in the targeted market(s).

Mature phase goals are as follows (Table 23):

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

Timeframe	2020 to 2025
Goals	• Phase up production over a five-year period for an accessible market of 1,600 near-zero-emission heavy-duty trucks per year (representing 10 percent of the ultimate market for port drayage and 10 percent of the primary market for local/regional delivery).
	 Deploy sufficient infrastructure to support truck deployment as needed in their daily operation in the target market(s).
	 Stage ongoing training and support for impacted fleets.
	 Have in operation an incentives-based purchase or lease system for fleets to obtain advanced trucks for their operations (with additional incentives provided for early mover fleets in the first few years of ramp- up).
Source: CALSTART	

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

GLOSSARY

BRAKE THERMAL ENERGY (BTE) - The ratio of brake power output to power input, the product of indicated thermal efficiency and mechanical efficiency.⁵⁷

BRITISH THERMAL UNIT (Btu) – The standard measure of heat energy. It takes one Btu to raise the temperature of one pound of water by one degree Fahrenheit at sea level. MMBtu stands for one million Btu.

CALIFORNIA AIR RESOURCES BOARD (ARB) - The "clean air agency" in the government of California, whose main goals include attaining and maintaining healthy air quality; protecting the public from exposure to toxic air contaminants; and providing innovative approaches for complying with air pollution rules and regulations.

CARBON DIOXIDE (CO_2) - A colorless, odorless, non-poisonous gas that is a normal part of the air. Carbon dioxide is exhaled by humans and animals and is absorbed by green growing things and by the sea. CO2 is the greenhouse gas whose concentration is being most affected directly by human activities. CO2 also serves as the reference to compare all other greenhouse gases (see carbon dioxide equivalent).

COMPRESSED NATURAL GAS (CNG) - Natural gas that has been compressed under high pressure, typically between 2,000 and 3,600 pounds per square inch, held in a container. The gas expands when released for use as a fuel.

DIESEL GALLON-EQUIVALENT (DGE) - The amount of alternative fuel it takes to equal the energy content of one liquid gallon of diesel gasoline.

GREENHOUSE GASES (GHG) – Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), halogenated fluorocarbons (HCFCs), ozone (O3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

HIGH EFFICIENCY TRUCK USERS FORUM (HTUF) - A national program based in Michigan that works with the U.S. Army to improve the efficiency of military and commercial trucks. CALSTART connects high-efficiency vehicle technology suppliers with commercial fleets, as well as military planners at the U.S. Army's Tank Automotive Research Development and Engineering Center (TARDEC) and military customers such as U.S. Army Tank-automotive and Armaments Command (TACOM) on projects that develop and demonstrate dual-use technologies in the following areas: vehicle electrification and efficiency, connected and automated vehicle technologies and vehicle cybersecurity.⁵⁸

HORSEPOWER (HP) - A unit for measuring the rate of doing work. One horsepower equals about three-fourths of a kilowatt (745.7 watts).

⁵⁷ The National Academies Press (https://www.nap.edu)

⁵⁸ CALSTART (https://calstart.org/)

LIQUEFIED NATURAL GAS (LNG) – Natural gas that has been condensed to a liquid, typically by cryogenically cooling the gas to minus 260°F (126.7°C) (below zero).

NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION (NHTSA) – An agency of the Department of Transportation whose mission is to save lives, prevent injuries, and reduce economic costs due to road traffic crashes through education, research, safety standards, and enforcement activity.⁵⁹

NITROGEN OXIDES (OXIDES OF NITROGEN, NOx) – A general term pertaining to compounds of nitric oxide (NO), nitrogen dioxide (NO2), and other oxides of nitrogen. Nitrogen oxides are typically created during combustion processes and are major contributors to smog formation and acid deposition. NO2 is a criteria air pollutant and may result in numerous adverse health effects.

ORIGINAL EQUIPMENT MANUFACTURER (OEM) – Makes equipment or components that are then marketed by its client, another manufacturer or a reseller, usually under that reseller's own name.

TECHNOLOGY READINESS LEVEL (TRL) – A type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the project's progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest.⁶⁰

UNITED STATES ENERGY INFORMATION ADMINISTRATION (U.S. EIA) - An independent agency within the U.S. Department of Energy that develops surveys, collects energy data, and does analytical and modeling analyses of energy issues. The Agency must satisfy the requests of Congress, other elements within the Department of Energy, Federal Energy Regulatory Commission, the Executive Branch, its own independent needs, and assist the general public, or other interest groups, without taking a policy position.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (U.S. EPA) - A federal agency created in 1970 to permit coordinated governmental action for protection of the environment by systematic abatement and control of pollution through integration or research, monitoring, standards setting and enforcement activities.

⁵⁹ National Highway Traffic Safety Administration (NHTSA) (https://www.nhtsa.gov/)

⁶⁰ NASA (https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html)