CALIFORNIA ENERGY COMMISSION

Energy Research and Development Division

FINAL PROJECT REPORT

Developing, Demonstrating, and Testing Advanced Ultra-Low-Emission Natural Gas Engines in Port Yard Trucks

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PREPARED BY:

Primary Authors:

Jonathan Leonard[1]
Patrick Couch[1]
Kent Johnson, Ph.D.[2]
Thomas D. Durbin, Ph.D.[2]

[1]Gladstein, Neandross & Associates
2525 Ocean Park Blvd., Suite 200
Santa Monica, CA 90405
(949) 852-7390
www.gladstein.org

[2]UC Riverside, College of Engineering Center for Environmental Research and Technology
1084 Columbia Ave
Riverside, CA 92507
(951) 781-5791
https://www.cert.ucr.edu/emissions-and-fuels

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PREPARED FOR:
California Energy Commission

Peter Chen
Project Manager

Jonah Steinbuck, Ph.D.
Office Manager
ENERGY GENERATION RESEARCH OFFICE

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research
- Natural Gas-Related Transportation.

Development, Demonstration and Testing of Advanced Ultra-Low-Emission Natural Gas Engines in Port Yard Trucks is the final report for the Development, Demonstration and Testing of Advanced Ultra-Low-Emission Natural Gas Engines in Port Yard Trucks project (Grant Number PIR-16-016). All work was conducted by prime contractor Gladstein, Neandross & Associates and its subcontractor, the University of California, Riverside College of Engineering Center for Environmental Research & Technology. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

This project demonstrated two precommercial liquefied natural gas-powered Capacity Trucks yard tractors with low-nitrogen oxides (NO_x) 6.7-liter natural gas engines (B6.7N) from Cummins Westport Inc. at Everport Terminals in the Port of Los Angeles. Capacity Trucks previously developed liquefied natural gas tractors using the Cummins Westport Inc. 8.9-liter natural gas engine (L9N), which was primarily designed for onroad heavy-duty vehicles but determined to be oversized for yard tractors. This project demonstrated these liquefied natural gas tractors using the emerging "right-sized" B6.7N engine while comparing performance, efficiency, and emissions to an L9N-equipped tractor and a diesel tractor. University of California, Riverside engineers also developed an advanced gas composition sensor technology to measure gas quality and potentially enable automatic engine adjustments in real-time. The university tested chassis dynamometer emissions on both types of liquefied natural gas yard tractors and a baseline diesel tractor. The university also performed multiple emissions tests on the B6.7N unit with gas blends of variable composition to evaluate the potential benefits of the gas composition sensor.

Both types of liquefied natural gas tractors had lower NO_x emissions than the diesel tractor. Cummins Westport Inc. was able to certify the B6.7N engine to the most stringent 0.02 grams per brake horsepower-hour NO_x heavy-duty on-road emission level. Demonstration results corroborated that the two B6.7N-equipped tractors performed as well as the L9N-equipped yard tractors while improving fuel efficiency by 15 to 20 percent. Capacity Trucks indicates that commercialization of near-zero emission natural gas yard tractors will focus on the B6.7N rather than the larger L9N. This project has shown that liquefied natural gas yard tractors with the B6.7N can provide an operationally feasible, low NO_x alternative to diesel units for use by California marine terminal operators.

Keywords: Liquefied natural gas; near-zero-emission, CWI ISB6.7 G; CWI B6.7N; yard tractors; development and demonstration; gas composition sensor; chassis dynamometer emission testing; marine terminal operator; cargo-handling equipment.

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EXECUTIVE SUMMARY

Introduction

Yard tractors (also called yard trucks, yard hostlers, and utility tractor rigs) are leading sources of harmful emissions in cargo-handling operations at major California seaports. At the Port of Los Angeles — America's largest seaport — marine terminals operate approximately 965 yard tractors (2019 inventory), of which 82 percent (790 units) is powered by heavy-duty diesel engines. The average yard tractor age for this fleet is about 10 years, and many units are near the end of their useful life. At the adjacent Port of Long Beach, marine terminals operate approximately 580 diesel yard tractors. This combined diesel yard tractor fleet of more than 1,400 units emits large portions of the carcinogenic diesel particulate matter, oxides of nitrogen (NO_x, the primary precursor for formation of ozone), and greenhouse gases (GHGs, which cause climate change) at the San Pedro Bay Ports. Controlling these emissions from diesel yard tractors and other cargo-handling equipment is a high priority under the ports' joint Clean Air Action Plan (https://cleanairactionplan.org/). Notably, other seaports in California (for example, the Port of Oakland) also operate large fleets of diesel yard tractors and have similar plans to reduce associated harmful emissions.

In 2016, Cummins Westport Inc. (CWI) developed and certified its first advanced, ultra-low-emission heavy-duty natural gas engine. CWI certified the 8.9-liter engine (eventually rebranded as the L9N model) to 0.02 grams per brake horsepower-hour (g/bhp-hr), which is the lowest tier of the California Air Resources Board (CARB) Optional Low NO_x Standard. This tier is generally called a "near-zero emission" NO_x level because it is 90 percent below the prevailing heavy-duty engine standard. Commercialization of the Cummins near-zero emission heavy-duty natural gas engines effectively opened the door for substantial new amounts of air quality incentive funding in California and across the United States, based on the "surplus" NO_x reductions such engines deliver.

Initially, heavy-duty natural gas vehicles using the CWI 8.9-liter near-zero emission engine were employed exclusively for on-road applications (for example, Class 8 drayage trucks, refuse trucks, and urban buses). In 2017, the California Energy Commission (CEC) teamed with Port of Los Angeles and industry cosponsors to launch a major project to demonstrate 20 precommercial liquefied natural gas-fueled yard tractors built by original equipment manufacturer (OEM) Capacity Trucks and powered by the CWI 8.9-liter near-zero emission engine. Everport Terminal was selected as the host site and a project partner. This CEC-funded sister project introduced the first off-road heavy-duty vehicle application for the emerging 8.9-liter near-zero emission engine.

Notably, the 8.9-liter natural gas engine is considerably larger in size than typical 6 to 7-liter diesel engines used in yard tractor applications. By mid-2017, there was an emerging opportunity under the project described to "right-size" the natural gas engine choice for yard tractor applications. Specifically, Cummins had recently certified a new 6.7-liter natural gas engine (the ISB6.7 G) to CARB's Optional Low NO_x Standard, at the level of 0.10 g/bhp-hr (50 percent below the prevailing heavy-duty engine standard).

CapacityTrucks was one of several yard tractor OEMs considering making the ISB6.7 G engine available for its yard tractor model lineup. There were significant risks in making this market decision, particularly when Capacity Trucks was already designing and building 20 liquefied natural gas (LNG) yard tractors with L9N engines. Similarly, marine terminal operators faced risks in procuring them, because there was limited real-world operational experience using these emerging ultra-low-NO_x natural gas engines — especially for off-road applications.

Concurrently, another potential commercialization barrier was emerging for heavy-duty natural gas vehicles. Increasingly, many natural gas vehicles employed in California would be operated on renewable natural gas instead of fossil gas to realize GHG reduction benefits associated with the low carbon intensity of renewable natural gas. Renewable natural gas sourced from biogas production facilities like dairies, landfills, and anaerobic digesters may have more varied gas composition than pipeline natural gas. An emerging potential solution, already under investigation by engineers and scientists at the University of California, Riverside, was to develop and employ an advanced gas sensor technology for heavy-duty natural gas engines that can monitor fuel quality in real time. If needed, this sensor could enable real-time changes in engine operating parameters that recognize incoming poor-quality gas and mitigate negative impacts on engine performance and emissions.

Project Purpose

The purpose of this project was to (1) demonstrate and emissions-test two yard tractors equipped with the emerging ISB6.7 G natural gas engine in a typical seaport cargo handling operation, while comparing results with other yard tractor options; and (2) demonstrate and assess the efficacy of University of California, Riverside's novel sensor that can measure natural gas fuel quality and potentially enable automatic engine adjustments in real-time.

Specific goals and objectives for the project included:

- Helping to commercialize ultra-low emission yard tractor technology (transferable to other off-road applications) that uses the smallest, most efficient natural gas engine available that can meet end user needs and expectations.
- Better understanding and characterizing the relative emissions and operational performances of low NO_x natural gas yard trucks, compared to baseline diesel and electric (if available) yard trucks.
- Providing a better understanding of the potential impacts of variable-quality natural gas on the emissions and performance of heavy-duty natural gas engines, and how to enable them to compensate for poor gas quality through real-time adaptations.

Project Approach

Yard Tractor Demonstration

This project engaged a major yard tractor OEM to design and build two pre-commercial LNG yard tractors as alternatives to LNG units powered by the CWI 8.9-liter natural gas engine (L9N). The project team hypothesized that integrating the emerging "right-sized" 6.7-liter CWI natural gas engine into two precommercial yard tractors would demonstrate a more optimal fit (closer in operational feasibility and efficiency to the diesel baseline) for port operations. Moreover, the project could motivate CWI to certify the 6.7-liter natural gas engine to the same near-zero emission level already achieved for the L9N engine based on the new market demand.

A key part of the approach was to leverage the separate CEC-funded project at Everport (Port of Los Angeles) to compare the two 6.7-liter LNG units to one of the 20 8.9-liter LNG yard trucks already being designed and built by Capacity. The intent was to compare the 6.7-liter LNG units to (1) a typical "baseline" yard truck used by the same marine terminal operators (powered by a 6.7-liter Cummins diesel engine), and (2) an emerging battery-electric yard tractor that the same host site was in the process of procuring.

To help ensure "apples-to-apples" comparisons, Capacity Trucks also designed and built the two LNG yard tractors with 6.7-liter low-NO_x engines. Capacity Truck's TJ9000 yard tractor was selected for the 6.7-liter LNG units; this same model is used in the 8.9-liter LNG and 6.7-liter diesel units at Everport.

Development and Testing of Gas Composition Sensor

Another key project objective was to further advance and test a prototype natural gas fuel quality sensor developed by the University of California, Riverside. The fuel quality sensor uses a combination of thermal conductivity and predictive measurement technology to estimate gas quality for a given natural gas fuel source. The university's original approach was to continue benchtop development of the sensor, and then integrate the latest version of the technology into a suitable natural gas engine (or one of the natural gas yard trucks) for additional laboratory testing. This would be used to validate the gas composition sensor response and utility when operated on variable gas composition, as might be encountered with renewable natural gas or in the natural gas pipeline. However, discussions with Cummins engineers indicated that integrating the sensor into an engine would not be necessary to demonstrate the following key benefits of the sensor:

1. Prevent engine knock, a type of abnormal combustion caused by low quality fuel, which can impact engine life, emissions, and fuel consumption.
2. Enable documentation of engine use and fuel quality history.
3. Improve future designs based on learnings from engine use and fuel quality history.
4. Enable considerations for widening fuel quality specifications based on sensor feedback.
5. Enable considerations of hydrogen injection into the natural gas system for future infrastructure decisions.

The university refocused its efforts on improving the sensor accuracy and conducting emissions laboratory experiments to evaluate the impacts of poor fuel quality on vehicle performance.

Chassis Dynamometer Emissions Testing

To validate expected emissions reduction advantages of ultra-low-NO_x LNG yard tractors as alternatives to diesel yard tractors, the university developed a detailed emissions testing plan, and Gladstein, Neandross & Associates procured multiple yard tractors from the host site for emissions testing. One of each yard tractor type ("right-sized" 6.7-liter LNG, 8.9-liter LNG, and baseline diesel) was transported to the university's laboratories for chassis dynamometer emissions testing.

Project Results

Demonstration at Interim Host Site (CalCartage)

In May 2019, after the completed design and construction, installation and initial equipment checks, California Cartage Express (CalCartage) began a 75-day stint as the interim host site for the project. The selected permanent host site Everport was not yet prepared to operate LNG yard tractors. CalCartage's off-port container yard offered two advantages as the interim host site:

- Existing operation of 17 LNG yard tractors (older units that pre-dated emissions control technology capable of certification to CARB's Optional Low NO_x Standard)
- An existing mobile LNG station "ORCA" supplied by Applied LNG

From early May until mid-July 2019, CalCartage personnel operated the two 6.7-liter LNG yard trucks with each unit logging about 100 engine hours of operation. Early hardware problems were documented and addressed through these initial efforts. For example, LNG yard trucks require a more robust bracket assembly compared to diesel yard tractors, which have shorter muffler stacks that are less prone to top-end vibration. This required Capacity to design and fabricate replacement brackets on all LNG yard tractors being demonstrated at Everport.

A survey of CalCartage personnel reported that performance and operational characteristics of the 6.7-liter LNG yard tractors were satisfactory and met expectations. One key observation was that LNG yard tractors should be equipped with tank cages to prevent damage to the expensive onboard LNG tanks during yard operation.

Demonstration at Permanent Host Site (Everport Terminals)

In July 2019, the two 6.7-liter LNG yard tractors were moved to the permanent host site Everport Terminals (a major Port of Los Angeles marine terminal). Unlike CalCartage, Everport personnel did not have prior experience operating LNG yard tractors (or any other type of heavy-duty natural gas vehicle). The project team designed and implemented a custom LNG training and safety session for key personnel at Everport. This included hands-on training to Everport executives and management staff, union officials, tractor operators, fuelers, and mechanics.

The project team compared fuel efficiency of the yard tractors with the B6.7N engine to those with the L9N engine three ways: (1) using Everport's records on aggregate LNG gallons dispensed at the site, (2) using engineering data and opinions provided by OEMs Capacity Trucks and Cummins, and (3) using the University of California, Riverside's chassis dynamometer emissions laboratory test data. The project yielded mixed results about relative fuel economy. Data from Everport combined with engineering opinions from Capacity Trucks and Cummins corroborate that a yard tractor with the "right-sized" B6.7N provides a fuel economy advantage of roughly 15 percent to 20 percent (assuming equal driving cycles and other factors) compared yard tractors with the larger L9N. Results on the university's chassis dynamometer were less conclusive. The most important result may be that Capacity Trucks ultimately decided that the B6.7N is the more-efficient and appropriate engine choice — as well as the lower-cost engine package — should it decide to fully commercialize natural gas yard tractors.

Like their counterparts at CalCartage, Everport drivers who operated both types of LNG tractors did not generally notice – or at least were unconcerned about – any operational differences between the 6.7-liter LNG tractors versus the 8.9-liter LNG tractors. Everport drivers did not observe any key differences in the performance of LNG yard tractors with the smaller engine. This finding corroborates Capacity Truck's choice to pursue the lower cost, more-efficient B6.7N option for its potential TJ9000 LNG yard tractor commercialization.

Gas Composition Sensor Development and Benchtop Testing

The research team further developed and tested technology designed to sense the composition of natural gas and detect "out-of-specification" fuel as it flows into the engine. The university's sensor technology predicts gas quality indices for a given natural gas source.

With enhancements such as improved thermal conductivity and sound velocity measurements, the university team found that predictions of test gas methane number within 10 percent of the actual methane number can be achieved. These results were discussed with Cummins Westport Inc. and Cummins. While the results were promising, Cummins suggested that predictions within 2 percent of the actual value — and in a worst-case scenario, up to 5 percent — would be necessary for commercial application. The university team concluded that additional improvements to achieve higher accuracy will be part of future research on the sensor development. For the remainder of the project, the university refocused its efforts on improving the sensor design through an upgraded sound speed sensor and conducting emissions laboratory experiments to evaluate the impacts of poor fuel quality on vehicle performance. This work was done through chassis dynamometer emissions tests.

Chassis Dynamometer Emissions Testing at University of California, Riverside

The university team planned and conducted a suite of chassis dynamometer emissions tests on one yard tractor for each of the following three different engine-fuel types: (1) CWI L9N natural gas certified to 0.02 g/bhp-hr NO_x, (2) CWI B6.7N natural gas certified to 0.10 g/bhp-hr NO_x, and (3) Cummins QSB6.7 diesel certified to 0.2 g/bhp-hr NO_x. Each yard tractor was tested over six driving cycles, including four designed to reproduce typical yard tractor use at a major marine terminal operator.

The university's chassis dynamometer testing confirmed that NO_x emissions for natural gas yard tractors (with either the B6.7N or L9N engine) are significantly lower than those from a diesel yard tractor with a state-of-the-art diesel emissions control system.

The university also conducted specialized testing on the yard tractor with the B6.7N natural gas engine while it was fueled with natural gas of varying compositions. Results using the test parameters indicated there were no significant differences in criteria pollutant emissions or engine performance as a function of natural gas composition. This suggests that a methane index sensor may not provide emissions or performance-related benefits or both in this yard tractor application. However, the researchers found evidence suggesting that benefits could be realized for larger engines in other important heavy-duty natural gas vehicle operations (on- or off-road).

Technology/Knowledge Transfer/Market Adoption (Advancing Research to Market)

Gladstein, Neandross & Associated and the University of California, Riverside collaborated to establish a technical advisory committee consisting of a strong mix of experts and stakeholders, including the South Coast Air Quality Management District, the engine OEM (CWI), the yard tractor OEM (Capacity Trucks), the interim and permanent host sites (California Cartage and Everport), an existing end user and producer of renewable natural gas (CR&R), a member of the renewable natural gas industry (RNG Coalition), a representative of the environmental community (Natural Resources Defense Council), the nation's largest renewable natural gas provider (Clean Energy), and the local gas utility (SoCal Gas). The advisory committee provided feedback on 1) how to expedite a decision by Capacity (the preferred OEM) to design and build the two proof-of-concept 6.7L engine LNG yard tractors, and 2) how the university research team could best develop and test the gas composition sensor. Both objectives were successfully accomplished.

The project team conducted several important activities to facilitate technology and knowledge transfer, including the following:

- **2019 ACT Expo Press Event and Static Display:** One "right-sized" 6.7-liter LNG yard tractor was featured during a press conference on the floor of the 2019 ACT Expo show in Long Beach (4,000 attendees – about 25 percent of which were heavy-duty vehicle fleet representatives).
- **Presentations at Natural Gas Vehicle Technology Forum:** The project team presented details and results from this project at the February 2018 and February 2020 natural gas vehicle technology forums (hosted by the National Renewable Energy Laboratory, in conjunction with the U.S. Department of Energy, the CEC, the South Coast Air Quality Management District, NGV America, and the Southern California Gas Company).
- **Liquefied natural gas fuel tank guards and mounting brackets:** CalCartage and Gladstein, Neandross & Associates assisted Everport to design, engineer, and fabricate LNG fuel tank guards for the 22 LNG yard tractors. In addition, the team collaborated with Agility Fuel Solutions to design new, more-rugged LNG tank mounting brackets.
- **Additional technology/knowledge transfer efforts:** These include disseminating the university's emissions testing report (which ultimately became Appendices A-E for this final report) via LinkedIn and an "eblast" to Gladstein, Neandross & Associates' fleet-and-transportation-oriented database (more than 180,000 contacts); and use of the Gladstein, Neandross & Associates-University of California, Riverside collaborative "Low and Zero Emission Readiness (LAZER) Initiative" (http://www.lazerinitiative.org/) for report dissemination.

Benefits to California

This project provided valuable experience and information to help advance the development and commercialization of heavy-duty natural gas engines and vehicles for off-road applications. Specific and important ways the project has helped provide benefits to ratepayers include the following:

- For the Port of Los Angeles, replacing 10 percent of the 790 in-use diesel tractors with units powered by the Cummins Westport Inc. near-zero emission B6.7N natural gas engine would reduce an estimated 8.5 tons of NO_x and 0.14 tons of diesel particulate matter per year, for the remaining useful lives of the replaced tractors.
- The project facilitated CWI's decision to certify the B6.7N natural gas engine to the 0.02 g/bhp-hr NO_x emission standard, representing a 50 percent reduction in NO_x emission level. This lower emission calibration will apply to other vehicle applications using the B6.7N engine, including school buses, shuttle buses, and other yard tractors.
- The project corroborated the likelihood that efficiency improvements delivered by the smaller "right-sized" B6.7N natural gas engine (in a yard tractor application) can improve fuel conservation efforts for natural gas tractor fleets - and reduce their direct-vehicle GHG emissions - relative to the larger L9N engine.
- The university's emissions testing advanced the knowledge base of how natural gas engines' ultra-low certification emission values compare to their NOx and particulate matter emissions in real-world port yard tractor use. The testing provided new data documenting that near-zero emission natural gas yard tractors emit much lower NO_x than state-of-the-art diesel yard tractors. This helps clearly demonstrate to California ratepayers that development, commercialization, and wide-scale deployment of heavy-duty off-road natural gas vehicles can provide important public health benefits.
- The project has provided — and will continue to provide — valuable and needed information about ultra-low-emitting natural yard tractors for the San Pedro Bay Ports Clean Air Action Plan and ongoing efforts to assess "feasibility" of near-zero emission cargo-handling equipment.

CHAPTER 1: Introduction

Problem Statement

Limited Options for/Knowledge About Ultra-Low Emitting Off Road Engines

Yard tractors (also called yard trucks, yard hostlers, and utility tractor rigs) are leading sources of harmful emissions in cargo-handling operations at major California seaports. At America's largest seaport, the Port of Los Angeles (POLA), approximately 965 yard tractors are operational today, of which 790 (82 percent) are powered by heavy-duty diesel engines. The average yard tractor age for this fleet is about 10 years. As shown in Table 1, this diesel yard tractor fleet emits large portions of fine particulate matter (PM), carcinogenic diesel PM, oxides of nitrogen (NO_x, the primary precursor for formation of ozone), and greenhouse gases (GHGs) that cause climate change.

Table 1: Key 2019 Emissions Contributions of Diesel Yard Tractors at Port of Los Angeles

CHE Type	Fine Particulate Matter ($PM_{2.5}$ + PM_{10})	Diesel Particulate Matter	Oxides of Nitrogen	Greenhouse Gases (CO_2 equivalents)
Diesel Yard Tractor Fleet (790 Units)	2.6	1.4	93.9	77,975
Total Diesel CHE Fleet (1,359 Units)	12.9	5.0	410.4	177,264
Contribution of Diesel Yard Tractors	~20%	~28%	~23%	~44%

Notes: Estimated emissions are for 2019, expressed in tons except greenhouse gases, which are reported as "carbon dioxide equivalents" (CO2e) in metric tons. CO2e emissions are those emitted at POLA tenant sites; they do not include upstream (full-fuel-cycle) GHG emissions.

This table shows that POLA's large diesel-fueled yard tractor fleet (790 units) contributes major percentages of the Port's air inventories for three key types of direct-vehicle emissions: diesel particulate matter, oxides of nitrogen, and greenhouse gases (reported as carbon dioxide equivalents, or CO2e).

Source: *Port of Los Angeles Inventory of Air Emissions - 2019*, *Technical Report APP# 191122-551 A,* September 2020, prepared by Starcrest Consulting Group, LLC, https://kentico.portoflosangeles.org/getmedia/4696ff1a-a441-4ee8-95ad-abe1d4cddf5e/2019_Air_Emissions_Inventory.

POLA is the largest seaport in America for cargo throughput. The Port of Long Beach (POLB) is immediately adjacent to POLA. Marine terminals at POLB operate an estimated 570 diesel yard tractors (about 72 percent of POLA's diesel yard tractor fleet). Roughly, this fleet emits 50 to 60 percent as much DPM, NO_x and CO_2e as the POLA diesel fleet.[1] Under the umbrella of their joint *San Pedro Bay Ports Clean Air Action Plan*, the two ports are working together to demonstrate and test emerging low- and zero-emission yard tractor technologies with potential to replace their combined inventory of nearly 1,400 diesel yard tractors. While each marine terminal is unique, yard tractors are used in very similar ways and duty cycles at the two ports. Any yard tractor fuel-technology platform that works well at POLA terminals is likely to also work well at POLB terminals.

In 2018, the two San Pedro Bay Ports prepared a joint "feasibility assessment" of low- and zero-emission cargo-handling equipment (CHE). In that report, the ports found natural gas (and battery electric) yard tractors to have good feasibility for near-term wide-scale use at POLA and POLB marine terminals. However, the Ports also found that even these two emerging clean yard tractor technologies lacked any significant demonstration time in real-world use at a major marine terminal. They concluded that marine terminal operators (MTOs) require extensive hands-on experience with pre-commercial natural gas and battery-electric yard tractors, before wide-scale commercialization and deployment was likely to occur at either POLA or POLB.[2]

Emergence of Near-Zero-Emission Heavy-Duty Natural Gas Engines

In 2016, Cummins Westport Inc. (CWI) – a joint venture between Cummins Inc. and Westport Innovations – developed and certified its first advanced, ultra-low-emission heavy-duty natural gas engine. CWI certified this 8.9L engine (later rebranded to the L9N) to the California Air Resources Board's (CARB's) Optional Low NO_x Standard (OLNS), at the lowest tier level of 0.02 grams per brake horsepower-hour (g/bhp-hr). This NO_x level – which has become informally but widely known as "near zero emission" (NZE) – is 90 percent below the prevailing heavy-duty engine standard of 0.20 g/bhp-hr. CWI's achievement of NZE heavy-duty natural gas engines effectively opened the door for significant new amounts of air quality incentive funding in California and across the U.S., based on the "surplus" NO_x reductions such engines deliver.

Initially upon its commercial entry in 2016, all heavy-duty vehicles using CWI's 8.9L NZE natural gas engine were for on-road applications (primarily Class 8 drayage trucks, refuse trucks, and urban buses). In 2017, the California Energy Commission (CEC) teamed with the Port of Los Angeles and industry co-sponsors to initiate the Advanced Yard Tractor Deployment and Eco-FRATIS Drayage Truck Efficiency Project (ARV-15-069) to demonstrate 20 LNG-fueled yard tractors powered by CWI's 8.9L NZE engine. This sister project introduced the first *off-road* HDV application for CWI's emerging 8.9L NZE engine.

[1] Port of Long Beach, *Port of Long Beach 2020 Air Emissions Inventory*, September 2020, Prepared by Starcrest Consulting Group, LLC.

[2] San Pedro Bay Ports, *2018 Feasibility Assessment for Cargo-Handling Equipment*, August 2019, https://cleanairactionplan.org/documents/draft-2018-feasibility-assessment-for-cargo-handling-equipment.pdf/.

Notably, an 8.9-liter engine is significantly larger in displacement (and power) than diesel engines used in yard tractor applications, which typically have 6 to 7 liters of displacement. By mid-2017, there was an emerging opportunity under the project described in this report to "right-size" the natural gas engine choice for yard tractor applications. Specifically, CWI had recently certified a new 6.7L natural gas engine (the ISB6.7 G)[3] to CARB's OLNS, at the level of 0.10 g/bhp-hr (50 percent below the prevailing heavy-duty engine standard of 0.20 g/bhp-hr). Initially, the ISB6.7 G was primarily designed for on-road HDV applications, such as school buses, medium-duty trucks and return-to-base vocational vehicles. However, yard tractor original equipment manufacturers (OEMs) like Capacity were considering making the ISB6.7 G available as a special-order-only option for their yard tractor model lineups. Meanwhile, the paucity of real-world operational experience and in-use emissions testing on HDVs using these emerging ultra-low-NO_x natural gas engines – especially for off-road applications – presented a significant barrier to full commercialization.

Poor Gas Composition as Potential Hinderance to Wider Natural Gas Vehicle Use

An important issue potentially impeding expanded use of ultra-low-emission heavy-duty natural gas vehicles (NGVs) relates to possible negative impacts of variable gas composition on emissions and/or performance. In particular, as this project was being developed, there was concern that renewable natural gas (RNG) composition may vary more than traditional pipeline natural gas, which in itself can have variable composition. There was concern that RNG produced at the site of biogas generation (for example, a landfill-based fueling station) might have significant concentrations of diluents in the fuel supply, which in particular could negatively impact heavy-duty NGVs equipped with emerging NZE engines.

In California, RNG quality has been fairly well controlled. However, the lack of consistent fuel quality in other U.S. regions (and in other parts of the world) remains a potential barrier to widen the marketplace for heavy-duty NGVs and reduce capital costs. Even in California – where fuel quality is more stringently controlled – RNG of variable quality could potentially be directly dispensed into heavy-duty NGVs domiciled near the site of RNG production.

Meanwhile, over the last several years RNG has been emerging as the dominant form of natural gas used in California NGVs. This is because the strong market pull of California's Low Carbon Fuel Standard (LCFS) has facilitated growing volumes of RNG with progressively lower carbon intensity (CI) ratings to replace fossil natural gas. In fact, over the last year, significant volumes of super-negative-CI RNG (produced from dairy waste) have become available to fleets. As these volumes have increased, the average CI rating of RNG used in California has dropped to well below zero (as of Q3 2020). Consequently, RNG is in strong demand from heavy-duty NGV fleets (on- or off-road) to replace fossil natural gas, as it provides full-fuel-

[3] In mid-2019, Cummins Westport reported that the ISB6.7 G engine was "no longer available" and had "been replaced by the B6.7N." The key difference appears to be that the B6.7N is officially listed as being "certified to (CARB's) Optional Low NO_x Standard of 0.02 g/bhp-hr." In this report and project, "ISB6.7G" and B6.7N are used interchangeably for this engine. For details about specifications for the B6.7N, see https://www.cumminswestport.com/models/b6.7n.

cycle GHG reductions exceeding 100 percent.[4] This has increased the stakes of this issue of variable fuel quality, if in fact RNG is more prone to having diluents.

At the University of California, Riverside College of Engineering Center for Environmental Research and Technology (UCR CE-CERT; abbreviated to UCR in this report), a team of scientists and engineers were exploring potential solutions for mitigating impacts of variable gas quality on the emissions and/or performance of heavy-duty NGS. For this project, they proposed to further develop test engine sensor technology that could potentially detect out-of-specification fuel quality and enable real-time engine corrections.

Project Purpose, Goals and Objectives

There were two overarching purposes of this project:

1. To demonstrate and emissions test two yard tractors powered with CWI's emerging 6.7L low-NO_x heavy-duty engine, in a typical seaport cargo handling operation, while making comparisons to yard tractors powered by 1) CWI's larger (8.9-liter) L9N low-NO_x natural gas engine, 2) a state-of-the-art diesel engine, and 3) a battery-electric system.
2. To demonstrate and assess the efficacy of UCR's novel sensor that can measure natural gas fuel quality and potentially enable automatic engine adjustments in real-time.

Specific goals and objectives for the project included the following:

- Help commercialize ultra-low emission yard tractor technology (transferable to other off-road applications) that utilizes the smallest, most-efficient natural gas engine available that can meet end user needs and expectations.
- Better characterize and understand the relative emissions and operational performances of low NO_x natural gas yard trucks, compared to baseline diesel and electric (if available) yard trucks.
- Provide a better understanding of the potential impacts of variable-quality natural gas on the emissions and performance of heavy-duty natural gas engines, and how to enable them to compensate for poor gas quality through real-time adaptations.

Technical Advisory Committee

GNA and UCR collaborated to establish the technical advisory committee (TAC) in Q4 of 2017 (Table 2). Collectively, TAC members represented a strong mix of experts and stakeholders, including the local air quality district (SCAQMD), the engine OEM (CWI), the yard tractor OEM (Capacity), the interim and permanent host sites (California Cartage and Everport), an existing end user and producer of RNG (CR&R), a member of the RNG industry (RNG Coalition), a representative of the environmental community (Natural Resources Defense Council), the nation's largest RNG provider (Clean Energy), and the local gas utility (SoCal Gas).

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[4] According to data provided by CARB's Low Carbon Fuel Standard "Dashboard" web page https://ww3.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm, the volume-weighted average carbon intensity rating for Bio-CNG and Bio-LNG in 2019 was ~35 gCO2e/MJ and ~60 gCO2e/MJ respectively, compared to fossil diesel at about 90 gCO2e/MJ.

Table 2: Organizations Represented on Technical Advisory Committee

Organization / Agency / Company	Role / Representing
South Coast AQMD - TAO	Government – Local
National Renewable Energy Lab	Government – Federal
Port of Los Angeles	Port Authority / Landlord
Pacific Merchant Shipping Association (PMSA)	Trade Org for MTOs
EverPort Terminal Services	End Users
California Cartage	
Cummins Westport, Inc.	Engine OEMs
Cummins Engine Company	
Clean Energy / CNGVP	RNG Provider / Trade Org
SoCal Gas	Local Gas Utility
Renewable Natural Gas Coalition	RNG Expert / Trade Org
California Energy Commission	Project Funder / Oversight
Gladstein, Neandross & Associates	Prime Contractor
UC-Riverside CE-CERT	Subcontractor

Source: Gladstein, Neandross & Associates

Early in the project, a TAC meeting was conducted to get TAC feedback about 1) how to expedite a decision by Capacity (the preferred OEM) to design and build the two proof-of-concept 6.7L engine LNG yard tractors, and 2) how the UCR team could best develop and test the gas composition sensor. Both objectives were successfully accomplished.

Coordination of Fuel, Engine, and Vehicle Vendors

The full project entailed coordinating a wide array of vendors. Table 3 summarizes the project's key fuel, engine, and vehicle vendors and their respective roles.

Table 3: Key Vendor Coordination Activities for the Project

Vendor Name	Vendor / Product Type	Project Role
Capacity	OEM for LNG yard tractors	Designed and built two pre-commercial LNG yard tractors with low-NO_x CWI 6.7 engines
Cummins / CWI	OEM for low-NO_x LNG engines	Provided project support to address engine-related issues, conduct emissions testing, and support advancement of gas composition sensor
Agility Fuel Solutions	LNG fuel system conversions	Conducted final LNG fuel system building and checkout for Capacity
Harbor Diesel	HDV service / maintenance	Performed scheduled and unscheduled maintenance / warranty repairs on yard tractors
AirGas	Specialty gas provider	Prepared gas blends used for emissions testing
Misc. truck transport co.	HDV / equipment transporter	Transported yard tractors for testing
Ugly Brothers LLC	LNG fuel system repairs	Trouble shot and repaired LNG regulator issue during UCR emissions testing

Source: Gladstein, Neandross & Associates

CHAPTER 2: Project Approach

Demonstration of Two "Right-Sized" Liquefied Natural Gas Yard Tractors

GNA's approach for this portion of the project consisted of the following two major components:

- Secure a commitment from, and establish a memorandum of understanding (MOU) with, a mainstream yard tractor manufacturer (the first choice being Capacity) to design, engineer, build and field-support two first-of-their-kind LNG yard trucks powered by CWI's ISB6.7 G engine (later rebranded to the B6.7N), certified to CARB's Optional Low NO_x Standard of 0.10 g/bhp-hr; and
- Secure a commitment from, and establish an MOU with, a MTO to demonstrate the two units in cargo-handling operations at the Port of Los Angeles (the first choice being Everport Terminals, Inc.), while making meaningful comparisons as described below.

The specific project intent was to affect the design and build of these two pre-commercial LNG yard tractors *as alternatives to LNG units powered by CWI's larger 8.9L natural gas engine* (now called the L9N). Yard tractors are typically powered by diesel engines with approximately seven liters of displacement. With 8.9 liters of displacement, the L9N was not a natural fit for use in yard tractor applications. The GNA-UCR project team hypothesized that building and deploying two pre-commercial yard tractors powered by CWI's emerging smaller 6.7L natural gas engine would give opportunity to prove this "right-sized" LNG yard tractor would provide a better fit (i.e., closer in operational feasibility and efficiency to the diesel baseline) for MTO operations. Moreover, the project could help convince CWI to also certify the 6.7L natural gas engine to the NZE level.

With the benefit of CEC funding under PIR-16-016, the two 6.7L LNG units could be built and compared to the 20 8.9L LNG yard trucks – already being designed and built by Capacity for deployment at Everport – in side-by-side field testing. Moreover, comparisons could be made to 1) typical "baseline" yard trucks used by the same MTO (powered by 6.7L Cummins diesel engines), and 2) emerging battery-electric yard tractors that the same host site was in the process of procuring.

Capacity was selected as the preferred vendor to design and build the two NG yard tractors with 6.7L low-NO_x engines. There were two key delays in getting Capacity under agreement to actually design, build and ship these two proof-of-feasibility yard tractors. First, there was emerging uncertainty among OEMs and end users that California would allow future use of cargo-handling equipment unless equipped with a zero-emission (ZE) architecture. Consequently, Capacity required significant additional convincing to ultimately decide to design and build the two pre-commercial LNG yard tractors with ISB6.7L engines. Second, Everport's planned LNG station for its 20 LNG tractor fleet was significantly behind schedule to be built, installed and permitted. This put into doubt whether the MTO would benefit from deploying two additional LNG yard tractors (the two with ISB6.7 G engines). Fortunately, both issues were resolved (with help from stakeholders on the TAC, such as representatives from the Port of Los Angeles). By April 2019, Capacity had completed its design, build and shipping of the two units.

Development and Testing of Gas Composition Sensor

For this key element of the project, the objective was to further develop and test a prototype natural gas fuel quality sensor that a team at UCR was developing. UCR's fuel quality sensor uses a combination of thermal conductivity and predictive measurement technology to interpolate Methane Index (MI)/methane number (MN), and Wobbe Index (WI) for a given natural gas fuel source. The fuel sensor itself is non-invasive, rugged, and compact and can overcome limitations such as the bulkiness and intrusive nature of conventional WI measurement technologies. The sensor design seeks to enable accurate on-board detection of fuel properties, and through integration with an adaptive engine control system, allow for real-time engine adjustments that help control and improve combustion.

UCR's approach was to continue benchtop development of the sensor, and then integrate the latest version of the technology into a suitable natural gas engine (or one of the natural gas yard trucks) for additional laboratory testing. This would be used to validate the gas composition sensor response and utility when operated on variable gas composition, as might be encountered with RNG and/or in the natural gas pipeline. As further described in this report, the original approach was modified as the project progressed with regard to 1) procuring gas blends of varying composition for testing the sensor response, and 2) actual testing of the sensor at the UCR laboratory.

Implementation of Chassis Dynamometer Emissions Testing

Another critical project objective was to corroborate expected emissions-reduction advantages of deploying ultra-low-NO_x natural gas yard tractors as alternatives to diesel yard tractors. UCR developed a detailed emissions testing plan, and GNA procured multiple yard tractors from the host site for emissions testing – including one "right-sized" LNG yard tractors with CWI's 6.7L engine. Using special "low-boy" trailers that can accommodate the weight, size and height of yard tractors, one of each yard tractor type (6.7L LNG, 8.9L LNG, and baseline diesel) was transported to UCR's laboratories in Riverside for a full suite of chassis dynamometer emissions testing. Further details for the actual yard tractors that were procured and tested – and the results of all tests – are provided below and in UCR's detailed emissions testing report (Appendix A) and related testing documentation (Appendices B-E).

CHAPTER 3: Project Results

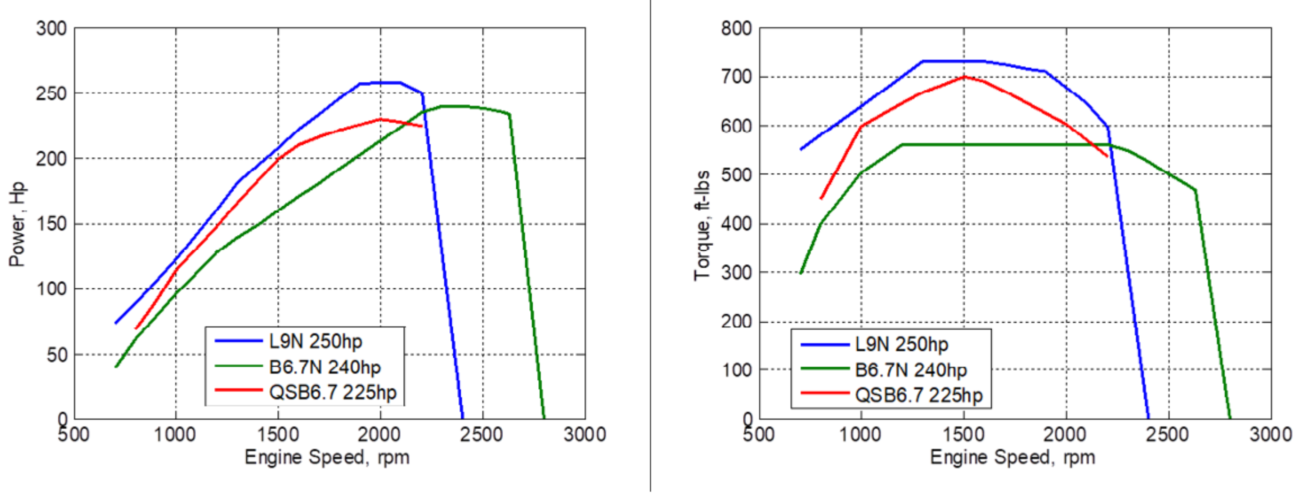
Final Set Up of Yard Tractor Demonstration

Matrix of Test Vehicles

Table 4 summarizes the yard tractor types that were ultimately compared in revenue service. All were Capacity TJ9000 4X2 On-Road models. As shown, there were two LNG yard tractors with B6.7N engines, one LNG yard tractor with an L9N engine, and one with a "baseline" Cummins 6.7L diesel engine (the QSB6.7).

Figure 1 compares performance curves for these three engine types. As shown, the CWI B6.7N natural gas engine provides lower peak power and torque than the larger CWI L9N natural gas engine and is closer in performance to the baseline Cummins QSB6.7 diesel engine. In fact, the B6.7N (originally called the ISB6.7 G) was based on the Cummins ISB6.7 diesel engine platform. Cummins re-designed the ISB6.7 diesel engine into the B6.7N as a dedicated spark ignition natural gas engine. The B6.7N can use either CNG or LNG as the on-board storage form of the fuel. The source of the natural gas for either fuel type can be pipeline biomethane upgraded to renewable natural gas (RNG), as long as the gas meets Cummins' / CWI's specifications for quality, including a methane number of at least 75.[5]

Figure 1: Comparison of Performance Curves for Field Demonstration Engines



L9N = CWI 8.9L natural gas engine **B6.7N = CWI 6.7L natural gas engine** **QSB6.7 = Cummins 6.7L diesel engine**

Performance curves showing horsepower (left) and torque (right) for the three test engines help make it clear that CWI's B6.7N natural gas engine (green curves) is closer in performance to the baseline Cummins QSB6.7 diesel engine (red curves) than to the CWI L9N engine (blue curves).

Source: Cummins, Inc personal communication to GNA, January 2021.

[5] See Cummins Westport's "Natural Gas as Fuel: Fuel Quality Calculator," https://www.cumminswestport.com/fuel-quality-calculator.

Table 4: Key Parameters for Four Yard Tractors Compared at Everport

Parameter	LNG 6.7L #1	LNG 6.7L #2	LNG 8.9L #1	Diesel Control #1
Yard (Truck) Tractor Manufacturer (Make)	Capacity	Capacity	Capacity	Capacity
Tractor Model	TJ9000 4X2 On-Road	TJ9000 4X2 On-Road	TJ9000 4X2 On-Road	TJ9000 4X2 On-Road
Model Year (Chassis / Engine)	2018 / 2018	2018 / 2018	2017 / 2018	2015 / 2014
Engine Displacement / # of Cylinders	6.7 liters / 6	6.7 liters / 6	8.9 liters / 6	6.7 liters / 6
Tractor Date of Manufacture	April 2019	April 2019	April 2019	November 2014
Shipping Weight (lbs)	15,000	15,000	Unknown	~14,000
Vehicle Identification Number (VIN)	4LMPJ2117JL027483	4LMPJ2115JL027482	4LMPJ2117HL026778	4LMPB2115FL025462
Gross Vehicle Weight Rating (lbs)	36,000	36,000	36,000	36,000
Gross Axle Weight Rating (lbs, Front / Rear)	16,000 / 70,000	16,000 / 70,000	16,000 / 70,000	16,000 / 70,000
Transmission	Allison RDS 3500	Allison RDS 3500	Allison RDS 3500	Allison RDS 3500
Engine Model #	Cummins B6.7N CM2380 B150B	Cummins B6.7N CM2380 B150B	Cummins L9N CM2380 L124B	Cummins QSB6.7 CM2350 B105
Engine Serial #	74425482	74428241	74319327	73760180
Engine Family #	JCEXH0408BBB	JCEXH0408BBB	JCEXH0540LBL	ECEXL06.7AAK
Engine CARB Executive Order	A-021-0678	A-021-0678	A-021-0681	U-R-002-0601-1
Engine Type/Key Emission Control Features	SI Engine w/ EGR, 3-Way Catalyst, Heated O2 Sensor	SI Engine w/ EGR, 3-Way Catalyst, Heated O2 Sensor	SI Engine w/ EGR, 3-Way Catalyst, Heated O2 Sensor	CI Engine w/ EGR, Diesel Oxy Cat, SCR
Detailed Emissions Control System Features	TBI, TC, CAC,ECM, EGR, TWC, H02S	TBI, TC, CAC,ECM, EGR, TWC, H02S	TBI, TC, CAC,ECM, EGR, TWC, H02S	EDI, TC, CAC, ECM, EGR, DOC, SCR
Engine Dry Weight (Lbs)	1150	1150	1625	1150
Maximum HP/Peak Torque @ Engine Speed	240 HP/560 lb-ft @ 1600 rpm	240 HP/560 lb-ft @ 1600 rpm	250 HP/730 lb-ft @ 1300 rpm	225 HP/660 lb-ft @ 1600 rpm

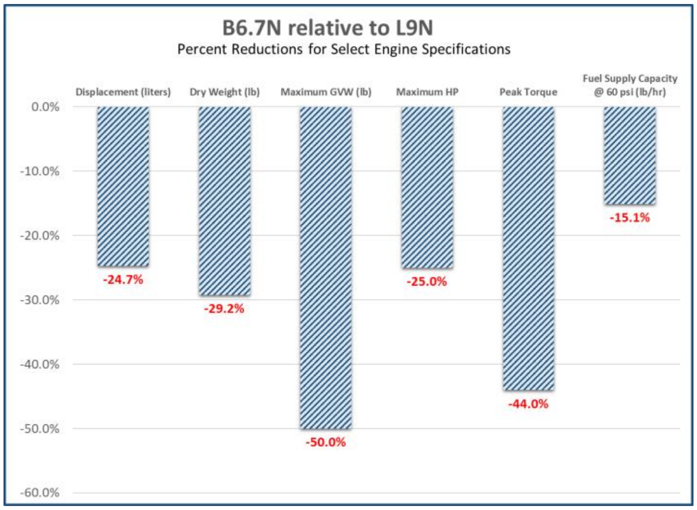
Parameter	LNG 6.7L #1	LNG 6.7L #2	LNG 8.9L #1	Diesel Control #1
Everport Terminals Internal Number	LN0341	LN0342	LN0323	YT0310
Fuel/Onboard Storage Type & Capacity	Natural Gas/127 LNG gal	Natural Gas/127 LNG gal	Natural Gas/127 LNG gal	Ultra-Low Sulfur Diesel/50 diesel gal
Emissions Certification Standard Met	0.1 g/bhp-hr OLNS	0.1 g/bhp-hr OLNS	0.02 g/bhp-hr OLNS	~0.3 g/bhp-hr (Tier 4 Final)

Source: Information gathered by GNA from Capacity Trucks, Everport and Cummins Westport, Inc.

Additional Performance Metrics for LNG Yard Tractors

As Figure 2 demonstrates, multiple engine parameters and specifications make it reasonable to hypothesize that CWI's B6.7N natural gas engine will be more fuel efficient its L9N natural gas engine – in any application for which it is operationally suited.

Figure 2: Comparison of B6.7N Engine to L9N for Select Specifications



Comparison of CWI B6.7N natural gas engine to the CWI L9N engine for displacement, weight, maximum gross vehicle weight, horsepower, torque and fuel supply capacity

Source: Cummins Engine Company, https://mart.cummins.com/imagelibrary/data/assetfiles/0063969.pdf (except fuel supply capacity, which was provided by Cummins to Capacity Trucks, then to GNA)

As this graph shows, relative to the L9N, the B6.7N is rated at lower horsepower and torque (-25 percent and 44 percent, respectively) and significantly smaller in displacement (-24 percent) and dry weight (-29 percent). Moreover, the fuel supply capacity for the B6.7N is about 15 percent reduced compared to the L9N.

However, prior to this project the relative efficiencies of these two ultra-low-emission natural gas engines had not been demonstrated or measured in actual yard tractor use at a major seaport terminal. A key project goal was to corroborate and quantify this advantage through testing, and also document relevant engineering opinions of the engine and yard tractor manufacturers.

Emissions Controls and Certifications for Low-NO_x Natural Gas Engines

The ISB6.7 G (now the B6.7N) followed on to the L9N as CWI's second engine to receive CARB's OLNS certification.[6] Notably, the CEC provided partial funding for CWI to achieve this milestone, under a separate project in conjunction with the Gas Technology Institute and CWI.

[6] Cummins Westport, *ISB6.7 G Mid-Range Natural Gas Engine Now in Full Production - Low Emission Engine Expands to Shuttle Bus, Medium-Duty Truck, and Vocational Segments*. Press release, December 8, 2016, https://www.cumminswestport.com/press-releases/2016/isb6.7-g-midrange-natural-gas-engine-now-in-full-production-low-emission-engine-expands-to-shuttle-bus-medium-duty-truck-and-vocational-segments.

Details are provided in the final report for that project, PIR-15-008.[7] As originally certified, NO_x emissions of the ISB6.7 G were 0.10 grams per brake horsepower-hour (g/bhp-hr), which is 50 percent lower than the current heavy-duty on-road engine NO_x standard of 0.20 g/bhp-hr. By contrast, CWI had already certified NO_x emissions of the larger L9N engine to 0.02 g/bhp-hr (90 percent lower than the current NO_x standard). Both engines were certified below the 2010 EPA standard for particulate matter (0.01 g/bhp-hr) and 2017 EPA greenhouse gas (GHG) emission requirements. As noted above, the fact that the L9N had already achieved this "near-zero-emission" (NZE) NO_x level was a key reason why the L9N – and not the B6.7N – was chosen by Capacity and the Port of Los Angeles for development and demonstration of 20 LNG yard tractors at Everport Terminals, under the CEC-funded Advanced Yard Tractor Deployment and Eco-FRATIS Drayage Truck Efficiency Project (ARV-15-069).

CWI designed both of these landmark natural gas engines to use spark-ignited, stoichiometric combustion with cooled exhaust gas recirculation (SEGR) technology; together, this combination of engine design and advanced aftertreatment enables them to achieve very low NO_x emission levels. Both engines feature electronic control with programmable features, a closed crankcase ventilation system, and maintenance-free three-way catalyst aftertreatment. By contrast, the diesel control yard tractor's QSB6.7 engine uses a diesel particulate filter and selective catalytic reduction (SCR) aftertreatment is required. Additional details are provided in the respective Executive Orders from the California Air Resources Board for these three engines.[8]

Final Demonstration Test Plan

The demonstration plan called for the four test vehicles to be operated and compared over six months (or more) of revenue service. The demonstration plan also called for comparison to a battery-electric yard tractor, if available. However, that was ultimately not possible, because the five battery-electric yard tractors that were delivered to the host site were not significantly operated in revenue service during the term of PIR-16-016. GNA prepared new forms for host site personnel to provide qualitative and quantitative evaluations of the two LNG yard tractor types (6.7L and 8.9L engine models) versus the baseline diesel tractor. Later, project evaluation forms were harmonized with those being used under the sister project at Everport to demonstrate 20 Capacity TJ9000 LNG yard tractors with L9N engines. This avoided the potential to confuse host site personnel with two different forms that essentially requested the same information.

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[7] Ptucha, Stephen (Cummins Westport Inc.) and Ted Barnes (Gas Technology Institute). 2020. *Development, Integration, and Demonstration of 6.7-Liter Natural Gas Engine in Medium-Size Heavy-Duty Vehicles*. California Energy Commission. Publication Number: CEC-500-2020-004. https://ww2.energy.ca.gov/2020publications/CEC-500-2020-004/CEC-500-2020-004.pdf

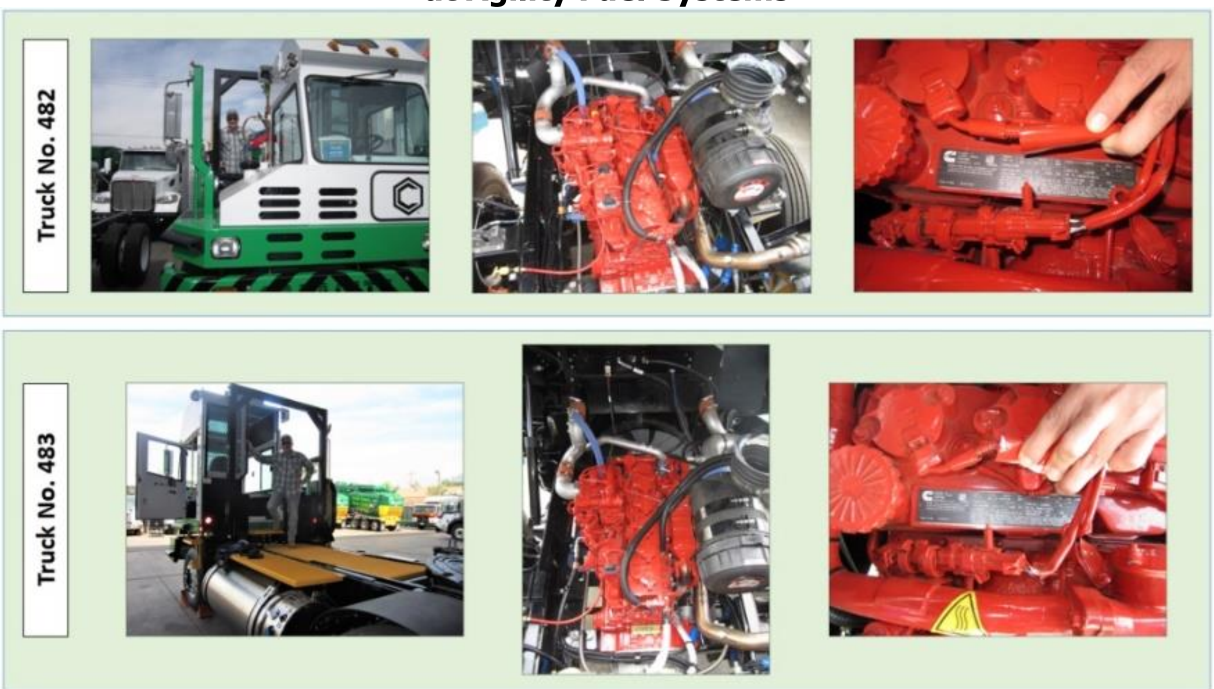
[8] California Air Resources Board. Executive Orders for MY2018 B6.7N, MY2018 L9N, and MY2014 QSB6.7. https://ww2.arb.ca.gov/sites/default/files/classic//msprog/onroad/cert/mdehdehdv/2018/cummins_mhdd_a0210678_6d7_0d10_ng.pdf, https://ww2.arb.ca.gov/sites/default/files/classic//msprog/onroad/cert/mdehdehdv/2018/cummins_mhdd_a0210681_8d9_0d02_ng.pdf, https://ww2.arb.ca.gov/sites/default/files/classic//msprog/offroad/cert/eo/2014/ofci/u-r-002-0601-1.pdf.

Demonstration Training, Deployment and Surveying

Initial Check Out at Agility Fuel Systems for Fuel System Integration

In early 2019, Capacity completed designing and building the two proof-of-concept LNG yard tractors with B6.7N engines. In April 2019, Capacity delivered both units to Agility Fuel Systems for final fuel system design, installation and check-out testing. The GNA-UCR team performed initial equipment checks on both units at Agility Fuel Solutions during the first week of May 2019 (Figure 3).

Figure 3: Initial Check Out of 6.7L Liquefied Natural Gas Yard Tractors at Agility Fuel Systems



These photos show initial check out of the two proof-of-feasibility Capacity yard tractors with CWI's 6.7L natural gas engine (B6.7N).

Photo Credits: Jon Leonard, GNA

Also at Agility, the GNA-UCR team configured "Portable Activity Monitoring System" (PAMS) dataloggers for both LNG yard tractors, to prepare for their subsequent installation in each tractor at the interim host site.

In parallel with checkout testing at Agility, GNA and Agility collaborated to plan and implement static display of one TJ9000 LNG yard tractor with the B6.7N engine at the ACT Expo conference in late April 2019. GNA planned and implemented a press event on the floor of ACT Expo, to announce the project and draw attention about the LNG yard tractor to attendees representing marine terminal fleets. Further details and photographs about the press event at ACT Expo are provided in CHAPTER 4:
Technology/Knowledge Transfer Activities.

Preparation and Training at CalCartage (Interim Host Site)

CalCartage Host Site Preparation

In May 2019, GNA executed a memorandum of understanding (MOU) with California Cartage Express (CalCartage) to serve as the project's interim host site. Use of an interim host site was necessary because the selected permanent host site Everport – a major marine terminal at the Port of Los Angeles (POLA) – was not yet prepared to operate LNG yard tractors due to delays in permitting an LNG station.

CalCartage's yard (2401 Pacific Coast Highway, Wilmington, California, [Figure 4]) was a well-suited choice to serve as an initial test site for moving containers in a port-like duty cycle, until the permanent host site was ready to receive the two proof-of-concept yard tractors.

Figure 4: CalCartage Container Yard in Wilmington, California

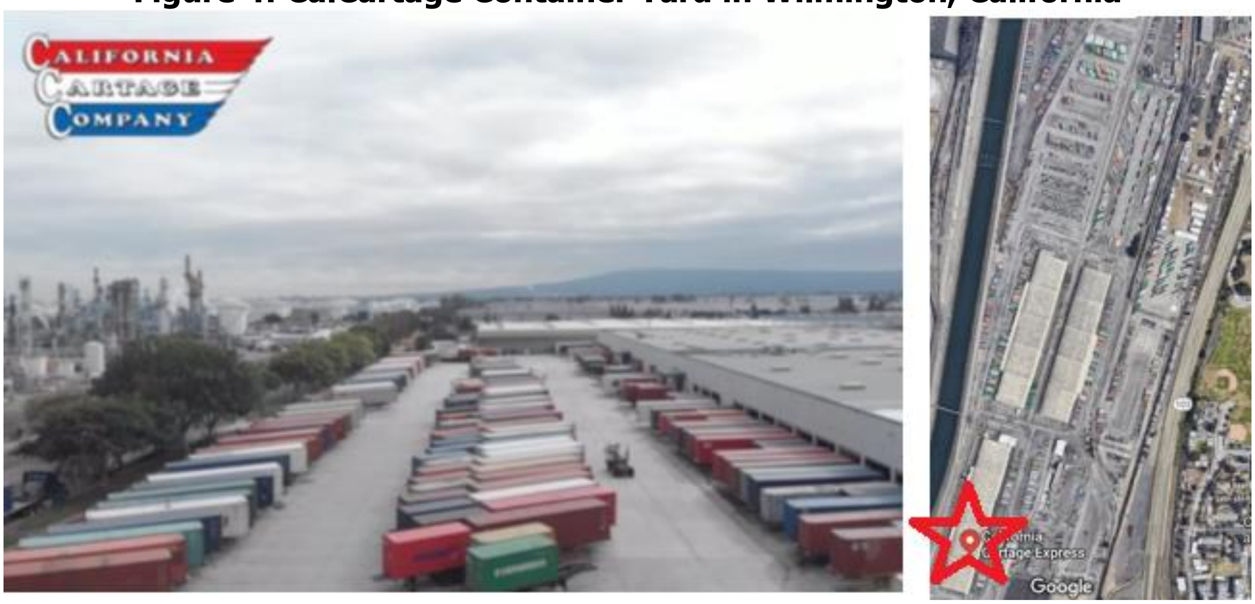


Photo Credits: CalCartage (left), Google Maps (right)

Specifically, CalCartage's off-port container yard offered the following advantages as the interim host site:

- Already operated 17 LNG yard tractors (older units that pre-dated emissions control technology capable of certification to CARB's OLNS).
- Had an existing mobile LNG station "ORCA" supplied by Applied LNG.
- Included site managers and drivers who were ready, willing and able to operate the two 6.7L LNG units in revenue service.

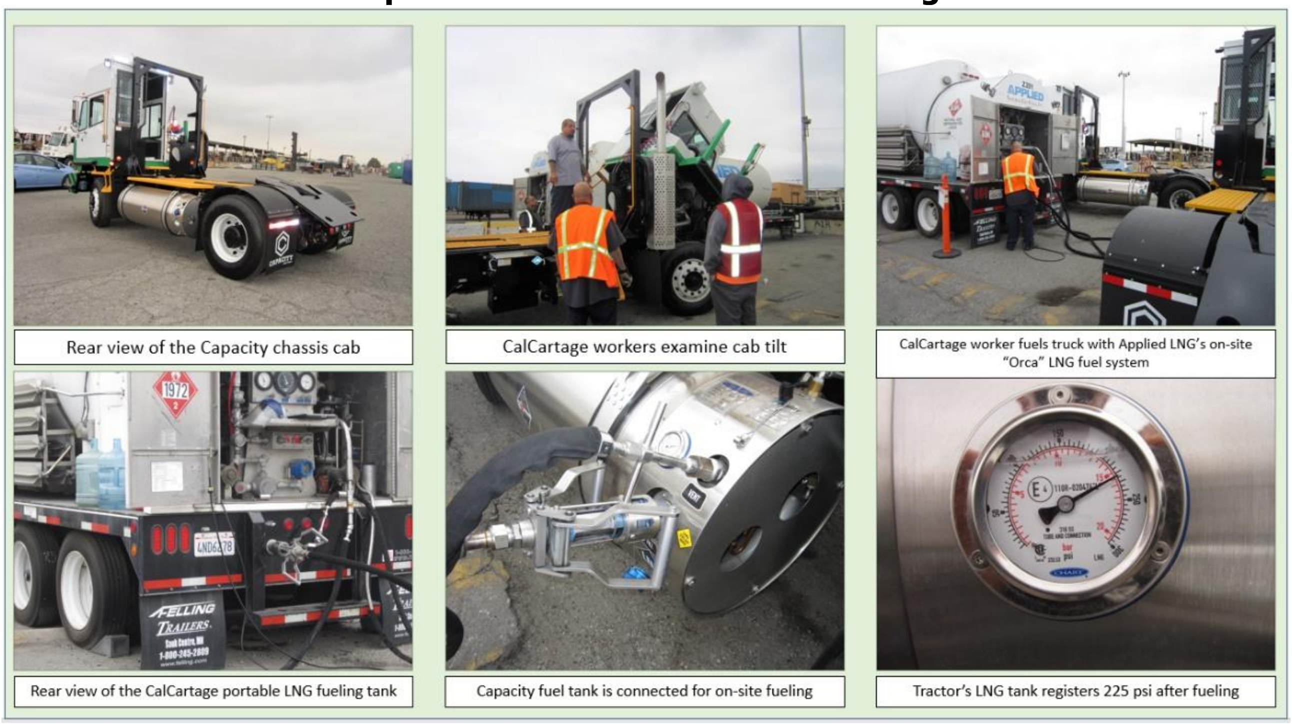
Notably, the CalCartage yard was scheduled to close permanently by late July 2019. Consequently, the site was being decommissioned during the relatively brief period (about 75 days) that the two 6.7L LNG units were undergoing initial proof-of-feasibility testing at CalCartage. In essence, CalCartage management provided a major in-kind contribution to the project. Specifically, they agreed to receive, operate, fuel, test and service the two LNG units on an interim basis, until nearby Everport Terminals was ready to receive them as the project's permanent host site (and eventual owner of the two proof-of-concept units).

This timing worked well; Everport Terminals was expected to be ready as the permanent host site no later than August 2019. Once at Everport, this would initiate testing of the two 6.7L LNG tractors in revenue service at a mainstream POLA marine terminal environment. It would also enable comparison of the two 6.7L LNG units to 1) a TJ900 8.9L LNG yard tractor (one of twenty in the process of being delivered to Everport under the sister Commission-funded project), and 2) the baseline TJ9000 unit with a 6.7L Cummins diesel engine.

Initial Inspection, Training and Checkout Testing

Figure 5 shows the two 6.7L LNG yard tractors undergoing initial inspection and checkout testing at CalCartage in May 2019.

Figure 5: 6.7-Liter Liquefied Natural Gas Yard Tractors Undergoing Inspection and Checkout at CalCartage



Rear view of the Capacity chassis cab

CalCartage workers examine cab tilt

CalCartage worker fuels truck with Applied LNG's on-site "Orca" LNG fuel system

Rear view of the CalCartage portable LNG fueling tank

Capacity fuel tank is connected for on-site fueling

Tractor's LNG tank registers 225 psi after fueling

The two 6.7L liquefied natural gas yard tractors were delivered to interim host site CalCartage in early May 2019, where the GNA team and CalCartage performed initial fueling and checkout testing.

Photo Credits: Jon Leonard, GNA

As shown, on-site personnel fueled the two LNG tractors using an existing portable "Orca" fueling station, which CalCartage first leased to fuel its fleet of 17 older-technology LNG yard tractors, nearly a decade earlier. CalCartage had obtained those 2011 model year units in 2010 under a grant from the Mobile Source Air Pollution Reduction Review Committee (known as the MSRC); they were built by Kalmar with 2010 Cummins B Gas engines and were the first natural gas fueled yard tractors demonstrated at a major California seaport.

In early May 2019, GNA trained CalCartage personnel how to operate the two (newer-technology) 6.7L LNG yard tractors from Capacity (Figure 6). CalCartage personnel were already very familiar with LNG as a fuel for yard tractors, including safety procedures associated with fueling and maintaining the units. Also, the GNA-UCR team installed one pre-configured PAMS datalogger in the data port of each 6.7L LNG tractor. This initiated automatic data collection part of the GNA-UCR demonstration plan, with intent to continue the data logging at Everport after transfer of the two yard tractors from the interim (CalCartage) to permanent (Everport) host site.

Figure 6: CalCartage Staff Training and Installation of Portable Activity Monitoring System Data Loggers

Trucks get Portable Activity Monitoring Systems (PAMS) installed; PAMS device plugged into the LNG UTR's J1939 port

GNA inspects Capacity UTRs and trains CalCartage drivers on UTR features and operational procedures.

LNG Unit No. 482 moves a full, extremely heavy 20-foot container at CalCartage.

LNG Unit No. 483 is connected to a container at CalCartage so GNA can observe warranty issue to address.

At the CalCartage interim host site, the project team trained personnel on the new-technology LNG yard tractors and worked with on-site personnel to perform checkout testing. UCR staff installed a PAMS data logger in each 6.7L LNG tractor. The bottom two photos show the successful inaugural towing of an exceptionally heavy, full container.

Photo Credits: Jon Leonard, GNA

Operations, Surveying and Warranty Repairs at CalCartage

From early May until mid-July (2019), CalCartage personnel operated the two proof-of-concept 6.7L LNG yard tractors in limited revenue service at the noted address. During this gradual decommissioning at the CalCartage site, each LNG unit logged approximately 100 engine hours of operation. While the yard tractors were operated sparingly, these efforts were very useful to OEM Capacity. They documented early problems and provided valuable anecdotal and qualitative information about the units, provided by the same CalCartage team that had extensive experience operating a fleet of older LNG yard tractors.

Specifically, during a July 2019 interview, CalCartage personnel (drivers, fuelers and the yard manager) provided their impressions about operating and fueling the two pre-commercial 6.7L LNG units. Table 5 summarizes these qualitative inputs.

Table 5: Summary of Qualitative Inputs from CalCartage Personnel

LNG Tractor Comparison Topic	Type of Personnel	Summary of Comments Made
Performance / Power / Torque	Drivers	• "As good (or nearly as good) as diesel" yard tractors for pulling fully loaded 40-foot container
Comfort and Ergonomics	Drivers / Yard Manager	• Cab layout and comfort "as good as diesel" • Ergonomics generally good, although some model improvements needed (compared to old Kalmar LNG units) • Bump on floor of cab creates a tripping hazard and should not be there
Ease of Fueling	Fuelers / Yard Manager	• Can be fueled in similar fashion and time as CalCartage's older LNG units, but fill-time is slower than diesel units
Ability to Perform Two Shifts on Single Fueling Event	N/A	• Not relevant or evaluated at CalCartage (singe shift facility)
Safety / Logistics	Yard Manager	• Absence of LNG tank guard risks major damage on $20k asset (LNG tanks) during a routine yard collision
Overall rating of 6.7L LNG units	All of the Above	• Very good overall, able to fully function in moving typical containers at the yard • The 6.7L LNG demo models were: ✓ Improved compared to CalCartage's older LNG units (2010 Kalmar models, obtained through an MSCR grant) ✓ Nearly as good as diesel yard tractors

Source: Interviews by GNA of CalCartage drivers and yard manager, July 2019.

As the table indicates, CalCartage personnel generally found that performance and operational characteristics of the 6.7L LNG yard tractors were satisfactory and met expectations. The aspects for which they recommended improvements primarily related to 1) ergonomics and layout of the cab, and 2) the need to install LNG tank guards to prevent damage during yard operation. The latter issue resulted in an important technology transfer activity for the LNG yard tractors (Technology / Knowledge Transfer section).

Despite these operational limitations associated with site decommissioning, CalCartage's two-month demonstration provided Capacity with important early inputs about product performance and durability. Most importantly, this interim host site helped Capacity document early hardware problems that required warranty work on these two first-of-a-kind units. As further described, these served as harbingers of problems later discovered at Everport on Capacity's fleet of 20 TJ9000 LNG yard tractors with the L9N engine.

As shown by the photo collage in Figure 7, the main hardware problem that occurred at CalCartage involved the muffler bracket assembly on both LNG yard tractors. In late-June 2019, CalCartage personnel discovered fractures on the higher end of the bracket assembly that affixes the muffler to the chassis. Ultimately, Capacity's service provider (Harbor Diesel) had to replace the bracket assembly on both units.

Figure 7: Warranty Fix of Muffler Bracket Assembly at CalCartage

Photo Credits: Jon Leonard, GNA

From this problem, Capacity learned that LNG yard trucks require a more-robust bracket assembly compared to Capacity's diesel yard tractors (fully mature technology), which have shorter muffler stacks that are less prone to top-end vibration. This required Capacity to design and fabricate a new stronger bracket that attached at the upper part of exhaust stacks on their LNG yard tractors. Later, based on this experience with the 6.7L yard tractors, Capacity replaced the same bracket on all twenty 8.9L TJ9000 LNG yard tractors being demonstrated at Everport under the sister CEC-funded project.

Preparation and Training at Everport Terminals (Permanent Host Site)

Everport Terminal Services is a large (205 acres), leading-edge containerized cargo MTO that operates Berths 226 to 236 at the Port of Los Angeles (Figure 8). For a variety of reasons, the project team chose Everport to be the project's permanent host site. In addition to being an exemplary large MTO that operates approximately 100 yard tractors within America's busiest seaport complex (POLA), Everport had already set in place plans to:

- Obtain and demonstrate 20 LNG yard tractors powered by CWI's larger 8.9L "NZE" natural gas engine
- Open an on-site LNG fueling station (unique for MTOs at a San Pedro Bay Port)
- Obtain and demonstrate a small fleet of battery-electric yard tractors

These logistics and existing plans at Everport made it an excellent choice to be the project's permanent host site. Moreover, the Everport management team was eager to add two additional LNG units (the "right-sized" 6.7L version) and use the opportunity for its operational personnel to compare them to the 20 LNG units powered by the larger L9N engines. Also, if the timing could work, Everport was ready and willing to compare the LNG units (of both types) to its small fleet of battery-electric yard tractors.

Figure 8: Aerial View of Everport Terminals, Port of Lost Angeles

Photo Credit: Google Maps

In July 2019, GNA executed a three-way MOU between GNA, Capacity and Everport. The MOU spelled out obligations for each party to participate in a revenue service demonstration for six (or more) months, comparing the two 6.7L LNG yard tractors to one diesel control unit and one 8.9L unit. As noted, Everport was also asked to allow the GNA-UCR team to document and compare one of its battery-electric yard tractors, if available (which ultimately, was not the case). The MOU called for Capacity to own the two 6.7L proof-of-concept LNG yard tractors throughout the demonstration, but upon conclusion, Capacity would transfer ownership of the two units to Everport.

With the Everport-Capacity-GNA MOU executed and CalCartage closing down, the two 6.7L LNG yard tractors were transported via flatbed truck to Everport in July 2019 (Figure 9).

Figure 9: Relocation of 6.7-Liter Liquefied Natural Gas Yard Tractors to Everport

Photo Credits: Jon Leonard, GNA

After transferring the two 6.7L units from CalCartage to Everport – GNA re-inspected the two tractors and conducted a vehicle orientation training session for Everport's yard managers and drivers (Figure 10). Unlike CalCartage, Everport personnel did not have prior experience operating LNG yard tractors (or any other type of heavy-duty NGV). As part of the CEC-funded sister project – in coordination with Capacity, Clean Energy, and the Port of Los Angeles – Everport was in the process of gradually receiving the 20 Capacity TJ9000 LNG yard tractors with the larger L9N engine. In parallel, Everport was working with Clean Energy and the City of Los Angeles to commission and permit its on-site LNG fueling station.

Figure 10: Initial Everport Orientation Training for 6.7-Liter Liquefied Natural Gas Tractors

These photos show the GNA-UCR team re-inspecting the two 6.7L LNG tractors and conducting vehicle orientation training for Everport's yard managers and drivers.

Photo Credits: Jon Leonard, GNA

Due to complexities of permitting Clean Energy's LNG station, Everport had to delay operating all 22 of its LNG tractors (two 6.7L and twenty 8.9L units) in revenue service, for several weeks after receiving them at the site. During this waiting time, the GNA-UCR team outfitted the other demonstration vehicles – one 8.9L LNG unit, one diesel control unit, and a battery electric unit (in the hope that it would later become operational) with the same type of PAMS dataloggers already installed on the two 6.7L LNG units. GNA also planned and conducted two LNG safety and handling training sessions for key Everport staff (see next subsection). Clean Energy provided training to Everport personnel about how to operate the LNG station and re-fuel all LNG yard tractors, under the CEC-funded sister project focused on the twenty 8.9L LNG YTs.

Training of Everport Staff on Liquefied Natural Gas Safety and Handling Characteristics

GNA designed and implemented a custom LNG training and safety session for key personnel at the Everport host site. GNA provided this hands-on training to Everport executives and management staff, union officials, tractor operators, fuelers, and mechanics who worked directly for Everport Terminals. It also included on-site (unionized) personnel representing Everport's contractor, Pacific Crane Maintenance Company (PCMC), which describes itself as the "largest provider of full-service waterfront maintenance in North America." Inclusion of high-level union personnel was important, because successful introduction of emerging clean CHE like LNG yard tractors at any San Pedro Bay marine terminal is greatly enhanced when there is "buy in" from union workers. GNA emphasized a key benefit of operating LNG yard tractors in place of baseline diesel equipment: elimination of diesel particulate matter (a known carcinogen) in their exhaust.

GNA planned and implemented two separate training sessions. The first session took place on July 23, 2019 (Figure 11); this initial event was geared and targeted for personnel at Everport and PCMC who were actually operating, fueling and/or maintaining Everport's 22 LNG yard tractors (two 6.7L units and twenty 8.9L units).

Figure 11: "LNG 101 & Live Demo" Training Session #1, July 2019

Photo Credits: Jon Leonard, GNA

On September 11, 2019, GNA conducted a second LNG handling and safety session (Figure 12); GNA specifically oriented that session for executive management at Everport (including President George Lang), as well as high-level union representatives who worked for PCMC.

Figure 12: "LNG 101 & Live Demo" Training Session #2, September 2019

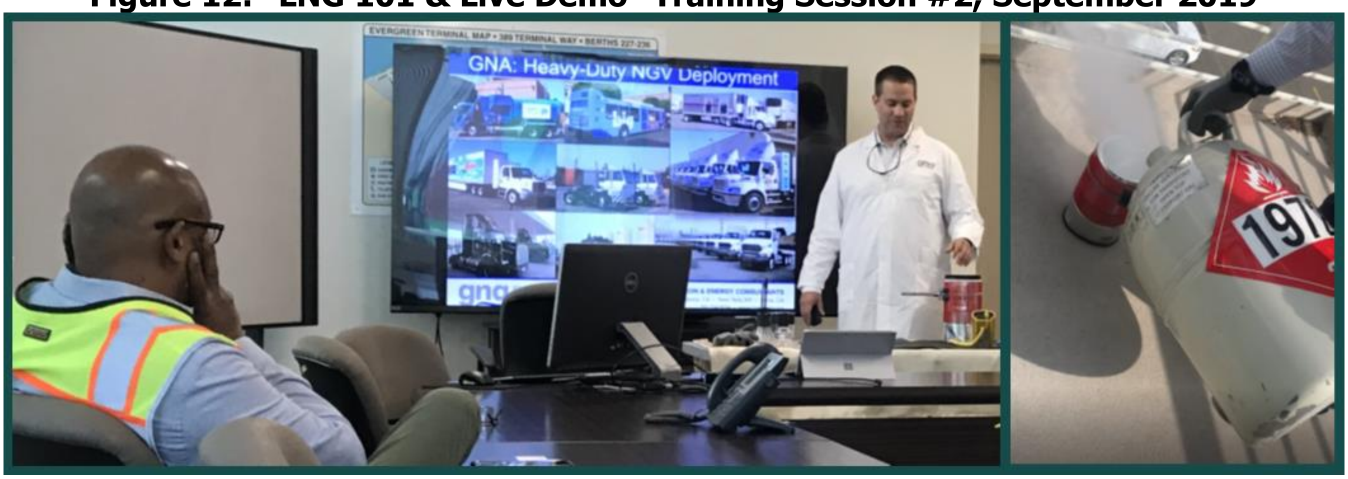


Photo Credits: Jon Leonard, GNA

As can be seen in the various photos, GNA's training session included a hands-on demonstration about LNG (such as how to safely handle and dispense it, how to observe and extinguish LNG fires), as well as a slide presentation that fully describes LNG's physical characteristics and material handling properties. Both training events were extremely well received by the attending personnel from Everport and PCMC.

Portable Activity Monitoring System Installation on Liquefied Natural Gas, Diesel and Battery Electric Yard Trucks

The project demonstration design called for automatic data collection using compact PAMS dataloggers, which had already been installed into the J1939 diagnostic ports of both 6.7L LNG yard tractors. In July 2019, the GNA-UCR team installed PAMS loggers on 1) a 6.7L diesel unit, 2) an 8.9L LNG unit, and 3) a battery-electric unit (Figure 13).

Figure 13: Installation of Portable Activity Monitoring System on Diesel, Battery-Electric, and 8.9-Liter Liquefied Natural Gas Yard Tractors

At Everport, PAMS data loggers were installed on a diesel (left), battery-electric (upper right), and 8.9L LNG tractor (lower right).

Photo credits: Jon Leonard, GNA

Operations, Surveying and Warranty Repairs at Everport

The demonstration at permanent host site Everport officially began in September 2019, after the Clean Energy LNG station was fully permitted by the City of Los Angeles. Figure 14 shows the station (left), with one of the 6.7L LNG yard tractors (Capacity ID #483 / Everport unit LN0341) at the station after being refueled (right).

Figure 14: Opening of Everport's Liquefied Natural Gas Station and a 6.7 Liter Liquefied Natural Gas Yard Tractor After Fueling

Everport's newly operational LNG fueling station

6.7L LNG tractor (#483) at Everport LNG fueling station

Photo Credits: Jon Leonard, GNA

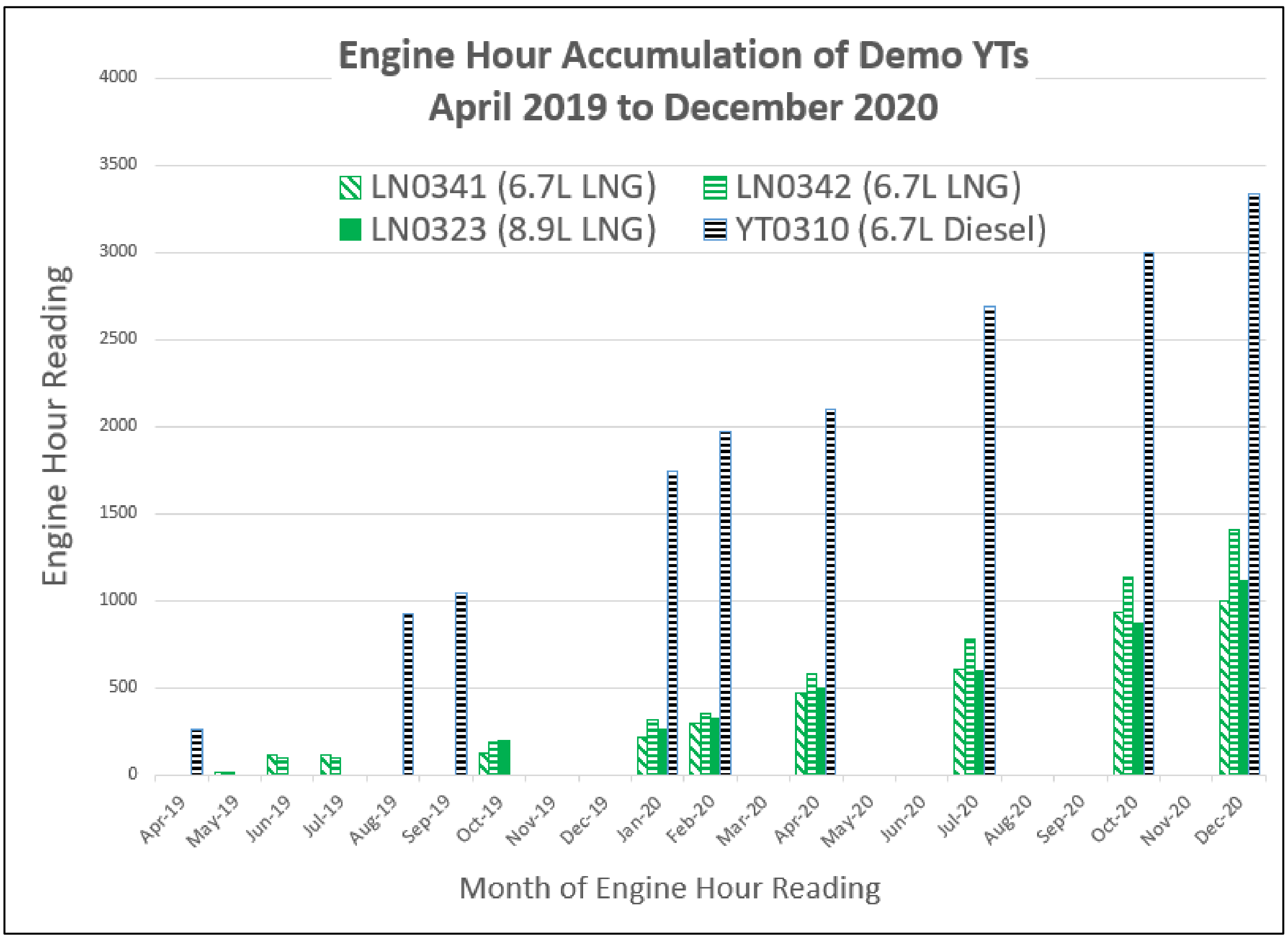
Summary of Yard Tractor Operation, May 2019 to December 2020

Figure 15 provides a summary of the engine hour meter readings taken from the three LNG yard tractors and the diesel control tractor. The battery-electric tractor was not operable during the demonstration timeline, so operational data was not collected for this technology type. Although the "official" demonstration at Everport started in September 2019 and ended in October 2020, engine hour readings are provided in the figure for a period of 18 months (ending in December 2020).

Additional notes and caveats about the engine hour accumulation on these four units are:

- The diesel tractor (LN0310) was already in service at Everport in April 2019; it had been received as a new unit and first deployed by Everport in late March 2019.
- The two 6.7L LNG tractors (LN0341 and LN0342) first began accumulating operational time at CalCartage, in early May 2019. The two 6.7L LNG units were transferred to Everport in July 2019. Everport staff received onsite training to safely operate the LNG units. Neither unit was used in revenue service for about six weeks because Everport's LNG fueling station was not fully permitted and operational until September 2019.
- Similarly, the 8.9L LNG tractor (LN0323) was not used by Everport until the LNG fueling station was permitted in September 2019.

Figure 15: Engine Hour Accumulations for Liquefied Natural Gas and Baseline Diesel Yard Tractors



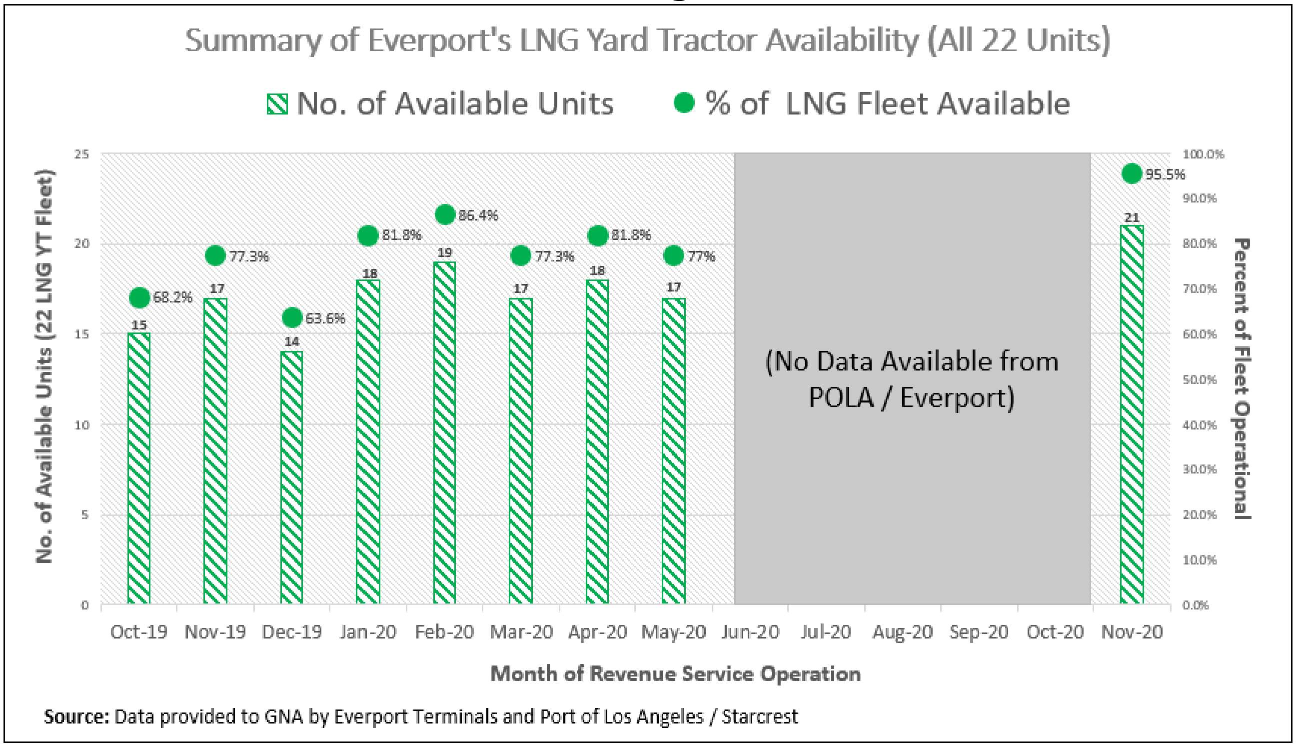
Source: Data collected by GNA and Everport Terminals (some provided by Port of Los Angeles / Starcrest)

As the graph indicates, the diesel yard tractor (LN0310) accumulated approximately three times (3X) more engine hours of operation than the three LNG tractors. This is primarily attributed to two factors, as follows:

1) The diesel control tractor was generally operated over two daily shifts, while the LNG units were operated one shift per day. Although all LNG yard tractors are equipped with sufficient LNG fuel capacity (about 120 usable gallons) to run a double shift, Everport cited fueling logistics as the main cause for limiting them to one shift. Specifically, Everport rapidly "wet fuels" all diesel yard tractors each night by bringing a mobile diesel refueler to the parked tractors. By contrast, each LNG yard tractor must be driven to the centralized LNG station to refuel. According to comments by Everport fuelers and management staff, this LNG tractor fueling process is resource and time intensive, and is not conducive to double shifting. This also suggests that Everport was able to fully meet its demand for container moves without needing to double shift the 22 LNG yard tractors.
2) All three LNG yard tractors were kept out of revenue service for significant periods to design, fabricate, and install LNG tank guards on each unit (see the Technology/Knowledge Transfer section). Variances in the engine hours accumulated among the three LNG yard tractors were generally attributable to the degree to which each unit received warranty repairs and the time spent offsite at UC Riverside for emissions testing.

Figure 16 summarizes the "availability" for use of all 22 LNG YTs from October 2019 through May 2020 and the month of October 2020 (data were not available from POLA for the summer of 2020). As the graph shows, the number of available LNG units during these months varied from a low of 64 percent (14 of 22 units) to a high of 96 percent (21 of 22 units). High availability that occurred at the end of period is likely indicative of successful efforts by Capacity to improve reliability on these pre-commercial natural gas tractors. This was accomplished by addressing and resolving various warranty issues, in conjunction with the engine OEM (Cummins), the host site (Everport), the fuel system upfitter (Agility Fuel Solutions), and Capacity's service provide (Harbor Diesel).

Figure 16: Summary of Liquefied Natural Gas Yard Tractor Availability October 2019 through October 2020



Source: Data collected by Everport Terminals and provided to GNA by Port of Los Angeles / Starcrest

Fuel Use and Fuel Economy Comparisons

As previously described, a key premise of the project was that the two Capacity TJ9000 LNG yard tractors with the B6.7N engine should be a more-efficient, "right-sized" choice for cargo handling operations at seaports, compared to the same Capacity model powered by the larger L9N engine. Basic parameters about the B6.7N (reduced size, power, fuel flow capacity relative to the L9N) make this finding seem intuitive. However, revenue service operation of yard tractors at a major seaport entails many variables, and corroborating real-world efficiency benefits of the smaller engine (if any) can be complex.

As described, the project's demonstration plan called for use of PAMS dataloggers to automatically collect detailed operational data during the demonstration, including fuel consumption per hour and duty cycle characteristics. The GNA-UCR team installed PAMS dataloggers into the diagnostic ports of both 6.7L LNG yard tractors (LN0341 and LN0342), the designated 8.9L yard tractor (LN0323), and the designated diesel tractor (YT0310). Unfortunately, unidentified personnel at the host site tampered with all of these data loggers. Virtually all useful PAMS data were lost to the project, although some data was recovered that enabled comparisons between one of the 6.7L LNG tractors and the diesel tractor (see Section titled "Operational Data at Everport from Portable Activity Monitoring System Dataloggers").

Ultimately, the GNA-UCR team used three different ways to compare fuel efficiency of the yard tractors with the B6.7N engine to those with the L9N engine:

1. Everport's high-level records on aggregate LNG gallons dispensed at the site

2. Engineering data and opinions provided by the yard tractor OEM (Capacity) and the engine OEM (Cummins / CWI)
3. Chassis dynamometer testing of the two LNG yard tractor types at UCR's laboratory

Findings from each of these input types are further discussed below.

Everport Data on Aggregate LNG Gallons Dispensed

Table 6 provides a summary of the engine hours of operation at Everport – along with the LNG gallons consumed – for all 22 LNG yard tractors (by engine size / type) during the period of approximately August 2019 through October 2020. This yields a "gallons per hour" metric for comparing LNG consumption rates during the field demonstration.

Table 6: Revenue Service Fuel Consumption (6.7-Liter versus 8.9-Liter Liquefied Natural Gas Units)

	Everport UNIT #	HRS	LNG Gal	Gal/HR
8.9L LNG Units	LN0321	958	4,967	5.18
	LN0322	860	3,761	4.37
	LN0323	925	4,034	4.36
	LN0324	679	3,307	4.87
	LN0325	703	3,058	4.35
	LN0326	287	1,992	6.94
	LN0327	1,110	5,440	4.90
	LN0328	672	3,853	5.73
	LN0329	859	3,790	4.41
	LN0330	539	2,921	5.42
	LN0331	909	3,946	4.34
	LN0332	1,100	5,586	5.08
	LN0333	1,305	7,691	5.89
	LN0334	961	5,759	5.99
	LN0335	950	4,947	5.21
	LN0336	1,040	5,463	5.25
	LN0337	1,114	6,220	5.58
	LN0338	892	4,626	5.19
	LN0339	1,027	5,190	5.05
	LN0340	911	4,896	5.37
6.7L LNG Units	LN0341	966	3,656	3.78
	LN0342	998	4,112	4.12

This table shows that the two 6.7L LNG units consumed 3.95 LNG gallons per hour (Gal/HR) of engine operation, while the twenty 8.9L units averaged about 5.2 LNG Gal/Hr (approximately 24 percent less LNG per hour of engine operation. Data on hours and LNG gallons consumed are totals measured between August 2019 and October 2020.

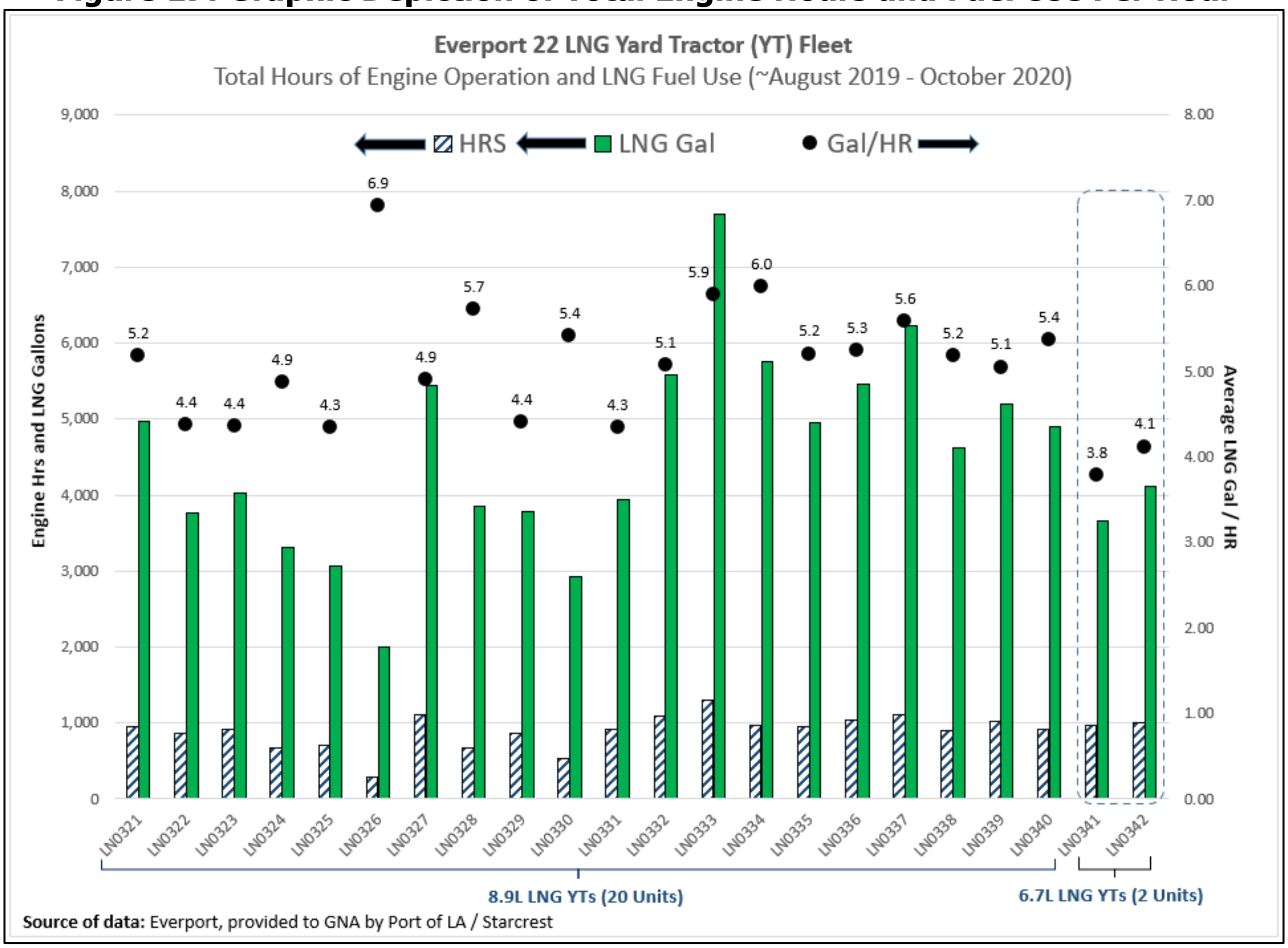
Source: Data collected by Everport Terminals and provided to GNA by Port of Los Angeles / Starcrest

As the table indicates, the two 6.7L LNG units (shaded blue at the table's bottom) consumed on average nearly four (3.95) LNG gallons per hour (Gal/HR) of engine operation, while the 20 8.9L units (shaded green) averaged about 5.2 LNG Gal/Hr. Thus, for this comparison, the two LNG yard tractors with the smaller 6.7L CWI engine consumed (on average) approximately 24 percent less LNG per hour of engine operation.

Notably, fuel burned per hour (in aggregate) is not a perfect metric. It does not fully account for variable LNG boil-off that may have occurred with any of the LNG yard tractors during multiple days of non-operation (this was not tracked by Everport). Nor does it account for any LNG fuel that may have been vented prior to repairs related to on-board fuel systems. However, it does provide a useful comparison from data collected at the demonstration site regarding the average fuel economy of the two LNG yard tractors with CWI's "right-sized" (6.7L) engine compared to the average of the 20 LNG yard tractors with the 8.9L engine.

The same basic data from the above table is depicted graphically in Figure 17. This helps to clearly visualize that the two 6.7L LNG units (the last two shown on the X axis) used roughly one-fourth less fuel per hour of operation than the twenty 8.9L LNG units.

Figure 17: Graphic Depiction of Total Engine Hours and Fuel Use Per Hour



In this graph, the stripped bars represent total engine hours at Everport for all 22 LNG yard tractors (Y axis on the left); the solid green bars tally total LNG gallons consumed (also left Y axis); and black dots indicate average gallons per hour of LNG consumed (Y axis on the right). NOTE: the final two bars show the "right-sized" 6.7L LNG tractors.

Source: Data collected by Everport Terminals and provided to GNA by Port of Los Angeles / Starcrest

Engineering Observations by Capacity and Cummins

As described, these findings about relative fuel efficiency from Everport's records during the field demonstration are consistent with engineering observations provided by representatives from yard tractor OEM Capacity and engine OEM Cummins.

- **Capacity Comments:** Capacity engineers confirmed that CWI's L9N natural gas engine is oversized for yard tractor applications. One key manifestation is that the L9N requires a significantly larger cooling fan. Stoichiometric natural gas engines run at relatively high temperatures compared to comparable diesel engines. Notably, the L9N engine's 250 horsepower rating for Capacity's yard tractor application is only about four percent higher than the 240-horsepower rating of the B6.7N engine. However, with about two more liters of displacement, the larger L9N engine can be used for a variety of larger on- and off-road HDV types; consequently, CWI designed it to deliver up to 320 HP. For this and other reasons, it was necessary for Capacity to equip the 8.9L LNG yard tractors with a significantly larger, more-energy-intensive cooling package than the 6.7L LNG tractors. (Capacity did not quantify the difference on size or power requirements for the respective cooling fans.) A larger cooling fan requires more engine power that otherwise would be available for performing work (moving cargo).[9] In effect this project provided Capacity with the opportunity to develop a more efficient, reduced cost pathway to commercializing natural gas yard tractors by downsizing the engine and reducing power requirements for critical systems like the cooling fan.
- **Cummins Comments**: Cummins engineering staff also provided input about the expected relative fuel efficiencies of Capacity's LNG yard tractors with the B6.7N engine versus the L9N engine. They noted that the fuel supply capacity of the B6.7N averages about 15 percent less than the L9N, although this difference varies significantly as a function of engine speed and torque. Taking into account duty cycle specifics, Cummins staff estimated that the B6.7N engine will "roughly" consume 11.5 percent less fuel compared to the L9N engine, in a yard tractor application. They emphasized that the B6.7N's specific fuel efficiency advantage will depend on how each yard tractor type is operated.[10]

UCR Chassis Dynamometer Emissions Testing

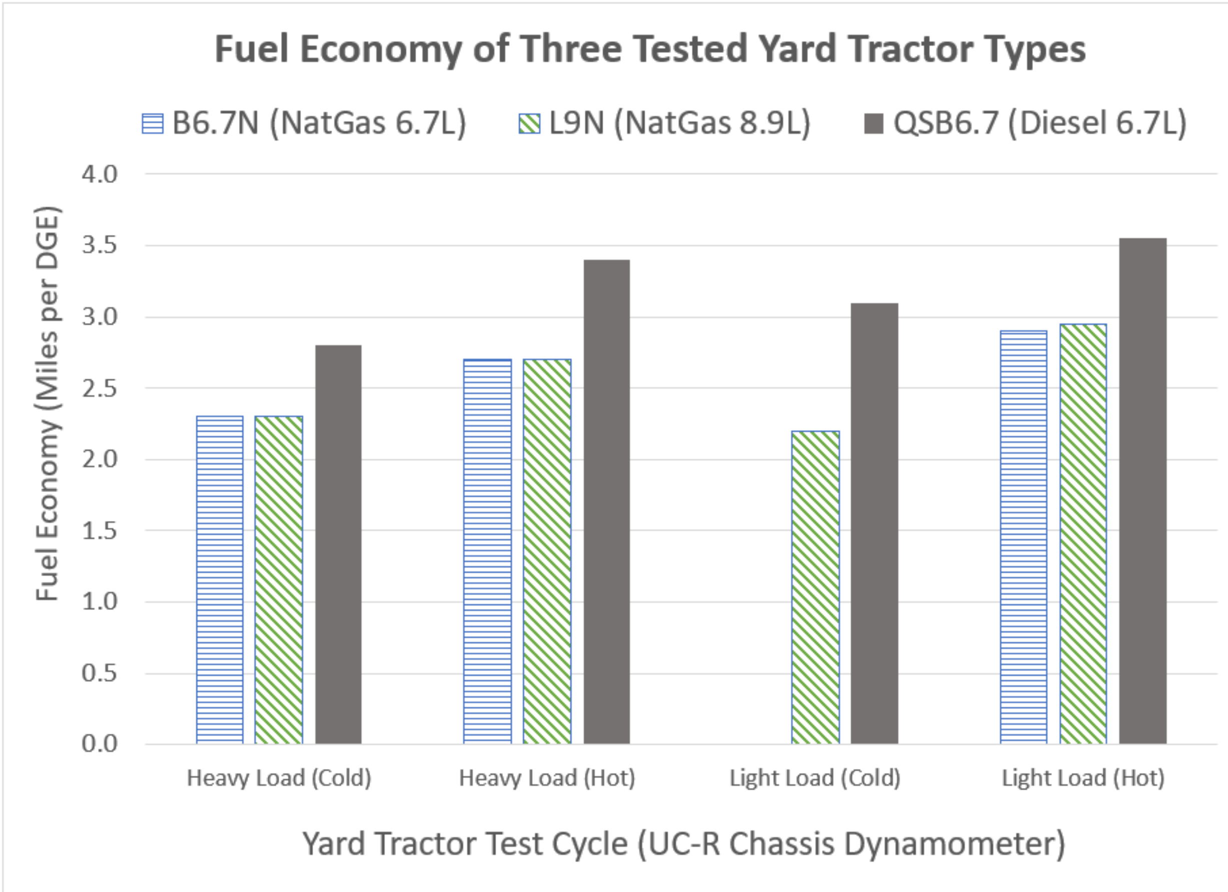
As detailed in Appendices A-E, the UCR team conducted chassis dynamometer emissions testing on one LNG yard tractor with the B6.7N engine and one with the L9N engine, across a variety of driving and duty cycles. UCR also tested the "baseline" yard tractor type with a Cummins QSB6.7 diesel engine (same test cycles). Using a standardized "carbon balance" method, UCR documented the relative fuel economies of all three tractors, reporting results on an energy equivalent basis (miles per diesel gallon equivalents, or DGE). UCR's testing included four different cycles specifically designed to simulate how yard tractors are operated at the San Pedro Bay Ports. Those four cycles simulate a heavily loaded yard tractor cycle

[9] Personal communication to GNA from Capacity's Director of Engineering, July 2020.

[10] Personal communication to GNA from Cummins Engineering department, February 2021.

(cold start and hot start condition), and a lightly loaded yard tractor cycle (cold start and hot start condition). Fuel economy results of these tests are summarized in Figure 18.

Figure 18: Fuel Economy Comparison from Chassis Dynamometer Tests



UCR compared fuel economy (miles per diesel gallon equivalent, or DGE) for the 6.7L LNG yard tractor (blue), the 8.9L LNG yard tractor (green slanted stripes), and the 6.7L diesel tractor (solid black). Four different test types were conducted to simulate yard tractor duty cycles, varied by load (heavy or light) and engine status (cold or hot start). Differences in the measured fuel economies of the two LNG tractor types were small (see text for further discussion).

Source: University of California, Riverside (see Appendices A-E)

UCR's chassis dynamometer emissions testing did not document significant fuel economy differences between the LNG yard tractor with the smaller 6.7L engine compared to the 8.9L engine. The only clear trend was that fuel economy in all four test cycles for both LNG yard tractors ranged from 17 to 21 percent lower than the diesel yard tractor.

It is expected that the diesel yard tractor would achieve higher fuel economy, compared to either LNG yard tractor type. This is attributable to the lean-burn nature of unthrottled compression-ignition diesel engines versus stoichiometric spark-ignition natural gas engines. Most notably, spark-ignition engines inherently entail significant engine throttling losses. The

California Air Resources Board assumes that heavy-duty natural gas vehicles entail at least a 10 percent fuel economy penalty relative to comparable diesel HDVs.[11]

Given the project hypothesis that the "right-sized" LNG yard tractor with the smaller (B6.7L) engine should theoretically be more efficient than the 8.9L version – and considering the factors described above that corroborate higher fuel efficiency (Everport data, OEM comments) – it was somewhat surprising that chassis dynamometer testing did not also quantify at least some fuel economy advantage. UCR's full emissions testing report (Appendices A-E) includes detailed discussion about these findings, and possible explanations. As described, one likely factor is that, compared to the chassis dynamometer test cycles at UCR's laboratory, revenue service at Everport included higher incidence of extended engine idle (see the next subsection).

In summary, the project yielded mixed results about the relative fuel economy of the "right-sized" Capacity TJ9000 LNG yard tractor with the smaller B6.7N engine, compared to the same model with the L9N engine. Data from Everport combined with engineering opinions from Capacity and Cummins corroborate that the B6.7N provides a fuel economy advantage of roughly 15 to 20 percent (driving cycles and other factors being equal). The most important result may be that Capacity ultimately decided that the B6.7N is the more-efficient and correct engine choice – as well as the lower-cost engine package – should it decide to fully commercialize natural gas yard tractors.

Operational Data at Everport from Portable Activity Monitoring System Dataloggers

Yard Tractor Duty Cycle Characterization

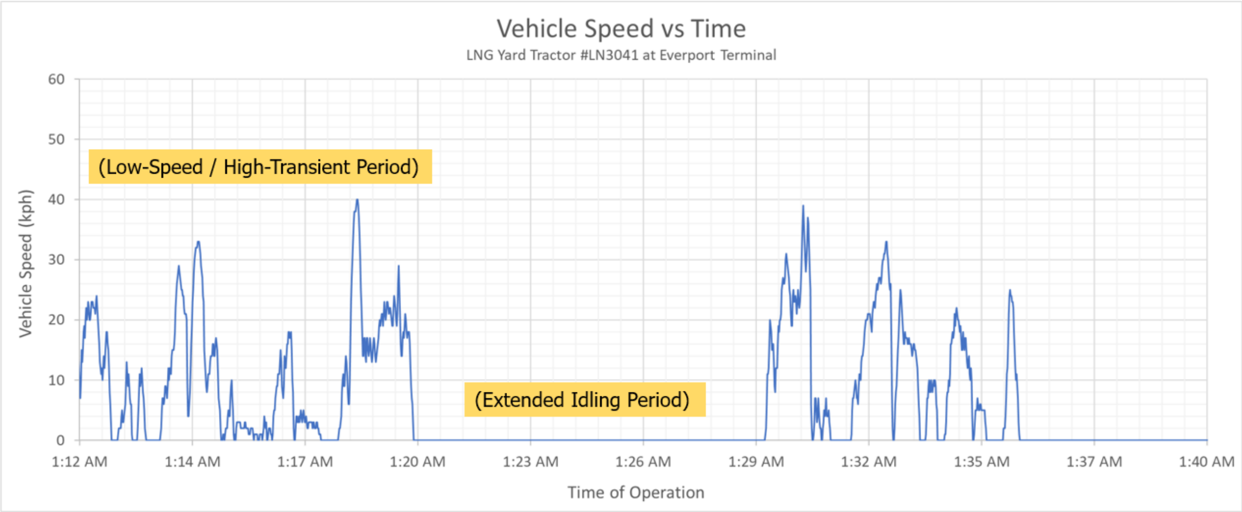
As previously described, most of the demonstration's quantitative data was lost due to tampering with PAMS dataloggers that occurred at Everport. However, the GNA-UCR team was able to recover limited PAMS data on one 6.7L LNG tractor, plus virtually all PAMS data from the baseline diesel tractor. This enabled meaningful comparisons of the yard tractors with two engines of equal size, but different fuels and combustion technologies. Unfortunately, PAMS data comparisons between the 6.7L and 8.9L LNG tractors were not possible, because all data was lost on the 8.9L LNG tractor.

First, the recovered PAMS data enabled better characterization of how yard tractors can be operated at a major marine terminal.

Figure 19 shows graphed PAMS data outputs depicting a speed-versus-time duty cycle for yard tractors used at Everport; at times, this can epitomize yard tractor operations at the San Pedro Bay Ports. As shown, for approximately 30 minutes, the Everport driver operated the 6.7L LNG unit (#LN0341) under alternating periods of low-speed high-transient operation (while moving a container short distances) and extended idling (while waiting for the next container move).

[11]California Air Resources Board, *Low Carbon Fuel Standard (LCFS) Guidance 20-04: Requesting EER-Adjusted Carbon Intensity Using a Tier 2 Pathway Application*, Table 5, April 2020, https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/guidance/lcfsguidance_20-04.pdf.

Figure 19: Duty Cycle of Liquefied Natural Gas Yard Tractor at Everport (Speed versus Time)



Speed-versus-time data recovered from PAMS datalogging on LNG yard tractor #LN0341 showed alternating periods of low-speed / high-transient operation followed by extended idling periods.

Source: Data Retrieved from PAMS by UCR, Reduced and Analyzed by GNA

Compared to yard tractors powered by baseline diesel (compression-ignition) engines, this type of duty cycle is not optimal for yard tractors powered by dedicated natural gas (spark-ignited) engines. As noted above, compared to unthrottled diesel engines, natural gas engines incur relatively high "pumping" losses as fuel is moved through the engine.

A real-world reflection of these dynamics for relative fuel efficiencies can be seen in a comparison of the same 6.7L LNG unit (LN0341) versus the baseline diesel unit (YT0310), as measured during revenue service at Everport using a PAMS datalogger on each tractor. These data and findings are further discussed in the next subsection.

Comparison of 6.7-Liter Liquefied Natural Gas and Diesel Tractors in Similar Duty Cycle

The GNA-UCR team downloaded sufficient data (prior to loss of the PAMS devices) to prepare an "apples-to-apples" comparison between a right-sized LNG tractor (LN0341 with CWI's B6.7N engine) versus the baseline diesel tractor (YT0341 with a Cummins QSB6.7 engine). To do this, GNA searched the two limited datasets and found documented time periods with similar operational characteristics for both tractor types.

Table 7 summarizes a comparison of PAMS data from the two yard tractors while being operated in a similar duty cycle at Everport.

Table 7: Data in Similar Use Characteristics for 6.7-Liter Liquefied Natural Gas and Diesel Tractors

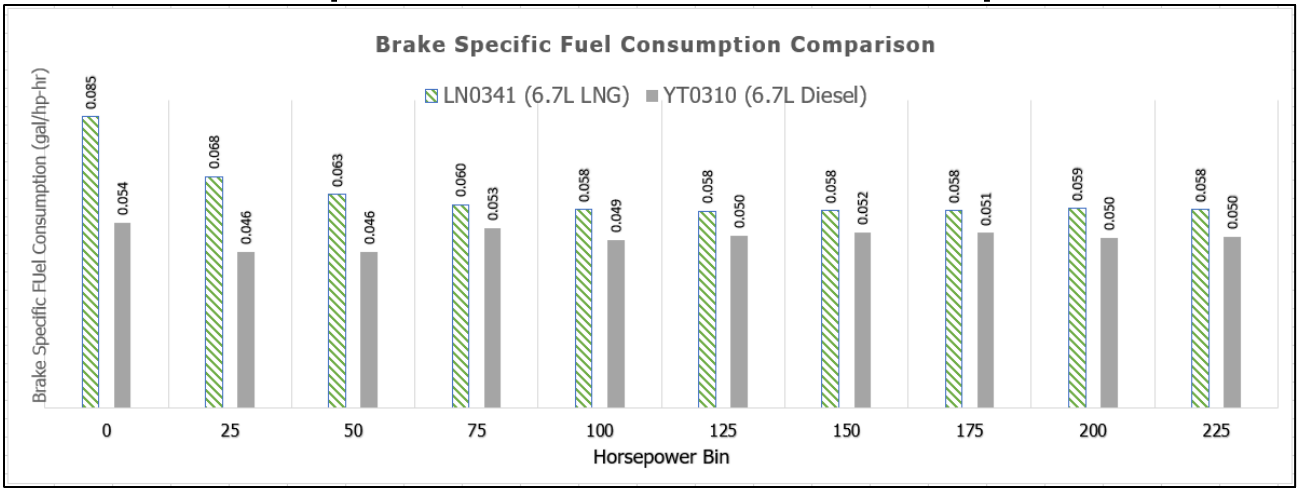
Test Yard Tractor Unit	YT483 (6.7L LNG)	YT0310 (6.7L Diesel)
Hours Operated	17.65	11.05
Distance (km)	203.8	120
Avg Speed (mph)	7.18	6.75
Avg Speed ex-Idle (mph)	17.0	14.9
% Idle	32%	27%
Avg HP	38.3	48.2
Avg Fuel Rate (liters/hr)	9.4	9.1
Avg RPM	1217	1278
Avg %Torque	25.3	24.6
Work Done (hp-hr)	676.6	532.3
Total Fuel Use (liters)	165.5	101.0
BSFC (gal/hp-hr)	**0.065**	**0.050**
Avg Fuel Economy (mpg)	2.91	2.81
Avg Fuel Economy (gph)	2.48	2.42

This table summarizes operational outputs collected by PAMS dataloggers on 6.7L LNG yard tractor LN0341 as compared to diesel control tractor YT0310 (similar duty cycles). The "BSFC" (bold line) compares a key efficiency parameter (see text).

Source: Data Retrieved from PAMS by UCR, Reduced and Analyzed by GNA

In general, these data confirm that the 6.7L LNG yard tractor can provide comparable performance to the diesel control yard tractor, when operating under similar duty cycles (e.g., speed, torque, idle time, and fuel rates). Average fuel economy for the LNG yard tractor was only about three percent less than the diesel yard tractor, in gallons per hour of operation. However, to characterize relative fuel efficiencies, *it is important to compare brake specific fuel consumption (BSFC)* during similar duty cycles. BSFC is derived by dividing the fuel mass flow rate by engine output power. Figure 20 compares BSFC for the LNG and diesel tractors across the same bins for outputted engine horsepower.

Figure 20: Portable Activity Monitoring System Fuel Efficiency Comparison of Liquefied Natural Gas versus Diesel at Everport



When compared in similar duty cycles and the same HP outputs, the LNG tractor (SI NG engine) exhibits significantly worse BSFC than the diesel tractor (CI engine), especially when operated at low HP.

Source: Data Retrieved from PAMS by UCR, Reduced and Analyzed by GNA

BSFC for the LNG yard tractor was significantly higher than the diesel tractor, ranging from 57 percent higher at lower engine power outputs to 16 percent higher at peak output (225 HP). This result is consistent with the fact that worst-case efficiency for spark-ignited natural gas engines occurs when operated during low-speed, low-load conditions. As discussed by UCR in its *Emissions Testing Report*, Appendices A-E, the natural gas engine emits much lower NO_x emissions in this operational mode. Whereas modern heavy-duty natural gas engines operate with very low NO_x in this duty cycle, state-of-the art diesel engines have been shown to emit high NO_x levels during low-speed, low-load conditions; this is due to inability of the SCR system to get up to full operational temperature under such driving conditions.[12]

Qualitative and Quantitative Inputs from Everport Personnel

A key objective of the project was to survey Everport personnel and ascertain if they observed the two 6.7L LNG tractors to be capable of performing the same basic performance and utility as the baseline diesel tractors – presumably while achieving higher efficiency than the 8.9L LNG units. To capture inputs (largely qualitative) from Everport personnel, GNA harmonized evaluation forms with the 8.9L LNG-focused Port of Los Angeles demonstration.

Table 8 summarizes inputs from 11 Everport drivers who collectively evaluated nine 8.9L LNG units across a variety of parameters (operational, performance, safety, and comfort).

[12] This phenomenon has been well documented in testing by UCR CE-CERT and at other laboratories. For example *Certification and In-Use Testing for Heavy Duty Diesel Engines to Understand High In Use NOx Emissions*, https://ww2.arb.ca.gov/carbmedia//research/seminars/durbin5/durbin_presentation.pdf.

Table 8: Summary of Qualitative Evaluation Inputs by 8.9-Liter Liquefied Natural Gas Yard Tractor Drivers

LNG Unit Comparison to Diesel Baseline?	Much Better	Better	Same	Worse	Much Worse	Comments / Notes
Cab entry / exit		4	1	4	2	5 comments: Bump on floor gets in way
Inside cab noise	7	3	1	0	0	
Outside noise	5	3	3	0	0	
HVAC	2	6	3	0	0	1 comment: HVAC did not work at times
In-cab controls	3	1	7	0	0	
In-cab visibility	3	2	4	2	0	1 comment: Cab visibility issues / blind spots
Maneuverability	0	1	7	2	0	2 comments: Turning radius larger than diesel
Connection to container	0	2	8	0	0	
Acceleration with no container	1	5	3	2	0	
Acceleration with container	2	4	1	3	0	
Pulling power with full container	0	4	4	3	0	1 comment: Less pulling power (off idle)
Shifting smoothness (acceleration)	4	4	1	1	0	
Braking (quickly and smoothly)	4	5	0	1	0	1 comment: Harder to stop than diesel
Ride comfort	5	5	0	1	0	1 comment: Backrest less comfortable
Overall unit rating	4	6	0	1	0	**4 comments: lower emissions noticed**

Rating columns are relative to baseline diesel tractors (6.7L Cummins engines). Values refer to numbers of drivers (out of 11 total) who rated 8.9L LNG yard tractors accordingly. Not all drivers rated every category. All drivers operated LNG tractors multiple times; 8 of 11 drivers operated them at least four times. Duty cycles were split roughly 50/50 between Rail and Yard operation.

Source: Data collected by Everport Terminals and provided to GNA by Port of Los Angeles / Starcrest

Table 9 summarizes inputs from two Everport drivers who completed the same evaluation form about the two 6.7 L LNG yard tractors.

Table 9: Summary of Qualitative Evaluation Inputs by 6.7-Liter Liquefied Natural Gas Yard Tractor Drivers

LNG Unit Comparison to Diesel Baseline?	Much Better	Better	Same	Worse	Much Worse	Comments / Notes
Cab entry / exit				2		1 comment: Bump on floor gets in way
Inside cab noise		2				
Outside noise		2				
HVAC		1				
In-cab controls			2			
In-cab visibility		1		1		1 comment: Cab visibility issues / blind spots
Maneuverability		1	1			
Connection to container		1	1			
Acceleration with no container		1	1			
Acceleration with container		1	1			
Pulling power with full container		1		1		
Shifting smoothness (acceleration)		1		1		
Braking (quickly and smoothly)		2				
Ride comfort	1	1				
Overall unit rating		2				

Rating columns are relative to baseline diesel tractors (6.7L Cummins engine). Values refer to numbers of drivers (out of 2 total) who rated 6.7L LNG yard tractors accordingly. Both drivers operated 6.7L LNG tractors multiple times, and cited "Yard" as primary duty cycle.

Source: Data collected by Everport Terminals and provided to GNA by Port of Los Angeles / Starcrest

As these ratings and other inputs imply (Table 10), Everport drivers who operated both types of LNG tractors did not generally notice – or at least were unconcerned about – any operational differences between the 6.7L LNG tractor type versus the 8.9L LNG tractor type despite receiving significant training about the distinction. The fact that Everport drivers did not observe any key differences in the performance of LNG yard tractors with the smaller, less-powerful engine seems to corroborate Capacity's choice to pursue the lower cost, more-efficient B6.7N option for its potential TJ9000 LNG yard tractor commercialization.

Table 10: Summary of Overall Evaluation by Everport Terminals Personnel

LNG Tractor Comparison Topic	Summary of Comments Made at Project Debriefing with Everport Personnel (June 2020)
Fuel Usage / Efficiency	• Everport does not track individual units for fuel efficiency / use • Advantage diesel YTs: wet fueling (fuel brought to parked units) • Advantage diesel YTs: may only require relatively quick "top off" each night (1-2 shifts) • Still "new to LNG fueling logistics," need more time to optimize • Currently, fueling LNG YTs at central station creates disadvantage relative to diesel (see below) • Refueling time for central bulk tank had to be manually tracked, created issues • LNG supplier was attentive; LNG system just too early stage for large-scale implementation
Fueling Process / Onboard Fuel Storage / Energy to Perform Two Shifts	• Fueling with LNG (either YT type) is biggest negative of project • Were originally running out of LNG in less than 1 shift (learned to make it work for 1 shift) • Baseline diesels are wet (mobile) fueled very quickly (about 2 to 5 minutes per YT) • LNG needs similar wet fueling option to work at a large MTO • Current system (central fuel station) would take 5 to 10 fuelers to fuel large fleet (~100 YTs) • It is hard to completely fill LNG tanks (capacity 127 gal /~70 DGE) • Further diminishes operating time between fills, relative to diesel • This (and Covid-19) generally limited LNG YTs to 1 shift • Requirement for fuelers to wear LNG protective gear can also slow process to fuel LNG YTs
Relative Performance and Utility of 6.7L LNG YTs	• Performs just as well as diesel YT for this application • Perceived no difference in performance / pulling power between 6.7L and 8.9L LNG YTs • 6.7L LNG YT "seems to be more fuel efficient," but they don't measure this • Operation of 5th wheel / hooking up containers works as good as diesel YT • Did not notice any difference in turning radius for 6.7L YTs (in fact, it's the same as the 8.9L YTs)
Warranty Repairs and Other Issues Related to	• All work performed under warranty; real challenge comes later when out of warranty • Warranty issues on LNG units reflected "growing pains" and improved over time

LNG Tractor Comparison Topic	Summary of Comments Made at Project Debriefing with Everport Personnel (June 2020)
Technological Robustness	• Advantage diesel: SI LNG engines run hot and require replacement of spark plugs • Advantage LNG: diesel get frequent issues with DPFs (e.g., plugging); LNG has simpler exhaust • Advantage LNG: no SCR system obviates need to carry / add diesel emission fluid (DEF) • Work on LNG units had to be conducted outside (too expensive to upgrade shop for safety) • LNG tank guards essential, must be offered from YT OEM; adding guards saved lots of money • 1st gen mounting brackets for LNG fuel tanks had to be redesigned by Everport and Agility
Safety / Emissions / Occupational Health / Odors	• Advantage LNG: personnel noticed / appreciated lack of smoke / diesel particulate emissions • Advantage LNG: drivers liked cleaner clothes at shift's end (diesel hard to clean off clothes) • "LNG 101 Safety and Handling" training was highly useful and informative
Overall unit rating	• Operationally, LNG YTs are good enough, even for tough MTO duty cycles • Clean burning natural gas / lack of diesel exhaust exposure is big advantage • However, fueling systems / logistics need improvement for mainstream MTO revenue service

Interviewed personnel from Everport included the Vice President and General Manager, Assistant Manager, and Maintenance & Repair Manager; personnel from Pacific Crane Maintenance Company included the General Manager and Yard Supervisor.

Source: Interview of Everport Terminal Personnel by GNA, June 2020

Warranty Repairs and Technology Transfer at Everport

During the extended demonstration period at Everport (about August 2019 to October 2020), all 22 of Capacity's TJ9000 LNG yard tractors required certain common unscheduled maintenance and repairs. Some issues arose on the 20 8.9L LNG yard tractors that did not occur on the 6.7L LNG yard tractors. Most problems were quickly diagnosed and resolved through warranty repairs performed at Everport by Harbor Diesel, with support from Capacity and/or Cummins. The following summarizes key issues encountered.[13]

[13] Most information cited here was provided to GNA by Harbor Diesel or Capacity Trucks, August 2019 through January 2020.

- Most of the 20 yard tractors with 8.9L engines experienced engine oil cooler issues while operating in service. This problem did not affect the two yard tractors with 6.7L engines, which is consistent with their smaller cooling fans and cooling packages. The problem on the 8.9L engines occurred when their oil cooler cores leaked, and pushed engine oil in the cooling system. Directly due to this problem, Harbor Diesel replaced the oil cooler for 12 of the 20 8.9L yard tractors during the demonstration period. The remaining 8.9L engine yard tractors received "proactive" oil cooler replacements. To resolve this problem, Capacity worked with vendors to design and fabricate a new oil cooler core made from stainless steel, to replace the original core made from aluminum.
- All 22 LNG yard tractors received new brackets that secure the single LNG tank to the frame rail. Everport reported that the problem had occurred on multiple LNG yard tractors, including units with "low hours" of accumulated operating time. Multiple units were experiencing broken rear brackets and/or bolts that fell out (Figure 21), causing (in some cases) the LNG tank to fall down to the asphalt. To resolve this problem, Agility Fuel Solutions worked with Capacity and Everport to design and install a more-robust mounding system.

Figure 21: Cracks in Liquefied Natural Gas Tank Mounting Bracket Troubleshooting at Everport

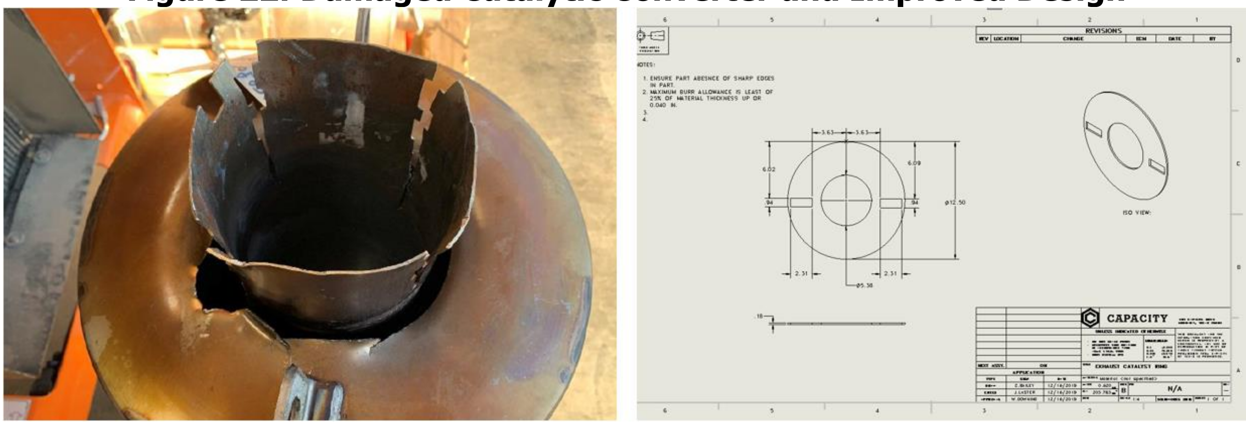
Cracks developed in LNG tank mounting brackets (left and middle, circled in red); the photo on the right shows Agility's troubleshooting work for this problem, conducted at Everport Terminals.

Photo Credits: Agility Fuel Systems

- All 22 LNG yard tractors received updated, more-robust support brackets on their vertical exhaust systems. This problem first occurred on the two 6.7L LNG units, when they were being operated at the interim host site, which was prior to launch of any LNG yard tractors at Everport. Ultimately, all LNG yard tractors needed replacement of these components with the more-robust design. The problem ultimately was found to result from lack of a brace to secure the exhaust system. This brace – which was unnecessary on diesel tractor exhaust systems – had to be specially designed for the LNG yard tractors. Capacity responded by designing and fabricating retrofit kits that included a new bracket, hardware, and clamps.
- Related to this excessive exhaust stack vibration, Harbor Diesel had to remove three-way catalytic converters from six of the 8.9L LNG yard tractors, and send them back to

Capacity for repair. To repair the damaged catalytic converters, Capacity fabricated and fitted a stainless-steel disc over each catalyst's damaged outlet port and the lifting eyes. The disc was welded using a gas metal arc welding process. Figure 22 shows one of the six damaged catalytic converter rings (left), and Capacity’s engineering drawing (right) for the new hardware configuration that resolved this exhaust ring issue. Figure 23 shows one of the newly designed rings installed on a catalytic converter.

Figure 22: Damaged Catalytic Converter and Improved Design



Physical damage found on the rings of six 8.9L LNG yard tractor catalytic converter units (left), and Capacity’s design for a stainless steel ring that made them more durable and robust (right).

Source: Capacity

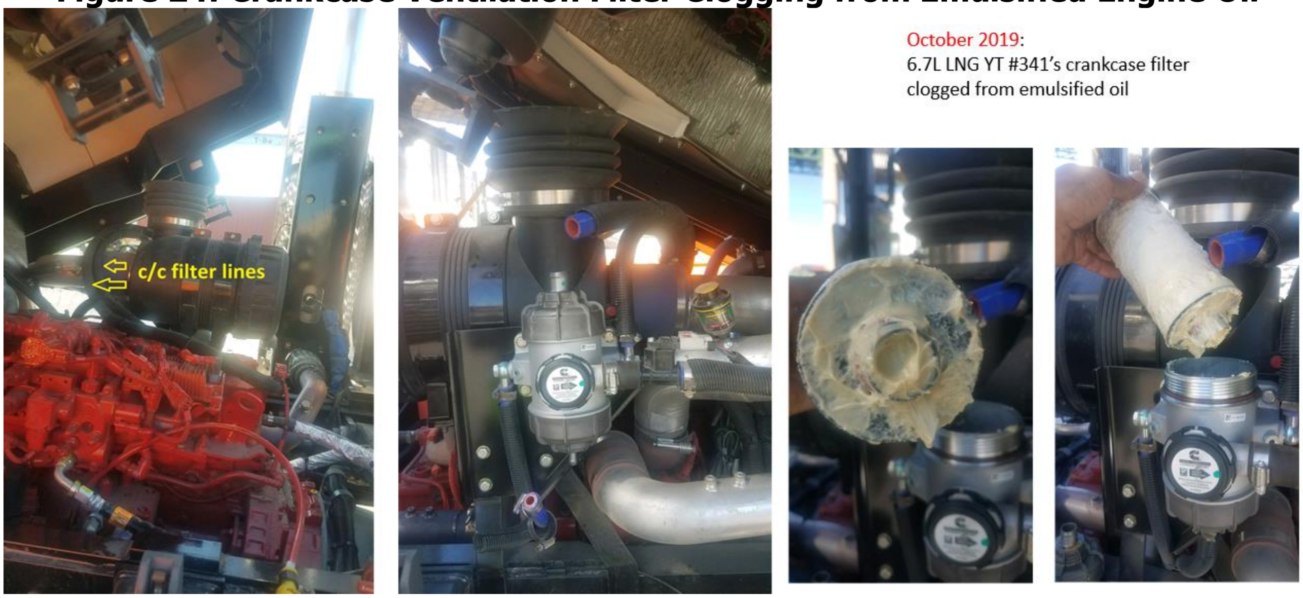
Figure 23. Newly Designed and Fabricated Ring on Catalytic Converter

This shows Capacity’s newly designed stainless steel ring that made the LNG tractors’ catalytic converters more durable and robust.

Photo: Capacity

One major problem at Everport was first encountered on one of the 6.7L LNG yard tractors. In Q3 2019, Harbor Diesel responded to a diagnostic signal from unit #LN0341 indicating it had excessive engine crankcase pressure. When the mechanic removed the engine's crankcase filter, it was found to be completely clogged with emulsified oil. In addition, the mechanic found other engine parts related to the crankcase ventilation system (CCV) to be problematic. Figure 24 provides photographs of this emulsification and CCV clogging problem, as documented by Harbor Diesel's mechanic working with a Cummins Field Engineer.

Figure 24: Crankcase Ventilation Filter Clogging from Emulsified Engine Oil



Documentation of 6.7L LNG tractor #LN034's problem with clogging of the crankcase ventilation filter with emulsified oil, which was resolved through cooperation between Capacity and engine OEM Cummins.

Photo Credits: Harbor Diesel

The following summarizes comments and findings from Cummins personnel about the cause of this engine oil emulsification and filter clogging problem, and how the problem was resolved.

- Diesel oil has additives to attract and hold soot that collects in the oil. If diesel oil is used (by mistake) in a natural gas engine (which has no soot), these additives emulsify with water molecules.
- Emulsifications are normal in natural gas engines; however, they become excessive if the engine is not routinely operated at sufficiently high load to achieve normal operating temperature.
- CWI's B6.7N and L9N engines at the demonstration cite should use only oils meeting specifications outlined in Cummins Engineering Standard (CES) for natural gas engines (CES 20092). This specification "requires a much stronger antioxidant combination to provide protection at the high temperatures experienced in modern (stoichiometric) natural gas engines." [14]

[14] Cummins Westport, Inc., "CWI Product Information Bulletin – Natural Gas Engine Oils," April 2018, https://www.cumminswestport.com/content/840/CWI%20Product%20Information%20Bulletin%20-%20Natural%20Gas%20Engine%20Oils_%20April%202018.pdf.

- The demonstration LNG tractor with its CCV filter plugged (LN0341, shown above) appeared to have an incorrect type of oil filter, and possibly the wrong type of engine oil.
- ECM images confirmed this LNG yard tractor (and others) had a high incidence of idle time (46 percent); Everport confirmed it was idled and moved (without load) around the demonstration site frequently, while awaiting opening of the LNG station.
- Cummins requires that CCV filters on its natural gas engines use blow-by ("breather") hoses that are properly insulated, to prevent freezing and reduce heat transfer. CWI supplies such hoses with the CCV kits in its ISB6.7G engines, but it appeared correctly insulated hoses were not installed on the 6.7L LNG yard tractor's engine that experienced the excessive oil emulsification and plugging problem at Everport. This problem also occurred in some of the 8.9L LNG yard tractors.
- The problem was resolved through cooperative efforts between Cummins, Harbor Diesel and Everport; they collaborated to change the engine oil and CCV filters (equipped with insulated breather hoses) on all 22 LNG yard tractors, as a preemptive measure and to ensure compliance with CWI requirement CES 20092.

Comments on Demonstration from Capacity

In July 2020, GNA conducted an initial telephone interview with staff from Capacity, including its Director of Engineering. GNA then conducted follow-up calls and emails with Capacity staff to further document the OEM's observations and "lessons learned" from participating in PIR-16-016.

Table 11 summarizes Capacity's comments to GNA about the value of the demonstration, specific to perceptions on the commercial viability of the two proof-of-feasibility "right-sized" TJ9000 LNG yard tractors with the smaller B6.7N CWI engine. Comparisons were made to Capacity's baseline product – the TJ9000 with a Cummins QSB diesel engine – and the 20 TJ9000s with the 8.9L L9N engine.

Table 11: Summary of Capacity's Comments on Precommercial Liquefied Natural Gas Yard Tractors

Topic for Comparing LNG Tractors	Summary of Capacity Engineering Departments Comments
Relative Fuel Efficiency	• 1st-gen LNG YT w/ CWI 6.7L engine is significantly more fuel efficient than 8.9L YT • L9N requires much-larger cooling fan (significantly higher auxiliary power requirement)
Relative Performance and Utility of 6.7L LNG YTs	• B6.7N is more suitable for MTO applications than L9N • LNG YTs (both types) have > wheelbase than diesel YTs to accommodate LNG tanks • Increases turning radius of LNG units; < wheelbase needed to meet MTO needs • Cab improvements planned for potential future natural gas tractor models ✓ Cab floor "bump" (cited as a tripping hazard by drivers) will be eliminated ✓ Other ergonomic and functional changes to be explored, based on feedback
Warranty Repairs and Other Issues Related to Technological Robustness	• Warranty issues presented learning experience; problem incidence improved over time • Harbor Diesel worked well to conduct warranty repairs for Capacity (on all 22 LNG YTs) • Important lessons learned / results obtained (Capacity and entire team) ✓ Oil emulsification issue: resolved by working with Cummins ✓ Key fix: switch to insulated hoses used in crankcase ventilation system ✓ Capacity, Everport, Agility improved robustness of onboard fuel system package ✓ Capacity redesigned standard exhaust system supports (location and robustness) ✓ Capacity repaired catalytic converter durability issues; fixed in-house, due to high cost of replacement units ($15,000 each) and long lead times ✓ Some problems were common to all 22 LNG tractors; all were resolved ✓ No further problems occurred on any systems after redesign and/or replacement

Topic for Comparing LNG Tractors	Summary of Capacity Engineering Departments Comments
LNG Tanks / Onboard Fuel Storage / CNG vs. LNG	• Capacity may pursue CNG option if/when it pursues full commercialization ✓ LNG has range / shift endurance advantage ✓ CNG has potential advantage on tank weight and packaging, fuel storage maximum ✓ CNG tank provides potential bridge to fuel cell yard tractors (compressed hydrogen)
Overall unit rating	• Compared to Capacity's TJ9000 with CWI L9N engine, TJ9000 with B6.7N is: ✓ Significantly more fuel efficient ✓ Proven to meet POLA MTO operational needs, likely at lower capital cost ✓ Likely pathway for commercialization of natural gas YTs (if pursued further)
Value of PIR-16-016 Funding Towards Potential B6.7N Tractor Commer-cialization	• Provided Capacity with opportunity to gain hands-on learning and tech transfer about heavy-duty off-road NGVs • Funding was instrumental to better understand fuel-technology pathways for NZE / ZE yard tractors • Helped choice to also pursue potential battery-electric and fuel cell YT models

Source: GNA and Capacity Engineering staff

Gas Composition Sensor Development and Testing

In parallel with the LNG yard tractor demonstration, the UCR team further developed and tested emerging technology designed to sense the composition of natural gas and detect "out-of-specification" fuel as it flows into the engine. This can enable real-time engine adjustments to compensate for specific gas constituents that are out of specification and have potential to cause performance and/or emissions issues.

Specifically, for a given natural gas source, UCR's sensor technology predicts methane index / methane number (MI/MN) and Wobbe index (WI), through a combination of thermal conductivity and sound velocity measurement technology. Under PIR-16-016, UCR enhanced this fuel quality sensor from an earlier version that solely measured WI. The UCR team developed a new version to measure MI/MN, providing a more critical metric to better understand the impacts of fuel quality on engine operation and combustion stability. The enhancements included improved measurements for thermal conductivity and the addition of a sound velocity measurement.

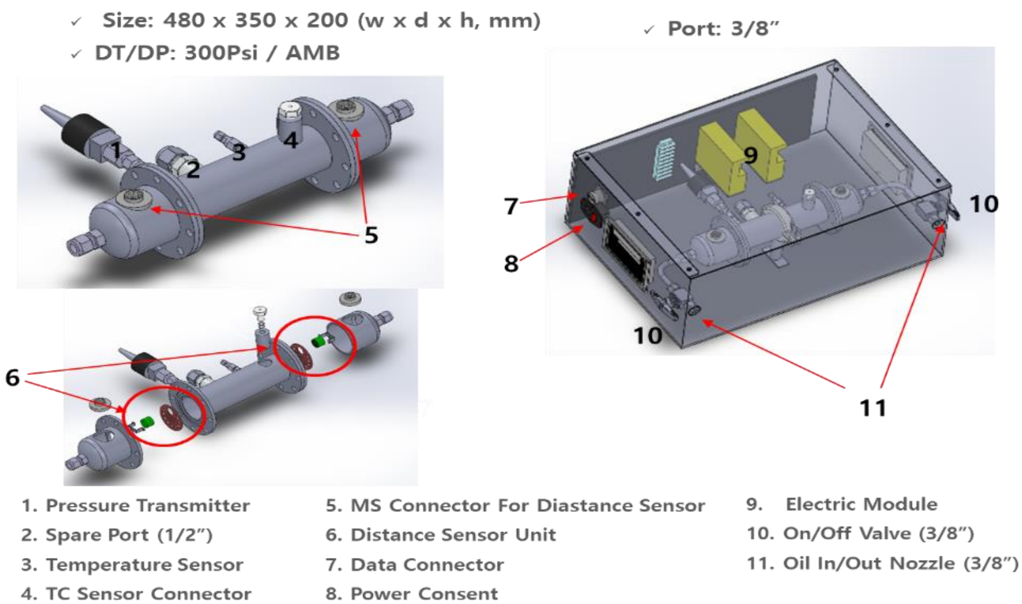
This section describes work by the UCR team to conduct bench-scale validation testing on the fuel composition sensor. Presented below are highlights about the sensor testing hardware, UCR's experimental methods, the mathematical algorithms used with the sensor to calculate MI/MN, and the test results. Full details are available (upon request) in UCR's September 2019 report for this work, *Gas Composition Sensor Development and Bench Testing*.

Appendix A-E provides extensive details about UCR's chassis dynamometer testing while using variable gas blends, which followed on to the benchtop testing. Specifically, UCR performed chassis dynamometer emissions testing on one 6.7L LNG yard tractors while using numerous multiple natural blends simulating gas composition variations heavy-duty NGV fleets might encounter in real-world use. For each gas blend, UCR measured impact on emissions and performance. As described in the Appendices A-E, this UCR work helped further inform whether and how fuel sensor technology can help heavy-duty NGVs make real-time adaptations that successfully mitigate episodes of poor fuel quality.

Design and Schematic of Gas Composition Sensor Unit

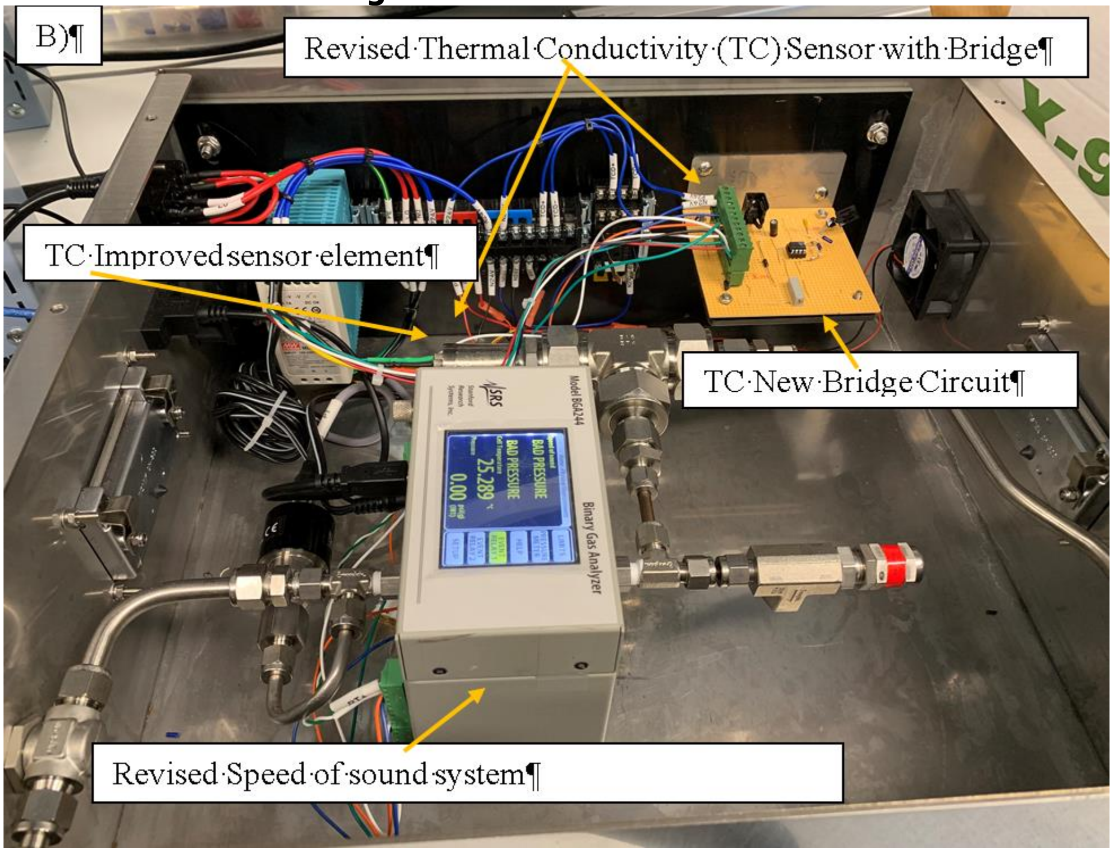
The UCR team designed and built a sensor test unit and bench-top evaluated it, using a variety of different natural gas blends under controlled temperature and pressure conditions. The test chamber for the sensor test unit is centrally located in the unit, and includes test ports for a temperature sensor, pressure transmitter, distance sensor, thermal conductivity sensor, and a speed of sound measurement system. The sensor testing unit/sensor schematic is shown in Figure 25. Figure 26 shows the sensor test unit.

Figure 25: Sensor Test Unit Schematic



Source: UCR CE-CERT

Figure 26: Sensor Test Unit



Source and Photo Credits: UCR CE-CERT

Test Methodology and Limitations

Prior to running the bench tests, the UCR team performed calibrations for each of the physical sensors, including Pressure, Temperature, Thermal Conductivity, and Sound Velocity. The thermal conductivity detector filament resistance was initially calibrated against temperature using a Low MN Gas. From this, the UCR team developed a calibration curve based on the voltage measurement from the filament, with the corresponding polynomial equation being was used for the thermal conductivity calculation.

UCR's experimental setup involved running several natural gas blends through the test chamber at various pressures and temperatures using a LabVIEW-based control program. Two main steps were used to determine methane number from the experimental sensor measurements. In the first step, UCR developed a database of MN, thermal conductivity, and speed of sound measurements for a range of natural gas blends with different gas composition – and under different pressure and temperature conditions. Table 12 provides a small portion of the large relational database that UCR developed for this process.

Table 12: Portion of Relational Database Developed by University of California, Riverside

Composition						Temp. (K)	Pressure, bara (psia)	Thermal Conductivity (W/m K)	Sound Velocity (m/s)	MN
CH_4	C_2H_6	C_3H_8	Iso-C_4H_{10}	N_2	CO_2					
0.828	0.045	0.088	0.012	0.027	0.000	26	6.89 (100)	0.03995	416.1	62.7
0.828	0.045	0.088	0.012	0.027	0.000	26	3.45 (50)	0.03692	412.3	62.7
0.828	0.045	0.088	0.012	0.027	0.000	26	1.22 (17.7)	0.03454	409.2	62.7
0.835	0.108	0.027	0.002	0.027	0.000	26	6.89 (100)	0.03211	419.9	69.5
0.835	0.108	0.027	0.002	0.027	0.000	26	3.45 (50)	0.03192	418.1	69.5
0.835	0.108	0.027	0.002	0.027	0.000	26	1.22 (17.7)	0.03183	417.6	69.5
0.872	0.045	0.044	0.012	0.027	0.000	26	6.89 (100)	0.03746	428.2	71.1
0.872	0.045	0.044	0.012	0.027	0.000	26	3.45 (50)	0.03583	425.3	71.1
0.872	0.045	0.044	0.012	0.027	0.000	26	1.22 (17.7)	0.03446	422.9	71.1
1.000	0.000	0.000	0.000	0.000	0.000	26	1.22 (17.7)	0.03405	450.0	100

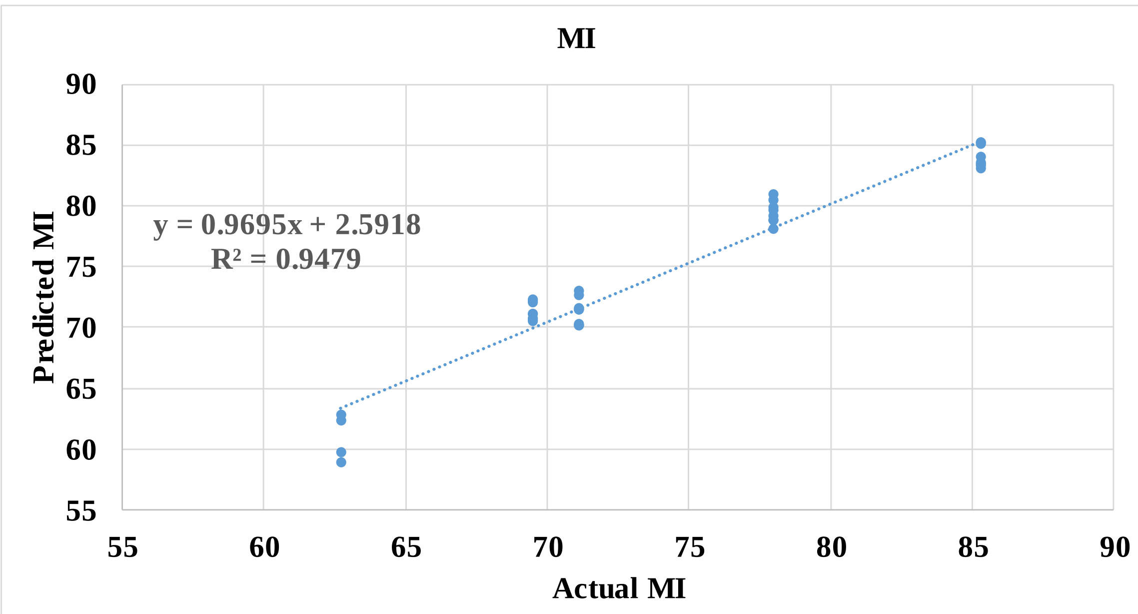
Source: UCR, "Gas Composition Sensor Development and Bench Testing," September 2019.

Using this database, UCR developed a regression relationship between the different measured parameters (specifically temperature, pressure, thermal conductivity, and sound velocity) and MN. This in turn enables the sensor technology to identify gases with different compositions, including those with "out-of-spec" constituents sometimes found in gas of poor quality. With ability to identify gas composition in real-time (and with sufficient accuracy), heavy-duty natural gas engines can be enabled to compensate when fuel of poor quality is encountered.

Results and Potential Benefits

Results from bench testing the sensor unit are shown in Figure 27. These results are based on 36 test combinations, which included six test gases tested at four pressures each (18, 30, 50, and 100 psia). The results are based on experimental values of thermal conductivity measured with version 01 of the sensor coupled with estimates of the sound velocity based on the replacement sound sensor in version 02 of the sensor.

Figure 27: Correlation Between Actual and Predicted Methane Index from Test Gases



Source: UCR CE-CERT

These results indicate that predictions of MN within 10 percent of the actual MN of a test gas can be obtained. The UCR team discussed these results with appropriate experts at CWI and Cummins. While these OEM representatives considered the results to be promising, they suggested that additional improvements will be needed before the sensor could be ready for commercial applications. In particular, Cummins suggested that predictions ideally within 2 percent – and in a worst-case scenario up to 5 percent – of the actual value would be required for commercial application. The UCR team concluded that additional improvements to achieve these higher accuracy goals will be part of future research on the sensor development. This could include enhancing and expanding the database model and improving the accuracy for the different measurements, such as thermal conductivity and sound velocity.

Other elements of the original testing plan (Task 4 of the overall project) included for UCR to model performance of the sensor with combustion modeling tools, integrate the sensor into a natural gas test engine, and demonstrate sensor based control strategy using hardware in the loop system over a range of fuel composition and operating load points. However, UCR's discussions with TAC members – specifically engineers from CWI and Cummins – indicated that hardware in the loop demonstration would not be necessary, as integrated engine control improvements would not be related to the sensor. The sensor would instead provide the following benefits:

1. Prevention of engine knock (longer life, lower emissions, fuel consumption and GHG).
2. History of engine use and fuel quality passing through engine.
3. Improved future designs based on ability to learn how engines are used.
4. Ability to consider widening fuel quality specifications based on sensor feedback.
5. Possibility to consider hydrogen injection into the fuel stream for future fuel infrastructure decisions.

Based on these various results and finding, UCR refocused its efforts on improving the sensor design through an upgraded sound speed sensor and conducting emissions laboratory experiments to evaluate the impacts of poor fuel quality on vehicle performance. This work was done through chassis dynamometer tests, as described in the next section.

Gas Sensor Technology/Knowledge/Market Transfer Activities

Efforts under this project to help heavy-duty natural gas engines accept / compensate for gas of variable quality – as may be encountered by off-road NGVs operating close to the site of RNG production – can help achieve wider usage of heavy-duty NGVs, while helping to continue expanded use of RNG. Project results have been – and will be further – disseminated via a variety of forums/media, including technical papers, meetings, presentations, and discussions with related stakeholders. For example, results have already been incorporated into two technical papers that have been published in peer review journals (see References section on page, Roy et al., 2018, 2019). As further discussed in the main section of this report about Technology/Knowledge Transfer (Chapter 4), the GNA-UCR team uses a variety of specific mechanisms and avenues to disseminate these and other project results.

Chassis Dynamometer Emissions Testing

The UCR team planned and conducted a suite of chassis dynamometer emissions tests. All tests were based on the Emissions Test Plan (completed in July 2019), and conducted at UCR's heavy-duty chassis dynamometer facility. Emissions measurements were obtained using the Mobile Emissions Laboratory (MEL). Full details about the testing facility and equipment, methodology, test cycles and results are provided in UCR's *Final Report for the 6.7L LNG, 8.9L LNG and Diesel Yard Tractor Emissions Testing*, included as Appendices A-E.

The following provides a summary of the testing conducted, and results obtained.

Yard Tractor Test Matrix

During this project demonstration, UCR conducted chassis dynamometer emissions testing on the following three different engine-fuel types, shown in Table 13 by chronological order of the testing.

Table 13: Three Yard Tractor Units Emissions Tested by University of California, Riverside

Test Tractor Identity	Engine / Fuel Type	Fuel Source for Testing	NO_x Emissions Certification / CARB Executive Order Number
Everport #LN0323	CWI 8.9L (L9N) / natural gas	• LNG (as-received from Everport / Clean Energy)	0.02 g/bhp-hr (OLNS, -90%) / A-021-0681
Everport #YT0310	Cummins 6.7L (QSB6.7) / diesel	• ULS Diesel (as-received from Everport)	0.2 g/bhp-hr (2010 standard) / U-R-002-0601-1
Everport #LN0341	CWI 6.7L (B6.7N) / natural gas	• LNG (as-received from Everport / Clean Energy) • CNG (specialty blends)	0.1 g/bhp-hr (OLNS, -50%)* / A-021-0678

OLNS = Optional Low-NO_x Standard

For details about each of these test tractors beyond those shown in the Table, refer back to Table 3 on page 12. All three engines were certified to a particulate matter (PM) level of 0.01 g/bhp-hr. Cummins "upgraded" #LN0341"s B6.7N engine to a 0.02 g/bhp-hr NO_x calibration, at the end of testing (see discussion below).

Source: GNA-UCR

UCR conducted additional, specialized testing on tractor #LN0341 (B6.7N engine). Specifically, it was tested while being fueled with natural gas of varying composition. The design, purpose, fuel blends and results of those tests are further discussed.

Each of the three yard tractors was tested over multiple speed/load driving cycles, designed to reproduce typical yard tractor use (YT cycles) at a major marine terminal. In addition, two other cycles were used to represent various HDV applications. Table 14 summarizes each of the six driving cycles used in the UCR testing.

Table 14: Driving Cycles Used for Emission Testing at University of California, Riverside

Test Cycle Name	Test Cycle Description	Simulated Test Weight (lbs)	Distance (mi)	Average Speed (mph)	Cycle Duration (sec)
YT_72K_CS	High Load / Cold Start	69,000	• 2.37	• 7.12	1200
YT_72K_2x	High Load / Hot Start	69,000	2.37 x 2	7.12	2400
YT_26K_CS	Low Load / Cold Start	26,000	1.76	5.27	1200
YT_26K_2x	Low Load / Hot Start	26,000	1.76 x 2	5.27	2400
CBD_3X	Central Business District	35,000	6.00	12.60	1680
SS Modes	Steady State	69,000	8.70	18.50	1695

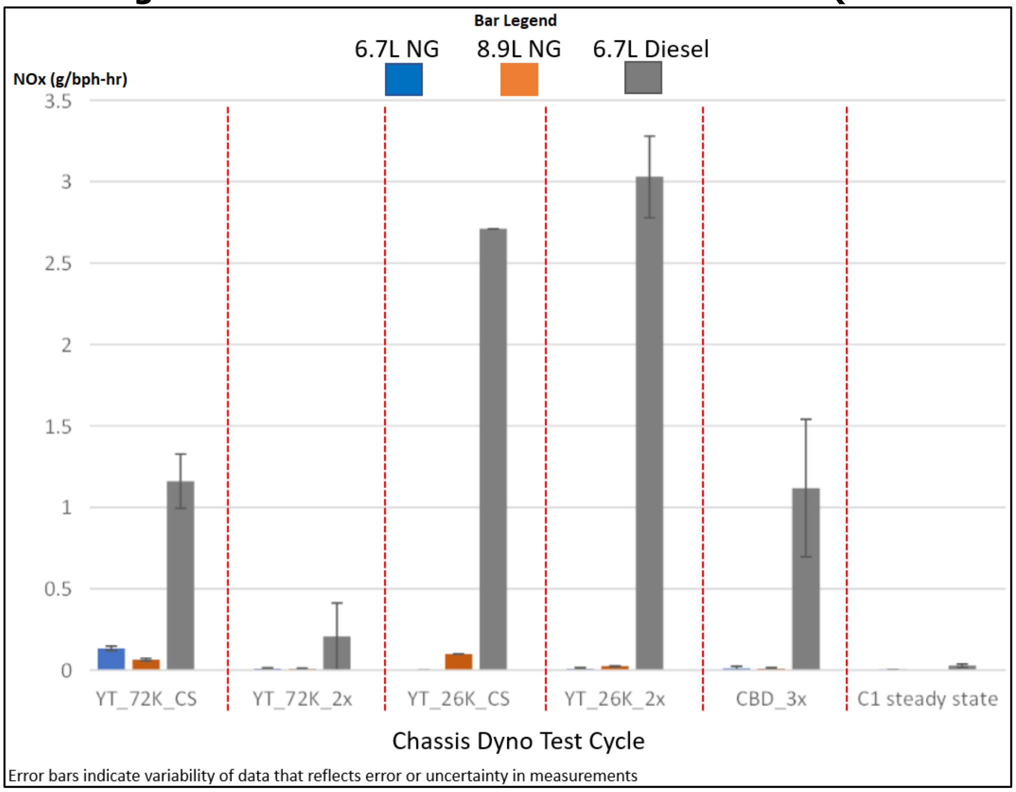
Source: GNA-UCR

Results and Key Takeaways

Comparison Between Natural Gas and Diesel Yard Tractors

The chassis dynamometer testing by UCR confirmed that NO_x emissions for natural gas yard tractors (of both types, with the B6.7N and L9N engines) *are significantly lower than those from a diesel yard tractor* with a state-of-the-art diesel emissions control system. Results are summarized in Figure 28.

Figure 28: Nitrogen Oxide Emissions for Test Yard Tractors (As-Received Fuel)



This graph compares NO_x emissions from the three tested yard tractors, with their as-received fuels while being driven over six different test cycles. As shown, NO_x emissions from the 6.7L LNG tractor (1st bar in cluster; blue) and the 8.9L tractor (2nd bar in cluster; orange) <u>were much lower than those from the 6.7L diesel tractor</u> (3rd bar in cluster; dark gray), across all six test cycles. The I-shaped bars at the top reflect error or uncertainty in each measurement.

Source: data from UCR; graph modified by GNA for clarity

Full details are provided in Appendices A-E. Highlights of UCR's testing include the following:

- Emissions for the diesel yard tractor were considerably higher than those for both LNG yard tractors, for all cycles.
- Average NO_x emissions for the three different test tractors ranged as follows:
  - **6.7L LNG yard tractor**: from 0.002 to 0.13 g/bhp-hr (0.014 to 0.730 g/mi)
  - **8.9L LNG yard tractor**: from 0.005 to 0.098 g/bhp-hr (0.025 to 0.491 g/mi)
  - **6.7L diesel yard tractor**: from 0.027 to 3.029 g/bhp-hr (0.150 to 12.739 g/mi)
- NO_x emissions from the two LNG yard tractors were consistent with their OLNS certification values. They produced most of their NO_x emissions during the initial

portions of the cycles with cold starts (i.e., before the three-way catalyst "lights off" at higher temperatures to maximize NO_x reduction). NO_x emissions throughout hot-engine portions of the test cycles were very low.

Emissions Testing with Variable Fuel Blends

As previously described, one project objective was to better understand the impact of variable-quality natural gas on the emissions and drivability of ultra-low-NO_x natural gas engines. Under this part of the chassis dynamometer efforts, UCR tested yard tractor #LN0341 (B6.7N engine) on multiple blends of natural gas. The intent was to determine – as a function of varying content for methane and other constituents – how susceptible the engine would be to engine knock during representative driving conditions. As shown in Table 15, the LNG tractor was tested repeatedly to measure impacts of six different natural gas blends. Methane content of the blends ranged from a low of 77 percent methane (by volume), to a high of 94 percent. The blends included variable percentages of ethane (C_2H_6), propane (C_2H_8), butane (C_4H_{10}), nitrogen (N_2), oxygen (O_2) and carbon dioxide CO_2). The intent was to simulate less-than-ideal gas compositions that can be found in real-world use for heavy-duty NGVs. Emissions testing was conducted over the same cycles previously described.

Table 15: Natural Gas Blends for Variable Composition Testing (Vol.%)

Test Fuel	Methane Index	CH_4	C_2H_6	C_3H_8	C_4H_{10}	N_2	O_2	CO_2
1. As-Received LNG	83.2	93.0	6.72	0.03	-	0.17	<0.1	<0.1
2. RNG 1	92.6	93.6	-	-	-	3.7	0.5	2.2
3. RNG 2	101.2	91	-	-	-	1.9	-	7
4. Extreme Pipeline	70.7	77	12	5	1	-	-	5
5. Extreme MI	67.5	89.5	-	10.5	-	-	-	-

MI= Methane Index as determined from CWI, https://www.cumminswestport.com/fuel-quality-calculator; RNG = Renewable Natural Gas (simulated blend)

Source: UCR, citing blend specifications from Airgas

In summary, UCR's results indicated that – at least under this specific case of test parameters – there were no significant differences in criteria pollutant emissions or engine knock as a function of natural gas composition. This suggests that a methane index (MI) sensor may not provide emissions and/or performance-related benefits, in this yard tractor application. However, UCR found evidence suggesting that benefits could be realized for CWI's larger engines in other important heavy-duty NGV operations (on- or off-road). Specifically, UCR found that CWI's 8.9-liter L9N and/or its 11.9-liter ISX12N engines with "tighter calibrations and less knock margin" could potentially benefit from gas composition technology. Examples of potential benefits include reduced deterioration and improved warranty coverage. Thus, the UCR team concluded that the issue of fuel quality for heavy-duty natural gas engines will likely remain important and may warrant further investigation. If the sensor technology can achieve greater accuracy (within 2 percent) – and it can be commercially produced at an affordable cost – they concluded that fuel quality sensors could play a valuable role in expanded commercialization and deployment of heavy-duty NGVs.

Appendices A-E provide full details about these and other conclusions by the UCR team, including the emissions test plan, gas blends that were chosen and tested, the methods that were used, and all emission results.

Recalibration of B6.7N Engine to Ultra-Low-NO_x Performance

During the time that the UCR team was emissions testing the 6.7L LNG yard tractor (#LN0341), they worked with Cummins engineers to "upgrade" the B6.7N engine's NO_x performance. Specifically, through a process performed remotely by Cummins with on-site assistance from UCR staff – the team recalibrated the B6.7N engine to the "NZE" NO_x level of 0.02 g/bhp-hr.

According to representatives from Cummins and UCR, this process did not require hardware changes to CWI's B6.7N engine (there was no requirement to increase catalyst loading, and/or increase the size of the cooling system). The callout box below summarizes the procedure, according to a Cummins representative. This information can be useful for fleets that deployed HDVs with earlier versions of the B6.7N engine (in any application), which may have pre-dated the switch by Cummins to sell only heavy-duty natural gas engines that have been certified to the lowest-tier of CARB's OLNS.

Cummins Comments on Changes Performed to Recalibrate ISB6.7 G Engine to Lowest-Tier Optional Low NO_x Standard (0.02 g/bhp-hr) for Yard Tractor #LN0341 (December 2020)

- Cummins Engineering confirmed that a software change alone can "recalibrate" (earlier versions of the B6.7N) engine "to 0.02 g/bhp-hr NO_x."
- They noted that "the next round of released calibration updates" for this engine line (6.7L natural gas) "will include 0.02 g/bhp-hr NO_x performance."
- However, these engines "will not be technically certified to 0.02 g/bhp-hr NO_x." That would require "going back to CARB for recertification," which Cummins estimates is "not worth the expense."
- Cummins confirmed that after "releasing" this calibration, any in-use (B6.7N version) engine can be updated by an authorized dealer, using the Cummins "Insite" software. It is believed that there will be a relatively small fee to perform this update.

Source: Tom Swenson, Cummins Engine Company, private communication to GNA, December 2020.

After Cummins "reflashed" the 6.7L LNG yard tractor's engine from its factory NO_x calibration of 0.1 g/bhp-hr down to the NZE level of 0.02 g/bhp-hr, UCR conducted a subset of additional emissions tests. The objective as to compare NOx emissions under the new calibration compared to the original calibration. UCR found "no statistically significant changes" in NO_x emissions during hot-start modes of operation. Where there were NO_x emission differences during cold-start modes of operation, the overall difference in mass NO_x emissions was low. UCR staff concluded that – in a yard tractor type of application and testing cycle – the difference in NO_x mass emissions between the original 0.01 g/bhp-hr calibration compared to the reflashed 0.02 g/bhp-hr calibration was not materially significant.

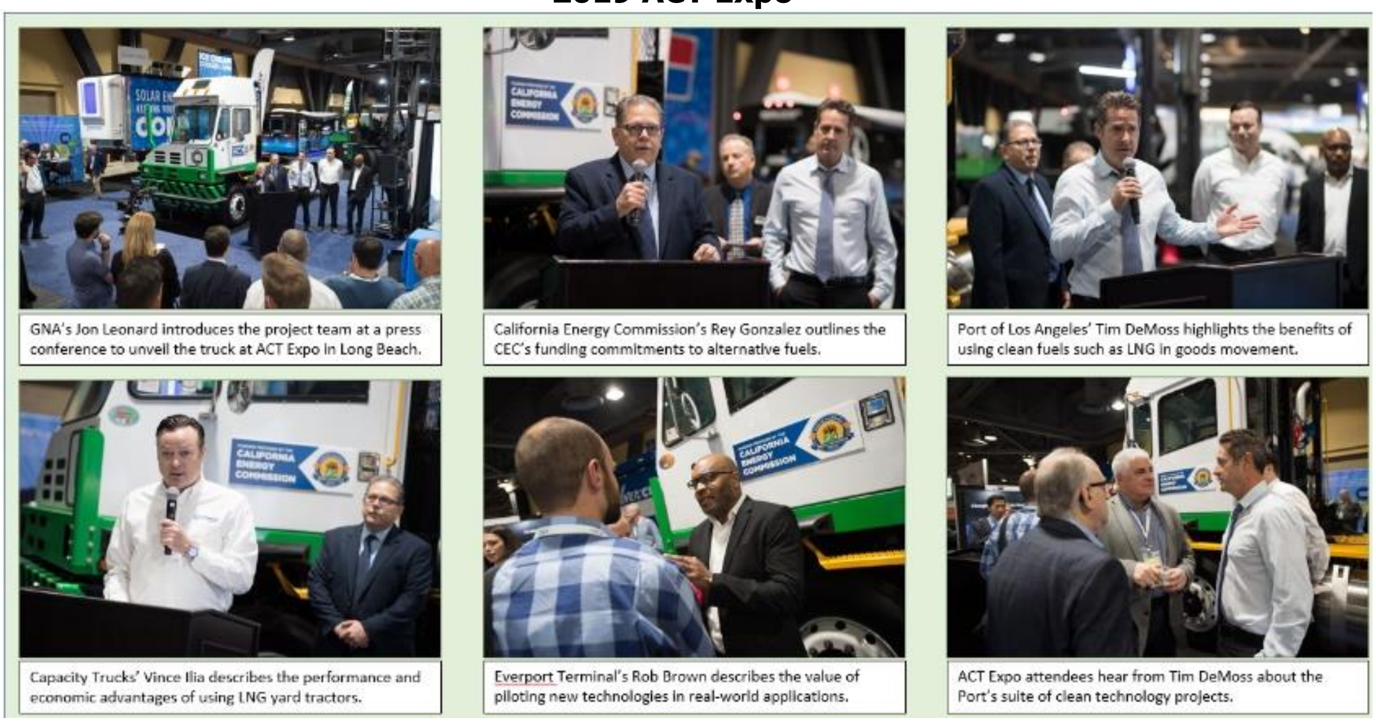
CHAPTER 4: Technology/Knowledge Transfer Activities

Over the project's term, the GNA-UCR team conducted a number of important activities to facilitate technology and knowledge transfer. Some of these efforts were discussed in previous sections, in the context of other project activities and accomplishments (such as the hands-on LNG training sessions that GNA conducted at Everport). Additional impactful technology and knowledge transfer activities are described below.

2019 ACT Expo Exhibition Display and Press Event

In April 2019, one "right-sized" LNG yard tractor was formally unveiled at the 2019 ACT Expo show in Long Beach, California. GNA was joined by representatives from the CEC, Capacity, POLA and Everport on the floor of the ACT Expo exposition, to hold a press conference and describe the merits of this proof-of-concept LNG yard tractor product line (Figure 29).

Figure 29: 6.7-Liter Liquefied Natural Gas Yard Tractor Unveiled at Press Event 2019 ACT Expo



GNA's Jon Leonard introduces the project team at a press conference to unveil the truck at ACT Expo in Long Beach.

California Energy Commission's Rey Gonzalez outlines the CEC's funding commitments to alternative fuels.

Port of Los Angeles' Tim DeMoss highlights the benefits of using clean fuels such as LNG in goods movement.

Capacity Trucks' Vince Ilia describes the performance and economic advantages of using LNG yard tractors.

Everport Terminal's Rob Brown describes the value of piloting new technologies in real-world applications.

ACT Expo attendees hear from Tim DeMoss about the Port's suite of clean technology projects.

Photo Credits: GNA Creative

ACT Expo is a major annual show that features and displays low- and zero-emission heavy-duty vehicles (on- and off-road). The 2019 show in Long Beach drew 4,000 attendees – about one fourth of whom were fleet representatives who largely operate heavy-duty vehicles. The show had 250 sponsors, exhibitors, and partners; 200 expert speakers; and eight co-located events.[15]

The audience make up – which was specifically targeted by GNA – included marine terminal operators and other interested fleets, as well as government representatives who help design and/or implement incentive programs for clean HDVs. Figure 30 provides an example of the Twitter feed that GNA used to announce the event and highlight useful information and sources.

Figure 30: Example of Twitter Feed and Link to Clean Tech News

Photo Credit: GNA Creative

Figure 31 shows the *ACT New Trucks Live* publication that GNA used to announce the press event and generate foot traffic on the Expo Hall floor. GNA featured this "right-sized" LNG yard tractor in this publication to generate maximum interest in the press event and static display in the exposition hall. This publication was distributed (at no additional charge) to thousands of conference attendees, including many who work at California MTOs like Everport.

[15] See https://www.actexpo.com/announcement/2019-act-expo-event-recap for details and highlights of this show.

Figure 31. ACT News Live Announcing Press Event in Expo Hall, April 2019

Photo and Production Credits: GNA Creative

Presentations at Natural Gas Vehicle Technology Forum

On two separate occasions, members of the GNA-UCR team presented details about and results from this project to attendees at the Natural Gas Vehicle Technology Forum (NGVTF). NGVTF is hosted by the National Renewable Energy Laboratory, in conjunction with the U.S. Department of Energy, the CEC, the South Coast Air Quality Management District, NGV America, and the Southern California Gas Company. This annual event provides "a focal point for discussions about data and research related to natural gas engines, vehicles, and infrastructure." Forum results are "used to develop next steps for research and development for natural gas vehicles and technology, regulations, market barriers, and opportunities."[16] The GNA-UCR team

[16] The National Renewable Energy Laboratory, "Natural Gas Vehicle Technology Forum," https://www.nrel.gov/extranet/ngvtf/.

presented at NGVTF events on February 21, 2018[17] and February 4, 2020[18]. Copies of the slide presentations are available upon request.

Host-to-Host Transfer of Design for Liquefied Natural Gas Tank Guards

One key project accomplishment occurred in Q3 of 2019, when interim host site CalCartage – with GNA's facilitation – assisted permanent host site Everport in the process to develop an engineering design for LNG fuel tank guards. As previously described, CalCartage was already operating LNG-fueled yard tractors when the two proof-of-concept Capacity LNG yard tractors arrived there in May 2019. Under a grant funding award from the Mobile Source Air Pollution Reduction Review Committee (MSRC), CalCartage received a fleet of nine LNG yard tractors in 2010. Those units were equipped with steel guards on each tractor's chassis that protected the LNG tank from denting and damage, in the event of collisions (which tend to be routine in busy container yards).

Although GNA was not able to corroborate the origin of (or design drawings for) the LNG tank guards at CalCartage (which were on Kalmar LNG tractors), CalCartage's onsite personnel immediately recognized the need to install LNG tank guards on the new LNG tractors from Capacity. With the two 6.7L LNG tractors on the verge of being transferred from interim host CalCartage to permanent host Everport, this began a series of communications between these two parties, with GNA facilitating. The result is summarized in Figure 32. CalCartage personnel assisted Everport's engineering staff and manufacturing shop to design, build and install LNG tank guards to the two 6.7L LNG tractors. Moreover, Everport built and installed the same LNG tank guard for all 20 of its 8.9L LNG tractors (received in July and August 2019).

[17] Natural Gas Vehicle Technology Forum 2018 Meeting Summary. https://www.nrel.gov/extranet/ngvtf/assets/pdfs/ngvtf-2018-summary.pdf.

[18] Natural Gas Vehicle Technology Forum 2020 Meeting Summary. https://www.nrel.gov/extranet/ngvtf/assets/pdfs/ngvtf-2020-summary.pdf.

Figure 32: Liquefied Natural Gas Tank Guard Technology Transfer from CalCartage to Everport

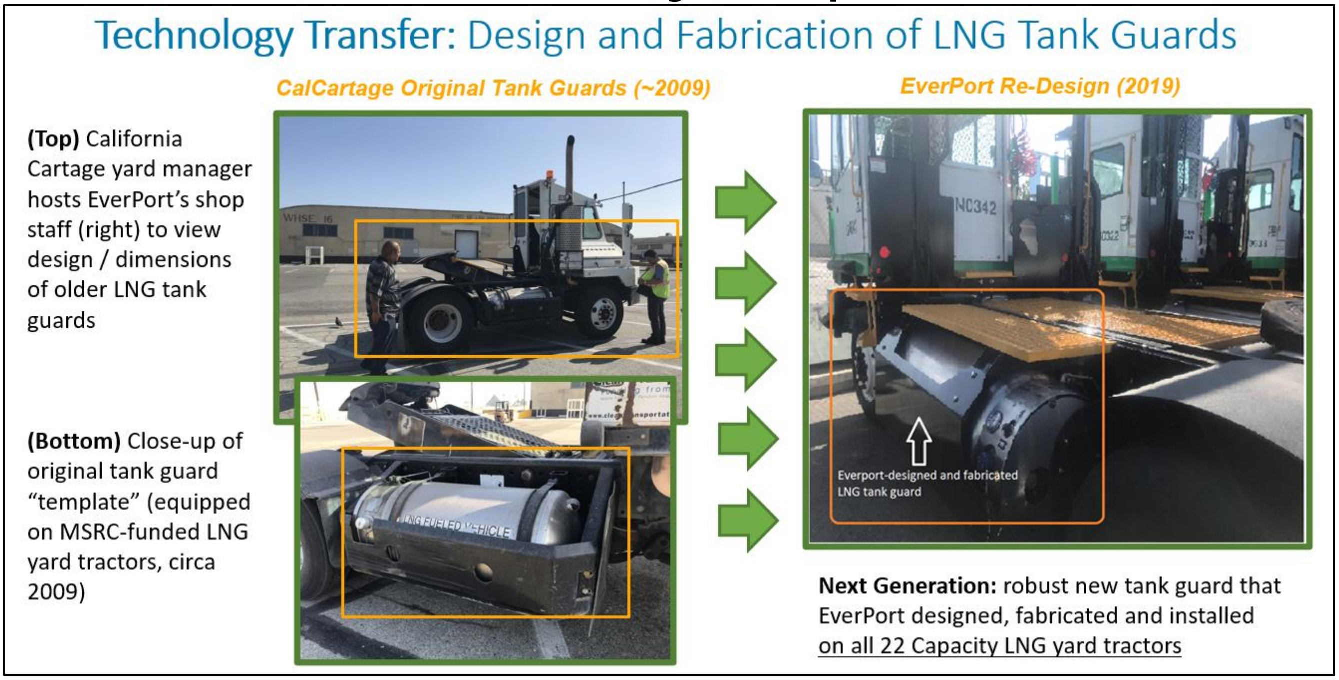
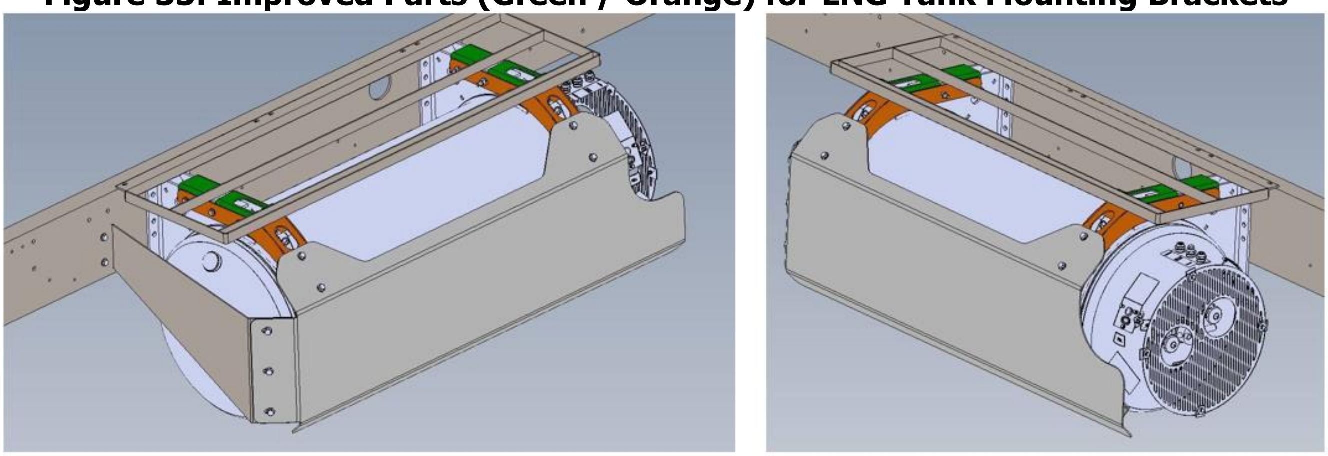


Photo Credits: Jon Leonard, GNA

In another important technology transfer effort at Everport, Capacity joined with Everport and partners such as Agility Fuel Solutions to design improved, more robust brackets that mount LNG tanks to each LNG tractor. After about 10 months of hard use at Everport, the original LNG tank brackets were experiencing failures (bolts and brackets). As shown in Figure 33, this team collaborated to design new LNG tank mounting brackets that could better withstand rugged operation typical of a major MTO environment.

Figure 33: Improved Parts (Green / Orange) for LNG Tank Mounting Brackets



The green and orange parts of the LNG tank mounting brackets were improved for robustness and durability.

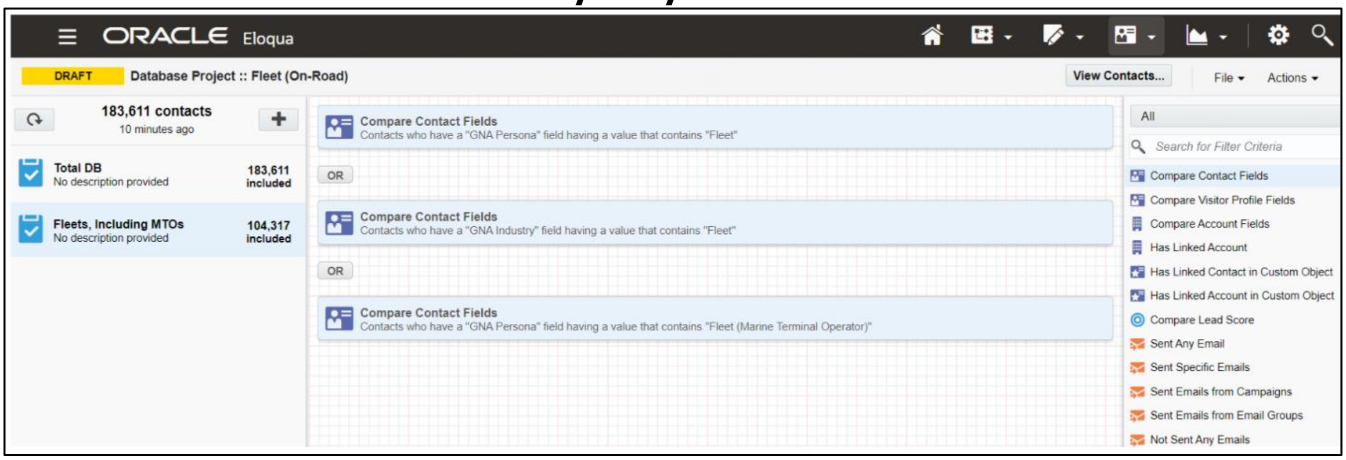
Source: Prepared by Agility, Provided to GNA by Capacity

Other Methods for Disseminating Project Results

Gladstein, Neandross & Associates Mailing List and Use of "Eblasts"

GNA maintains a robust fleet-and-transportation-oriented database with more than 180,000 contacts. As can be seen from Figure 34, this includes approximately one hundred thousand individual fleet contacts, most of which operate heavy-duty vehicles, including yard tractors used by MTOs at California ports.

Figure 34: Screenshot of Gladstein, Neandross & Associates Extensive Database for Heavy-Duty Vehicle Fleets



Source: GNA Programs Department

GNA strategically leverages this database for events and webinar marketing, customer relationship management, and other outreach efforts. Contacts are assigned into specific "Personas and Industries" bins to enable targeted outreach, and are routinely evaluated for readership/event attendance as part of GNA's strategy for optimal content engagement. In August 2020, GNA used this database to disseminate (via "eblasts") a courtesy copy of UCR's interim emissions testing report. GNA is using this same database and methodology to disseminate UCR's final emissions testing report (such as additional eblasts or mass emails to share the Appendices A-E for this final report). The database allows GNA to specifically target fleets and other types of stakeholders associated with commercialization and deployment of heavy-duty off-road vehicles. This includes all major California ports and their tenant MTOs, at which approximately 2,000 diesel yard tractors are currently still in operation.

LinkedIn

The GNA-UCR team uses LinkedIn as one avenue for disseminating project results. For example, in July 2020 GNA posted[19] a copy of UCR's newly released report for PIR-16-016, titled "Interim Report for the 8.9-liter LNG and Diesel Yard Tractor Emissions Testing" (which ultimately became Appendices A-E for this final report). This post has received more than 400 views.

[19] LinkedIn.com, post by Jon Leonard, July 2020, https://www.linkedin.com/in/jonathan-leonard-83713411/detail/recent-activity/shares/.

Figure 35: Gladstein, Neandross & Associates LinkedIn Post to Disseminate Emissions Testing Report

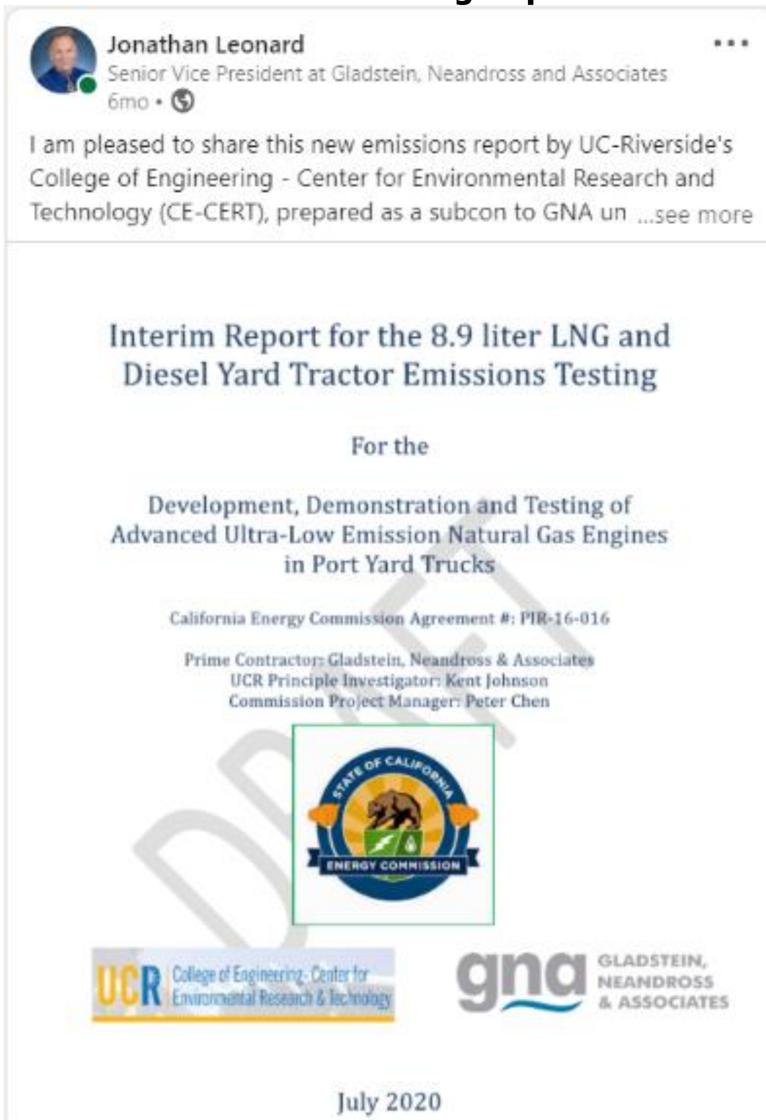
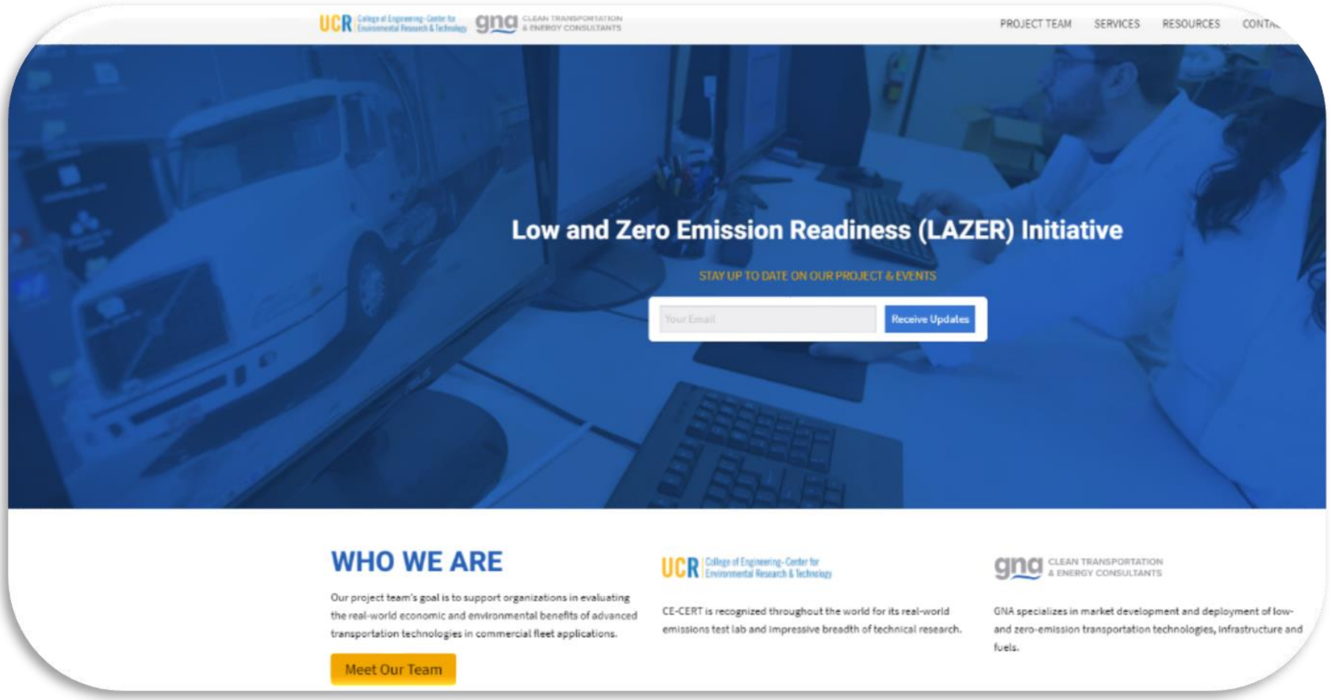


Image Credit: Jon Leonard, GNA

LAZER Initiative

In April 2019, GNA collaborated with UCR to form the Low and Zero Emission Readiness (LAZER) Initiative. Through LAZER (www.lazerinitiative.org), GNA and UCR combine to support organizations in evaluating the real-world economic and environmental benefits of advanced transportation technologies in commercial fleet applications. The final report for PIR-16-016 – as well as other project reports and deliverables – are posted or will be posted on this web site, with related announcements by GNA and/or UCR directing web traffic to the site using key search words and phrases.

Figure 36: Landing Page of Joint LAZER Initiative



Website Design and Image Credit: GNA Creative

CHAPTER 5: Conclusions and Recommendations

Conclusions

This project has helped advance the development and commercialization of heavy-duty natural gas engines and vehicles for off-road applications. In addition to important ways the project has helped provide benefits to ratepayers, it has successfully resulted in the following milestones and accomplishments:

- Designed, built and deployed two "first-of-their-kind" LNG-fueled yard tractors equipped with an emerging 6.7L natural gas engine (B6.7N) certified to CARB's Optional Low-NO_x Standard.
- Enabled yard tractor OEM Capacity to corroborate expectations that the CWI B6.7N is "right-sized" for this application, i.e., capable of meeting rigorous performance requirements of marine terminal operators, while improving fuel economy and efficiency relative to CWI's 8.9-liter L9N natural gas engine (designed primarily for on-road heavy-duty NGV applications).
- Provided Capacity with valuable "lessons learned" about the company's evolving endeavors to develop, improve and potentially commercialize ultra-low-emission yard tractors using LNG (or CNG), as well as zero-emission fuel cell yard tractors that would also use compressed gaseous fuel (hydrogen).
- Provided engine OEM CWI/Cummins Inc. with valuable documentation and end user inputs about product design and durability for two of its three commercially available heavy-duty natural gas engines (the B6.7N and L9N) while being used in rigorous duty at a major California marine terminal.
- Enabled successful technology and knowledge transfer among OEMs, end users, and various other types of stakeholders about heavy-duty natural gas engines, NGVs, on-board fueling systems, fuel safety/handling, and fueling equipment and procedures.
- Provided new chassis dynamometer emissions test data further corroborating that heavy-duty natural gas yard tractors with engines certified to CARB's Optional Low-NO_x Standards (in particular, the NZE level of 0.02 g/bhp-hr) have in-use emissions that 1) are consistent with their ultra-low-NO_x certification values, and 2) can be an order-of-magnitude lower than in-use NO_x from state-of-the-art diesel yard tractors.
- Helped highlight an apparent remaining barrier for wider use of LNG (or CNG) yard tractors: the current lack of a practicable system to deliver natural gas fuel to yard tractors, to emulate "wet hosing" procedures used efficiently and effectively by MTOs to nightly fuel diesel yard tractors. Under the fueling system for the demonstration, it was necessary to drive each of 22 LNG tractors to the centralized LNG station. This was identified by host site personnel as a major obstacle to achieving two full shifts of LNG tractor operation. Notably, the same refueling infrastructure barrier also exists for refueling heavy-duty fuel cell vehicles with hydrogen, or recharging heavy-duty battery-electric vehicles with electricity. Solving this problem for heavy-duty NGVs could help

advance the potential for a similar solution for other HDVs with NZE or ZE fuel-technology platforms.

- Helped better understand the need for – and potential benefits and limitations of – natural gas composition sensor technology as a means to improve the commercialization potential of heavy-duty NGVs, by sensing gas of poor quality and enabling engine adjustments to improve emissions and/or performance.
- Facilitated CWI's decision to certify the B6.7N engine at 0.02 g/bhp-hr as an NZE engine option for off-road applications, including yard tractors.
- Facilitated and enabled Capacity to discover that a 6.7L LNG yard tractor is a "less costly, more efficient product" for MTOs to displace diesel yard tractors and achieve near-zero levels of NO_x emissions.
- Facilitated and enabled Capacity's decision to consider offering future natural gas yard tractor models that can use either LNG or CNG as their on-board fuel storage system, with the two types being essentially interchangeable for packaging on the yard tractor chassis.
- Helped support a key goal of the San Pedro Bay Ports: to deploy, test and characterize the feasibility of NZE and ZE yard tractor fuel-technology platforms by providing first-of-a-kind MTO operational experience and comparative testing versus baseline diesel yard tractors.

Recommendations

Expanded Testing and Deployment of Natural Gas Yard Tractors

- The San Pedro Bay Ports should use results of this project to help inform their next "Feasibility Assessment" for cargo-handling equipment (to be prepared in 2021). Specifically, this project can help provide quantitative and qualitative information relating to each of the following key areas that are likely to be updated in the next Feasibility Assessment:
  - Commercial availability.
  - Technical viability (technology readiness level).
  - Operational feasibility including fueling infrastructure.
  - Economic workability, including availability of incentive funds under changing benchmarks.
  - In-use emissions performance vs baseline diesel.
- MTOs (and industry associations), as well as the San Pedro Bay Ports, can apply lessons learned from this project to improve outcomes of other demonstrations involving emerging NZE and ZE off-road vehicles at marine terminals, such as:
  - The need for fuel tank / energy storage protective cages.
  - Effective ways to conduct hands-on fuel handling and safety training.

  - Methods to improve pre-commercial HDV component ruggedization (for example, improved designs for the fuel tank, brackets, and connectors).
  - The need for measures to prevent tampering with datalogger systems during field demonstrations.
  - The importance of developing improved ways to fuel heavy-duty NGVs (and other types of NZE / ZE fuel-technology architectures) that emulate diesel refueling procedures (bringing fuel to parked HDVs), to improve operational efficiency and better enable two shifts of operation per day.
- The CEC may wish to join with other appropriate agencies (such as the South Coast Air Quality Management District) and stakeholders involved with natural gas fueling infrastructure to investigate barriers and opportunities for practical, affordable systems capable of "wet hosing" heavy-duty off-road NGVs, especially in applications where bringing fuel to parked vehicles is the standard practice. Such work could have potential applicability to fueling hydrogen fuel cell vehicles.

Continued Work on Natural Gas Quality and Composition Sensor Technology

- The CEC may decide to join with other appropriate agencies and stakeholders to further evaluate natural gas fuel quality at remote in-state sites that are now producing (or will produce) RNG for use in heavy-duty NGVs. This can help the CEC further understand the extent of out-of-specification gas in California, and therefore determine the need for further development and incorporation of on-board gas composition sensor technology.
- UCR should consider joining with appropriate government agencies like the CEC and U.S. Department of Energy – in conjunction with industry stakeholders like Cummins Inc. – to improve fuel sensor technology accuracy from the demonstrated value (within 10 percent) down to within 5 percent – and more optimally, within 2 percent. Research and development efforts could focus on improving the underlying methane number database as a function of 1) thermal conductivity and the speed of sound; and 2) improving individual electronic components.

CHAPTER 6: Benefits to Ratepayers

Advancement of Commercialization for Near-Zero Emission Yard Tractors

The demonstration conducted under this project (PIR-16-016) has provided valuable experience and information that has clearly helped advance commercialization of NZE yard tractors. Specific positive impacts that have been realized are further described below, by various project partners and stakeholders:

Capacity – This project provided Capacity with invaluable experience to compare two proof-of-feasibility TJ9000 LNG yard tractors powered by CWI's B6.7N medium-heavy duty natural gas engine, while operating in revenue service at a major marine terminal. These two pre-commercial tractors were compared to 20 pre-commercial Capacity TJ9000 yard tractors powered by CWI's larger L9N engine. The L9N engine was Capacity's early choice based on its first-of-a-kind NZE emissions profile, but not necessarily for its efficiency and/or utility in the application. By comparing these two natural gas engines in otherwise-similar LNG-fueled TJ9000 yard tractors, Capacity engineers were able to document that the smaller B6.7N is "right-sized" and the better engine choice should Capacity choose to proceed with full commercialization of natural gas yard tractors. Moreover, the project enabled Capacity to document initial problems with parts and systems equipped on these "Gen 1" LNG tractors (of both engine sizes), providing the engineering team with vital information to refine design, lower costs, and improve product durability and reliability.

Everport Terminals – As the permanent host site of this project, Everport gained (and continues to gain) essential experience in evaluating NZE natural gas yard tractors of two engine sizes. In addition to this head-to-head natural gas engine comparison, they have been able to compare competing fuel-technology platforms (state-of-the-art diesel and zero-emission battery-electric technology). Everport personnel (and those from its union partner PCMC) learned techniques and procedures to improve the performance and operation of its LNG yard tractor fleet. Everport participated in essential hands-on LNG safety training that helped its employees and unionized partners understand that natural gas is a safe, ultra-clean-burning yard tractor fuel. It helped them better understand and fully appreciate that natural gas yard tractors do not emit diesel particulate matter. This important health benefit not only directly improves the lives and health of people who work where heavy-duty vehicles and equipment are operated; it also makes them more likely to support a large-scale transition to much cleaner alternative fuel platforms like NZE natural gas tractors.

Cummins / Cummins Westport – As the manufacturer of these two heavy-duty natural gas engines (B6.7N and L9N) demonstrated at Everport, Cummins gained valuable experience with its heavy-duty natural gas engine technology while being used in the demanding, rigorous operational environment of a major marine terminal at the San Pedro Bay Ports. Cummins understands that to continue making and selling heavy-duty alternative fuel-technology powerplants for off-road applications in California, it must continually drive down NO_x and PM emissions to very low levels, while also pursuing systems with no direct emissions (ZE architectures). This project enabled Cummins to further improve its NZE off-road natural gas engines, while also gaining important insights about how to build ZE architectures (e.g., hydrogen fuel cell systems) in the future that have commonality and synergy with natural gas systems.

Moreover, the project helped convince Cummins to certify its B6.7N engine down to the same lowest-tier OLNS level (0.02 g/bhp-hr.) that was initially achieved with the L9N engine. In addition to enabling a "right-sized" NZE engine option to power yard tractors, this provided an NZE option for multiple other HDV types, because the B6.7N also powers medium-duty trucks, shuttle buses, and school buses.

Other Natural Gas Supply Chain Constituents – This project has helped vendors – including but not limited to Clean Energy, Agility Fuel Systems, Harbor Diesel, and Ugly Brothers – gain valuable field experience and understanding about how to provide effective support services for heavy-duty off-road NGVs. This includes better ways to fuel vehicles (e.g., the need to consider ways to "wet fuel" NGVs, like diesel tractors), to improve fuel system design and safety (for example, more-robust exhaust brackets and inclusion of LNG tank guards), improve scheduled maintenance procedures (for example, ensure that correct engine oil is used instead of diesel engine oil), and troubleshoot field problems (for example, repairing failed LNG pressure valves and avoidance of emulsifications forming in crankcase ventilation filters).

Air Pollutant Reductions from Wider Use of Near-Zero Emission Yard Tractors

The emissions testing performed by UCR helped advance the knowledge base of NZE yard tractors' NO_x and PM emissions performance *in real-world use*, compared to their ultra-low certification emission values. It also provided new data further documenting that in-use emissions from natural gas yard tractors are *much lower* than those from diesel yard tractors. Expansion of this knowledge and database helps clearly demonstrate to California ratepayers that development, commercialization and wide-scale deployment of heavy-duty off-road NGVs can provide important public health benefits. Specifically, it can reduce ozone-precursor NO_x emissions by at least 90 percent relative to baseline HDVs, and entirely eliminate emissions of carcinogenic diesel particulate matter. Further estimates for benefits as relating to the POLA emissions inventory are described below.

NO_x Emission Reduction Benefits: There are approximately 790 diesel yard tractors currently serving POLA marine terminals. Most of these (about 87 percent) were certified to the current cleanest heavy-duty engine standard for NO_x of 0.2 g/bhp-hr (although some were certified at higher NO_x levels). The most-recent POLA emissions inventory estimates that collectively, this fleet of 790 diesel yard tractors emitted 93.9 tons of NO_x in 2019. If only 10 percent of those were replaced with yard tractors powered by CWI's B6.7N natural gas engine (now certified to the NZE NO_x level of 0.02 g/bhp-hr), an estimated 8.5 tons/yr of NO_x would be reduced from this fleet, as follows:

93.9 tons/yr NO_x * 90% reduction * 10% penetration
= **8.45 tons/yr of NO_x reduced**

DPM Emission Reduction Benefits: Because heavy-duty natural gas engines do not emit diesel particulate matter (DPM), the same 10 percent penetration for B6.7N engines in the POLA yard tractor fleet would reduce annual DPM by 0.14 tons per year, as follows:

1.4 tons/yr DPM * 100% reduction * 10% penetration
= **0.14 tons/yr of DPM reduced**

Greenhouse Gas Emission Implications of Right-Sized Liquefied Natural Gas Yard Tractors

Additionally, the project has corroborated good likelihood that efficiency improvements delivered by the smaller "right-sized" B6.7N natural gas engine (in a yard tractor application) can reduce direct-vehicle GHG emissions relative to the larger L9N engine. Specifically, extrapolating from fuel-use data from Everport – and taking into account engineering judgements from Capacity and Cummins – it appears that using B6.7N engines in a yard tractor application at a major marine terminal will provide an efficiency benefit of roughly 15 to 20 percent. Notably, chassis dynamometer test results conducted during the project were less conclusive about this benefit, but this may be attributable to less idle time that occurred while testing at UCR compared to how the yard tractors were being operated at Everport.

Estimation of GHG Emission Reduction Benefits from Improved Efficiency: Higher efficiency delivered by yard tractors with the B6.7N engine will result in proportional GHG reductions (mostly CO_2) at the tailpipe, relative to tractors with the L9N. However, the POLA yard tractor inventory for GHG emissions (77,975 metric tons of CO2e in 2019) is specific to direct emissions from 790 *diesel* yard tractors. Thus, it is not relevant or possible to estimate a specific quantity of GHG reductions (tons per year) that would be achieved by using yard tractors powered by the B6.7N instead of the L9N in this fleet. To accurately quantify GHG emissions implications of replacing the POLA-serving fleet of 790 diesel tractors with natural gas yard tractors using B6.7N engines, it would require a full-fuel-cycle (aka "well-to-wheels") comparison. This would need to estimate how many tractors would likely use low-CI renewable fuel (RNG in the case of natural gas tractors, and renewable diesel in the case of diesel tractors). Given that virtually all natural gas dispensed at or near the San Pedro Bay Ports is now RNG (with negative average CI ratings) – and currently few if any yard tractors are using renewable diesel – the B6.7N natural gas yard tractors would likely fare well in this well-to-wheels GHG comparison, despite having lower BSFC efficiency relative to diesel tractors.

Advancement of Gas Composition Sensor Technology

This project helped to advance existing knowledge about how to build, test and commercialize gas composition sensors for potential use in heavy-duty natural gas engines. To improve accuracy and commercial viability, the sensor technology that was further developed and tested will require further research. This could include enhancing and expanding the database model and improving the accuracy for the different measurements, such as thermal conductivity and sound velocity. Such improvements could enhance commercialization of heavy-duty natural gas engines with "tighter calibrations and less knock margin" (such as

CWI's L9N and ISX12N, when used in certain applications). Examples of potential benefits include reduced deterioration and improved warranty coverage. If the sensor technology can achieve greater accuracy (within 2 percent) – and be commercially produced at an affordable cost – fuel quality sensors could play a valuable role in expanded commercialization and deployment of heavy-duty NGVs.

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LIST OF ACRONYMS

Term	Definition
CAM	Commission Agreement Manager
CARB	California Air Resources Board
CE-CERT	College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)
CEC	California Energy Commission
CH_4	Methane
C_2H_6	Ethane
C_3H_8	Propane
C_4H_{10}	Butane
CHE	Cargo handling equipment
CNG	Compressed natural gas
CO_2	Carbon dioxide
CWI	Cummins Westport Inc.
d	Distance
EGR	Exhaust gas recirculation
GHG	Greenhouse gas
G/BHP-HR	Grams per Brake Horsepower Hour
HD	Heavy-duty
HDV	heavy-duty vehicle
LAZER	Low and Zero Emission Readiness (LAZER) Initiative
LNG	Liquefied natural gas
MI	Methane index
MIDB	Methane index database
MN	Methane number
NG	Natural gas
NGV	Natural gas vehicle
N_2	Nitrogen
NO_x	Oxides of nitrogen

Term	Definition
NZE	Near zero emission – a NO_x emission certification level 90 percent below the prevailing heavy-duty engine standard of 0.20 g/bhp-hr
O_2	Oxygen
OLNS	Optional Low-NO_x Standard
P	Pressure
PCMC	Pacific Crane Maintenance Company
PSIA	Pounds per square inch absolute
PM	Particulate matter
QA/QC	Quality assurance/quality control
RNG	Renewable natural gas
SCR	Selective Catalytic Reduction
SV	Sound velocity
T	Temperature
TAC	Technical Advisory Committee
TC	Thermal conductivity
Tf	Temperature of filament
Ts	Temperature of surrounding gas
UCR	University of California, Riverside
WI	Wobbe Index - higher heating value divided by the square root of the specific gravity with respect to air
YT	Yard tractor

APPENDICES

The following appendices are available under separate cover (Publication Number CEC-500-2021-037-APA-E):

- Appendix A: Chassis Dynamometer Emissions Test Report
- Appendix B: Test Cycle Descriptions
- Appendix C: Road Load Determination
- Appendix D: Detailed Test Results
- Appendix E: Real-Time Plots