Zero-Emission Cargo Transport II:
San Pedro Bay Ports Hybrid & Fuel Cell Electric Vehicle Project

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[Project ID # elt158]

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Project Overview

Timeline

- Project Award: 10/1/14
- Contractor Kickoff: 12/16/15
- Project Completion: 2/28/24

Contractors & Projects

- BAE/CTE: Fuel cell range extended drayage truck
- TransPower: Fuel cell range extended drayage truck
- U.S. Hybrid: Fuel cell powered drayage truck
- Hydrogenics: Fuel cell range extended drayage truck
- BAE/GTI: CNG hybrid with Near Zero CNG Engine

Barriers & Challenges

- Fueling Infrastructure: Availability and location
- Costs: Fuel Cells, batteries and infrastructure
- System Integration: Safe and efficient deployment of the technology Barriers

Budget

- DoE: $10,000,000
- Funding partners: $7,467,473
- Contractors: $3,075,841
- Total Cost:$20,543,314

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Relevance: Goals & Objectives

2021/2022 Objectives

- Complete development of Cummins fuel cell truck
- Develop commercialization roadmap

Results

- Six demonstration trucks including fuel cell range extended and CNG hybrid truck completed demonstration
- Portable hydrogen fuel onsite supported demonstration trucks
- Debugging and improvement while demonstrating by lessons-learned Vehicle performance data provided from demonstration trucks

Impact

- Pushing Zero Emission Technology and Industry Envelope by Demonstrating First Fleet of FCEV's in Drayage Service in California

Remaining Challenges & Barriers

Fueling Infrastructure - Availability and location

- All temporary hydrogen fueling is in place and being used for the demonstration
- Secure hydrogen fuel supply will be a challenge – South Coast AQMD is working with partners on a solution (Renewable hydrogen station, Mobile refueler, retail stations)

System Integration: Safe and efficient deployment of the technology

- Six of seven vehicles completed the demonstration including CNG hybrid truck
- Design improvement and system optimization
- Analyze data collected and secure reliability
- Build a solid commercialization pathway

Costs and Application

- Costs will remain a challenge for the near and mid term
- Penetration into mid or long range application (currently ~200 miles range)

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Approach

2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021

100mi
150mi
200mi

Early Demo
Honda FCX

Data analysis
Toyota Highlander
Hyundai Tucson

ZECT II
Fuel Cell
/CNG Hybrid
$20M($2.5M)

CTE-OCTA
Fuel Cell Bus

ZANZEFF
Toyota-KW
Fuel Cell Truck

Hyundai
Fuel Cell Truck

CEC ARFVTP
Cummins
Fuel Cell truck
$5M($0.6M)

(500mi)

** $ Total Project Cost(SCAQMD Cost-share)*

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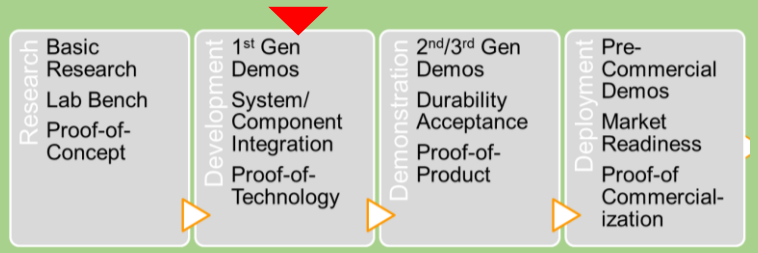
Approach

Vehicle Development and Deployment



	FUEL CELL TRUCKS				PHET/CNG
	TransPower	Hydrogenics (Cummins)	US Hybrid	BAE/Kenworth	
# of Vehicles	2	1	2	1	1
Platform	International	Freightliner	Kenworth T800	Kenworth T370	Kenworth T680
Mfg: Fuel Cell / APU	Hydrogenics	Hydrogenics	PureMotion	Ballard	CWI L9N NZE
Fuel Cell Power	60 kW	60 kW	80 kW	85 kW	n/a
Battery Capacity	125 kWh	100 kWh	26 kWh	100 kWh	100 kWh
Battery Chemistry	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion
Traction Motors	2x 150 kW	1x 320 kW	1x 320 kW	1x 420 kW	1x 420 kW
Range (per fueling)	200 miles	150 miles	150-200 miles	112 miles	150 miles
Fuel Cap.: H2 (kg) / CNG (DGE)	27 kg @350 bar	30 kg @350 bar	20 kg @350 bar	30 kg @350 bar	45 DGE
	Deployed		Deployed	Deployed	Deployed

In-use Demonstration and vehicle performance Analysis

TCO Analysis and Commercialization Roadmap

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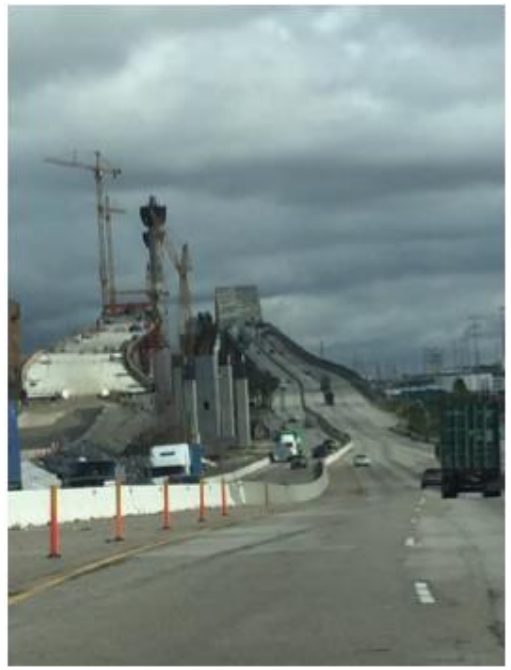
Fuel Cell Truck – System Design

- **Two electric motors with 270 kW combined power output - comparable to a current Class 8 truck engine's power output.**
- **100 kWh Li-ion batteries,**
- **85 kW (net) fuel cell system**
- **Hydrogen storage capacity is 30 kg (25 kg usable)**

Target Performance

Performance Parameters	Expected Performance*
Fuel Economy	4.5 to 6.0 mi/kg
Hydrogen Storage	30 kg storage and 25 kg usable
Range	112 miles
Gradeability and Start-ability	6.5% grade at 35 mph 5.0% grade at 40 mph 15 second start-ability at 30% grade
Top Speed	70 mph
Operating Temperature	-4 F (-20 C) to 115 F (46 C)

* Note: All performance parameters tested with a vehicle GVW of 65,0000 lbs.



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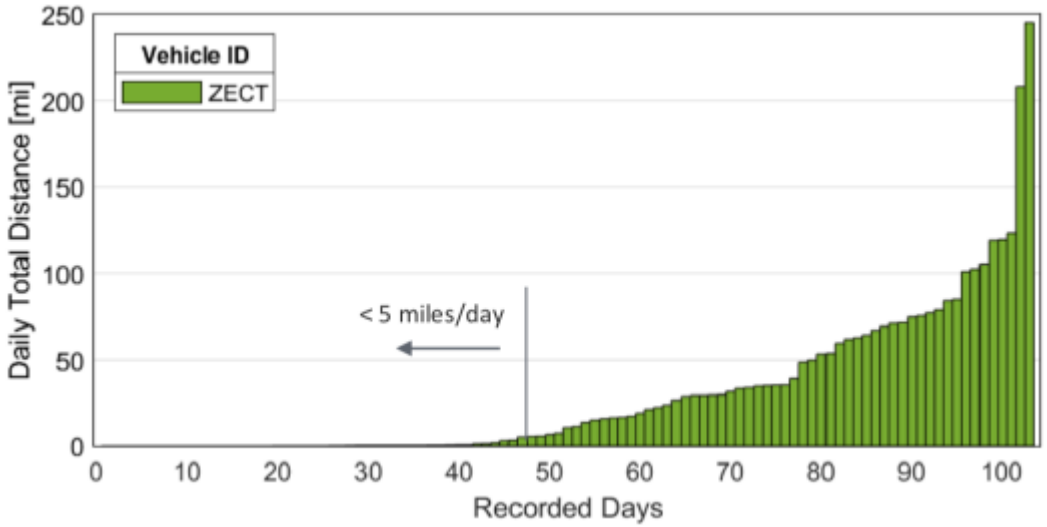
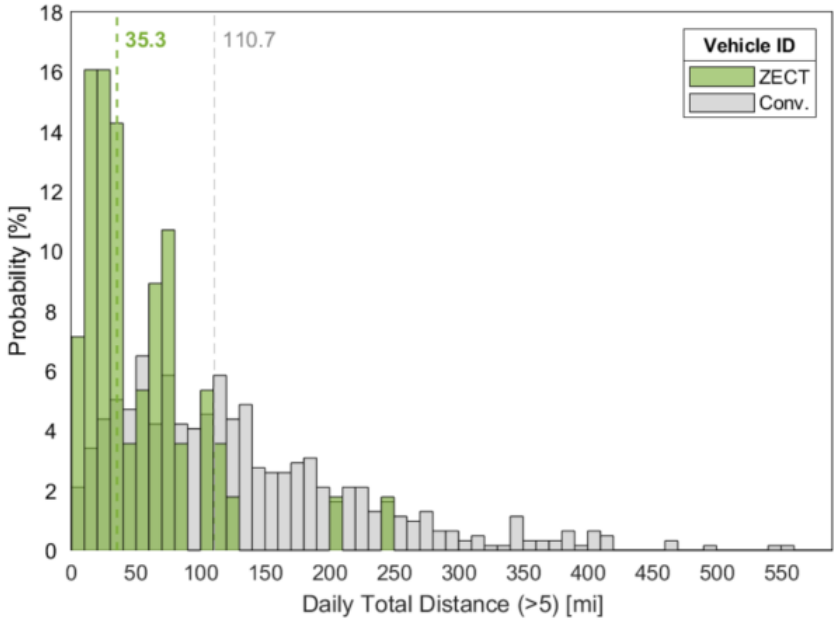
Fuel Cell Truck – Vehicle In-service Operation

- 24-month deployment on regularly scheduled routes - off the I-710 freeway in the ports and in the I-710/CA-60 and I-10 corridor in Los Angeles
- NREL managed the data collection process for all ZECT II projects
- The performance analysis of the Kenworth truck initially focused on building out summary data and overview plots - Detecting overall trends and spotting days of service, more specific to the operator, TTSI





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Fuel Cell-dominant vs. Battery-dominant

150miles

60kW Fuel Cell stack

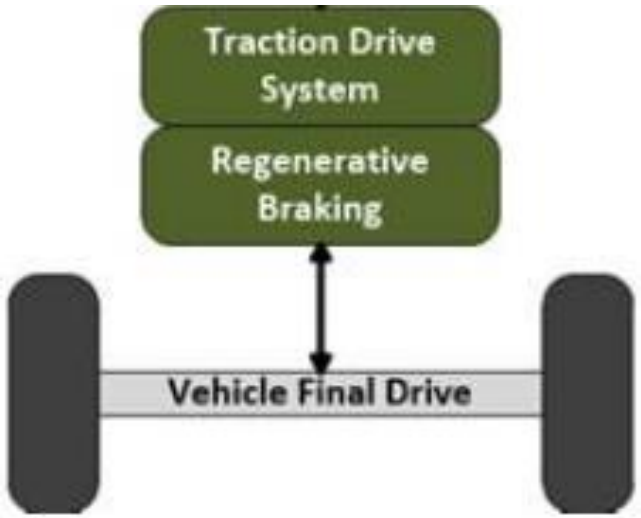
120kWh Battery

Battery-dominant

100kW Fuel Cell stack

80kWh Battery

Fuel Cell-dominant



Not-to-scale

500miles

100kW Fuel Cell stack

400kWh Battery

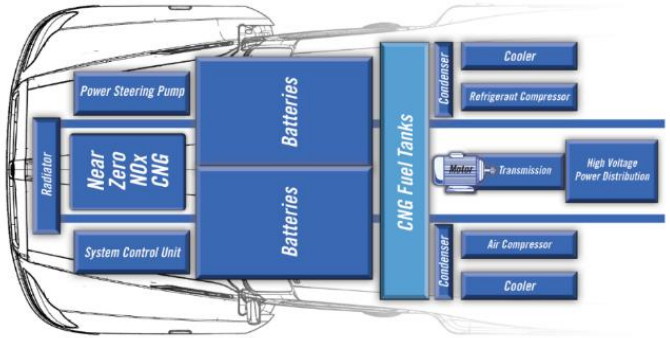
Battery-dominant

180kW Fuel Cell stack

75kWh Battery

Fuel Cell-dominant

CNG Hybrid Truck – System Design



CNG Range-Extender Truck Layout

Major Components	Detailed Information
Chassis	Kenworth T680 Daycab
Control System	BAE
Traction Motor	AM Racing, 2 x 160kW
Energy Storage System	XALT, 100kWh, 650V
Range Extender	Cummins-Westport L9N, 230kW with BAE integrated starter-generator (ISG)
Transmission	4-speed Eaton Automated-Manual (AMT)

Key Engine Attributes

- Certified to CARB's Lowest Optional Low NOx Standard (0.02g/bhp-hr)
- 4 cycle, spark ignited, in-line 6 cylinder, turbocharged, CAC
- Displacement - 8.9 Liter (540 cu. In.)
- Exceeds 2017 EPA GHG requirements
- 2018 On-board Diagnostic (OBD) compliant
- Dedicated 100% natural gas engine
- Peak rating: 320 hp, 1000 lb-ft

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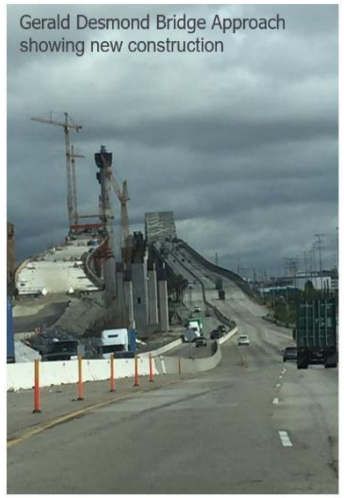
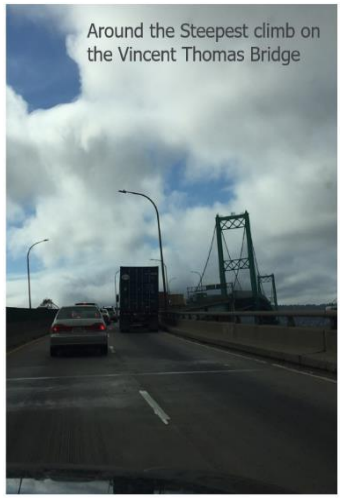
CNG Hybrid Truck – Target Performance

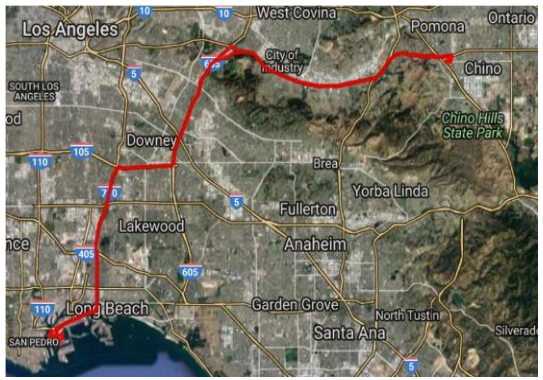
Performance Parameter	Expected Performance	Observed Performance
Range	150 miles	284 miles
Top Speed	62 mph	65 mph
Gradeability	6.5% grade at 20 mph 5% grade at 30 mph	~8.5%+ at 20 mph* ~5.5%+ at 30 mph* *(simulation results)
All-Electric Range	20 miles or 1 hour	26 miles
Startability	30% (stretch goal)	20%





Navigate the steep approach to a couple of bridges at POLA while carrying 80,000 lbs of cargo.

Drayage service to Inland empire warehouses and near the port operation



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CNG Hybrid Truck – Targeting Commercial Operation

- The duty cycles in commercial operation were measured and characterized by CALSTART
- The truck reliability was not without an issue, but the problems were not of systemic nature, and related to the novel components (sensors, fuses, electric air compressor)

  - Range - 230kW CNG engine can generate enough power to sustain the vehicle at 60mph
  - Startability - successfully launched on the 20% grade while loaded to the target weights
  - Gradeability - perform sustained hill climbs
  - Powertrain Systems Vehicle Acceleration Through Gears

Vehicle	Transmission	Rear Axle Ratio:1	GVCW (lb)	0-30mph (s)	0-60mph (s)	45-60mph (s)	Thru Intersection (s)
HECT	4-speed AMT	5.38	78,140	16	74	37	12
1706 – 430 hp MX-11	12-speed PACCAR AMT	2.85	76280	25	79	33	17

  - Electrical/Electronics - EMI/EMR, vibration & environmental testing, salt fog, water intrusion, freeze-thaw cycle, gravel, UV and fluid compatibility, low voltage systems, and high voltage specific test
  - Aerodynamics
  - Noise, Vibration & Ride
  - Structural Evaluation & Durability
  - Thermal Management

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CNG Hybrid Truck - Vehicle In-service Operation

- The vehicle has accumulated 8,835 miles of commercial service through the conclusion of the project in November 2020
- Data was tracked using the Aptiv Qualifier System Validation Service and transferred to PACCAR. The data was accessible to CALSTART and NREL. CALSTART has performed the analysis of operational data
- CALSTART has performed in-use emissions testing with a Portable Emissions Measurement System (PEMS) supplied by Sensors
- HECT vehicle has met or exceeded its overall performance attributes expected of a high-volume production vehicle
- A few areas where opportunities for improvement exist are as follows:
  - High-voltage (HV) fuse reliability for accessory loads
  - Transmission shifting
  - Electrified accessories

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CNG Hybrid Truck – PEMs Test

	Total Days in Operation	Avg. Fuel Consumed	Avg. Efficiency
Plug-In Hybrid	64 Days	20.72 dge	6.62 mi/dge
CNG	38 Days	15.36 dge	5.1 mi/dge
Diesel	52 Days	n/a	n/a

- Performed the standard drayage duty cycle up to 284.61miles.
- Averaged more miles per diesel-gallon equivalent than the baseline CNG over the course of the demonstration period
- Performed averagely on the emissions test.
- The demonstration vehicle was very popular with the drivers.
- Further testing under better operating conditions would be ideal.

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CNG Hybrid Truck -Vehicle In-service Operation

- The vehicle has accumulated 8,835 miles of commercial service through the conclusion of the project in November 2020
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Commercialization Roadmap

	Pros	Cons
Diesel	• The most common fuel type for decades, so capital costs are low and fueling locations are common • Range only limited by driver's 10 hour driving limit	• Biggest polluter of particulate matter and greenhouse gases • Loud and odorous operation • Relatively high maintenance costs • Being phased out by California and port regulations
CNG	• Less emissions than diesel • Quick refill like diesel • ~ 300 mile range • Fueling infrastructure relatively common • Fuel slightly less expensive than diesel • Quieter operations	• Not zero-emission • Although highly commercialized now, gained a reputation for not being reliable when first entering the market • Emits about 75% as much CO_2 and 10% as much NO_x as diesel trucks
Battery Electric	• Zero tailpipe emissions • Ability to opportunity charge while idling • Quiet operations • Reduced maintenance costs • Torque / acceleration	• Slow charging times • Limited range currently up to 150 miles • High MSRP • Installing charging infrastructure can be expensive, time consuming, and takes up space • Heavy battery can lead to weight issues (maximum gross vehicle weight limit of 82,000 lbs)
Hydrogen Fuel Cell	• Zero tailpipe emissions • Quick refueling (10 minutes) • Expected 300+ mile range • Quiet operations • Reduced maintenance costs • Possibility for extended range with 700 bar fueling • Torque / acceleration	• Least commercialized option with fewest vehicles on the road • High MSRP • High fuel cost • Fueling infrastructure not commonly available

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Commercialization Roadmap

Comparison of key performance metrics for diesel, CNG, hydrogen fuel cell, and battery electric heavy-duty trucks

	Diesel	CNG	Hydrogen Fuel Cell	Battery Electric
MSRP	$120,000	$202,624	$520,000	$340,000
Miles / diesel gallon equivalent (DGE)	6.3	5.7	6.0 / kg H_2	2.6 kWh / mile
$ / DGE	$3.53	$3.00	$10.90 / kg H_2	$0.10 / kWh

Role of Hydrogen & CNG(Hybrid) Trucks

- Hydrogen: quick refueling, an ability to scale the infrastructure to serve many vehicles, and a much desired longer range than current BEV technology

- CNG(Hybrid): The significant progress of the CNG technology has made over the past decade – reliability and performance of engine with low emission. Many fleets now operate CNG trucks and some even prefer the technology over diesel because it can meet the required duty cycles with a quieter, cleaner, and odorless ride.

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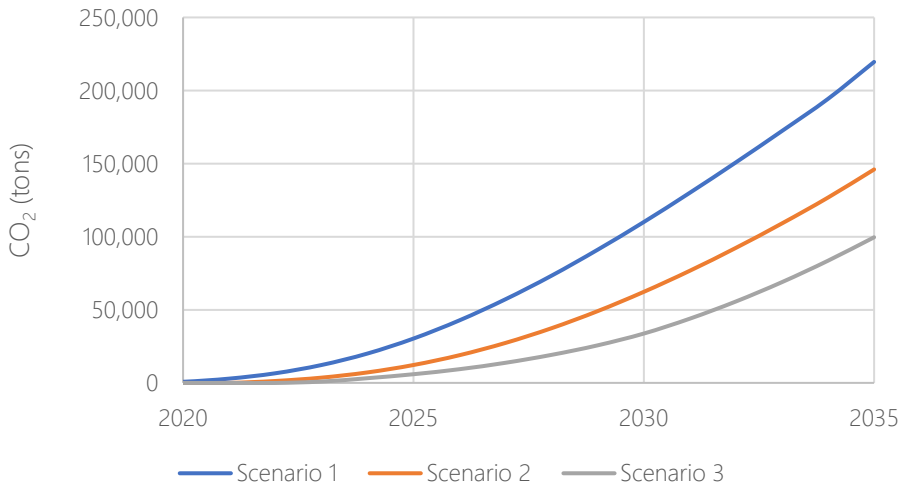
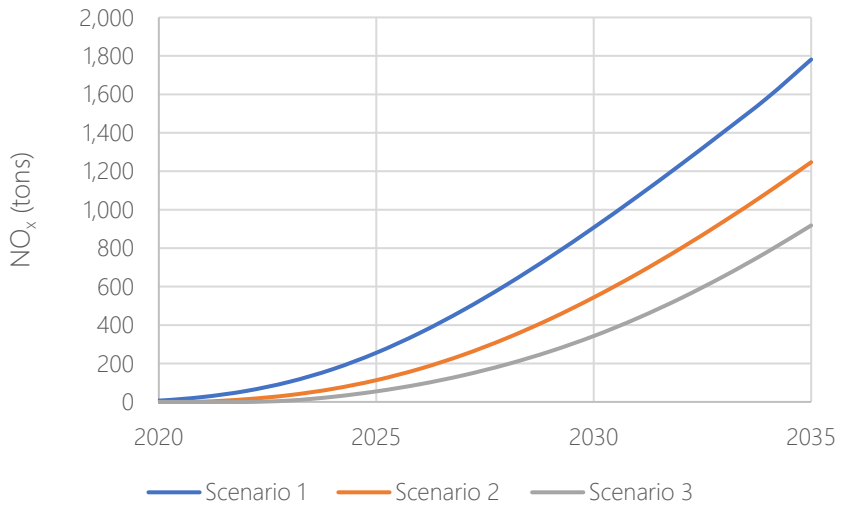
Commercialization Roadmap

Emission reduction Impact

	Zero-Emission Sales By 2035	Scenario Basis
Scenario 1	100%	Governor Newsom's Executive Order (N-79-20) mandating 100% of zero-emission drayage trucks by 2035.
Scenario 2	75%	An intermediary outcome between Scenario 1 and Scenario 3 where 75% of sales of zero-emission drayage trucks are realized by 2035.
Scenario 3	40%	The Advanced Clean Truck Rule's mandate of 40% sale of zero-emission Class 7-8 Tractors by 2035.





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Conclusion

More Stop-n-Go

Higher fuel economy

Metric	Units	Baseline* Conventional	Kenworth ZECT
Date range		2014–2015	6/13/2019 – 1/15/2021
Number of total days recorded	#	557	103
In-service days with >5 miles	#	—	56
Max daily distance	mi	—	245.2
Avg daily distance	mi	127.9	53.9
Avg operating time (key-on)	hr	10.1	6.9
Avg driving time	hr	4.5	2.6
Avg speed	mph	14	8.4
Avg driving speed (speed>0)	mph	26.5	20.0
Kinetic intensity	1/mi	0.64	1.1
Avg stops/day	#/day	124.9	176.1
Avg stops/mi	#/mile	1.38	4.7
Median stop duration	sec	40.8	7.4
Avg daily fuel use (H_2)	kg	—	8.4
Avg daily fuel use (diesel equiv.)	gal	23.7	7.4
Avg fuel economy (diesel equiv.)	mi/gal	5.7	6.5
Avg fuel cell efficiency	%	—	52.1%

ZECT II milestone report: Baseline Vehicle Data Collection and Analysis Report – Port Drayage

- The largest strides in Technology Readiness Level (TRL) on the overall vehicle design and architecture.
- Improvements to packaging and vehicle control strategies to increase efficiency
- Challenges
  - ✓ Lack of standardization in componentry
  - ✓ Improving reliability across the system
  - ✓ Deploying a larger numbers of vehicles
  - ✓ Reliable H2 fuel supply

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Future Research

1. **Collect real operation data from demonstration**
   - Continue demonstration to collect more data
   - Analyze vehicle performance data by NREL
     - GPS data,
     - average daily VMT,
     - Kinetic intensity
     - Fuel economy
   - Compare to conventional truck data with similar operating route

2. **Analyze Total Cost of Ownership**
   - Vehicle, Fuel, Maintenance cost
   - Assessment of infrastructure cost
   - Assessment of operating penalty (time, weight)

3. **Study a roadmap for commercialization roadmap**
   - Market development strategy
   - Leverage the knowledge from this demonstration for other projects
   - Accelerate participation of OEMs

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