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Developing Markets for Zero Emission Vehicles in Short Haul Goods Movement

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A Research Report from the National Center for Sustainable Transportation

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16. Abstract
The potential for zero emission heavy duty trucks (ZEHDTs) is examined via simulation modeling, case studies, interviews and a survey. Impacts of ZEHDTs on freight operations are assessed. Costs and benefits of using diesel, natural gas hybrid and battery electric vehicles are compared for 2020, 2025, 2030. ZE applications are limited in the near term due to range and charging limitations, but as ZE performance improves and prices go down, they are viable for a larger segment of the market. Hybrid vehicles are the most cost effective alternative for reducing air toxics, but ZEHDTs reduce air toxics the most by 2025. The report presents recommendations for promoting and increasing the market share of ZEHDTs and hybrids.

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The METRANS Transportation Center was established in 1998 through the Transportation Equity Act for the 21st Century (TEA-21) as the first University Transportation Center in Southern California. METRANS is a partnership of the University of Southern California (USC) and California State University Long Beach (CSULB). METRANS is committed to solving transportation problems of large metropolitan regions through interdisciplinary research, education, and outreach. More information is available at www.metrans.org.

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Developing Markets for Zero Emission Vehicles in Short Haul Goods Movement

A National Center for Sustainable Transportation Research Report

November 2020

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Developing Markets for Zero Emission Vehicles in Short Haul Goods Movement

EXECUTIVE SUMMARY

Achievement of a zero emissions vehicle (ZE) fleet is part of the long range plans for California, the South Coast Air Quality Management District (SCAQMD), and more recently the San Pedro Bay Ports and many local jurisdictions. A zero or near zero vehicle fleet is core to achieving California's greenhouse gas reduction goals. The use of ZEHDTs for freight movement remains a challenge particularly in the heavy duty sector. Zero and low emission technologies are not yet competitive with the traditional diesel engine for hauling heavy loads. This research examines the potential for ZE or near-ZE vehicles with respect to freight operations, economic impacts, and environmental benefits. We focus on heavy duty trucks (HDTs) used in short-haul drayage services, one of the most promising market segments for early adoption. Drayage service is defined as short haul pickup and delivery of goods to and from ports, warehouse and distribution centers, and intermodal facilities. In order to provide a comprehensive assessment of the market potential for ZE and near-ZE HDTs, we consider several dimensions of their costs and benefits.

Impacts of ZEHDTs on freight operations

First, we consider impacts on freight operations. ZE HDTs have different performance characteristics than conventional diesel HDTs, namely range, load capacity, and refueling time. For a given set of pickups and deliveries, the number of trucks required depends on the range of the vehicle and its load capacity. These in turn determine miles traveled (including associated labor costs) and refueling time costs. Near ZE HDTs, such as hybrid electric, have similar performance characteristics to conventional diesel.

We develop a simulation model and use actual drayage trip data to generate a set of simple (single or two stop) drayage demands to be accomplished over a single eight-hour shift day. The simulation model optimizes routes so that total costs are minimized. Using an all diesel fleet as the base case, we use the simulation model to estimate the number of trucks required to serve all the demand. We incrementally introduce ZE trucks into the fleet with subsequent model runs. We run the model until the maximum possible number of ZE trucks is reached.

We consider three target years, 2020, 2025, and 2030, and three vehicle technologies: diesel, natural gas hybrid, and battery electric. Performance attributes for 2020 are based on data from field tests; attributes for 2025 and 2030 are based on most recently available data on expected improvements in the various technologies. Our results are as follows:

- In 2020, the maximum possible share of ZEHDTs is 75%, and requires a near doubling of the fleet, due to limited range and charging times for ZEHDTs

- In 2025 and 2030, the maximum possible share of ZEHDTs is 96%. The vehicle fleet increases by about one third in 2025 and by about 20% in 2030. Fewer additional vehicles are required due to increased range and shorter charging time of ZEHDTs.

We conduct two case studies of short haul firms to test the potential penetration of ZEHDTs with more realistic truck activity. The case study data allows us to consider both range and charging constraints, as well as the additional effect of the gross vehicle weight restriction. One firm is a mostly single shift operation; the other uses vehicles for two or three shifts per day. We estimate that the share of activity that could be operated by ZE for the first firm is 18% for 2020, 43% for 2025, and 58% for 2030. The numbers for the second firm are 2%, 12% and 22% respectively, reflecting the impact of operating vehicles nearly 24 hours per day, which therefore does not allow sufficient time for charging between vehicle shifts.

Benefits and costs

We use our simulation results to generate four scenarios: all diesel, all hybrid, midpoint ZE, and maximum ZE. Diesel and hybrid trucks have similar range and refueling requirements, so differ only in emissions and costs. Table E-1 summarizes operating emissions per day for PM 2.5, NOX, and CO2. It can be seen that the max ZE alternative has the lowest emissions for every pollutant and every year except for NOX in 2020.

Table E-1. Emissions per day for four vehicle scenarios

2020	All Diesel	All Hybrid	Midpoint ZE	Max ZE
PM 2.5 (g)	62.2	52.8	48.1	29.9
NOx (kg)	11.9	1	9.2	5.7
CO2 (kg)	18314	13068	15563	12008
tot veh	19	19	25	36
2025				
PM 2.5 (g)	31.1	26.4	18.5	1
NOx (kg)	5.9	1	3.5	0.2
CO2 (kg)	16211	11569	12132	6493
tot veh	19	19	22	26
2030				
PM 2.5 (g)	31.1	26.4	18	1
NOx (kg)	5.9	1	3.4	0.2
CO2 (kg)	14536	10374	11014	6440
tot veh	19	19	22	23

We generate annual capital, operating and driver costs for each of the scenarios, and then compare the incremental savings in emissions with the incremental costs, relative to diesel.

Results are shown in Table E-2. Numbers in parenthesis are savings rather than costs. The all hybrid alternative is the least cost alternative for all emissions and all target years. This is due to the lower operating costs of hybrids and lower emissions relative to diesel. At the same time, the hybrid alternative does not require additional vehicles, and therefore has much lower capital costs than the ZE alternatives. The max ZE alternative generates modest savings in 2030, but of much lower magnitude than the hybrid alternative. Our results illustrate the contrast between possible policy objectives. If reducing emissions is the most important objective, ZEHDTs meet that objective, but at very high cost relative to other alternatives.

Table E-2. Cost per unit of emissions removed, relative to all diesel

Cost per emissions reduced	All Hybrid	Midpoint ZE	Max ZE
PM 2.5 (per gram)			
2020	$(130.74)	$172.76	$208.55
2025	$(251.52)	$21.79	$19.27
2030	$(222.68)	$21.22	$(9.41)
NOX (per kg)			
2020	$(112.75)	$902.21	$1,086.49
2025	$(241.26)	$114.42	$101.76
2030	$(213.59)	$111.18	$(49.68)
CO2 (per kg)			
2020	$(0.23)	$0.89	$1.07
2025	$(0.25)	$0.07	$0.06
2030	$(0.25)	$0.08	$(0.03)

Industry Perspective

We conducted two rounds of interviews and a small stated preference survey to gather information on how firms are using demonstration vehicles, their willingness to experiment with hybrid and ZE trucks, and their willingness to purchase ZE trucks. Our first round of interviews was with drayage firms and OEMs producing ZE and hybrid vehicles who were participants in the first round of demonstrations (2016-2018). Observations from the interviews included: 1) the real-world range of BETs is below manufacturer estimates; 2) grades substantially reduce range; 3) most trucks are kept close to the home base due to range anxiety; 4) hybrid trucks are preferred due to lower cost and better performance.

The second round of interviews was conducted to learn what drayage operators knew about alternative fuel trucks and their perceptions of the technology. The purpose was to get a better understanding of ZE potential markets. Findings from the second round survey include: 1) unless the firm had participated in one of the demos, respondents had little knowledge of ZE technology; 2) vehicle and charging facility costs were major concerns; 3) respondents expressed willingness to use ZEHDTs, as long as the price was reasonable and the range adequate; 4) the most common response for adequate range was 300 miles; 5) only very short trips were seen as feasible with existing ZE technology.

We conducted a stated preference survey to obtain information on willingness to purchase and use ZEHDTs. The survey was structured to include time savings as an incentive to purchase

ZEHDTs, in this case having priority entry at terminal gates. Results showed that ZE choice probability is about 16%, even though choices between diesel and ZE were comparable with respect to cost and attributes. Consistent with our interviews, purchase price, range and charging times were significant factors in vehicle choice. Potential for time savings was also significant. The stated preference results suggest that ZEHDTs would have to have comparable attributes to conventional diesel in order to be attractive to fleet owners and managers.

Findings and Recommendations

Our research leads to the following findings and recommendations

Finding 1: At the current state of BEV technology, BE ZEHDTs have limited application in the short haul heavy truck market.

Recommendation: State and local policy should take into account the full impacts of ZEHDTs on freight operations and costs

Finding 2: Natural gas hybrid near zero vehicles are preferred in the short term

Recommendation: State and local policy should be more flexible and consider hybrid technologies as viable near and middle term options for GHG and other emissions reductions

Finding 3: The medium term market is promising and depends critically on the rate of improvement of battery technology and rate of decline in vehicle price

Recommendation: Continue to promote and invest in battery technology improvements

Finding 4: The medium term market depends on charging infrastructure and energy availability

Recommendation: Develop a comprehensive investment plan for public charging stations and identify a funding source

Finding 5: The medium term market depends on subsidies

Recommendation: Develop a comprehensive subsidy and incentive program to promote ZE and near-ZE purchase and use, and fund at a sufficiently high level

Chapter 1. Introduction

Achievement of a zero emissions vehicle fleet is part of the long range plans for California, the SCAQMD, and more recently the San Pedro Bay Ports and many local jurisdictions. A zero or near zero vehicle fleet is core to achieving California's greenhouse gas reduction goals. Through a variety of incentives (e.g., tax benefits, use of high occupancy vehicle lanes), California has made significant progress in growing the share of ZEVs (battery electric, fuel cell) and near-ZE (plug-in hybrid electric) passenger vehicles. In 2017 California sales were half of all zero emission passenger vehicle sales in the U.S., and from 2017 to 2018, California ZE sales increased by 62%, to over 150,000 vehicles.("Percent Share of US EV Sales By State – EVAdoption," n.d.)

Progress has also been made in introducing alternative fuel vehicles into public sector fleet vehicles (e.g., transit vehicles). The major transit operators in the Los Angeles region have made commitments for all electric fleets by 2030. However, the use of ZEHDTs for freight movement remains a challenge particularly in the heavy duty sector. Zero and low emission technologies are not yet competitive with the traditional diesel engine for hauling heavy loads. It is expected that this gap in performance of ZEHDTs will exist for a period of time. However, there are freight transport submarkets where a given ZE technology may be feasible. Currently promising technologies and fuels are being demonstrated, including electric vehicles for local package delivery, short-haul rail, and electric or hybrid heavy duty trucks. How do these demonstrations help to inform more strategic implementation of ZE technologies?

This research examines the potential for ZE or near-ZE vehicles with respect to freight operations, economic impacts, and environmental benefits. We focus on heavy duty trucks (HDTs) used in short-haul drayage services, one of the most promising market segments for early adoption.

1.1 Evaluating the Market for ZE-HTDs

In order to provide a comprehensive assessment of the market potential for ZE and near-ZE HDTs, we consider several dimensions of their costs and benefits.

First, we consider the impacts on freight operations. ZE and near-ZE HDTs have different performance characteristics than conventional diesel HDTs, namely range, load capacity, and refueling time. For a given set of pickups and deliveries, the number of trucks required depends on the range of the vehicle and its load capacity. These in turn determine miles traveled (including associated labor costs) and refueling time costs. ZE and near-ZE HDTs currently have a shorter distance range than diesel HDTs. There are fewer refueling stations for ZE and near-ZE HDTs, and typically refueling takes more time (as in recharging a battery). Therefore, a larger number of vehicles and/or a greater total amount of truck vehicle miles traveled (VMT) would be required to operate the same service. In addition, space must be found for refueling facilities. We use simulation modeling to examine the effects of performance characteristics on fleet size and cost. We generate scenarios for 2020, 2025, and 2030 using best available estimates of battery technology improvements. We also include hybrid electric trucks, which have the same operational characteristics as conventional diesel, but lower emissions. We compare costs of various scenarios with emissions reductions achieved.

We support the simulation study with two case studies of drayage firms. We use actual truck routes, assignments, and loads to estimate the share of operations that could be performed with ZEHDTs. We use the same ZE performance assumptions for 2020, 2025, and 2030 as in the simulations. The case studies enrich the results from the simulation analysis, and together provide some initial estimates of market potential.

Second, we consider ZE and near ZE HDTs from the perspective of the user—the trucking firm. Ultimately the market will be determined by the choices of fleet owners and operators. At the time this research project was approved, it was anticipated that a SCAQMD demonstration project testing 43 HDTs using various technologies would be conducted in time to provide data for this project. Unfortunately, the deployment of demonstration vehicles proceeded more slowly than anticipated, and none of the data were available for this research. We therefore collected data via interviews and surveys to better understand both operational experiences with demonstration vehicles and perceptions regarding willingness to purchase or use ZE HDTs.

We conducted a stated preference survey to elicit information on willingness of fleet managers to purchase ZEHDTs. This survey, together with our interviews, provides a comprehensive picture of industry perceptions.

1.2 Expanding and promoting the market for ZE HDTs

The second part of this research addresses the potential for expanding and promoting the market for ZEHDTs. We explore the extent to which the drayage market can be served currently, in 2025 and in 2030. Assumptions about the trajectory of battery technology and vehicle prices play a strong role. There are also many other considerations, including fleet turnover, location and phasing of charging stations, and independent owner-operators.

Progress to date in California is the result of public policy decisions—investment in demonstrations, subsidies for vehicle purchase, etc. An Advanced Clean Truck Program that includes a ZE HDT sales mandate was issued just after this study was completed. We consider an array of policies that may promote accelerated adoption of ZE HDTs. Our assessment is based on our analysis results, as well as stakeholder interviews and surveys.

1.3 Organization of Report

This report is organized somewhat differently than the tasks described in the statement of work. Table 1 shows how the chapters are related to the tasks. Chapter 2 presents a comprehensive literature review on EV research, short haul markets, demonstrations, and models for estimating costs of ZE and near-ZE HDTs. Chapter 3 provide a description of the California demonstrations and their status. Chapter 4 addresses the impacts of using ZEHDTs in drayage services and includes a simulation analysis and two case studies. Chapter 5 examines ZEHDTs from the industry perspective. Chapter 6 evaluates potential markets in the context of the findings of Chapters 4 and 5. The concluding chapter presents potential policy strategies and recommendations for accelerating the adoption of ZEHDTs in the short-haul market.

Table 1. Relationship of Statement of Work Tasks to Report Chapters

Task	Chapter
1. Conduct literature review	Chapter 2 Literature review
2. Build databases on SCAQMD demonstration	Chapter 3 California demonstrations
3. Develop and evaluate scenarios	Chapter 4 Impacts of using ZEHDTs in short haul freight operations
4. Estimate costs and benefits	Chapter 4 Impacts of using ZEHDTs in short haul freight operations
5. Conduct market analysis	Chapter 5 Industry perspective
6. Identify potential markets	Chapter 6 Potential market for ZEHDTs
7. Summarize potential policy strategies	Chapter 7 Policy strategies and recommendations
8. Develop recommendations	Chapter 7 Policy strategies and recommendations

Chapter 2. Literature Review

This chapter provides a review of the literature on heavy duty zero and near zero emission heavy duty vehicles. It includes a summary of findings from work performed in the early stage of this research and a section on truck choice modeling.

2.1 Summary of Findings

This section summarizes an earlier report, Developing Markets for ZEHDTs in Goods Movement (Giuliano, White, & Dexter, 2018), that conducts a comprehensive review of the literature to assess the market status and potential market penetration of ZEHDTs and near-ZEHDTs in the California heavy vehicle market. It evaluates alternative technologies, primarily battery electric, fuel cell, and hybrid technologies, and compares them to existing gasoline, diesel, and natural gas vehicles used in comparable applications. Refueling infrastructure requirements and logistics planning are considered along with vehicle technology.

The report's primary focus is on intra-urban, as opposed to long haul, deployment scenarios. Intra-urban scenarios produce the greatest potential for reduction of pollutant exposure while minimizing problems associated with the reduced range of some developing vehicle technologies. In early 2018 within California, there were approximately 2080 hybrid, 300 medium duty and 40 heavy duty electric vehicles in demonstration or revenue service. There are currently plans to deploy several dozen heavy duty fuel cell vehicles in the near future.

The literature review finds that while there are substantial existing studies providing direct comparisons between light-duty electric and fossil-fueled vehicles during actual operation, heavy-duty electric vehicles (e.g., class 8) have been less well studied. Fuel cell vehicle studies are also very sparse and are primarily available in the public transit sector for buses. ZE vehicles are still comparatively more expensive to purchase, though they have much higher fuel efficiency when compared with traditional diesel technology. Medium- and heavy-duty electric vehicles intended for hauling loads still face logistic, range, charging, and weight limitations.

2.1.1 Findings from Demonstration Projects

Existing demonstration projects reviewed as of early 2018 provide insights as to the current extent of these limitations and recent developments in this area, as well as strategies employed in some demonstration projects to make use of these vehicles feasible. Demonstration projects show a wide variety of performance characteristics such as fuel economy. Battery electric demonstration projects tend to outperform fuel cell technologies in terms of fuel efficiency when measured on a diesel gallon equivalent basis.

The literature review overall emphasizes that heavy-duty electric vehicles are only just beginning to undergo extensive demonstration, while medium-duty electric vehicles have been used successfully in quite wide-spread demonstrations yet are still only suitable for limited applications where ranges are fairly short and vehicles return to a home-base to recharge regularly. For battery electric freight trucks, demonstration projects showed operating ranges of between 70-100 miles per charge. Operating range was also found to vary significantly based on payload and operating conditions. Due to range restrictions, these vehicles would also require additional attention to routing and refueling, which at present is considered on a case-by-case basis by each company and thus has limited comparability. Reliability and durability of battery-based systems was found to have steadily improved in recent years.

Battery electric recharging stations for trucks are sparse but deployment is potentially straightforward given the extensive network of light duty recharging stations already in place. However, the larger footprint of truck charging facilities must also be considered. Another concern is the draw on the power grid from trucks, particularly if they are required to refuel during the day. Commercial refueling infrastructure for fuel cell trucks does not yet exist. Demonstration projects therefore rely on non-commercial hydrogen sources. Given the volatility of hydrogen, operators would require substantial safety training to refuel on their own. The paucity of battery electric and fuel cell truck demonstrations means that some information on battery life and performance has been gleaned from transit bus demonstrations.

Fuel cell vehicle demonstrations outside the public transit sector are scarce, and this technology is still extremely expensive with fuel cell buses costing upwards of $1,000,000 for recent demonstration projects. Hybrid vehicles have no range or reliability issues, but like electric vehicles they suffer from a loss of payload capacity due to the weight of battery systems and other electric/hybrid components. As of 2020, ultra-low NOx vehicles are beginning to enter the market, with 8.9L and 11.9L natural gas trucks meeting the 90% CARB standards of 0.02 g/bhp-hr. for NOx emissions currently in operation.

Overall, the demonstration projects show that ZE and near-ZE heavy-duty vehicles are able to operate along selected routes during pilot projects but have also revealed areas for improvement and highlighted the importance of operational characteristics. Maintenance costs for battery electric vehicles were found to be roughly in line with diesel and CNG technologies. The operational compromises necessary for heavy-haul operation of battery electric and fuel cell trucks are generally higher than for medium-duty trucks due to the less predictable pattern or origins and destinations.

2.1.2 Economics

The economic estimates of purchase cost of freight ZEHDTs are highly speculative due to lower production volumes. The cost of battery electric trucks for drayage operation is estimated at approximately three times that of diesel alternatives. While battery electric trucks would have lower per mile refueling costs, their limited range means that the amortization costs would be spread over fewer productive miles driven per day. The cost of the battery system can be over 50% of the cost of the truck. Fuel cell vehicles offer a range comparable to that of diesel equivalents but have even higher upfront capital costs given current production volumes.

2.1.3 Future Market Penetration

Even if the economics of ZEHDTs become more favorable due to technological improvements, subsidies, or scale economies, the long operating life of diesel trucks will slow the adoption of

ZEHDTs. In addition, California's diesel fleet is relatively young due to strict air quality requirements prompting upgrades in recent years, which means that most diesel trucks will stay on the road for many years into the future. The medium projection for market penetration for trucks class 3-8 by the California Electricity Commission (CEC) estimates that diesel electric hybrid, electric, and natural gas trucks would have equivalent market share in 2030. If combined, these three technologies would be about 7 percent of the 2030 California truck fleet. Note that these projections predate the recent Executive Order N-79-20, which calls for a much more rapid adoption and integration of zero emission vehicles.

2.1.4 Short-Haul Markets Defined

It is anticipated that the initial markets for ZEHDTs will be short-haul due to their limited range and lack of refueling facilities. Per the Motor Carrier Safety Administration, short haul is defined as 100 miles or less and likely make up a substantial share of urban truck traffic. (Motor Carrier Safety Administration, 2015) Types of operations in the short haul market are package deliveries as well as truckload container shipments. Medium haul is between 101-500 miles, and long haul is defined as those trips of more than 500 miles.

Medium-duty commercial vehicles (classes 4–6) are used for high volume local pickups and deliveries, such as UPS or FedEx deliveries. This size category may also serve perishables, particularly to smaller businesses. Heavy commercial vehicles (classes 7–13) operate in short, medium and long-haul operations. Both medium and heavy commercial vehicles through class 8 are targets for ZE technology. Class 9 and higher heavy-duty trucks are deemed out of scope for ZE technologies at this time. ("Compilation of Existing State Truck Size and Weight Limit Laws - FHWA Freight Management and Operations," n.d.; "Light-Duty Vehicles Heavy-Duty Vehicles," n.d.; "MAG Internal Truck Travel Survey and Truck Model Development Study Appendix," n.d.)

2.1.5 Status of ZE and Near-ZE Vehicles

The types of ZE and near-ZE vehicles are discussed in detail. Technologies suitable for zero-emission drayage trucks include electric and hydrogen fuel-cell vehicles. (Port of Long Beach & Port of Los Angeles, 2016) Near-zero-emission trucks include those making use of hybrid technologies, with the electric charging capabilities paired with an internal combustion engine (ICE) engine fueled by either conventional or alternative fuels. Alternative fuels in these hybrid arrangements may include compressed natural gas (CNG), liquified natural gas (LNG), liquified petroleum gas (LPG), biomethane, ethanol, methanol, hydrogen, and others.

Battery electric vehicles use electricity from the grid to recharge on-board batteries. This eliminates tailpipe emissions, though there are still remote emissions associated with the electricity generation. Charging time can vary between manufacturers and battery size. (CARB, 2015b) A quick charge may take only 10 minutes for a very limited range and full charge 4-6 hours or longer. A number of different battery technologies are available, including lead acid, nickel-metal hydride, lithium-ion, molten salt, and flow batteries. Lithium-ion batteries are most likely to be used in medium- and heavy-duty trucks and buses over the near term per

CARB. (CARB, 2015b) Battery efficiency declines over time, so the capacity/range of battery electric vehicles will decrease as the vehicle's battery ages.

Freight that electric trucks are able to haul or transport can be reduced due to the additional weight of battery systems. In trials at the port of LA, the battery systems weighed 6,000 lbs. which resulted in an equivalent reduction in vehicle payload because of maximum road weight limits (80,000 lbs.). (Port of Los Angeles, 2016) If battery energy-to-weight ratios can be improved in future through technological improvements, this problem will be lessened. This also applies to battery systems in hybrid vehicles which can also add considerable weight to a truck, and hence can reduce vehicle payloads like battery electric trucks.

Fuel cell vehicles use a fuel cell stack to convert hydrogen into electricity, which in turn powers the vehicle. The only by-products of the reaction are water vapor and heat, meaning that fuel cell vehicles produce no harmful tailpipe emissions. Hydrogen fuel for the fuel cell is stored in cylinders on the truck, sometimes requiring significant additional storage space. These vehicles can use either a fuel-cell dominant or battery dominant configuration, with the fuel-cell dominant configuration requiring a smaller battery. (CARB, 2015c) Fuel cell trucks require hydrogen, which at present is only available in limited locations. Like battery electric vehicle charging, hydrogen production creates emissions associated with the electricity generation and depends on the source.

ZE and near-ZE technology for heavy-duty transport is still expensive and developing. All of the demonstration projects discussed in the report are financed at least partially by public funds, and in California several organizations (CARB, AQMD, USDOE) are providing extensive funds for development of heavy-duty ZE technologies. Support is provided through multiple funding instruments including Proposition B and proceeds from California's cap-and-trade auction. CARB in partnership with CALSTART has offered the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP), which provides point-of-sale discounts to vehicle purchasers. (AFDC, 2018; CARB, 2017; Eudy, Prohaska, Kelly, & Post, 2014; South Coast AQMD, 2018a, 2018b; U.S. DOE, 2018)

California has been a leader in advancing medium- and heavy-duty electric and fuel cell vehicle technology, but these technologies are still in the early stages of commercialization. In a series of 2015 technical reports, CARB classifies medium- and heavy-duty hybrids as largely available commercially, while medium- and heavy-duty electric vehicles have limited commercial availability, and medium- and heavy-duty fuel cell vehicles are largely in the demonstration phase. Numbers of vehicles in service, demonstration, or planned demonstration are only a very tiny portion of vehicles currently on the road in California: 2,080 hybrid vehicles, over 300 medium-duty electric vehicles, and about 40 heavy-duty electric vehicles. Fuel cell vehicle numbers are much lower, with only 88 vehicles combined in service/demonstration or planned for demonstration. (CARB, 2015c, 2015b, 2015a)

2.2 Truck Choice Models

Truck choice models typically create scenarios either using an idealized economic analysis or through scenario assumptions. They do not attempt to incorporate various policies levers and understand their effect on the real-world decision-making process for vehicle purchases. To better understand real world decision-making researchers have developed vehicle choice models. (CARB, 2009, 2012; Fulton & Miller, 2015; McCollum, Yang, Yeh, & Ogden, 2012; Morrison et al., 2015; Yang, McCollum, McCarthy, & Leighty, 2009; Yang, Ogden, Sperling, & Hwang, 2011).

Vehicle choice models create a discrete choice formulation that includes a number of important factors that will influence individual decision-makers' preferences among a suite of vehicle technology options. These factors include private economic costs, such as vehicle purchase price, maintenance costs and fuel costs, non-monetary costs, such as aversion to new and uncertain technologies or lower availability of fuel infrastructure, and incentives or subsidies. The utility of each vehicle technology is estimated for different vehicle purchase decision-makers. As these factors change over time, the utility for the various vehicle technologies may change resulting in variation in market share for these technologies. For example, fuel cell vehicles presently are expensive, lack extensive fueling infrastructure, and are largely an unknown technology to many potential purchasers. Over time, the capital cost is expected to decrease substantially, hydrogen infrastructure likely will be increased significantly, and people will become more familiar with the technology. These trends will reduce the disincentive to purchase fuel cell vehicles, and market share will increase.

The vast majority of work has focused on light-duty vehicle (LDV) choice models. The landscape for LDV applications and consumers is much simpler than that for trucks. Different LDV models estimate the probability a household would own a given number of cars based on household income, the average cost of cars, and travel opportunities. Vehicle type choice models are typically estimated as a conditional choice: vehicle type given the choice to purchase a vehicle. These models characterize vehicle types using parameters such as vehicle price, fuel economy, and weight and assume variation in consumer tastes.

While there have been a number of LDV choice studies, there exists very little work in the trucking sector (Berkovec, 1985; Burns, Golob, & Nicolaidis, 1976; Cardell, Dobson, & Dunbar, 1978; Choo & Mokhtarian, 2002; Greene et al., 2014; C. A. Lave & Train, 1979; C. Lave & Train, 1976; Lerman & Ben-Akiva, 1976; *LVChoice: Light Vehicle Market Penetration Model Documentation*, 2012; Mannering & Winston, 1985; National Research Council, 2013; Tardiff, 1980). LDV consumers typically have a modest range of driving styles, and surveys can capture consumer preferences on important purchase factors. Trucking applications, on the other hand, vary widely. Long haul trucks drive primarily at high speeds on highways and can travel more than 125,000 miles per year. Drayage trucks spend a high percentage of the time idling or driving at speeds below 15 mph. Transit buses have frequent stops and starts and may average less than 5 mph while medium-duty urban trucks, such as delivery vans, have driving patterns closer to LDVs. LDV consumers may vary in their attitudes towards new technologies, but they generally purchase and operate 1 or 2 vehicles at a time. Trucks may be purchased by an owner-operator who owns and operates a small number of trucks or by fleet managers who may purchase large numbers of trucks for varying applications in a year. Understanding how fleets make purchase decisions entails significant uncertainty.

2.2.1 UC Davis Model

A vehicle decision choice model developed at UC Davis focuses on trucks in California. The model considers the following technologies: gasoline, diesel, hybrid, natural gas (CNG and LNG), battery electric, and fuel cell. The model's monetary factors include capital cost, operating cost, incentives, and carbon tax. Non-monetary factors include environmental public relations, uncertainty (risk associated with reliability, sales into secondary markets, maintenance issues), refueling inconvenience (difficulty finding stations, long refueling times), and model availability. (Miller, Wang, & Fulton, 2017)

Advanced technology vehicles generally have a higher capital cost than conventional vehicles. The increased capital cost may be offset by lower operating costs; for example, the fuel cost may be lower because increased fuel efficiency leads to lower fuel use. In addition, maintenance costs may be lower. In considering alternative vehicle purchases, fleet managers often calculate the cost to own and operate the vehicle (total cost of ownership) over a fixed period of time to understand if there are financial benefits to the new technology.

The "payback period" is the length of time required to recover the cost of an investment (i.e., the additional capital cost of the vehicle). Fleet managers desire short payback periods of roughly 2-3 years but may consider somewhat longer ones in certain cases. The UC Davis choice model includes a payback period to compare total cost of ownership.

The model was applied to estimate the monetary incentives that might be required to achieve various ZE targets to 2050. The necessary incentive per vehicle starts as a significant percentage of the capital cost but drops to a small fraction of that cost in most cases, as market shares of ZE technologies rise toward the target. The total incentives required to meet a 25% mandate for all truck types are quite high ($7.7 and $9.6 billion). However, for medium duty trucks the incentive requirements are much lower—in the range of $165 million.

Chapter 3. California Demonstration Projects

California has been the leader in heavy duty ZE demonstrations. This chapter summarizes the California demonstrations, and then discusses the SCAQMD demonstrations most closely related to short haul freight applications.

3.1 California Demonstration Projects

Within California, demonstration projects of medium- and heavy-duty electric vehicles have included transit buses, school buses, shuttle buses, medium-duty trucks, and heavy-duty trucks. The Air Resources Board (ARB) has commissioned numerous studies, many of which are currently in progress. Literature on demonstration results is sparse, and original equipment manufacturers (OEMs) do not share results of internal tests on prototypes. It is notable that no public records could be located discussing findings of the demonstration projects for the 38 medium-duty fuel cell vehicles active or planned demonstration in California.

Of particular interest is a demonstration study by the Port of LA. This project tested pure battery electric class 8 heavy duty trucks to reliably haul loads of up to 80,000 lbs. There are seven of these trucks in total, with four of them in use with port operators since late 2015, and three more undergoing testing prior to assignment to operators as of mid-2016. The seven trucks have so far accumulated a combined 25,000 miles of test driving. Each of the four battery electric trucks currently in service with operators at the Port of LA has a slightly different configuration, as these trucks were rolled out successively so lessons from each previous truck's demonstration testing can be incorporated in the subsequent trucks' design. These trucks were also all assigned to different terminals and operators, to experience different driving conditions. The demonstration trucks manufactured by TransPower were able to travel 70-100 miles at average load of 65,000 lbs. gross combination weight rating (GCWR) while consuming less than 3-kilowatt hour (kWh) per mile at average load. The vehicles are capable of meeting minimum specified operating requirements for range and load hauling. However, reports also indicate that these vehicles at present require considerable calibration and frequent upgrades and maintenance to address issues including those with electrical and software systems, such that these vehicles appear to not yet be ready for use outside dedicated demonstration projects.

Hybrid vehicles in the class 6-8 range have been developed and tested to reach the in-production stage of commercial viability. Included are class 4 medium-duty truck trials by Fed-Ex and UPS, and a class 8 hybrid truck trial by Coca Cola. FedEx found that the hybrid vehicles could be integrated with minimal technical or operational issues into delivery routes.

Foothill transit is comparing 12 Proterra electric buses to CNG buses. This demonstration of electric buses is notable in that it used a fast charger at the midpoint of the bus route to recharge the electric buses in less than 10 minutes, allowing the buses to operate reliably despite having limited battery capacity. The buses were capable of operating along the selected routes and had no major issues with the advanced fuel technology components. The project also noted that the bus routes had to be carefully selected due to the range limitations of battery buses.

Fuel cell demonstrations are limited to buses. The largest of these projects is Zero Emissions Bay Area (ZEBA) transit project that compares the operation of fuel cell buses to diesel buses. Like a Foothill transit demonstration, it provides detailed maintenance and reliability assessments. The fuel cell buses improved their reliability over the course of the study, though their maintenance costs were found to be twice that of the diesel buses.

3.1.1 Findings from the Demonstrations

Overall, demonstration projects indicate that ZE and near-ZE heavy-duty vehicles are able to operate along selected routes during pilot projects but have also revealed areas for improvement and highlighted the importance of operational characteristics. On fuel efficiency, these projects have also shown strengths of ZE and near-ZE vehicles. However, fuel cell vehicles currently have much poorer fuel economy than electric vehicles, and fuel cell bus demonstrations have not yet met the US DOE technical target of 8 miles/DGE set for fuel cell electric buses. In existing comparative demonstration projects, medium- and heavy-duty electric trucks and electric buses have shown high fuel economy compared equivalent diesel trucks. Mixed results were noted with hybrid trucks; some demonstrations did not find significant differences in fuel economy compared to standard gasoline delivery trucks while others found significant fuel economy benefits.

Range of electric and fuel cell vehicles can limit applications of this technology, and both availability of fueling stations and time taken for vehicles to refuel can raise concerns. Demonstration projects often observed that the actual vehicles ranges fell short of the range promised by the manufacturer. In bus applications, electric buses could only be deployed on selected routes due to inability to meet range requirements of some routes, and Foothill transit used a fast charger at the midpoint of the route to allow frequent recharging. Electric vehicles are considered to be promising for class 6 and smaller, especially in applications where they can frequently return to a home base to refuel.

Access to fueling is an issue. According to the California Fuel Cell Partnership (CAFCP), there are no public hydrogen truck fueling stations available. There are three fueling stations for buses in operation, but these all have limited capacity and are costly to construct. For the ZEBA project, the station cost $10 million. Although there are numerous existing hydrogen fueling stations available statewide for passenger vehicles, these cannot be used without some major modification for medium and heavy-duty trucks due to the station layout, fuel capacity, and pressure requirements.

Access to battery electric vehicle charging is also an issue. Public truck charging is not available. It is expected that charging will occur at home base, but chargers and the electric infrastructure are expensive. Chargers can range from $1,000 for a basic charger using mains power and accommodating a single vehicle to $350,000 for a fast charger able to accommodate multiple vehicles. Space for this equipment may also be a problem. In medium-duty applications, the higher fuel economy of battery electric delivery trucks is expected to lead to cost savings relative to deployment of diesel vehicles. However, concerns over cost of electricity increasing subject to tiered rates as more electric vehicles were added to the fleet was also noted.

Zero emission buses in demonstration projects still do not match ICE vehicles in terms of reliability. Alternative fuel buses also had lower availability than the equivalent ICE buses they were compared to. Maintenance was an issue for the Foothill electric bus demonstration due to lack of availability of some component parts when repairs were needed. In European pilots, limited or late technical support for maintenance and repairs has also been an issue with electric freight vehicle adoption. Numerous issues for inverters, software, battery modules, and battery configurations were observed during the class 8 truck demonstrations at the Port of LA, some of which were easily fixed and some of which required more extensive downtime for trucks to allow repair.

The expected lifetime of alternative fuel vehicles remains somewhat uncertain due to the recent adoption of these technologies, and also due to the continuous improvements still currently being made to these technologies. The Department of Energy has set a target for fuel cell buses to have a lifetime of 12 years/500,000 miles, but the status of buses in 2012 indicated that lifetime would likely be 5 years/100,000 miles, far short of requirements. For trucks, longevity is not yet fully known, because HDT ZE trucks have only been deployed in the past few years.

Electric vehicles are considerably more expensive than diesel vehicles at present, sometimes three to eight times the cost of a comparable diesel vehicle. Batteries are an expensive component in electric, hybrid, and some fuel cell vehicles. Maintenance cost information is largely limited to bus experiences and are affected by transit agency staff learning how to troubleshoot problems with the new vehicles. Maintenance costs may decrease in future as staff gain familiarity with the technology. For the hybrid trucks, mixed results were seen: some maintenance costs were lower while others higher.

3.1.2 California Forecast for ZE and Near-ZE Trucks

A recently released energy forecast by the CEC includes a stock forecast for medium- and heavy-duty vehicles in California. Due to slow turnover of truck stock (every 5-7 years or every 20 years depending on truck vocation), even a high market share for alternative fuel vehicles (AFVs) is expected to result in only modest increases in AFV percentage of vehicle stock over the study horizon (2017-2030) (see Table 2). For heavy-duty trucks (class 7-8), diesel is expected to remain the dominant fuel while natural gas is expected to be the dominant AFV type for all policy scenarios with high, mid, or low support for battery vehicles; diesel-electric hybrid trucks are expected to reach significant numbers only in the high case. Battery electric and hybrid truck numbers are expected to grow much more quickly for classes 4-6 with over 50,000 of these vehicles projected to be on-road by 2030.

Table 2. California truck stock forecast (classes 3-8) by fuel type and policy scenario (CEC)

		2017	2020	2025	2030
High case	Diesel	748,041	852,973	886,491	887,741
	Diesel-Electric Hybrid	2,802	10,449	21,169	41,715
	Electric	1,166	6,690	19,851	42,580
	Ethanol		756	2,639	16,085
	Gasoline	233,183	243,272	245,682	231,347
	Gasoline Hybrid		112	694	5,045
	Natural Gas	9,939	13,164	33,307	61,117
	Propane	1,996	3,156	4,785	5,829
Mid case	Diesel	710,322	757,938	827,310	866,487
	Diesel-Electric Hybrid	1,919	6,665	18,244	32,233
	Electric	1,020	4,207	16,562	29,722
	Ethanol		441	2,707	16,582
	Gasoline	229,129	229,248	235,893	237,505
	Gasoline Hybrid		54	597	3,826
	Natural Gas	9,642	11,919	17,938	29,653
	Propane	1,626	2,349	3,616	4,622
Low case	Diesel	712,314	754,492	823,344	877,244
	Diesel-Electric Hybrid	1,999	6,490	16,707	29,683
	Electric	830	819	1,099	5,085
	Ethanol		323	1,775	10,459
	Gasoline	229,485	231,473	241,053	242,483
	Gasoline Hybrid		99	679	4,429
	Natural Gas	9,658	11,562	15,090	18,664
	Propane	1,672	2,451	3,460	4,174

Source: Giuliano, 2018

Battery costs as a percentage of the total truck cost range from 38% to 70%. This is expected to fall dramatically by 2030 as production increases. Estimates of costs in 2017 covered a wide range, from 180-500 $/kWh. For electric vehicles to be competitive, the cost of batteries will need to fall below $150/kWh.

It may be noted that hydrogen fuel cell vehicles are not part of these forecasts. Projections for California fuel cell truck volumes are sparse. We did find one estimate from the California Energy Commission (CEC) that forecasted commercialization in the mid-2020s. CEC estimates have a wide range: between less than 100 to a maximum of 4400 for medium and heavy-duty hydrogen fuel cell trucks in 2030, a tiny share of the overall market. The wide range reflects uncertainties regarding future price of fuel and development of a fueling network. As with BEHTDs, manufacturing costs would have to decline significantly for these vehicles to become competitive (Mcbride & Van Der Werf, 2019).

3.2 Summary of SCAQMD Demonstration Projects

The SCAQMD began heavy-duty zero emission truck demonstration projects for two primary reasons: to develop the technology and to demonstrate capabilities in real-world drayage operations with fleet partners. It was important to collaborate with fleets to assess the viability of the products as well as to promote the products. The demonstrations leveraged both state and federal funding and provided performance information back to OEMs for subsequent versions. (Choe, 2016)

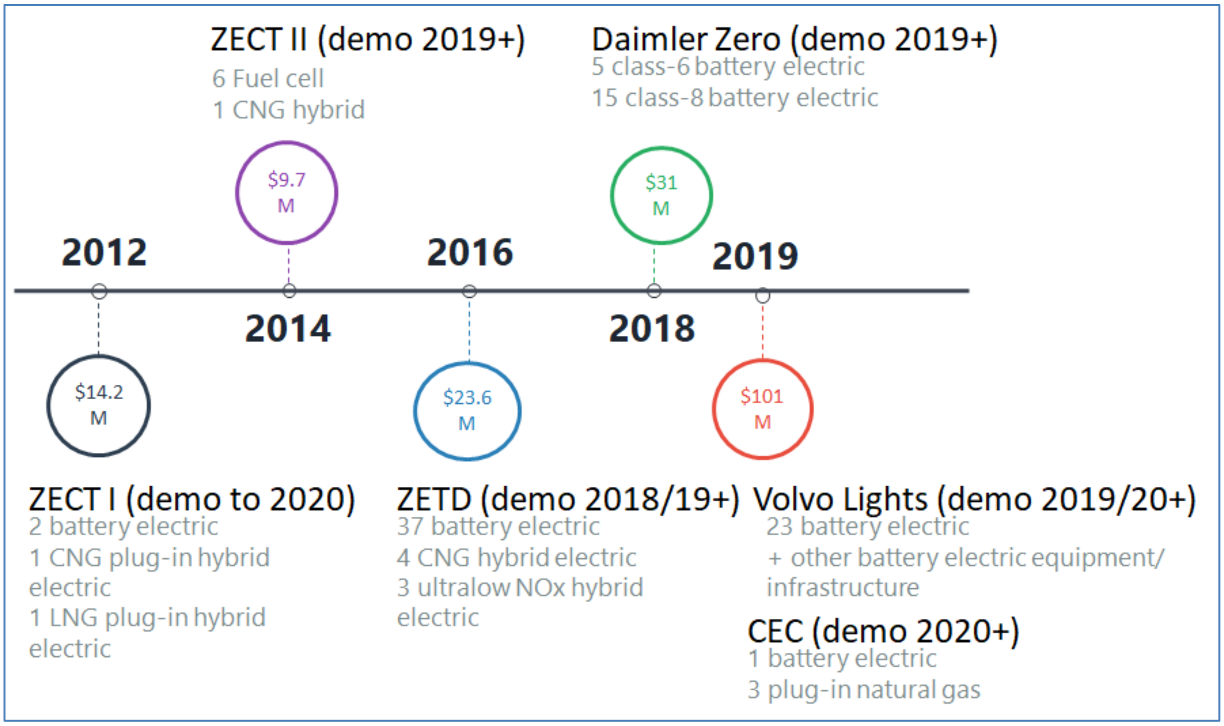

Figure 1. Timeline of zero and near-zero truck demonstration projects in California

Figure 1 shows the timeline of the major demonstrations. The first trials of BEV class-8 trucks launched in 2012 by the SCAQMD with $4.2 million from the DOE. Called the Zero Emission Cargo Transport Demonstration Project (ZECT I), TransPower and US Hybrid trucks were chosen to demonstrate zero emission capable heavy-duty drayage trucks in four different architectures: two battery electric and two plug-in hybrid electric drivetrains (one CNG, one LNG). Eleven total vehicles were deployed in drayage operations in the LA/Long Beach port area. The project has been extended twice to allow for additional data collection and analysis to improve the second versions of the technologies; 2 of the trucks are still in demonstration.

The second trial (ZECT II) was launched in August 2014 by the SCAQMD with $9.7 million from the DOE for seven trucks: six fuel cell and one CNG hybrid. The fuel cell vehicles are being manufactured by Kenworth/BAE Systems, TransPower, and Hydrogenics; the plug-in hybrid by Kenworth/BAE Systems. Most have been delivered in 2019 and are currently under demonstration.

Other demonstrations are underway. SCAQMD received $23.6 million from CARB under their Low Carbon Transportation Greenhouse Gas Reduction Fund Investments Program in 2016 to develop 44 class-8 zero and near-zero emission truck technologies. The project is called Zero Emission Drayage Truck Demonstration Project (ZEDT). It is not strictly for Southern California but state-wide including Oakland, Stockton, and San Diego. Collaboration with four other air districts is a key component to the project. Drayage is, once again, the focus of these demonstrations. The manufacturers selected are for battery electric: BYD (25 trucks) and Peterbuilt/TransPower (12 trucks); for hybrid electric, Kenworth/BAE Systems (4 CNG) and Volvo (3 ultralow NOx). The timing of vehicle launch is 2018-2020.

Daimler Zero Emission Trucks and EV Infrastructure Project will deliver five each class 6 and fifteen class 8 eCascadia model battery-electric trucks for demonstration in commercial fleet operations, especially in and around SCAQMD environmental justice communities. The fleet operators are Penske Truck Leasing and NFI. Most of these vehicles were to be delivered in December 2019. Funding of $31 million is provided by Daimler Technologies North America, SCAQMD, the Ports of Los Angeles and Long Beach, and EPA.

The Volvo Lights program will deploy 23 class-8 battery electric commercial trucks and fast charging infrastructure at a freight handling location. This $91M program funded by CARB, Volvo, and SCAQMD will also provide monies for 29 off-road battery electric yard tractors and forklifts to load and unload containers at freight locations in Southern California. Deployment is targeted for late 2019 and throughout 2020.

Lastly, SCAQMD received $10 million from the CEC under the Alternative and Renewable Fuel and Vehicle Technology Program to demonstrate zero and near-zero emission truck technologies. Four drayage trucks (1 battery electric, 3 plug-in electric with a natural gas engine) will be demonstrated by EDI/Cummins/Freightliner. Electric top handler equipment for port operations is also included in the funding pot. Launch is planned for 2020.

Delays in delivery of various truck technologies has put the ZECT I and ZECT II programs behind schedule, so information on demonstration projects is sparse. However, manufacturers are starting to deliver products en masse to the field for testing. 2020 should see a big uptick in the results for these zero and near-zero trucks made available to the AQMD and research community.

We started contacting operators and manufacturers of the demonstration vehicles in June 2018 to elicit information on the real-world operation of the vehicles. Results of the interviews are presented in Chapter 5.

Chapter 4. Impacts of Using ZE HDTs in Drayage Freight Operations

The lack of sufficient field data for examining impacts of using ZEHDTs in drayage operations motivated a different approach for estimating impacts. First, we develop a simulation model to estimate how using ZEHDTs affects freight operations, and hence costs and emissions. Our simulation model is based on survey data from the LA/LB ports. Second, we conduct two case studies of drayage firms. We use actual data on truck assignments and tours to estimate what share of their operations could be served with ZEHDTs. We generate scenarios for 2020, 2025, and 2030. The 2020 scenario is based on actual operation of ZEHDTs currently in demonstration. The 2025 and 2030 scenarios are based on expected improvements in battery technology. The scenarios compare conventional diesel, CNG hybrid, and BEVs.

4.1 Simulation of Using ZEHDTs

We use simulation to compare performance of diesel, natural gas (NG) hybrid and BE trucks. We explain the drayage operation scenarios, the optimization model used to represent these scenarios, and then present the simulation results.

4.1.1 Description of three different short-haul service scenarios

For the simulation we focus on trucks entering and exiting the port, delivering and picking up containers. The destinations are usually close to the port which a truck can reach through local roads. We evaluate drayage operations in which there is a direct trip from the port to a depot/warehouse/customer with the possibility to do one other pickup at another location before returning to the port. Figure 2 shows the types of trips that a truck is allowed to make. Notice that we assume there is no demand between locations A and B. Therefore, when the truck is travelling between these locations, it is not hauling a container.

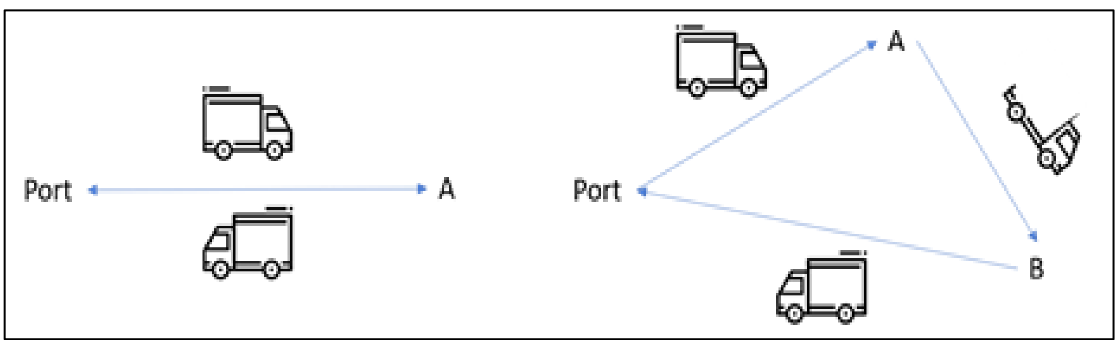

Figure 2. Two Types of Trips a Truck can Travel

We also make the following assumptions:

- For each trip, all trucks must start from the port and then return to the port.
- Demands are in the form of the number of containers and they only exist between the port and the other locations. The containers are either fully loaded or empty.

- All trucks operate under three different states: carrying no container, carrying an empty container and carrying a fully loaded container.
- Trucks have different power consumption rates for each different operating state. That is, diesel and NG hybrid trucks have different miles per gallon (mpg) values and ZEHDTs have different battery consumption rates.
- All ZEHDTs are battery powered and the charging stations are located within the port.
- There are no refueling detours for any truck because fueling stations are pervasive for diesel trucks and ZEHDTs charge at the port.
- With a given demand, the problem objective is to minimize the total miles travelled as well as the fleet size to serve the current demand under the above assumptions.

We are interested in evaluating the potential of replacing diesel trucks with NG hybrids or ZEHDTs. Thus, three different cases are simulated: the present (2020), year 2025 and year 2030. And in each case, we also are interested in studying the sensitivity of how increasing the ratio of the ZEHDTs in a fleet affects the fleet size.

4.1.1.1 Inputs (Data/Assumptions)

Next, we describe the input data to our simulation. We obtained survey data from the Port of Long Beach and Port of Los Angeles that contains origins and destinations for container demands across the years 2010-2012. The data not only describes the origins and destinations, but also the direction and container types. In other words, one can tell how many containers (fully loaded or empty) are sent from the port to a particular location and how many are sent from a particular location back to the port. The data involves 450 locations. Since our simulation is on a daily basis, we need to derive a daily demand value from the raw data. Ten days were selected out of the original data. The demand was averaged, and the result served as the input to our model. The 10 days that were selected are representative of the raw data. The daily average demand involves 135 empty containers and 176 loaded containers across 94 locations.

The assumptions for the parameter values we use are listed below. In order to be as realistic as possible, we use parameter values as reported in our demonstration interviews for the current year (2020) estimation. We categorize our assumptions into four groups. The first group describes the speed levels that are used. Then the parameters for the different types of trucks are listed in the next two groups. Finally, we have some general parameters in the fourth group which are also important for the simulation.

1. <u>Speed</u>

- Short distance average speed – 20 miles/h
- Long distance average speed – 45 miles/h
- Long distance criteria – > 5 miles of radius (10 miles of round trip)

2. Diesel trucks

- Estimated refueling time – 0.25 h
- Tank capacity – 226 gallons (FEV North America Inc, 2015)
- MPG under different states (no container, empty container, fully loaded container) – 8 | 7 | 5 mpg

3. ZE trucks

- Charging time – 3 hours for 0-80% and another 2 hours for 80-100% (based on demonstration interview results). This is the same for all years which reflects the development of the charging technology. That is, the battery size is expected to increase in future years but the charging time is assumed to remain the same due to improved charging technology.
- Charging pattern – 0-20% should be left unused in order to keep the battery from degrading too much (interview results).
- Battery capacity – See Table 3.
- Battery consumption rate under the different states (no container, empty container, fully loaded container) – See Table 3.
- Vehicle range under the different states (no container, empty container, fully loaded container) – See Table 4.

4. Other Parameters

- Truck daily operation time limit – 8 hours (Including traveling and refueling times).
- Truck refueling detours – None. Detours for diesel trucks are omitted due to the pervasiveness of diesel gas stations, and detours for ZE trucks are omitted since we assume charging only occurs at the truck depots located near the Port.
- Distance increase factor – 1.25, based on prior research on network distance vs straight line distance.

4.1.1.2 Technology Improvement Trends (Tech Forcing)

We use prior research at UC Davis on technology improvement trends to obtain battery consumption rates and battery sizes for the present year and future years as shown in Table 3. The ranges in Table 4 are generated using the battery information in Table 3.

Table 3. Battery Information for the Different Years

Year	Consumption Rate with Fully Loaded Container (kwh/mile)	Consumption Rate with Empty Container (kwh/mile)	Consumption Rate with No Container (kwh/mile)	Battery Capacity (kwh)
Present*	4	2.82	2.4	240
2025	3.37	2.1	1.6	525
2030	3.18	2.01	1.5	650

*240kwh for present year is based on demonstration interview results & US Hybrid Battery Electric Class 8 Truck Spec Sheet.

Table 4. ZE Ranges for the Different Years

Year	Fully Loaded Container (mile)	Empty Container (mile)	No Container (mile)
Present*	60	85	100
2025	156	250	328
2030	204	323	433

*The first row of data is based on demonstration interview results.

4.1.1.3 Outputs (VMT/Costs/Emissions)

The outputs of our simulation contain three parts: 1) The total vehicle miles travelled needed to satisfy the daily drayage operation demand under each scenario; 2) The number of vehicles (diesel, NG hybrid, and ZE) needed under each scenario which serves as the input to calculate the costs; 3) The corresponding pollutant and GHG emissions under each scenario.

4.1.2 Description of Optimization Model

We now briefly present the models we developed as well as the algorithms that are used to solve them.

4.1.2.1 Development Process/Validation

Instead of solving the problem using a single model, we solved the problem using a two-stage approach. Figure 3 shows the two-stage approach. We first formulate a minimum cost circulation problem which outputs the minimal total miles travelled to satisfy the total demand and the optimal trips for the trucks to travel. Then, we take the optimal trips as an input into a bin-packing problem to minimize the fleet size. Note that by using a two-stage process, the total vehicle miles are fixed, and the bin packing problem is to estimate the minimum number of vehicles required to serve demand at the VMT minimum.

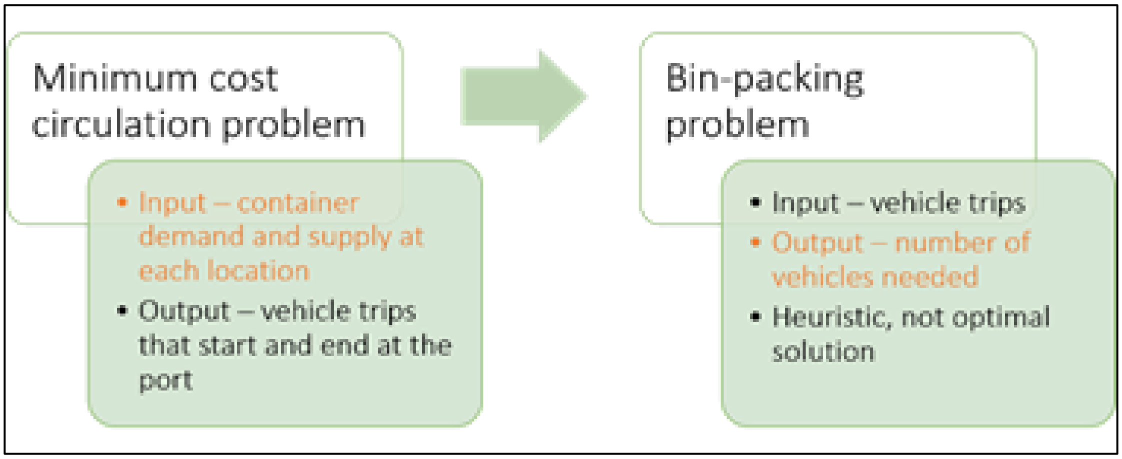

Figure 3. Two-Stage Approach

The two sub-problems, minimum cost circulation and bin-packing problems, are well known problems in the optimization literature. The minimum cost circulation problem can be formulated into a linear programming problem (LP) and solved by a standard LP solver. The bin-packing problem, on the other hand, is NP-hard which means there are no optimal algorithms that can solve this problem in polynomial time. Therefore, we adapted a heuristic algorithm which can produce sufficiently good solutions in fast computation time. For more details on the models and solution algorithms, please see Appendix A.

4.1.3 Optimization Results

4.1.3.1 VMT, Fleet Size for Each Scenario

The results of all the cases are shown in Table 5–7. Since hybrid electric trucks have the same operational performance characteristics as diesel trucks, the number of vehicles required to fulfill the demand is the same as for diesel. We therefore compare only diesel and ZE for VMT and fleet size. In each table, the first column is the ratio of the number of ZE trucks in a fleet. For each scenario, we estimate the outcomes of an increasing share of ZE trucks until the maximum possible share is reached. The maximum possible share is the point at which the required trips can no longer be performed by ZEHDTs because of range and charging constraints. The next set of 3 columns give distance traveled by diesel trucks, ZE trucks, and the total fleet, respectively. Total distance is constant, because the optimized set of routes is the same in every case. The following set of 3 columns gives the number of diesel trucks, ZE trucks, and total number of trucks in the fleet for each ratio level. The remaining columns give average number of trips for diesel and ZE, and ZE average charging time in hours per day. The charging time is only for the 8-hour shift simulated.

Each row increases the share of ZE by roughly 10%; however, it is not exact because the total number of trucks required to service the demand is an integer. The last row represents the highest possible ratio of ZE trucks to meet the demand.

Table 5. Distances and Fleet Size under Different ZEHDT Ratios – 2020

Total Miles				Fleet Size			Trips per vehicle		Charging Time
Share electric	Distance diesel	Distance electric	Total Distance	N diesel	N electric	Total N	Ave diesel	Ave electric	Ave per vehicle per day (hrs)
0	6223	0	6223	19	0	19	8.2	0.0	0.00
0.10	6052	172	6223	18	2	20	6.9	15.0	1.38
0.19	5833	390	6223	17	4	21	6.1	13.0	2.35
0.27	5575	648	6223	16	6	22	5.6	11.0	2.81
0.35	5229	994	6223	15	8	23	5.1	9.8	3.59
0.44	4813	1410	6223	14	11	25	4.8	8.0	3.74
0.57	4283	1940	6223	13	17	30	4.2	5.9	3.55
0.68	3602	2621	6223	11	23	34	3.6	5.0	3.68
0.75	2990	3234	6223	9	27	36	3.1	4.7	3.81

Table 6. Distances and Fleet Size under Different ZE Ratios – 2025

Total Miles				Fleet Size			Trips per vehicle		Charging Time
Share electric	Distance diesel	Distance electric	Total distance	N diesel	N electric	Total N	Ave diesel	Ave electric	Ave per veh per day (hrs)
0	6223	0	6223	19	0	19	8.2	0.0	0.00
0.15	5878	346	6223	17	3	20	6.2	16.3	0.10
0.20	5457	766	6223	16	4	20	5.2	17.8	0.72
0.30	4946	1278	6223	14	6	20	5.0	14.2	1.18
0.41	4372	1852	6223	13	9	22	4.4	10.9	1.40
0.50	3694	2529	6223	11	11	22	3.8	10.3	1.69
0.61	2942	3281	6223	9	14	23	3.9	9.1	1.67
0.71	2203	4021	6223	7	17	24	2.4	8.1	1.72
0.80	1449	4775	6223	5	20	25	2.0	7.2	1.71
0.88	733	5491	6223	3	23	26	1.3	6.6	1.66
0.96	198	6025	6223	1	25	26	1.0	6.2	1.63

Table 7. Distances and Fleet Size under Different ZE Ratios – 2030

Total Miles				Fleet Size			Trips per vehicle		Average Charging Time
Share electric	Distance diesel	Distance electric	Total distance	N diesel	N electric	Total N	Ave diesel	Ave electric	Ave per veh per day (hrs)
0	6223	0	6223	19	0	19	8.2	0.0	0.00
0.15	5863	361	6223	17	3	20	6.2	16.7	0.00
0.20	5405	818	6223	16	4	20	5.1	18.2	0.22
0.30	4901	1322	6223	14	6	20	4.9	14.3	0.50
0.38	4283	1940	6223	13	8	21	4.2	12.5	0.79
0.50	3602	2621	6223	11	11	22	3.6	10.5	1.00
0.59	2834	3389	6223	9	13	22	2.8	10.0	1.01
0.70	2098	4125	6223	7	16	23	2.3	8.7	1.07
0.82	1338	4886	6223	4	18	22	2.2	8.1	1.11
0.87	733	5491	6223	3	20	23	1.3	7.6	1.10
0.96	198	6025	6223	1	22	23	1.0	7.0	1.08

Table 5 through Table 7 lead to the following observations. First, under all scenarios, as expected the total miles travelled by ZEHDTs increases as the percentage of ZEHDTs in the total fleet increases. At the small ratio of ZE fleet size, the average number of trips per vehicle is much higher for the ZEHDTs than the diesel trucks because the electric trucks are primarily used for the shortest trips. Thus, they perform more trips per day.

Second, for the 2020 scenario and assuming 75% of the fleet as ZEHDTs, only 52% of the total miles travelled can be operated by ZEHDTs. In this case, the total fleet size is nearly double that of a 100% diesel fleet. With today's battery technology and assuming charging only occurs at the depot, the driving range is not sufficient to cover all the demand and there is still a need to maintain a diesel fleet.

Third, with more efficient battery technology projected for Years 2025 and 2030, the performance of the ZEHDTs significantly improves. In these scenarios, only one diesel truck is required in the fleet to cover the demand that is far away from the ports. Assuming 96% of the fleet as ZEHDTs, the total fleet size is 26 which is 5 more trucks than the 100% diesel case in Year 2025 and the total fleet size is 23 which is 4 more trucks than the 100% diesel case in Year 2030. Also, with the more efficient battery technology the average number of trips for the ZEHDTs increases and the charging time reduces significantly.

Figure 4–6 show the differences in fleet size across the scenarios. The figures show how dramatically battery performance affects the results. At present, any large introduction of ZEHTDs would involve very high costs due to the need for a much larger fleet. In contrast, by 2030, almost all of the demand can be served by ZE HDTs with an approximate 20% increase in fleet size. Notably, up to 6 ZEHDTs could be used while only increasing the fleet size by one, and the 6 ZEHDTs would cover about 21% of the VMT.

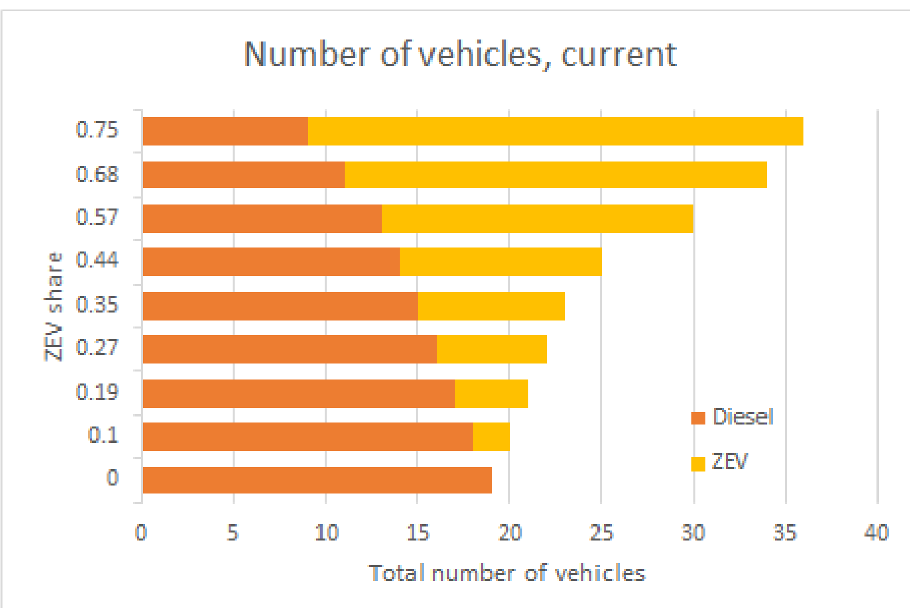

Figure 4. Fleet Size Information for 2020

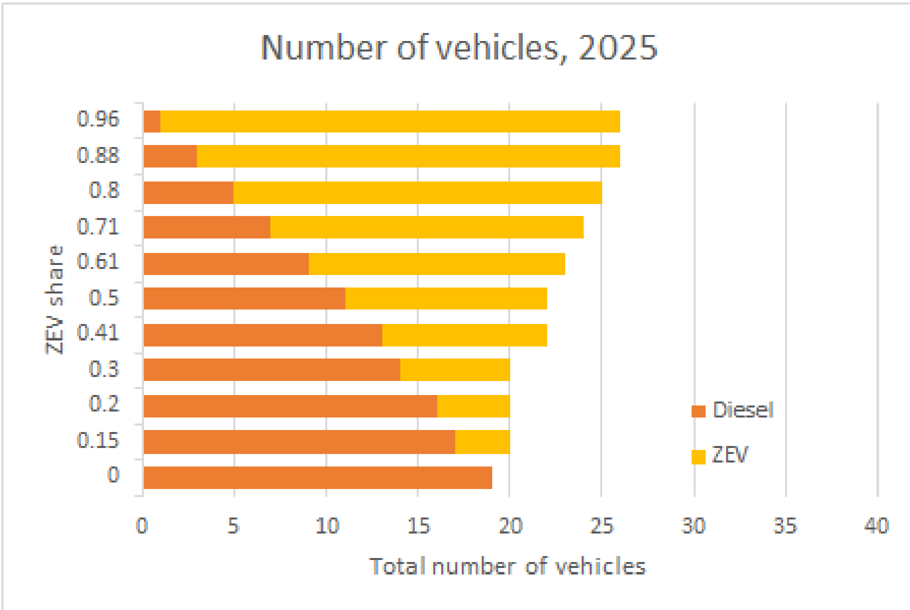

Figure 5. Fleet Size Information for 2025

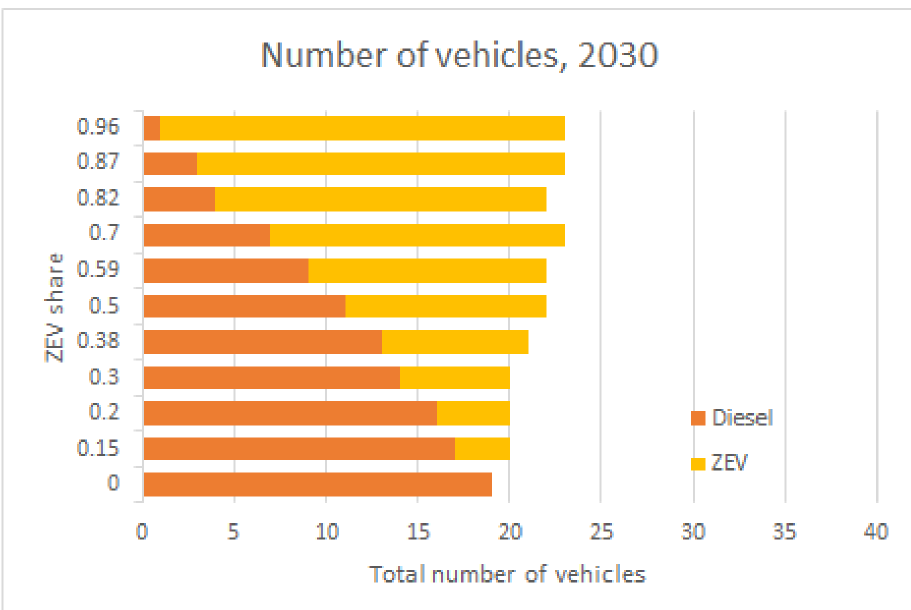

Figure 6. Fleet Size Information for 2030

4.1.4 Limitations of the simulations

We would like to point out the limitations of our simulations. All of the results above are based on a subset of the many drayage patterns that exist. In reality, drayage tours are more complex than the ones we use here. We are assuming a single 8-hour shift for vehicle operations while in the real world there may be longer single shifts or multiple shifts, which would have an effect on the fleet size. We do not consider weight limits; we assume that each truck is able to carry the same load, even though ZEHDTs have a greater gross weight due to the weight of the battery pack. All of these factors would increase the number of required vehicles. Due to the lack of current charging infrastructure in the field, we are assuming all charging is performed at the port. This limits the range of the ZE trucks in the simulations, because the truck must return to the port before its range limit is reached. Future research should take into consideration available charging stations outside the port and more complex drayage tours.

4.2 Case studies

The simulations allow us to generate general information on the trade-offs between using diesel or hybrid electric trucks vs ZEHDTs, but the demand portrayed is quite simple. Each truck either makes one round trip (empty/full or full/empty), or a two stop round trip (full/empty – chassis only – full/empty), and all tours start and end at the ports. We conduct two case studies of drayage firms to better understand the actual patterns of drayage operations. We use actual operations to estimate what share of current demand could be provided by ZEHDTs.

Two Los Angeles based trucking firms provided daily truck movement data for detailed analysis. For the purpose of this report, both firms requested that we do not identify them by name. OD trip data can provide information on where trucks are going and the distance between the start and stop locations. However, only some types of firms run consistently back and forth between OD-pairs. Most trucks have several pick-ups and deliveries a day. That is, trucks typically make daily tours that include multiple pick-ups and deliveries. To understand a fleet's operation, one must analyze the combination of trips taken in a 24-hour period.

These two companies have very different patterns of operation, which results in different challenges and barriers they will face in the electrification process. Firm 1 is a drayage and delivery service company. Their trucks are operated only during the daytime, sometimes with multiple tours in a day. Trucks return to their yard at night, which makes it possible for overnight charging if using electric vehicles. Firm 2 is also a drayage firm, but this is not the lion's share of their business. The bulk of Firm 2's business is direct store delivery; they operate both in the daytime and at night. That means, if they use electric vehicles in the future, charging can only be conducted between two delivery tasks, which is not always at night. Comparing these two firms can provide insight on how different business types can transition to electrification.

The operational data collected from each firm is similar. Data included: Truck ID, Driver ID, Date/Time, Geographic Coordinates for each stop, Load Weight, and Trip Distance. Two months of data was provided by Firm 1, and one month of data for Firm 2. After cleaning the data, trips and tours by specific trucks were constructed based on movement throughout the day. A trip refers to an origin-destination pair without any stops, with the same load weight. A tour is the combination of multiple trips starting or ending at a firm location, in one or more days. The second concept—a tour—is the key to examining the operating patterns of a trucking firm. From examining the behavior of tours, one can estimate whether or not electric trucks are feasible for a specific truck on a specific day.

Range is a function of distance, load weight, terrain, and traffic conditions. This study only considers distance and load weight, as data on terrain and traffic conditions are not available. For electric vehicles, fuel economy is inversely related to load weight. So, when trucks are loaded with extremely heavy loads, range shrinks significantly. In addition, the battery (which can weigh thousands of pounds) reduces maximum cargo weight due to state and federal gross vehicle weight limits.

Given the limited range of current electric trucks as well as lack of charging stations, we assume that drivers can only charge their trucks at the firm home base. Therefore, the distance and loads of a single tour determines whether diesel trucks can be replaced by electric trucks. If the single tour distance can be covered by the range of an electric truck, then electrification would be possible. However, we discovered that range is not the only factor for determining whether a truck was a good candidate for a ZE model. Charging time is also a factor. In some instances, trucks will not have enough time for charging (at least one hour for fast charging and four to six hours for regular charging) when they return to home base because they operate continuously. That means that some trucks may have to complete multiple tours in a day before the trucks are set to rest. Taking this scenario into account, we also calculate the total daily distance if more than one tour is recorded per day.

We generated trips, tours and daily distance by day from the data. Distance travelled was organized into four categories: short (0-40 miles), medium (40-80 miles), long (80-120 miles), and extra-long (>120 miles). These categories were chosen based on the potential ZE range over the target years.

4.2.1 Firm 1 operational characteristics

Firm 1 is a drayage and direct delivery transportation company specializing in chemicals, liquids, and dry bulk items. The firm *owns* all their operating truck assets and the trucks operate 1-2 shifts per day. The company is based in the City of Carson. Two months of operational data was provided; results indicate that both months share similar patterns.

Table 8 and Figure 7 give the distance distribution for single tours, meaning one round trip from home base and back to home base. Around 70% of the tours are within 80 miles for both months. This range is feasible for the current generation of electric trucks (see blue and green bars in Table 8 and Figure 7 below). March 2019 has more trips within 80 miles than October 2018. There are a large number of very short trips, again very favorable for BEHDTs.

Table 8. Firm 1 single tour distance (miles)

Single Tour	< 40 miles	40-80 miles	80-120 miles	>120 miles
18-Oct	54%	15%	8%	23%
19-Mar	59%	14%	6%	21%

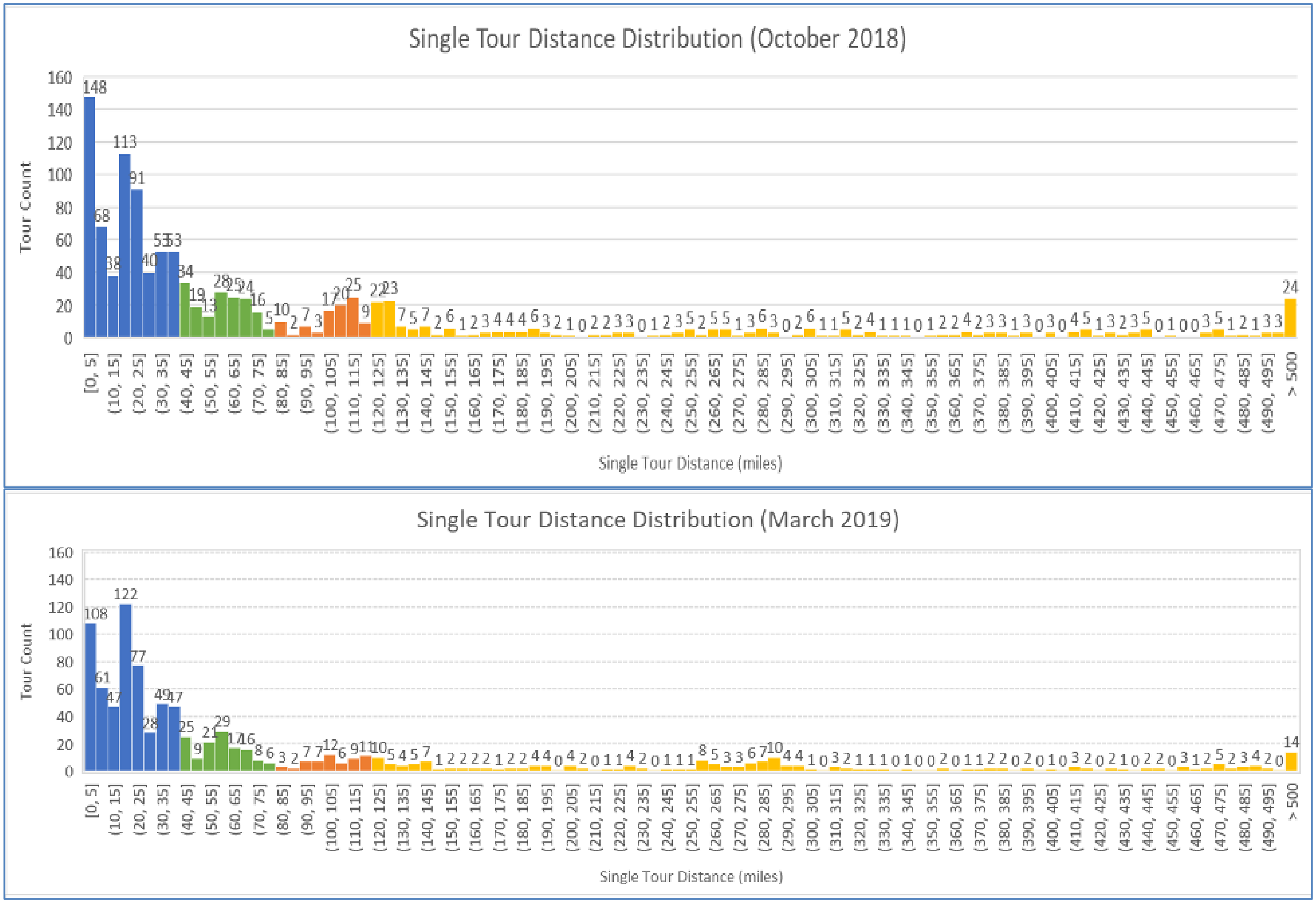

Figure 7. Firm 1 single tour distance distribution for October 2018 and March 2019 (miles)

Single tours do not tell us how much of the firm's activity could be performed by ZEHDTs, because these tours are linked with others over the course of the day. ZE trucks require hours to refuel, hence the entire day's work must be considered. Thus, the question is whether a ZE truck can perform the entire day's work either without charging, or with enough idle time to allow for charging.

Table 9 and Figure 8 give the distance distribution for daily tours. When we aggregate to tours, the very short trips decline, and the distribution clusters in the range of 50 to 100 miles. The percentages of daily distance within 80 miles is 26% for October 2018 and 40% for March 2019 (see blue and green bars in Table 9 and Figure 8 below). If only distance is considered, an average of 28% of daily shifts could be performed by electric trucks for Firm 1.

Table 9. Firm 1 daily tour distance (miles)

Daily Distance	< 40 miles	40-80 miles	80-120 miles	>120 miles
18-Oct	4%	22%	18%	56%
19-Mar	13%	27%	13%	47%

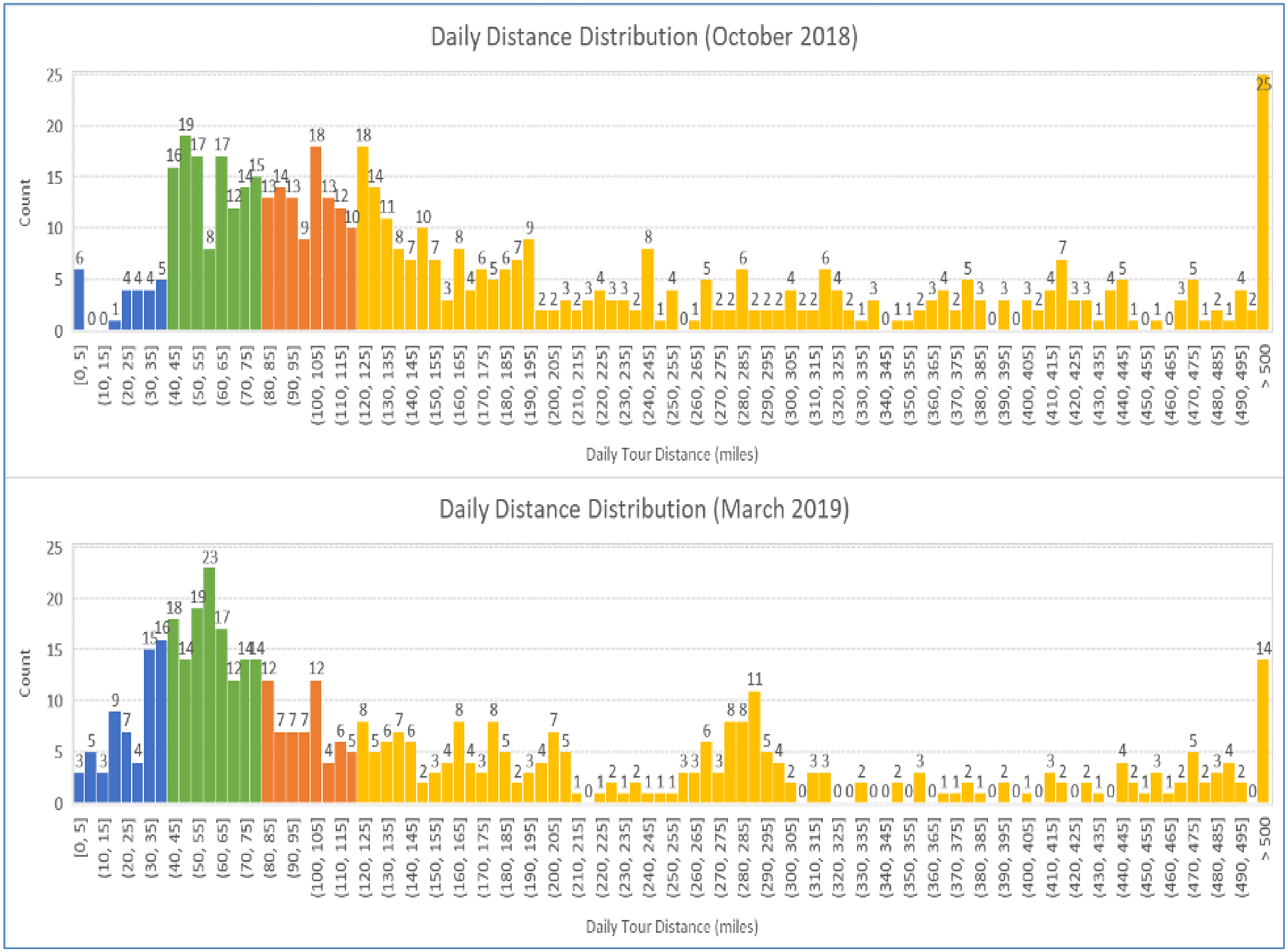

Figure 8. Firm 1 daily tour distance distribution for October 2018 and March 2019 (miles)

A possible way to reduce potential range anxiety is to install charging stations where trucks frequently travel and the home base is not nearby. A kernel density map that shows clusters of Firm 1's trip destinations can help identify locations for public charging stations. See Figure 9. The yellow star in each panel is the home base for Firm 1. The areas in deep orange and blue shades—Long Beach, Los Angeles, Anaheim, Huntington Beach, Corona, and Rancho Cucamonga—can be considered as places with priority for charging station installation.

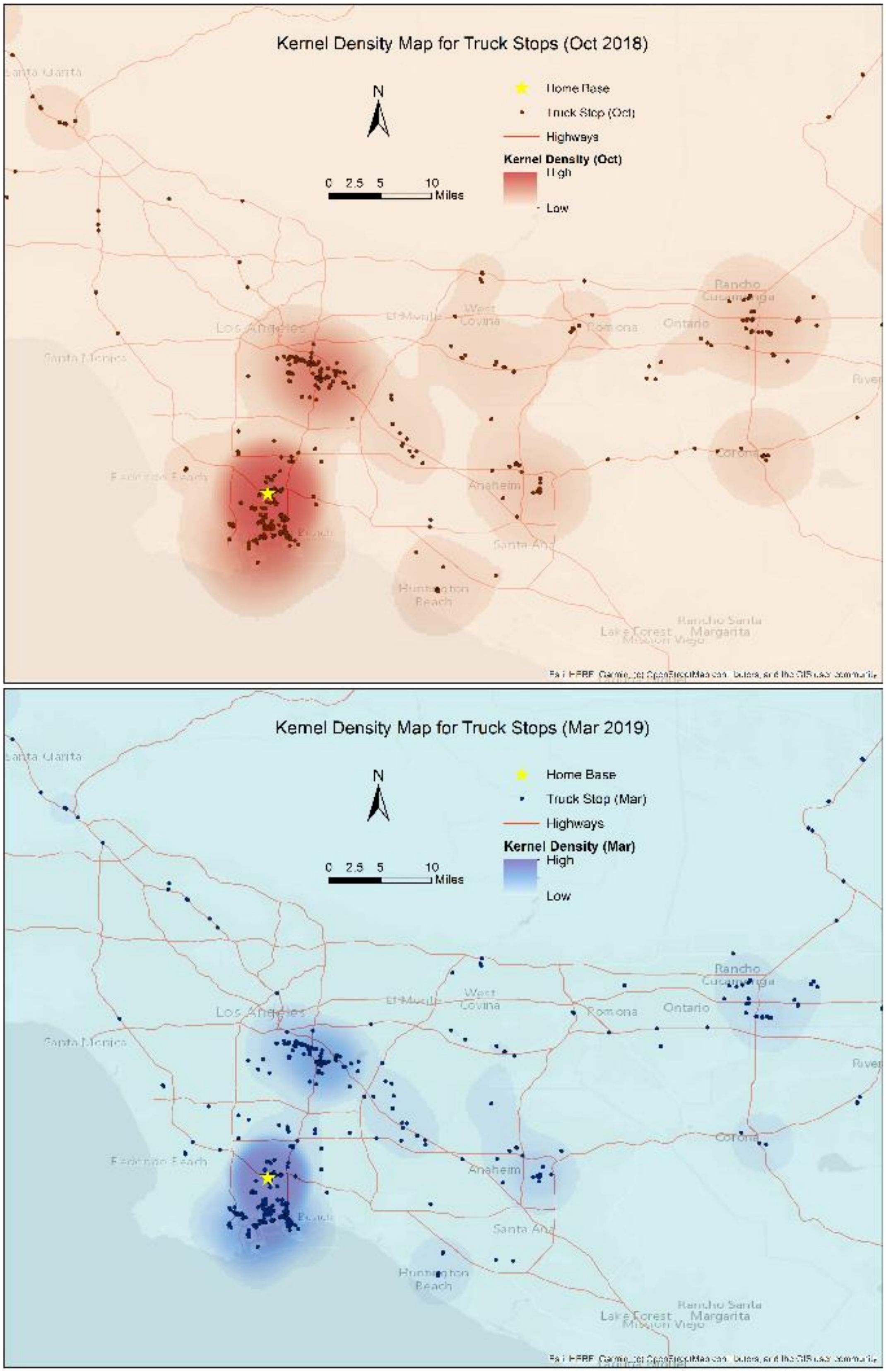

Figure 9. Firm 1 density maps of trip destinations

4.2.2 Firm 2 operational characteristics

Firm 2 is quite different from Firm 1. Firm 2 is a drayage and direct delivery freight company for natural foods. It leases all its trucks and the trucks operate multiple shifts a day. Many trucks operate around the clock seven days a week. The company is based in Buena Park. We obtained one month of its operational data (March 2019). Table 10 and Figure 10 give the distance distributions for both single tours and daily distance. Firm 2 has a much higher share of single tours of less than 80 miles, (nearly 2/3 of the total), but just 22% of daily tours fall into the first two categories. Figure 10 shows the big difference between tours and daily distance. This is a result of the intensity of use of the trucks. With 2/3 of daily tours more than 120 miles, charging time must be considered. The Firm 2 data shows that the idle time between tours is barely enough for charging (1–2 hours).

Table 10. Firm 2 single tour and daily distance (miles)

	< 40 miles	40-80 miles	80-120 miles	>120 miles
Single Tour	20%	44%	17%	19%
Daily Distance	10%	12%	12%	66%

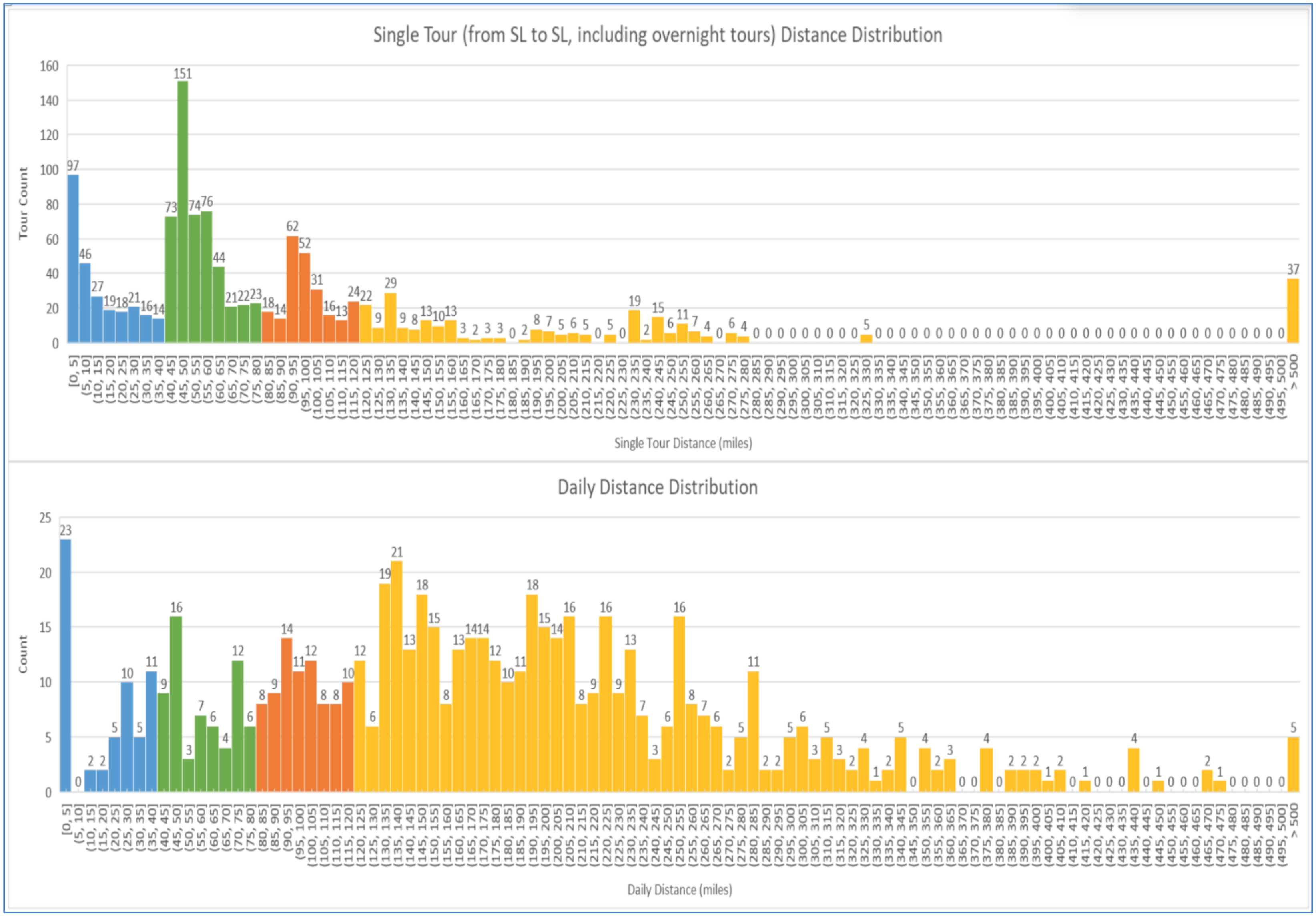

Figure 10. Firm 2 tour and daily distance distributions for March 2019

Finally, Figure 11 shows the kernel density map of Firm 2 trips. The yellow dots denote the locations of Firm 2. Two main clusters are quite visible, with corridor concentrations expanding from them along the major freeways. Some trips are quite long, with a significant concentration as far south as San Diego. In this case charging stations would be essential, as the trips exceed the current range of ZEHDTs.

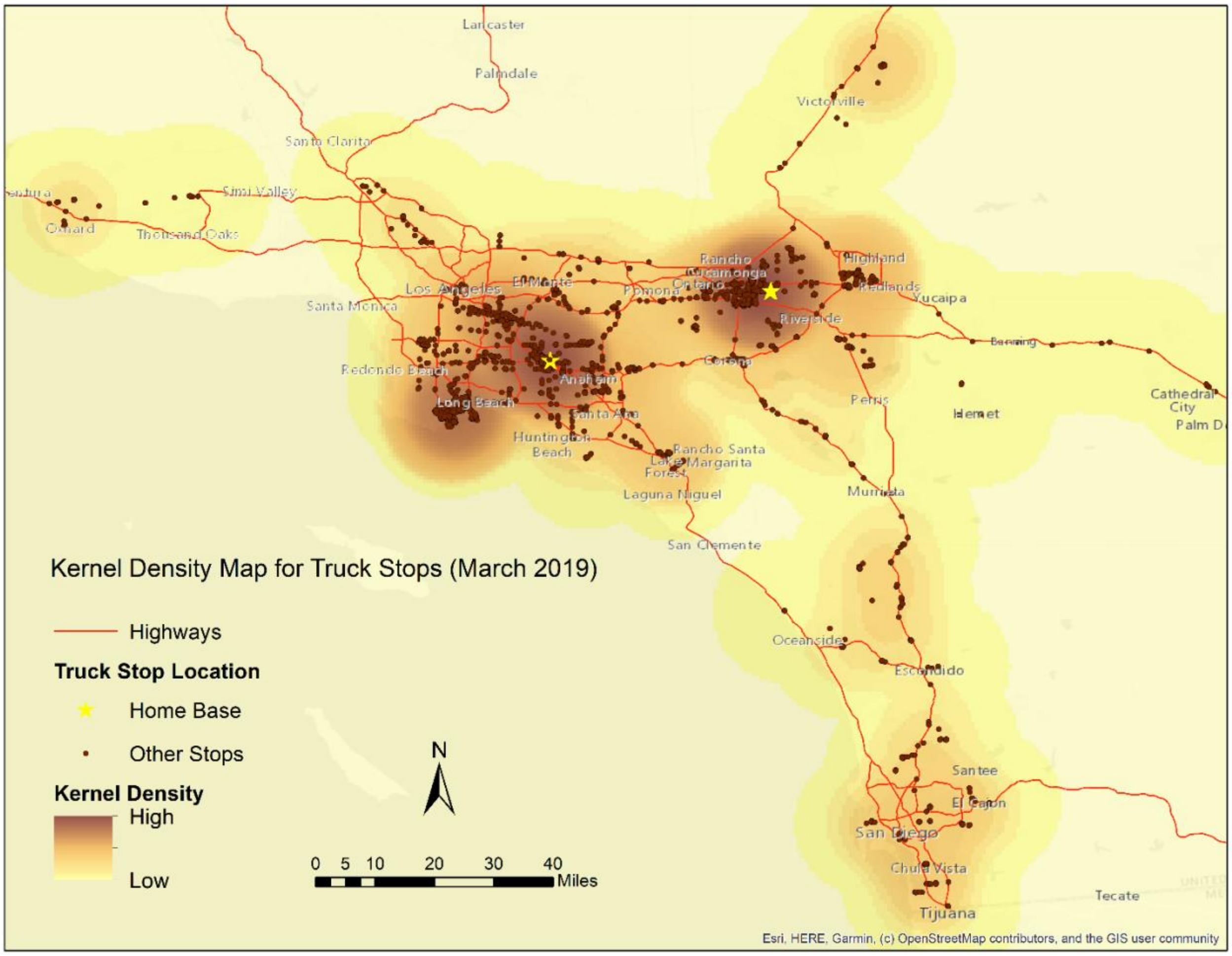

Figure 11. Firm 2 density maps of trip destinations

4.2.3 Use of ZEHDTs: Ability to meet demand

We use the firm data to estimate what share of operations can be served by ZEHDTs in 2020, 2025, and 2030. As in the simulation analysis, we assume the same set of daily tours for each target year. As discussed above, two major considerations play a factor in range: distance travelled and total load weight. The battery consumption rate goes up as the load weight increases. Given the distance and battery consumption rate (based on load weight) for each trip in a tour, we calculate how much electricity a truck would consume for each trip, and then get the total energy consumption in a tour by aggregating all the trips in that tour. Specifically, the calculations can be divided into several steps:

- Step 1: For Trip i in Tour k, select ***battery consumption rate*** γ_{ik} (kwh/mile) based on load weight (w_{ik}). Here, we use the same assumptions regarding energy consumption rates, battery capacity, and range as in Section 4.1 and presented below in Table 11:
    - If w_{ik} > 0, use fully loaded container consumption rate γ_m
    - If w_{ik} = 0, use empty container consumption rate γ_0
- Step 2: Calculate ***battery consumption*** E_{ik} (kwh) based on ***battery consumption rate*** γ_{ik} (kwh/mile) and trip distance D_{ik} (miles) for Trip i in Tour k:

$$E_{ik} = \gamma_{ik} * D_{ik}$$

- Step 3: Calculate total battery consumption E_k (kwh) for Tour k by summing up all the *n* trips in Tour k:

$$E_k = \sum_{i=0}^{n} E_{ik}$$

- Step 4: Calculate the total battery consumption E_T (assuming *m* Tours) between two charging time slots.
    - For Firm 1: Trucks can only be charged during the night at firm's home base, hence distance determines whether a given ***daily*** tour is feasible for ZE
    - For Firm 2: Trucks can only be charged at the home base during breaks no shorter than 4 hours; if the break is less than 4 hours, the next daily tour must be added to the first daily tour. Distance of daily tours or connected daily tours determines feasibility for operation by ZE.

$$E_T = \sum_{k=0}^{m} E_k$$

- Step 5: Calculate the share of days (or connected days for Firm 2) *X* in a month whose battery consumption E_T is within the battery capacity for that target year. The total number of tours in a month is Y:

$$s = \frac{X}{Y}$$

Table 11. Battery consumption rate based on load weight

Year	Consumption Rate with Fully Loaded Container (kwh/mile)	Consumption Rate with Empty Container (kwh/mile)	Battery Capacity (kwh)
2020	4	2.4	240
2025	3.37	1.6	525
2030	3.18	1.5	650

In addition to battery capacity, the gross weight limitation is another constraint that needs to be taken into consideration, since the electric battery pack adds additional weight to the trucks. In this analysis, we assumed that the weight of an electric truck (including tractor trailer, chassis and empty container) is 40,000lbs, which is heavier than conventional diesel trucks that are currently being used by the firms. The gross vehicle weight limit for a truck is 80,000 lbs. Loads in excess of 40,000 lbs. therefore cannot be carried by the BEV. Adding the load weight constraint further reduces the number of tours that can be served by BET.

4.2.3.1 Firm 1 Results

Table 12 gives the results from the above steps for Firm 1. If there is no weight limit, on average about 30% of the daily tours can be serviced by electric trucks in 2020. The share increases in the target years, reaching 61% in 2025, and 82% in 2030. However, if we take the current gross weight limit into consideration, the percentage of operations that could be serviced by electric trucks is substantially reduced in each target year. Nevertheless, Firm 1 shows that a significant share of daily tours can be serviced by BETs even in 2020.

Table 12. Firm 1 operations that could be serviced with ZE trucks

Firm 1	Target year:	2020	2025	2030
Battery Capacity (kwh)		240	525	650
October (% of truck days that can be operated by ZEHDTs)	Without Weight Limits	21%	58%	76%
	With Weight Limits	17%	51%	67%
March (% of truck days that can be operated by ZEHDTs)	Without Weight Limits	39%	65%	88%
	With Weight Limits	19%	35%	49%
Average (% of truck days that can be operated by ZEHDTs)	Without Weight Limits	30%	61%	82%
	With Weight Limits	18%	43%	58%

4.2.3.2 Firm 2 Results

For Firm 2, although single tour distances are shorter than Firm 1, the lack of charging time makes it more difficult to use ZEHDTs. Instead of using a 24-hour day as the unit of calculation, we had to consider the entire time period before the next available charging time slot (breaks that are no shorter than 4 hours), given that the firm has a multi-shift operation using its truck resources nearly 24 hours a day. We call these connected tours. As would be expected, using trucks nearly 24 hour per day leaves little time for charging. See Table 13. Just 8% of tours could be served in 2020. If we consider the gross vehicle weight limit, the share is reduced to 2% in 2020. Even in 2030 just a little more than one fifth of tours could be served.

Table 13. Firm 2 operations that could be serviced with ZE trucks with weight limitations

Firm 2	Target year:	2020	2025	2030
Battery Capacity (kwh)		240	525	650
March (% of truck days that can be operated by ZEHDTs)	Without Weight Limits	8%	38%	64%
	With Weight Limits	2%	12%	22%

The difference in results between the two firms illustrate the diversity of operations even within the drayage industry. Firm 1 owns its own trucks. Because it hauls liquid chemicals, trucks are on a strict cleaning schedule and some down time is part of the business. Thus, there is less incentive to use them as intensively as possible. In contrast, Firm 2 leases all its trucks, and therefore has every incentive to use them as intensively as possible. The firms also serve different markets. Delivery time windows are likely more constrained for liquids or chemicals, as people and equipment must be in place to receive such deliveries. Firm 2 deals with food; warehouses and retail outlets tend to operate 24/7, making it possible to run night delivery shifts.

How do our case study results compare to the simulation results? First, as noted earlier, the simulation results are based on much simpler tours and do not consider the gross vehicle weight limitations. The simulation adds more vehicles to achieve the target ZE share, as the multiple tours that can be performed by one diesel truck are split among more than one ZE truck. In the case studies we take the existing tours as given, and simply estimate what share of the existing daily tours can be operated by ZEHDTs. Essentially, we are asking, how many ZEHDTs could be used without changing operations. Consequently, our estimates are below that of the simulations.

4.2.4 Conclusions on ZEHDTs and freight operations

The short-haul heavy-duty market for ZE trucks is limited at the present time mostly due to range limitations, but other factors, like gross weight limit also plays a role. In general, firms with low weight cargo, operating 1 or 2 shifts, and travelling very short daily distances (less than 80 miles) are good candidates for this technology. The two-firm case study above demonstrates that specific operational characteristics of the firm must be clearly understood to gauge the extent of how ZEHDTs can be deployed in the firm without causing severe disruptions. This includes how and when trucks are used (total daily distance requirements, freight weight) and when they are not used (recharging opportunities). Taking range, charging and weight limit into considerations, currently no more than 20% of the truck daily tours can be achieved by electric vehicles (Firm 1 is 18%, and Firm 2 is only 2%). With some operational modifications, fleets may be able to utilize ZE trucks for specific routes/destinations, like adjusting load weights to avoid overweight issues, or changing the operation hours so that trucks can have enough time for charging. However, major operational modifications (or high costs) will be a reason for firms to reject the technology.

We note that the picture changes dramatically in 2025 and 2030. With better performing ZEHDTs, the potential market, from a purely operational perspective, greatly increases. We turn now to estimating benefit and costs to further evaluate the heavy duty ZE markets.

4.3 Benefits and Costs

In this section we estimate benefits and costs from the simulation data. Benefits include reduced emissions of PM 2.5, NOx, and CO2; costs include the capital and operating costs of the fleet.

4.3.1 Benefits

The optimization results provide detailed information for the total miles and fleet size of each scenario; however, estimating reduced emissions from ZEHDTs and hybrids is not straightforward. The miles travelled by different truck types must be translated into emissions data.

Drayage trucks emit both criteria pollutants and greenhouse gases. The criteria pollutants of interest in the South Coast region are $PM_{2.5}$ and NO_X emitted locally. Greenhouse gases emitted from any part of the fuel pathway negatively impact climate change. The estimation of drayage truck emissions includes tailpipe emissions of criteria pollutants but full well-to-wheels emissions of greenhouse gases.

The San Pedro Bay Ports Clean Action Plan includes estimates of $PM_{2.5}$ and NO_X emissions from a new 2018 model year diesel truck (San Pedro Ports 2018). The tailpipe emissions from battery electric truck are zero. The California Air Resources Board (CARB) has regulations constraining criteria pollutant emissions for present trucks, but no future regulations are in place. A CARB staff white paper discusses possible mid-term technical reductions in diesel truck emissions. They estimate that both $PM_{2.5}$ and NO_X could be reduced to roughly half the present emissions standard (CARB 2019) before 2025. We use the Clean Air Action Plan estimates for 2020 diesel trucks and reduce those numbers in half for 2025 and 2030 timeframes.

Few studies have been done on natural gas (NG) hybrid heavy-duty truck emissions. The San Pedro Bay Ports Clean Air Action Plan estimates PM emissions from conventional natural gas drayage trucks to be essentially the same as diesel PM emissions (i.e., no emissions reductions from the diesel values). The Clean Air Action Plan estimates that NO_X emissions from conventional natural gas drayage trucks will be reduced by 90% from diesel truck values (Ports 2018, Table 37).

To estimate the PM and NO_X emissions from a natural gas hybrid drayage truck, we used the Clean Air Action Plan results and lowered them by the expected increase in fuel economy for a natural gas hybrid drayage truck over a conventional natural gas truck. To estimate the increase in fuel economy for a hybrid natural gas truck, we used fuel economy results from a simulation study of both conventional NG and hybrid NG heavy-duty trucks (Zhu 2014). This study used the Advisor dynamic simulation model to calculate fuel economy for both conventional NG and hybrid NG heavy-duty trucks. We assume that the NO_X emissions in g/mile of a hybrid and conventional NG heavy-duty truck will be roughly proportional to the fuel economy. The increase in hybrid fuel economy is roughly 18%.

As discussed above, we assume the NO_X emissions from diesel trucks will be reduced by 50% in 2025 from 2020 values. We do not assume that NO_X emissions from the natural gas trucks will be further reduced from their 2020 value.

The San Pedro Bay Ports Clean Air Action Plan also estimates the carbon intensity (gCO2e/MJ) for diesel, hybrid natural gas, and battery electric trucks. The BEHTDs have two carbon intensity—traditional and time-of-use (TOU). The TOU estimate is the carbon intensity for electricity delivered between 9 pm and 5 am. The carbon intensities are shown in Table 14.

Table 14. Carbon intensity for diesel fuel and electricity

	Carbon Intensity (gCO2e/MJ)	
Technology	Traditional	TOU
Diesel	100.45	
Hybrid NG	79.21	
BEV	93.75	91.27

To convert from MJ to diesel gallons and kWh we use the conversions of one diesel gallon equals 146.5 MJ and one kWh equals 3.6 MJ. We use the BEHTD fuel economy from the Advisor simulation runs for drayage trucks. Those median values are 2.94 (2020), 2.76 (2025), and 2.58 (2030) kWh/mi. Surveys of present drayage truck operators found that the fuel economy of a loaded diesel drayage truck is roughly 5 mi/gal. Using simulations with the Advisor dynamic vehicle model we estimate that a 2030 diesel drayage may have a fuel economy that is 26% higher than present trucks or 6.3 mi/gal. We assume 2025 diesel trucks will have a fuel economy midway between the present and 2030 estimate (5.65 mi/gal). Note that these fuel economy estimates are somewhat different from those used in the simulation. These are in effect averages that take into account the share of miles traveled loaded and not loaded.

We use the fuel economy estimated in the Zhu paper for hybrid natural gas trucks and assume it increases in the same proportion as diesel trucks do for years 2025 and 2030. Emissions factors are summarized in Table 15. These are operating emissions only.

Table 15. Emission Rates for Diesel Trucks, NG Hybrid Trucks and BEHDTs

	Criteria Pollutant Emissions		CO2 Emissions	
Vehicle Technology	**$PM_{2.5}$ (g/mile)**	**NO_X (g/mile)**	**CO2 (g/mile)**	**CO2-TOU (g/mile)**
Diesel Present	0.01	1.91	2943.0	N/A
Diesel 2025	0.005	0.96	2605.0	N/A
Diesel 2030	0.005	0.96	2336.0	N/A
NG Hybrid Present	0.008	0.16	2100.0	N/A
NG Hybrid 2025	0.004	0.16	1859.0	N/A
NG Hybrid 2030	0.004	0.16	1667.0	N/A
BEHTD Present	0	0	992.0	966.0
BEHTD 2025	0	0	932.0	907.0
BEHTD 2030	0	0	871.0	848.0

We use the mileage and number of vehicles data from the simulation to generate emissions for each scenario and each target year. Recall that the hybrid alternative is the same as diesel, as hybrids are able to serve all of the demand in each year. We show results for BEHDTs first; see Tables 16–18. In each table, the first four columns are the same as in Tables 5-7, the next three columns give diesel truck emissions, the following two columns give BEHTD emissions and the last two columns give the reduction in CO_2 emissions. Notice that "CO_2" and "CO_2-TOU" are both CO_2 emissions for BEHDTs; they represent two different carbon intensities: traditional and time-of-use (TOU). The TOU estimate is the carbon intensity for electricity delivered between 9 pm and 5 am.

Table 16. Estimated Emissions for Diesel Trucks and ZEHDTs – Present

	Total Miles			Diesel Truck Emissions			BE Emissions		CO2 Reduction	
ZE_Ratio	**D_Dist (mile)**	**E_Dist (mile)**	**Total_Dist (mile)**	**PM2.5 (g)**	**NOx (kg)**	**CO2 (kg)**	**CO2 (kg)**	**CO2-TOU (kg)**	**CO2 (kg)**	**CO2-TOU (kg)**
0	6223	0	6223	62.2	11.9	18314.3	0.0	0.0	0.0	0.0
0.10	6052	172	6223	60.5	11.6	17811.0	170.6	166.2	332.7	337.1
0.19	5833	390	6223	58.3	11.1	17166.5	386.9	376.7	760.9	771.1
0.27	5575	648	6223	55.8	10.6	16407.2	642.8	626.0	1264.3	1281.1
0.35	5229	994	6223	52.3	10.0	15388.9	986.0	960.2	1939.3	1965.1
0.44	4813	1410	6223	48.1	9.2	14164.7	1398.7	1362.1	2750.9	2787.5
0.57	4283	1940	6223	42.8	8.2	12604.9	1924.5	1874.0	3784.9	3835.4
0.68	3602	2621	6223	36.0	6.9	10600.7	2600.0	2531.9	5113.6	5181.7
0.75	2990	3234	6223	29.9	5.7	8799.6	3208.1	3124.0	6306.6	6390.7

Table 17. Estimated Emissions for Diesel Trucks and ZEHDTs – 2025

	Total Miles			Diesel Truck Emissions			BE Emissions		CO2 Reduction	
ZE_Ratio	**D_Dist (mile)**	**E_Dist (mile)**	**Total_Dist (mile)**	**PM2.5 (g)**	**NOx (kg)**	**CO2 (kg)**	**CO2 (kg)**	**CO2-TOU (kg)**	**CO2 (kg)**	**CO2-TOU (kg)**
0	6223	0	6223	31.1	5.9	16210.9	0.0	0.0	0.0	0.0
0.15	5878	346	6223	29.4	5.6	15312.2	343.2	334.2	555.5	564.5
0.20	5457	766	6223	27.3	5.2	14215.5	759.9	740.0	1235.6	1255.5
0.30	4946	1278	6223	24.7	4.7	12884.3	1267.8	1234.5	2058.8	2092.0
0.41	4372	1852	6223	21.9	4.2	11389.1	1837.2	1789.0	2984.7	3032.8
0.50	3694	2529	6223	18.5	3.5	9622.9	2508.8	2443.0	4079.3	4145.0
0.61	2942	3281	6223	14.7	2.8	7663.9	3254.8	3169.4	5292.3	5377.6
0.71	2203	4021	6223	11.0	2.1	5738.8	3988.8	3884.3	6483.3	6587.8
0.80	1449	4775	6223	7.2	1.4	3774.6	4736.8	4612.7	7699.5	7823.6
0.88	733	5491	6223	3.7	0.7	1909.5	5447.1	5304.3	8854.4	8997.1
0.96	198	6025	6223	1.0	0.2	515.8	5976.8	5820.2	9718.3	9875.0

Table 18. Estimated Emissions for Diesel Trucks and ZEHDTs – 2030

	Total Miles			Diesel Truck Emissions			BE Emissions		CO2 Reduction	
ZE_Ratio	D_Dist (mile)	E_Dist (mile)	Total_Dist (mile)	PM2.5 (g)	NOx (kg)	CO2 (kg)	CO2 (kg)	CO2-TOU (kg)	CO2 (kg)	CO2-TOU (kg)
0	6223	0	6223	31.1	5.9	14536.9	0.0	0.0	0.0	0.0
0.15	5863	361	6223	29.3	5.6	13696.0	358.1	348.7	482.8	492.2
0.20	5405	818	6223	27.0	5.2	12626.1	811.5	790.2	1099.4	1120.7
0.30	4901	1322	6223	24.5	4.7	11448.7	1311.4	1277.1	1776.8	1811.1
0.38	4283	1940	6223	21.4	4.1	10005.1	1924.5	1874.0	2607.4	2657.8
0.50	3602	2621	6223	18.0	3.4	8414.3	2600.0	2531.9	3522.6	3590.8
0.59	2834	3389	6223	14.2	2.7	6620.2	3361.9	3273.8	4554.8	4642.9
0.70	2098	4125	6223	10.5	2.0	4900.9	4092.0	3984.8	5544.0	5651.3
0.82	1338	4886	6223	6.7	1.3	3125.6	4846.9	4719.9	6564.4	6691.5
0.87	733	5491	6223	3.7	0.7	1712.3	5447.1	5304.3	7377.6	7520.3
0.96	198	6025	6223	1.0	0.2	462.5	5976.8	5820.2	8097.6	8254.3

As we can observe from the above tables, replacing diesel trucks with ZEHDTs in drayage operations can reduce over 60g PM2.5 and almost 12kg NOx per day. The reduction in CO2 is even more significant, using the values in Table 18, more than 600kg CO2 are removed daily when 15% of the fleet is replaced by ZEHDTs. The number is 10,782.3kg when 96% of the fleet are ZEHDTs. That is more than 10 tons of CO2 removed when replacing a fleet of 19 diesel trucks with 25 ZEHDTs and 1 diesel truck. Figure 12 compares the net reduction of CO2 for the three scenarios, we can see that there is a clear trade-off between emissions reductions and larger fleet size. Notice that the net reduction in general decreases from Year 2025 to Year 2030, because of the improvement of diesel truck in CO2 emission (see Table 19).

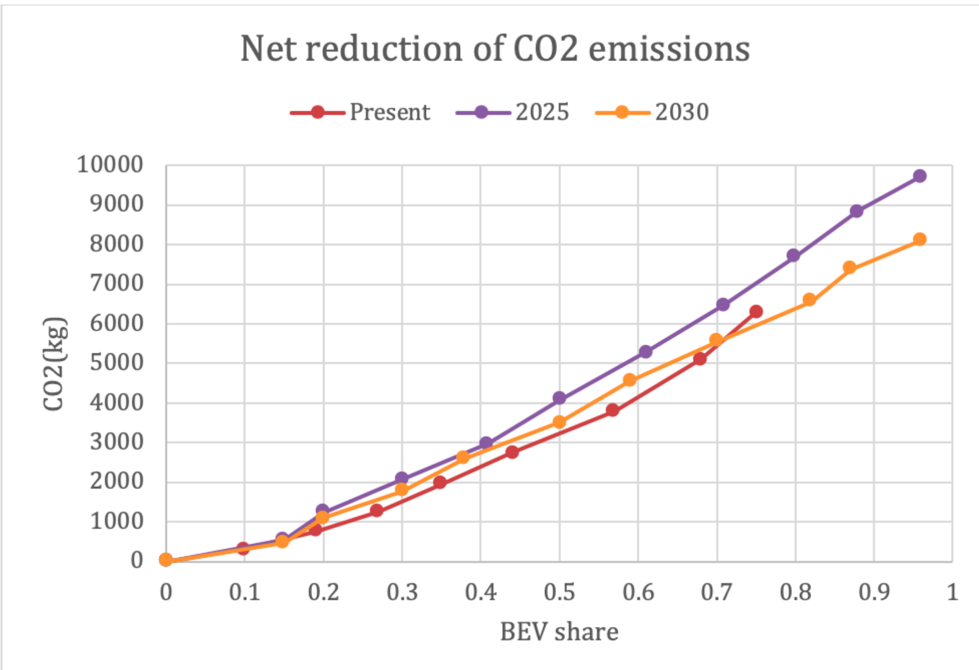

Figure 12. Net Reduction of CO2 for the three target years – Diesel vs ZE

Considering the potential technical or financial barriers of purchasing and operating BEHDTs, we also examined the option of replacing diesel trucks with Natural Gas Hybrid trucks, which might be more feasible in current circumstances. Table 19 shows the comparative emissions for all-hybrid-truck fleet and all-diesel-truck fleet. Replacing the entire diesel-truck fleet with NG hybrid trucks can significantly reduce PM2.5, NOx and CO2 emissions. In addition, the PM2.5 and CO2 emissions of hybrid trucks also decrease over time. The net emissions for PM 2.5 drop because of the improvements in emissions technology for both diesel and hybrid by 2025. The NOx emissions reductions follow the same pattern as PM 2.5, again a result of assumptions regarding emissions technology improvements. The net emission reduction for CO2 decreases over time, from 5246kg per day to 4642.3kg, and then to 4163.2kg per day. This is the result of assumptions; both diesel and hybrid CO2 emissions are assumed to decline at the same rate. The net reduction is therefore a constant percentage.

Table 19. Estimated Emissions for NG Hybrid Trucks and Diesel Trucks

	Total Miles	All-Hybrid Truck Fleet Emissions			All-Diesel Truck Fleet Emissions			Net Emission Reduction (Diesel – Hybrid)		
Year	Total_Dist (mile)	PM2.5 (g)	NOx (kg)	CO2 (kg)	PM2.5 (g)	NOx (kg)	CO2 (kg)	PM2.5 (g)	NOx (kg)	CO2 (kg)
Present	6223	49.8	1.0	13068.3	62.2	11.9	18314.3	12.4	10.9	5246.0
2025	6223	24.8	1.0	11568.6	31.1	6.0	16210.9	6.3	5.0	4642.3
2030	6223	24.8	1.0	10373.7	31.1	6.0	14536.9	6.3	5.0	4163.2

We now compare diesel, hybrid, and ZE emissions benefits. Table 20 gives emissions for four scenarios in each target year: all diesel, all hybrid, midpoint ZE (the middle BEHTD penetration in Table 16–18), and maximum ZE (largest possible BEHTD penetration in Table 16–18). Cells with the least emissions in each row are highlighted. We observe that for all emissions except NOx in 2020, the maximum ZE alternative dominates in every year, but at the price of increasing the total number of vehicles required. Hybrid and mid-point ZE have offsetting advantages. Hybrid does better for NOx in 2020, midpoint ZE does better for PM 2.5, and hybrid does better for CO2 throughout. The difference between hybrid and midpoint ZE is the result of the large number diesel trucks that remain in the mixed fleet. Note that Table 20 gives estimates per day. We annualize these estimates to make comparisons with costs.

Table 20. Emissions per day for four vehicle scenarios

2020	All Diesel	All Hybrid	Midpoint ZE	Max ZE
PM 2.5 (g)	62.2	52.8	48.1	29.9
NOx (kg)	11.9	1	9.2	5.7
CO2 (kg)	18314	13068	15563	12008
tot veh	19	19	25	36
2025				
PM 2.5 (g)	31.1	26.4	18.5	1
NOx (kg)	5.9	1	3.5	0.2
CO2 (kg)	16211	11569	12132	6493
tot veh	19	19	22	26
2030				
PM 2.5 (g)	31.1	26.4	18	1
NOx (kg)	5.9	1	3.4	0.2
CO2 (kg)	14536	10374	11014	6440
tot veh	19	19	22	23

4.3.2 Costs

This section estimates the costs for each of our test scenarios. To simplify the analysis, we treat each scenario in each target year as a new service, meaning that we use purchase cost as capital costs for the vehicles. We do not consider life cycle costing but rather only the direct costs of purchase and operating the vehicles. We annualize costs and benefits to generate comparisons across the scenarios and target years.

4.3.2.1 Capital and operating costs

Vehicle cost is calculated by considering the total cost as a sum of component costs. The components for vehicles include: glider, engine, transmission, engine after treatment system (EATS), fuel storage, battery, and motor/controller.

Capital cost for diesel trucks

The cost of diesel trucks is generated from either published sources or a survey of prices on commercial vehicle sales websites. The EPA Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles Phase 1 and Phase 2 rules detail requirements for trucks to meet emissions and fuel economy standards. The rules provide some cost estimates for compliance, and these estimates were applied for the relevant timeframes for diesel engines, transmissions, EATS and vehicles (EPA Phase 1, EPA Phase 2). For example, the rules provide estimates for weight reduction, aerodynamic improvements, and the shift to automated transmission. The fraction of the vehicle price associated with engine and after-treatment are estimated based on an NRC report (NRC 2010). In 2025, an additional $750 is added to the after-treatment price to recognize the likely implementation of lower NOx standards. The value was chosen as a mid-point of the estimate which was provided in the Petition to EPA for ultra-low NOx (EPA 2016).

Glider cost is estimated by starting from a full diesel vehicle and then subtracting off the cost of the engine, transmission, and EATS. The advanced vehicle costs (battery electric and natural gas hybrid) start with the glider and add relevant components such as battery, motor/controller, and natural gas fuel tank. Table 21 shows costs for a diesel drayage truck for years 2020 through 2030. Transmission costs rise significantly due to a shift to automated transmissions.

Table 21. Drayage diesel truck cost (total costs rounded to nearest $100 in total)

Drayage Truck	Glider	EATS	Engine	Transmission	Total
2020	$82,741	$15,000	$16,091	$5,000	$118,800
2025	$83,585	$15,750	$16,881	$8,549	$124,800
2030	$84,428	$15,750	$17,670	$12,098	$129,900

Capital costs for battery electric truck

The cost for a present day (2020) battery electric drayage truck is taken from OEM estimates in the San Pedro Bay Ports Clean Air Action Plan (Posts 2018) and assumed to be $300,000. To estimate the battery electric drayage truck cost for future years, we add appropriate component costs to the glider costs in Table 21. The component costs for a battery electric truck are the motor/controller and the battery. The motor/controller size and battery sizes were estimated by using the Advisor dynamic vehicle simulation program (Burke and Zhao

2015) on a drayage port drive cycle (NREL 2016). The motor size is 350 kW and battery sizes are shown in Table 22. Note these are the same values as used in the simulations.

Table 22. Battery Pack Size for drayage truck

Year/range	Battery Pack Size (kWh)
2020	240
2025/150 miles	525
2030/200 miles	650

Battery pack costs have decreased significantly in recent years, and Bloomberg New Energy Futures has very aggressive projections for battery costs through 2030 (BNEF 2019). The International Council on Clean Transportation (ICCT) has less aggressive projections (Moultak 2017). We use costs that are roughly midway between the Bloomberg and ICCT projections extrapolated out through 2050. These costs are to the original equipment manufacturer (OEM) from battery manufacturers. We assume an integration cost factor of 1.2 to get a final component cost in the vehicle. Figure 13 shows the assumed cost of batteries to the OEM truck manufacturer. To estimate future truck costs, we used a battery pack cost of $109/kWh in 2025 and $80/kWh in 2030. The cost of power electronics in 2025 and 2030 is assumed to be $30/kW with an integration cost factor of 1.2 (Burke 2020).

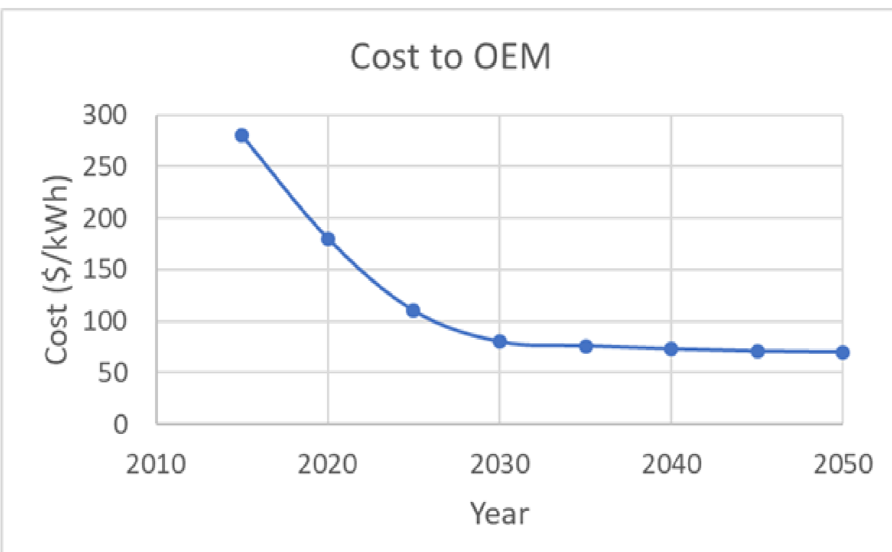

Figure 13. OEM battery cost

The cost for battery electric drayage trucks is given in Table 23 for the years 2020-2030.

Table 23. Battery electric drayage truck capital cost (total costs rounded to nearest $100)

Year	Glider	Power Electronics	Battery	Total
2020	n/a	n/a	n/a	$300,000
2025	$83,585	$12,600	$68,670	$164,900
2030	$84,428	$10,500	$62,400	$157,300

Capital costs for natural gas hybrid drayage truck

To estimate the natural gas hybrid drayage truck cost, we add appropriate component costs to the glider costs in Table 21. The component costs for a natural gas hybrid truck are the engine, fuel tank, motor/controller, battery, and minor accessories. Zhu calculated the incremental costs for a natural gas hybrid heavy-duty truck for timeframes out to 2030 (Zhu 2014). We use those numbers but substitute our battery costs using $180/kWh (2020), $109/kWh (2025), and $80/kWh (2030). The natural gas hybrid truck design uses a 15 kWh battery pack for present trucks and a 13 kWh battery pack in 2025 and 2030. The results for natural gas hybrid drayage truck costs are shown in Table 24. The capital costs fall in 2025 due to less expensive components for the natural gas truck. In 2030 the costs rise due to expected increases in the glider and transmission costs (see Table 21).

Table 24. Natural gas hybrid drayage truck costs

Year	Diesel	Incremental Cost	Battery	Total
2020	$118,800	$22,700	$3,240	$144,800
2025	$124,800	$13,250	$1,700	$139,700
2030	$129,900	$13,250	$1,250	$144,400

Operating costs

The fuel economy for diesel, battery electric, and natural gas hybrid trucks were calculated using the Advisor simulation model (Burke and Zhao 2015) on a port drayage drive cycle. The fuel economies are shown in Table 25. The fuel economy for battery electric trucks was calculated for trucks operating with 1/2 payload assuming the trucks travel roughly 1.4 local miles and 20 highway miles off the port.

Table 25. Fuel economies for diesel and battery electric drayage trucks

Year	Diesel (mi/DGE)	Battery Electric (kWh/mi)	Natural gas hybrid (mi/DGE)
2020	5.0	2.94	5.53
2025	5.65	2.76	6.24
2030	6.3	2.58	6.96

Fuel and maintenance costs are given in the San Pedro Bay Ports Clean Air Action Plan (Ports 2018). These costs are shown in We assume that Low Carbon Fuel Standards (LCFS) credits are not used to reduce the cost of electricity.

Table 26. The electricity cost (battery electric fuel cost) assumes the electricity comes from the utility LADWP. We assume that Low Carbon Fuel Standards (LCFS) credits are not used to reduce the cost of electricity.

Table 26. Fuel and maintenance cost for diesel and battery electric trucks

	Diesel truck	Battery electric truck	NG hybrid truck
Fuel cost	$3.88/ DGE	$0.151/kWh	$2.92 / DGE
Maintenance cost ($/mi)	0.16	0.08	$0.16

Driver costs

The operating costs described above do not include driver costs. It seems reasonable to assume that driver costs should be consistent across the vehicle technologies. That is, there is no reason to pay premiums to drivers of hybrids or BEHDTs. If our scenarios consisted of exactly the same number of vehicles, drivers and shifts, we could omit driver costs without affecting results. However, the ZE scenarios require more vehicles, and hence more drivers. We therefore add driver costs to operating costs. We use a flat rate of $27/hour, including wages and fringe benefits. This is the national average as reported by the American Transportation Research Institute (ATRI) for 2016 (ATRI, 2017).

4.3.3 Comparing benefits and costs

The last step in our analysis is to compare benefits and costs. It is beyond the scope of this project to conduct a formal cost/benefit analysis. We do not monetize the benefits of emissions reduction, but rather consider the costs of using the various alternative fuel technologies relative to the quantity of emissions reduced. We conduct our comparison on the basis of annualized costs: the costs of providing services for one year compared to the emissions produced over one year. The all diesel scenario is the base case, hence we compare the incremental costs of service provision relative to diesel with the incremental emissions savings compared to diesel.

4.3.3.1 Annualized costs

We compute annualized capital costs in order to spread the costs over the expected life of the vehicle. As noted in Section 4.3.2 above, we consider each target year as a new scenario. We assume that the fleet operator purchases a new fleet, and that the service life of each vehicle is seven years. We know that diesel trucks have a much longer service life, but we assume that increasingly stringent emissions requirements will force their early retirement. We do not have enough information on hybrids or BEHDTs to know their service life. Batteries are expected to last 5-7 years, but lose capacity over time. Presumably technology improvements will rather quickly make older hybrids and BEJTTs outdated, so we cannot predict whether there will be any resale market for them beyond 5 or 7 years. We assume no residual value for any of the vehicles, which therefore gives advantage to hybrid and BEHDT. We use the purchase prices in Section 4.3.1 and the number and type of required vehicles to generate the annualized capital cost. Costs are all in 2020 dollars; we do not account for inflation. Table 27 gives annualized capital costs for the scenarios. The differences between all diesel and all hybrid reflect the difference in purchase costs between the two types of vehicles. The ZE scenarios reflect both differences in purchase costs and fleet size.

Table 27. Scenario annualized capital costs

	All Diesel	All Hybrid	Mid ZE	Max ZE
2020	$358,891	$437,437	$789,135	$1,457,874
2025	$377,017	$421,838	$506,682	$675,318
2030	$392,426	$436,221	$502,304	$570,874

We use the data in Section 4.3.2 and generate annual operating costs. Annualized costs are based on 5 days per week operation, 50 weeks per year. Table 28 gives operating costs The cell in each row with the least cost is highlighted. The first set of rows gives vehicle operating costs, the second set gives driver costs, and the third gives the combined vehicle and driver costs. With regard to vehicle operating costs, all diesel is the highest across all target years. This is due to greater fuel efficiency of hybrids and much lower fuel and maintenance costs for BEHDTs. If we were considering vehicle operating costs only, any scenario would be preferable to diesel. There would savings both in operating costs and in emissions.

The second panel gives driver costs. As noted above, we use a flat rate of $27 per hour. Our simulations assumed an 8-hour shift per vehicle. The driver costs across the scenarios therefore reflect the required size of the vehicle fleet. Diesel and hybrid are the same for all scenarios, as there are the same number of vehicles in every scenario. Driver costs are higher for the ZE alternatives, but decline over time as the number of required vehicles declines. Combining vehicle and driver costs results in hybrid having the lowest costs due to lower vehicle operating costs and minimum fleet size.

Table 28. Annual operating costs by scenario, target year

Vehicle operating costs	All Diesel	All Hybrid	Midpoint ZE	Max ZE
2020	$1,456,182	$1,070,401	$1,310,931	$1,123,265
2025	$1,317,293	$976,931	$1,094,283	$786,000
2030	$1,207,064	$901,620	$1,004,675	$741,824
Driver operating costs	**All Diesel**	**All Hybrid**	**Mid ZE**	**Max ZE**
2020	$1,026,000	$1,026,000	$1,350,000	$1,944,000
2025	$1,026,000	$1,026,000	$1,188,000	$1,404,000
2030	$1,026,000	$1,026,000	$1,188,000	$1,242,000
Total operating costs	**All Diesel**	**All Hybrid**	**Mid ZE**	**Max ZE**
2020	$2,482,182	$2,096,401	$2,660,931	$3,067,265

2025	$2,343,293	$2,002,931	$2,282,283	$2,190,000
2030	$2,233,064	$1,927,620	$2,192,675	$1,983,824

Finally, we combine both capital and operating costs. See Table 29. Once again hybrid is the lowest cost scenario across all target years.

Table 29. Total annual costs

Total annual costs	All Diesel	All Hybrid	Mid ZE	Max ZE
2020	$2,841,073	$2,533,838	$3,450,066	$ 4,525,139
2025	$2,720,310	$2,424,769	$2,788,965	$ 2,865,318
2030	$2,625,490	$2,363,841	$2,694,979	$ 2,554,698

4.3.3.2 Benefit and cost comparisons

Table 30 gives net emissions savings relative to diesel for the scenarios. Max ZE has the greatest emissions saving in all years for both PM 2.5 and CO2 across all target years. For NOX all hybrid is better in 2020, but all ZE dominates in the later years. Next, we consider whether the incremental benefits of ZE are offset by the incremental costs of ZE.

Table 30. Net emissions savings, relative to diesel

Net emissions savings	All Hybrid	Midpoint ZE	Max ZE
PM 2.5 (g)			
2020	2350	3525	8075
2025	1175	3150	7525
2030	1175	3275	7525
NOX (kg)			
2020	2725	675	1550
2025	1225	600	1425
2030	1225	625	1425
CO2 (kg)			
2020	1311500	687750	1576500
2025	1160500	1019750	2429500
2030	1040500	880500	2024000

Table 31 gives our benefit and cost comparison results. Note that we are comparing incremental costs and benefits, relative to diesel. Because of the lower total costs of hybrid relative to diesel, emissions savings come with *cost savings* for each pollutant and for every target year. Even for PM 2.5, all hybrid is the most cost effective alternative. In 2030 costs turn positive for all ZE, but notably below the savings for hybrid. The midpoint ZE scenario has the worst of both worlds because of the large number of vehicles required and the number of diesels in the fleet.

These results suggest that if cost effectiveness is the criterion for selection, a policy to shift to a hybrid fleet would be preferred through 2030. However, if maximizing PM 2.5 or CO2 reductions is the criterion, our results show what the incremental cost of doing so would be.

Table 31. Cost per unit of emissions removed, relative to all diesel

Cost per emissions reduced	All hybrid	Midpoint ZE	Max ZE
PM 2.5 (per gram)			
2020	$(130.74)	$172.76	$208.55
2025	$(251.52)	$21.79	$19.27
2030	$(222.68)	$21.22	$(9.41)
NOX (per kg)			
2020	$(112.75)	$902.21	$1,086.49
2025	$(241.26)	$114.42	$101.76
2030	$(213.59)	$111.18	$(49.68)
CO2 (per kg)			
2020	$(0.23)	$0.89	$1.07
2025	$(0.25)	$ 0.07	$0.06
2030	$(0.25)	$0.08	$(0.03)

4.3.4 Conclusions on benefits and costs

Our results should be interpreted with caution. As noted earlier, the simulation scenarios include daily tours that are much simpler than actual tours. While our numbers are based on the best available information, they are estimates with some (unknown) degree of uncertainty. Hence small differences in alternatives are likely not significant. We assume just one shift per day, and do not take into account weight limits. If we accounted for multiple shifts or weight limits, costs for the ZE alternatives would increase because the number of vehicles required would have to increase. Therefore, these estimates are likely optimistic for the ZE alternatives.

Although we have taken into account performance differences and their impact on freight operations, we have not taken into account weight limit restrictions or other issues. First, we have not considered infrastructure costs. Large numbers of BEHDTs would require an extensive infrastructure of charging stations. If firms are expected to provide their own charging stations, they would need both the space and the funds to do it. NG hybrids less of a problem. Natural gas is widely available, but home-based fuel facilities would also require substantial investment.

Second, we have not considered the organizational costs of incorporating a new technology into its operations. A mixed fleet requires vehicle type specific maintenance practices. In the case of BEHDTs, operations would have to be restructured to accommodate shorter range vehicles. By definition the new route structure would be less efficient, leading to higher overall costs for the firm in an industry with narrow profit margins. All of these issues add to the costs of using hybrids or BEHDTs.

Finally, our results do not consider uncertainty. Even if hybrids or BEHDTs dominate in 2025 or 2030 based on annualized costs, it doesn't imply that fleet owners would automatically switch. The results for hybrids are a case in point. If hybrids lead to cost savings to the firm, why are we not seeing an expanding market for them? Possible explanations include the slow turnover of truck fleets, uncertainty regarding regulation, or uncertainty regarding the performance of the technology.

Chapter 5. Industry Perspectives

Chapter 4 presented the impacts of using ZEHDTs on drayage operations and estimated costs and benefits across target years. We turn now to the industries expected to produce and use the vehicles. An assessment of the market for ZEHDTs requires understanding of the perceptions and concerns of potential purchasers and users. We conducted two rounds of interviews and one survey. This chapter presents results.

5.1 Round one interviews

The first round of interviews was conducted to gather information on the experiences of vehicle manufacturers and fleet operators with these early ZE demonstrations. The first round interviews were conducted in summer 2018. The goals of the analysis were to determine how the trial zero and near-zero emission vehicles were being utilized by the representative companies. In addition, the team sought to understand how real-world operation impacted the range and operating parameters of the vehicles in order to better estimate how a replacement of conventional vehicles with zero and near-zero alternatives might impact short haul trucking operations in the Southern California region.

We interviewed two manufacturers and three fleet operators. We do not identify respondents by name to preserve confidentiality. The two manufacturers were BYD and US Hybrid. Information on the three operators is summarized in Table 32. We summarized findings from interviews, perceptions of real-world performance, and common themes.

Table 32. Summary of operators interviewed, number and types of Class 8 trial drayage vehicles

Operators	Fleet Size (including Demo vehicles)	Business Model	Number/Type of Class 8 Demo Vehicles
Firm A	15-20	Company Owner\Operator	2 BYD BEV
Firm B	+1200 (nation-wide)	Company Owner\Operator	1 TransPower BEV
Firm C	80	Company Owner\Operator	1 US Hybrid CNG Hybrid 1 US Hybrid LNG Hybrid 1 US Hybrid Fuel Cell Hybrid 1 BYD BEV

5.1.1 Manufacturers

5.1.1.1 OEM 1

OEM 1 manufactures fully electric commercial vehicles used for taxi fleets, transit operation, and freight operations such as drayage. As of August 2018, OEM 1 had several battery electric freight vehicles out for trial. Generation 1 trucks currently on trial are prototypes, and adjustments have been made to improve their performance. Generation 2 trucks have been designed to make improvements over the first generation with input from trial performance.

Generation 2 trucks were expected to begin use in March of 2019. They have a predicted range of 120 miles on a full load and 160 when loaded half the time. This assumes 50% surface street and 50% highway driving. If dray trucks are driven in heavily congested conditions, this would mimic the operation of city street driving. Range also depends on driver behavior; drivers who are trained to drive to preserve battery life with slow acceleration and maximized battery regeneration while braking will extend range. Other impacts that take a toll on range include sustained grades such the Gerald Desmond Bridge. Depending on the EV technology, some trucks may not be able to make it over the bridge.

Due to the lack of long-term trial data, it is too early to determine the useful lifetime of the batteries in the BEV dray trucks. Analysis of OEM 1EV buses shows a retention of 70% of the original range after 8 years. The interviewee estimated a savings of about 50% on long term maintenance costs over a comparable diesel truck. OEM 1 hopes to get into the drayage market with generation 2 trucks that can make trips as far as the Inland Empire, taking advantage of quick "opportunity charging" while in the inland empire to prolong range. This would require additional charging facilities. OEM 1 is currently experimenting with different battery chemistry that, it is hoped, will be less volatile and more durable.

5.1.1.2 OEM 2

The executive of OEM 2, has worked in the battery electric vehicle industry for many years, having begun his career with GM on the EV1 project. Currently, OEM 2 manufactures hybrid, BEV, and fuel cell powertrains for Class 8 vehicles. As of August 2018, OEM 2 was testing its Battery Electric, LNG hybrid, and CNG hybrid trucks.

OEM 2's battery electric trucks were built for drayage in the area around the Ports of LA and Long Beach. The interviewee stated that the useful range of the trucks is between 80–100 miles. The trucks have batteries built that carry 240 KWh of charge. There is demand for more range, but it is difficult to provide given the operating constraints of Class 8 BEV dray trucks at this time. With a long term perspective on battery improvement technology, the interviewee sees little possibility that battery electrics will experience substantial growth in range in the near future unless they are willing to sacrifice carrying capacity. He stated that his customers will demand the full carrying capacity of conventional diesel trucks.

OEM 2's LNG hybrid trucks have about 300 miles of range and can operate with a charged or dead battery. They are difficult to refuel because the required refueling infrastructure is not ubiquitous. Furthermore, there are significant concerns with GHG emissions during the refueling process due to evaporative emissions of methane. Due to these concerns and the fact that CNG hybrid trucks have adequate range. OEM 2 has decided not to move forward with LNG Hybrid trucks.

OEM 2 expected the next phase of demos to begin in February 2019 with phase 2 CNG Hybrid trucks. These CNG Hybrid trucks are expected to have a range of 350–400 miles and can also operate with a dead battery. In addition, they get about 20 miles of pure battery electric range which could enable them to perform short inter-terminal moves. Refueling time is comparable to diesel trucks.

Fuel Cell trucks built by OEM 2 are also currently being tested. These trucks get about 200 miles of range. They are driven by an 80kwh battery, but the fuel cell can provide for continuous operation. The estimated range is based on a typical dray duty cycle in the Ports of LA and LB area.

OEM 2's strategy moving forward is to focus on CNG plug-in drayage trucks as the technology can be brought in line with the costs of conventional full-CNG trucks. There is political difficulty in marketing CNG and LNG trucks because the technology is seen as "2nd Class" to fully electric—meaning that politicians seem to have committed to the rhetoric of "zero emissions" and are loathe to entertain other technologies, even if these technologies are just as clean in practical terms as battery electric or fuel cell trucks. The interviewee was positive about the long-term potential for fuel cell technology given ranges that can be attained for manageable costs. He was concerned that if efforts were made to artificially force the mass adoption of electric only trucks, it may actually hinder the adoption of fuel cells.

5.1.2 Operators

5.1.2.1 Firm A

Firm A currently has a fleet of between 15–20 class 8 trucks used for drayage. In its current pilot with OEM 1 it had run 2 trucks for about 6 months as of September 2018. The truck's range was reported to be between 80–90 miles depending on conditions. The EV dray trial trucks are run twice per day to the port and back, about 60 total miles running loaded 50% of the time. After maintenance issues were resolved, the trucks have since been able to be routed via freeways. There are concerns with the weight of the trucks as full containers may cause loads to be over the legal limit.

Use of the ZE trucks has mostly occurred during the daytime. This is advantageous given the vehicle's limited range, because the wait times at the port during the day are long, so all trucks perform fewer trips and need to cover fewer daily miles. This also allows the trucks to charge later at night (on 480-amp chargers) with off-peak electricity prices.

5.1.2.2 Firm B

At present, Firm B is testing one battery electric truck. The fleet operator has kept it operating within a 10- to 12-mile radius from the port due to range concerns. The interviewee stated that estimates advertised by companies like OEM 1 claiming that the trucks have a 100-mile range are wildly inflated. The actual range in their experience is about 60 miles. He estimates that the trucks could get 100 miles of range if they were driven in a straight line, but that drayage services significantly limit their range due to frequent stops and starts and the need to rapidly accelerate to highway speeds. Their trucks spend half of their time waiting and then accelerating while pulling a 60,000-pound load. This type of operation uses more energy. One time as an experiment, Firm B sent a ZE to Chino and ended up having to tow it back because the battery ran out.

Firm B decided to use the same driver every day, so they would only have to train one person. Fuel cost savings were not as high as expected, because the truck had to charge during the day when rates are high. The truck operated at night due to the PierPass program, which at the time imposed a fee on containers moving in or out of the ports during the day.

In the interviewee's view there is no way that the $300,000 investment for a battery electric truck can be justified. For comparison sake, the cost of their new diesel trucks is about $98,000 and $157,000 for natural gas. He estimates that if they went to all electric trucks their drayage rate would have to double or triple. The test truck is still parked at the facility awaiting a battery replacement from the OEM. They tested it for about 14 months.

The test truck was frequently taken offline at the request of the OEM, who would come in periodically to tweak the software. Firm B currently has another truck on the yard that is a battery electric with a CNG range extender. It has not yet entered service.

5.1.2.3 Firm C

Firm C is currently testing different alternative trucks from two different manufacturers, OEMs 1 and 2. One is battery electric, and the other is an LNG hybrid. The drivers like the LNG hybrid due to comparable performance to traditional diesel trucks. The trucks have a fully electric idle at low speeds and can be charged to boost the all-electric range - the operating parameters are set by the OEM. An LNG truck without a hybrid drive trialed by Firm C was also favored by drivers for its comparable performance to diesel. The fuel is $1 less than diesel at an equivalent volume. In a month the trucks travel from 4000–5000 miles which can result in a significant fuel savings.

The battery electric truck is not as useful to drivers as it can only operate for about half of a daily shift. Drivers have found the useful range to be closer to 50–70 miles with some issues related to slow acceleration on prolonged grades. Firm C owns its fleet of 80 trucks. Fleet managers assign trucks to trips based on their range and performance. Due to the better range of the LNG trucks over traditional CNG trucks, Firm C plans on pursuing reliable sources of LNG fuel to utilize LNG trucks. It also, however, plans to continue testing CNG hybrid trucks.

Firm C had just received a third test vehicle, a fuel cell truck. It has a useful range of about 200 miles with an extra 50 with a 4-cylinder Ford motor. The truck is currently refueled on site with a mobile hydrogen fuel station. At the time of the interview, there was little driver feedback on the vehicle due to its recent arrival.

5.1.3 Observations from Round 1 interviews

The following common themes are drawn from the interviews:

- Drayage firms appreciate the ability to market their services in offering BEV dray trucks, but the range at this point is not practical.
- CNG Hybrid trucks seem to be the reasonable short- term solution because they have a comparable range to conventional diesel trucks with very few emissions.
- Fuel cell technology is not as prevalent in the United States but may provide better performance than BEV in the long run.
- BEV trucks have a niche market in local drayage, especially port related activities that involve extensive periods of idling.

The interviews yielded the following observations. First, depending on the technology being tested, the real-world functional range for battery-electric technologies ran from 60-90 miles. Actual use of the vehicles on a daily basis tends to be even less. Most trucks have been kept in local inter terminal service due to range anxiety. Second, battery electric trucks were generally seen to have adequate acceleration and performance though one firm reported some concerns with getting up to highway speeds when fully loaded.

Third, PierPass presented another constraint to the operation of electric trucks for port drayage due to the daytime fee. However, in late 2018 the PierPass program moved to a flat fee structure that eliminates the price advantage of night drayage. Finally, LNG and CNG Hybrid trucks provide more than adequate range for drayage operation and cost substantially less than a BET. Thus, drayage firms are more favorable to the hybrid option.

5.2 Round 2 interviews

During the 4th quarter of 2019, nine in-depth interviews with fleet managers in the Los Angeles region were conducted. The purpose was to understand what drayage operators knew about zero and near-zero heavy-duty truck technology, and any reservations they had in the near-term. Questions regarding operations were also asked to provide insight on how range, type of freight, and drivers may or may not hinder implementation of new truck technologies. The goal was to gain a better understanding of the potential market for ZEHDTs in our target year time frame.

The surveys were conducted in person or by phone. They included questions on the firm's operations, as well as open-end questions on perceptions and understanding of BEHDTs. The full survey questionnaire is available in Appendix B.

5.2.1 Firm and operational characteristics

Each of the nine fleet companies differs from one another in terms of size, goods moved, and truck ownership. They predominately run operations in Los Angeles, San Bernardino, and Riverside counties with hubs in various locations such as Long Beach, Carson, El Segundo, and

Fontana. Two of the largest companies have locations in other states, as well as California. The firms serve customers in a range of industrial, consumer products, and agricultural products. Although all companies are considered drayage companies, they also do short-haul (6), long haul (3), and less-than-truckload (1). Details of firm characteristics are summarized in Table 33.

Because of the differences in markets served, the fleets vary considerably in size, type, and distance traveled. The average fleet size is 53, with the largest having over 500 trucks and the smallest only 23. Some companies own their trucks (7), lease (4), and/or use subcontractor vehicles (4). Like truck-ownership, flexibility is also seen in driver employment status. The majority both employ and subcontract their drivers. The number of drivers ranges from 24 to 100 drivers, with an average of 53.5 (excluding the largest company).

Table 33. Round 2 Interviews, Firm characteristics

Size of fleet	Average = 53, Range = 23 to 105 (excluding very large firm with over 500 trucks)
Type of operation	Drayage = 9 Short Haul = 6 Long Haul = 3 Less than Truckload = 1
Truck ownership	Own = 7 Lease = 4 Use Carriers and Owner Operators = 4
Type of freight	All but one handles a variety (bulk, chemical, food, beverage, consumer products, electronics, furniture) No Parcel Delivery
Number and status of drivers	Average = 53.5, Range 24 to 100 (excluding large firm with over 500 trucks) Employees only = 2 Subcontract Only (incl. owner operators) = 3 Mix Employees and Subcontracts = 4

For all firms interviewed, the average operates two shifts a day Monday through Sunday. Each tour (as defined as starting and ending at the hub location) services 2.75 customers on average and travels 93 miles. However, miles traveled in a shift varies considerably from as short as 15 miles to/from the port complex and local warehouse to more than 300 miles. The number of turns per shift varies from a low of 1 to a high of 8. The higher turns are from repeated drayage trips to and from the port complex. Surprisingly, 42% of total driver time on average is spent waiting at the port or a customer’s facility. This is in part due to customer satisfaction metrics that gauge on-time delivery performance as requiring drivers to arrive at a specified time. To ensure on-time performance, drivers arrive early and wait. Port queues are also mentioned as a significant contributor for waiting. Statistics are shown in Table 34.

Table 34. Round 2 Interviews, Operations characteristics

Number of shifts per day	Average = 2, Majority Work Weekends
Number of customers served on a tour	Average = 2.75
Number of miles per shift	Average = 93, Low = 15, High = 300
Number of turns per shift	Average = 2.6 Low = 1, High = 8
How much time spent waiting	Average = 42%

Fleets are managed quite differently, but dispatchers predominately dictate routes. Drivers do not always use the same trucks, but 44% on average do. Fueling and maintenance of trucks is not standardized. Firms choose to use outside companies to service their vehicles twice as often as hiring staff to maintain them. Likewise, for those facilities fueling on-site, 57% schedule fuel deliveries via wet-hose versus 43% who pump from permanent tanks on site. Alternative fuel vehicles (CNG, LNG) are fueled off-site. Table 35 summarizes fleet management responses.

Table 35. Round 2 Interviews, Fleet management

Who assigns routes	Dispatcher = 7 Drivers = 2
Are trucks assigned to drivers	Yes = 4 No = 1 Mix = 2 Do not know = 2
Who maintains the trucks	Firm (maintenance tech) = 2 Outside company = 4 Do not know/no answer = 3
Where are trucks fueled	On-site exclusively = 1 (wet hose) Off-site exclusively = 1 Mix on and off-site = 5 Do not know = 2 Wet hose = 4 Fuel tank = 3

5.2.2 BEHDTs and truck purchases

The second part of the survey was aimed at learning how much these firms knew about AF trucks and what their perceptions were regarding interest or willingness to purchase and use BEHDTs.

By and large, the firms interviewed had some knowledge of alternative fuel trucks. Several firms are involved with demonstration vehicles, so they had more experience than the others. Two other firms had not been educated on alternative fuel trucks. LNG and CNG trucks had the highest average knowledge at 1.4 (on a scale of 0 to 3), which was more than “a bit of knowledge" and less than "more than most." Comments included knowing more about those vehicles that had been around longer. Respondents said they had heard about the demonstration projects being conducted in Los Angeles. Their impression is that BEHDTs perform poorly due to range, and CNG/LNGs performed well. One related a story about a BEHDT being towed on the 710 freeway. Few commented about the technology not being mature at this point but thought that strides were being made to improve the technology.

Table 36 shows the average score for all firms.

Respondents said they had heard about the demonstration projects being conducted in Los Angeles. Their impression is that BEHDTs perform poorly due to range, and CNG/LNGs performed well. One related a story about a BEHDT being towed on the 710 freeway. Few commented about the technology not being mature at this point but thought that strides were being made to improve the technology.

Table 36. Round 2 Interviews, Summary of alternative fuel trucks responses

Knowledge of alternative fuel technology:	Scale: 0 to 3 (none to a great deal)	Comments
BEHDT trucks	1.3	1 firm demo equipment
Hydrogen fuel cell trucks	1.1	1 firm demo equipment
CNG trucks	1.4	1 firm demo equipment
LNG trucks	1.4	1 firm demo equipment
Hybrid trucks	0.9	

The top concerns about alternative fuel trucks are cost for the vehicles (89% of respondents have concerns) and charging equipment (89%), followed by fueling/charging time and performance (both at 78%), fueling charging location (75%), range (67%), maintenance cost (67%), and fuel cost (63%). Specific comments regarding the concerns are listed in Table 37.

Table 37. Round 2 Interviews, Concerns about technology

Concerns about technology	% responding yes	Comments
Truck cost	89%	Very expensive now, expecting will come down over time
Fuel cost	63%	
Maintenance cost	67%	Lack of skilled mechanics
Charging equipment cost (BEHDT)	89%	Lease property problem: major capital investment that may be sunk into property that is not yours
Fueling/charging location	75%	Lack of infrastructure (site and public access); where will non-fleet trucks charge? All would install charging equipment at site. Large fleet operator: there is not enough space in yard (or power) to do 125 trucks at once
Fueling/charging time	78%	Specifically BEHDT, split on whether would do quick charges during the day due to productivity concerns
Range	67%	Specifically BEHDT. Drayage is relatively short distances. Long-haul ops are not feasible.
Performance	78%	Hills, heavy loads
Other concerns	--	Resistance to change, lifespan of batteries, disposal of batteries

Truck acquisition cost is recognized as being expensive at the current time, but once economies of scale are realized, prices will decrease. The lack of public charging stations for quick charges or non-fleet vehicles is a concern. Dedicated space for charging in already crowded yards is also a worry, as well as investing in costly charging electrical infrastructure. Leaseholders would be hesitant to improve property they do not own.

Range was not more of a concern given the promise of increased distances for the next generation of vehicles and relatively low tour mileage of drayage operations. However, 300 miles was given as a minimum range between charging to alleviate range anxiety.

The last part of the interview focused on the intent to purchase alternative fuel vehicles. See Table 38. 67% of respondents said their firm would consider purchasing or leasing a truck now if costs were more reasonable and range was, on average, 287 miles or more. Incentive schemes are seen as problematic and challenging to use, and not well understood. Education in this area is lacking.

Finally, from the perspective of greening the supply chain, all but one firm thinks that zero or near-zero emission trucks are a useful marketing tool. Most have carbon reduction goals in their mid-term strategic plans.

Table 38. Round 2 Interviews, Purchasing alternative fuel trucks

Incentives	6 of 9 had used incentives in the past, but most had trouble with them, especially the first time around. Mixed knowledge of current incentives.
Consider purchasing/leasing now?	6 of 9 would consider purchasing/leasing now if cost not an issue, and they were available. The minimum range that the firm would need is 287 (average), with 300 miles being the predominant answer.
Are green operations a competitive marketing tool?	All but one agreed. Most have incorporated some sort of sustainability goals into their strategic plan.

5.2.3 Findings from Round 2 survey

The sample size is small, but some interesting conclusions can be drawn from the responses. Most respondents did not understand the technology well, although all had been approached by alternative fuel truck manufacturers. Within the group, two firms were actively involved with demonstrations of new heavy-duty truck technology (battery electric, LNG, CNG, and fuel cell). As would be expected, these managers had a better understanding than others of new technology since they were engaged with it on a regular basis. Concerns about vehicle and charging infrastructure costs were high, followed by fueling/charging time/location and performance. Numerous comments were made about the maturity of the technology, but all were looking forward to vehicles that had both range and performance at a reasonable cost. The minimum range that vehicles needed to provide for full-scale adoption was on average 287 miles loaded; the most common response was 300 miles. Six firms would purchase zero and near-zero emission trucks now for trials if incentives would bring costs down considerably for both the vehicle and charging equipment. Only firms with short trips could see themselves adopting the technology now, unless trucks were cherry-picked for specific routes/customers with low range requirements.

5.2.4 Conclusions on surveys

Education about available technologies and results of demonstration projects will have a profound impact on fleets considering adoption for trial purposes. The cost of the equipment (both vehicle and charging equipment) is a huge hurdle for companies to overcome. Most of the companies interviewed would like to try the technology (even with current limitations), so incentives are necessary to get the products in the field. Incentives are confusing and hard to understand for fleets, let alone single owner operators. Streamlining the process and providing education on incentives is required. Range is a big deterrent at this time since most firms require trucks to go at least 300 miles between fueling. Most firms are not keen to quick charge during a shift due to impacts in productivity; a truck charging is one not working. Currently, the long charging times may exclude those firms with more than two shifts.

Respondents agreed that green operations are good for business and the community. Alternative fuel trucks can help firms address sustainability in their strategic plans. Congestion and waiting (on highways, at the port, customer locations) currently cause significant externalities from trucks idling. If alternative fuel trucks can impact idling pollution, a major source of truck pollution will be addressed.

5.3 Stated preference survey

In this section, we describe a data-driven experiment designed to estimate how electric truck pricing, operating costs, and other factors could affect their ability to penetrate the short-haul trucking market. Because there are very few electric trucks operating in that market, a "stated-preference choice experiment" was developed and deployed, based on state-of-the art statistical and experimental-design methods.

At the heart of this experiment is an online survey that asks trucking industry decision makers to choose between conventional diesel and electric trucks after comparing their purchase prices (after rebates), fuel costs, maintenance costs, ranges, refueling/recharging times, and the availability of charging stations. The survey also introduces a hypothetical "Green Truck Sticker" program, where electric trucks are badged with a sticker that entitles them to priority service at the ports. It is analogous to California's Clean Air Vehicle Decal Program for low-emission vehicles, permitting access to faster travel using high-occupancy vehicle lanes. This feature allows for estimating how time-saving programs might incentivize electric truck adoption.

From our survey responses, we find statistically-significant evidence that policies governing pricing, operating costs, time-savings, and other factors may indeed be effective in incentivizing the adoption of electric trucks. However, these findings are best viewed as preliminary and illustrative, considering that they are based on a small sample of respondents. Statistical significance was achieved through clever experimental design, but the statistical estimators employed generally rely on larger samples to be deemed reliable enough for policy use. Arguably, the greatest value delivered by this research effort is a state-of-the-art experimental design and survey that is ready to deploy through a larger-scale outreach effort. The online survey, deployed in Qualtrics, can be viewed here: AQMD Electric Truck Survey[1]

Our small sample size resulted from the extraordinary difficulty we encountered in recruiting survey respondents from the trucking industry. In fact, there is a great deal of value in the lessons learned from that effort. Simply stated, there appears to be a pervasive attitude of resistance to and mistrust about electric trucks—at least among Southern California's trucking community.

[1] https://csulb.qualtrics.com/jfe/form/SV_4Vmyp5vC3kN0vNH

The survey was distributed with the assistance of the Harbor Trucking Association (HTA), the Los Angeles Transportation Club (LATC) and the Harbor Transportation Club (HTC). All represent various segments of the trucking industry, including drayage and intermodal. Email versions of the survey were distributed to the approximately 400 members of the LATC and 260 members of the HTC. Follow-up requests were made at association board meetings. The HTA provided the METRANS research team a booth at its annual Dray Tech Forum in June 2019 in Long Beach CA in order to share information on the research project and circulate the survey. In addition, the research team used a booth at the September 2019 Intermodal Association of North America (IANA) Expo, also in Long Beach, to disseminate the survey and gather industry input on the questions asked in it. Follow-up phone calls were made to industry leaders to encourage responses. No compensation was offered for responses, based on feedback from those leaders.

The relatively few number of responses outlined in the analysis below, despite a very targeted outreach approach, reflects the context in which the research was undertaken. Survey dissemination coincided with the debate surrounding - and ultimate adoption of - California's Assembly Bill (AB) 5. AB 5 redefines independent contractors and impacts not only trucking companies, but leased owner-operators as well. Other hiring entities, including carriers, brokers and shippers which engage with the trucking industry may also be impacted.

As the survey was directed at the independent owner operator or company official responsible for making decisions about fleet purchases, our research team was conducting outreach to a group with its focus clearly on Sacramento. The push for use of electric trucks in the drayage sector was viewed as part of a broader state effort to regulate the trucking sector; and the survey seen in part as a way to justify legislative efforts that the industry itself was not fully, if at all, behind. In our in-person outreach, it was common for stakeholders to ask about the relationship between our work and CARB regulations.

5.3.1 Stated preference survey and choice experiment

The focal point of the survey is a stated-preference choice experiment, where respondents are asked to make hypothetical choices between conventional diesel trucks and an electric truck when making new truck purchases. Each choice involves a comparison between truck prices, operating costs, operating characteristics, refueling/recharging times, the availability of chargers at diesel stations, and the potential for port-visit time savings through a hypothetical "Green Truck Sticker" program. This design allows for estimating how each of those features affects the probability of choosing an electric truck over a diesel one and, therefore, how changing those features could incentivize the market penetration of electric trucks.

Before being presented with each choice scenario, respondents were given the following instructions:

You will now be shown six hypothetical scenarios in which you are asked to choose between purchasing a new Diesel truck or Electric truck for your business, assuming those are the only available choices. Each scenario will be slightly different.

Here are some assumptions about each scenario:

- *You must purchase a new truck because your old truck is no longer serviceable. Used trucks no longer comply with environmental regulations.*
- *You will finance your purchase with a 5-year loan at a competitive interest rate. You will not lease the new truck as you intend to keep it for its entire 12-year service life.*
- *The new truck will be used primarily for drayage/short-haul operations, with one shift per day (i.e., no "slip seating").*
- *Diesel and Electric trucks have the same dimensions and hauling capacities.*
- *Electric trucks may be charged at your yard or at select diesel stations throughout the region.*
- *Electric truck prices may reflect rebates from a zero-emissions incentive program.*
- *Electric trucks automatically qualify for a "Green Truck Sticker" program, which grants them access to priority lanes and services at the ports that may reduce waiting times.*

In each scenario, you will be shown a side-by-side comparison of Diesel and Electric truck characteristics. Here are some brief descriptions of those characteristics:

- ***Purchase Price**: the truck's purchase price and monthly payment.*
- ***Fuel Cost**: the cost per mile and per month of fueling a Diesel truck or charging an Electric truck.*
- ***Maintenance Cost**: the truck's cost per mile and per month for maintenance.*
- ***Total Cost of Ownership**: the truck's combined monthly payment, monthly fuel cost, and monthly maintenance cost for:*
    - *the first 5 years*
    - *the following 7 years (after all loan payments have been made)*

  Also shown is the total of those monthly costs over the truck's entire 12-year lifespan.
- ***Range**: the truck's range with a full diesel tank or fully-charged battery.*
- ***Fueling/Charging Time**: the time it takes to refuel a Diesel truck or recharge an Electric truck.*
- ***% Diesel Stations with Chargers**: the percentage of Diesel stations that have chargers for Electric trucks. For example, "20%" means that one out of every five diesel stations has chargers.*
- ***Green Truck Sticker Savings**: the average amount of time saved per port visit due to priority access and services for Electric trucks.*

The key attributes to be considered are purchase price, fuel cost per mile, maintenance cost per mile, range, fueling or charging time, percentage of diesel stations with chargers, and Green Truck Sticker time savings. While not used explicitly in estimation, the total cost of ownership for each truck type is also presented to respondents in order to ease the computational burden of jointly considering prices and operating costs in their decision making. Those total costs exactly correspond to the individual prices and operating costs presented.

Figure 14 below shows one of many possible choice scenarios presented to each respondent. In each scenario, respondents were asked "Which vehicle would you purchase" and indicated their choice by clicking on a "Diesel Truck" or "Electric Truck" button.

	Diesel Truck	Electric Truck
Purchase Price	**$110,000**	**$323,000**
Monthly Payment for 5 Years	$2,127	$6,244
Fuel Cost per Mile	**$0.65**	**$0.32**
Monthly Fuel Cost	$3,088	$1,520
Maintenance Cost per Mile	**$0.19**	**$0.09**
Monthly Maintenance Cost	$903	$428
Total Costs of Ownership		
Cost per month for first 5 Years	$6,117	$8,192
Cost per month for next 7 years	$3,990	$1,948
12-year total cost of ownership	$702,156	$655,110
Range	**600** miles	**100** miles
Fueling or **Charging Time**	**15** min.	**60** min.
% of Diesel Stations with Chargers		**75**%
Green Truck Sticker Savings		
Average time saved per port visit		**30** min.

Figure 14. Example of a choice scenario

Attribute levels, such as purchase prices (after rebates), fuel costs, maintenance costs, and ranges, were initially based on estimates generated by the METRANS research team and from those cited in the *San Pedro Bay Ports Clean Air Action Plan 2018 Feasibility Assessment for Drayage Trucks*. Those levels were then modified to create a baseline scenario in which a rational respondent, from a cost perspective, should be roughly indifferent between the two truck types. Those attribute levels were then pseudo-randomly "perturbed" upward or downward by about 5% to 15% in order to create variation in those levels and elicit meaningful choices. Note that scenarios in which one truck type strictly dominated the other type were discarded, such as an electric truck with a higher purchase price, operating cost, and no time savings.

Each respondent was presented with six scenarios like that in Figure 14, but with different attribute levels, thereby eliciting six truck-type choices from each respondent. This was necessary to obtain enough variation in responses for estimation purposes—especially if relatively few respondents were anticipated. There were, of course, an extremely large number of possible combinations of attributes that could have been presented. The actual combinations presented were based on a "D-Optimal" design schema with the goal of choosing sets of attributes, from all possible sets, that maximize the information in the sample. Twenty-four attribute sets were algorithmically generated and divided into four blocks of six sets. Each respondent was then randomly assigned to one of those four blocks and presented with six choice scenarios based on the six sets of attributes in that block. While this process was highly computationally intensive, it was essential to securing optimal variation in attribute levels in order to achieve statistically-significant estimates.

Table 39 below provides a summary of the attributes presented to our survey respondents.

Table 39. Summary statistics for choice scenario attributes

	Mean or %	Std. Dev.	Min.	Max.
Diesel Truck Attributes				
Price ($)	$106,633	$4,004	$100,000	$110,000
Fuel Cost ($/mile)	$0.64	$0.05	$0.59	$0.72
Maintenance Cost ($/mile)	$0.19	$0.02	$0.17	$0.21
Range (miles)	600	0	600	600
Refueling Time (minutes)	15	0	15	15
Electric Truck Attributes				
Price ($)	$336,531	$12,975	$323,000	$357,000
Fuel Cost ($/mile)	$0.36	$0.03	$0.32	$0.39
Maintenance Cost ($/mile)	$0.08	$0.01	$0.07	$0.09
Range (miles)	149	52	100	250
Recharging Time (minutes)	64	22	30	90
% of Diesel Stations with Chargers	48.6%	30.5%	10%	90%
"Green Truck Sticker" Port Visit Time Savings for Electric Trucks (minutes)	15	9.4	0	30

Despite the considerable outreach efforts discussed above, only fourteen survey responses were obtained. Fortunately, the design schema described above yielded fifty choice responses (noting that not all survey participants responded to every choice scenario). That was sufficient to achieve significant estimates, but the caveat remains about relying too heavily on estimates based on such a small sample size.

The majority of respondents were trucking company owners or fleet managers. Two of those respondents operated very large fleets, which was controlled for in the estimation process. The remaining respondents were logistics managers or experts in logistics with truck-purchasing experience. Most operated or managed container cargo movements, some dealt with parcel movements, and the rest moved finished automobiles. Table 40 below summarizes characteristics of our respondents' trucking operations. Those characteristics were controlled for in the estimation process where appropriate.

Table 40. Summary statistics for trucking operations

	Mean or %	Std. Dev.	Min	Max
Industry Role				
Trucking Company Owner or Fleet Manager	76%	-	-	-
Logistics Manager or Expert	24%	-	-	-
Industry Purpose		-	-	-
Port Drayage and Other Short Haul	46%	-	-	-
Non-Port Short and Long Haul	36%	-	-	-
Vehicle Delivery	18%	-	-	-
Cargo Type		-	-	-
Container Cargo	58%	-	-	-
Automobiles	30%	-	-	-
Parcel	12%	-	-	-
Most Recent Truck Purchase				
New	87.5%	-	-	-
Used	12.5%	-	-	-
Number of Trucks	337	394	8	1300
Daily Miles per Truck	259	119	50	500
Daily Shifts per Truck	1.36	0.69	1	3
Daily Port Visits per Truck	1.52	1.16	0	3
Average Truck Age (years)	4.8	2.2	2	8

Our survey also elicited attitudes about electric trucks. The majority of respondents claimed to be "somewhat" knowledgeable about electric trucks. Surprisingly, all respondents who claimed to be "very knowledgeable" about electric trucks never chose one when facing the choice scenarios discussed above. Respondents were also asked to choose a preferred government program to ease the introduction of electric trucks to their industry. Most respondents preferred "no government program", and those same respondents never chose an electric truck in their choice scenarios. These findings shed light on our difficulties in securing survey participants. There may be an anti-electric-truck sentiment among the Southern California trucking community. On the other hand, all respondents who chose an electric truck in at least one of their choice scenarios indicated a preference for "Low Interest Loans or Leases" or "Purchase Price Rebates" as government incentives. Among all respondents, the largest concerns about introducing electric trucks to their industry were "Purchase Price" and "Range". Table 41 below summarizes these attitudinal responses.

Table 41. Summary of attitudes about electric trucks

Survey Question	%
How knowledgeable would you say you are about electric trucks?	
Very	24%
Somewhat	66%
Not at All	10%
What is your biggest concern about electric trucks?	
Purchase Price	24%
Range	24%
Charging Locations	12%
Maintenance Costs	12%
Charging Costs	10%
Hauling Capacity	6%
Charging Times	0%
Charging Equipment Costs	0%
Combination of the Above Factors	12%
If you could choose one type of government program for bringing electric trucks to your industry, which of the following would you choose?	
No Government Program	38%
Low-Interest Loans or Leases	26%
Purchase Price Rebates	23%
Charging Equipment Rebates	13%
Income Tax Credits	0%
Charging (Electricity) Discounts	0%

5.3.2 Market penetration and incentives required

Our fourteen survey respondents yielded 50 choices between diesel and electric trucks from choice scenarios like that presented in Figure 14 above. From those scenarios, 16% indicated that they would choose an electric truck, while 84% indicated that they would choose a diesel truck. Loosely speaking, if electric truck prices were subsidized or evolved to the point that the total costs of ownership for diesel and electric trucks were similar, we would expect a 16% market share for electric trucks. That also assumes the existence of a time-saving program that would entitle at least some electric truck owners priority service at the ports.

To estimate how changes in attributes such as pricing and operating costs could incentivize electric truck market penetration, which could be realized by government programs such as purchase-price rebates or electricity subsidies, we applied discrete-choice econometric methods to the choice-scenario responses. Specifically, we employed a binary logit model, where the dependent variable is equal to one if an electric truck was chosen, conditioned on diesel and electric truck attributes. Ideally, we would use panel-data methods to exploit the fact that each respondent made multiple choices. And we would have preferred to interact certain attributes with operator types to determine, for example, how container cargo carriers might respond differently to pricing incentives. However, our low survey-response rate allowed for only a baseline analysis. To account for the repeated choices made by our respondents, we employed clustered standard errors to acknowledge that the choices made by each respondent were not independent.

The model we employed can be written as

$$P_j = \frac{e^{x\beta}}{1 + e^{x\beta}} \tag{1}$$

where P_j is the probability that a truck-purchasing decision maker chooses an electric truck, based on the attributes, x, of *both* the electric and diesel trucks presented to them, along with other factors. Those attributes include all of those listed in Our survey also elicited attitudes about electric trucks. The majority of respondents claimed to be “somewhat” knowledgeable about electric trucks. Surprisingly, all respondents who claimed to be “very knowledgeable” about electric trucks never chose one when facing the choice scenarios discussed above. Respondents were also asked to choose a preferred government program to ease the introduction of electric trucks to their industry. Most respondents preferred “no government program”, and those same respondents never chose an electric truck in their choice scenarios. These findings shed light on our difficulties in securing survey participants. There may be an anti-electric-truck sentiment among the Southern California trucking community. On the other hand, all respondents who chose an electric truck in at least one of their choice scenarios indicated a preference for “Low Interest Loans or Leases” or “Purchase Price Rebates” as government incentives. Among all respondents, the largest concerns about introducing electric trucks to their industry were “Purchase Price” and “Range”. Table 41 below summarizes these attitudinal responses.
Table 41 above. The coefficients, β, are used to determine how factors such as pricing would change the probability that an electric truck is chosen; they were estimated using maximum likelihood estimation methods. On their own, only the signs of those coefficients are useful; they tell us if an increase in the variable they belong to, such as purchase price, would increase or decrease the probability of choosing an electric truck. To estimate the size of that effect, we use the following calculation:

$$\frac{\partial P_j}{\partial x_k} = P_j(1 - P_j)\frac{\partial x\beta}{\partial x_k} \tag{2}$$

This tells us the percentage-point change in the probability of choosing an electric truck if the variable x_k were to increase by one unit. For example, it would tell us how the probability of choosing an electric truck would increase if the price an electric truck were reduced by one thousand dollars (presumably through a rebate program).

Table 42 below displays our estimates of those coefficients, where the dependent variable is equal to one if an electric truck is chosen. Note that several control variables are suppressed; only coefficients used in calculating effect sizes like those discussed above are displayed.

Table 42. Choice model coefficient estimates

Variable	Coefficient Estimate	Robust Standard Error	Significance Level
Purchase Price ($)	-0.000418	0.000117	0.000
Fuel Price per Mile ($/mile)	-21.14	13.38	0.114
Maintenance Price per Mile ($/mile)	-114.35	38.91	0.003
Range (miles)	0.039	0.020	0.052
Refueling/Recharging Time (minutes)	-0.249	0.083	0.003
% of Diesel Stations with Chargers	0.082	0.028	0.003
"Green Sticker" Program Port Time Savings (minutes)	0.251	0.152	0.100
More than 1,000 Trucks (dummy)	44.41	4.63	0.000
Container Cargo Carrier (dummy)	41.41	5.47	0.000

The significance level reported in Table 42 indicates the precision of each coefficient estimate. All significance levels are based on the robust standard errors reported in the table, which are robust due to the clustering employed in accordance with the repeated choices made by respondents.

In Table 42, we see that all coefficient estimates are statistically-significant at reasonable significance levels, and all variables have the expected sign. Increasing the price, operating costs, and recharging time of an electric truck would reduce the probability of choosing one. Increasing the range of an electric truck and the availability of chargers at diesel stations enhances the probability of choosing an electric truck. The ability to reduce port visit times through priority service for electric trucks increases the probability of choosing one. Holding all other factors constant, cargo container carriers are more likely to choose an electric truck. And trucking companies with large fleets are more likely to choose electric trucks, perhaps due to capital advantages and the ability to install additional charging infrastructure.

Table 43 provides various effect sizes implied by those coefficient estimates. For each variable, a policy-oriented incentive is mapped to its estimated effect on the market penetration of electric trucks. Importantly, the total costs of purchasing and operating diesel and electric trucks are assumed to be somewhat comparable at the outset through existing purchase-price rebates. Significance levels are calculated using a delta method approximation of standard errors for those effect sizes.

Table 43. Market penetration effects of electric truck incentives

Electric Truck Incentive	Percentage-Point Increase in the Probability of Choosing an Electric Truck	Significance Level
Additional $10,000 Purchase Price Rebate	17.0	0.000
$0.10 per Mile Reduction in Charging Costs	8.6	0.066
$0.10 per Mile Reduction in Maintenance Costs	46.6	0.003
100 Mile Range Increase	16.0	0.039
10 Minute Decrease in Charging Time	10.1	0.000
10%-point Increase in Diesel Stations with Chargers	3.4	0.000
10 Minute Reduction in Port Visit Time (Green Sticker)	10.2	0.078

Table 43 shows, for example, that increasing the rebate for an electric truck purchase by $10,000 would increase the market share of electric trucks by 17 percentage points. Again, this assumes a market scenario in which electric trucks have either declined in price or are subsidized enough for them to be a realistic alternative to diesel trucks. Put differently, electric trucks purchases are already heavily subsidized and have virtually zero market share (at the time of this writing). This analysis is designed to guide electric-truck policies once a realistic market for electric trucks has evolved.

The table also shows that modest reductions in fuel and maintenance costs, whether through subsidies or technological improvements, could have relatively large impacts on market penetration, as could efforts to improve electric battery ranges and charging times. Increasing the availability of charging facilities at diesel stations has a smaller than expected effect, perhaps because respondents envisioned sufficient charging facilities at their yards.

A striking finding is that enabling electric trucks to reduce port visit times through priority service at the ports implies a one percentage-point market share increase for every minute saved. This finding is corroborated by a similar effect for each minute of reduced charging time. Perhaps the lessons learned from California’s Clean Air Vehicle Decal Program, allowing low-emission vehicles to use high occupancy vehicle lanes, can be applied to port congestion.

Not shown in Table 43 is the finding that large trucking companies—those with more than 1,000 trucks in our case—are 70 percentage-points more likely to adopt electric trucks. As noted above, this may be due to larger capital reserves and the ability to develop charging infrastructure. Also, container cargo carriers are 37.1 percentage points more likely to adopt electric trucks. From a policy standpoint, initial efforts to penetrate the trucking market with electric trucks might best be spent on large trucking firms and those specializing in container movements.

The statistical significance of these findings is encouraging, but it bears repeating that the above estimates are based on a relatively small sample of respondents from the Southern California trucking community. It may be better to view these findings as a “proof of concept” for a survey-based research program that is ready to be deployed on a much larger scale and with a much larger (albeit more costly) outreach effort. The biggest impediment to achieving a greater response rate has been what appears to be a general sentiment among the trucking community that electric vehicles are being legislatively forced upon the industry.

Chapter 6. Potential markets for ZEHDTs

Chapters 4 and 5 provide a comprehensive analysis of the costs and benefits of using ZEHDTs and a detailed portrayal of industry perceptions, concerns, and willingness to purchase and use ZEHDTs. Most of our research has focused on the drayage market. In this chapter we use the SCAG regional transportation model data to generate a broader analysis of potential in short-haul markets. We then summarize findings from Chapters 4 and 5 to present an assessment of potential near and medium term markets.

6.1 Potential markets in the region

In order to identify potential markets for ZEHDTs in the region, we would need comprehensive data on freight operations across industry submarkets such as the data we presented in our case studies. We would need to know how vehicles are used, how far they travel per day, and the weight of loads they carry. Such data do not exist. In fact, there is no source for data on heavy duty truck origins and destinations, and surprisingly little data on truck flows.

In the absence of actual data, we turn to simulated data. The Southern California Association of Governments (SCAG) has a heavy duty truck component in its regional transportation model. The truck model is based on truck survey data and selected screenline counts. The truck model gives truck volumes on the transportation network and origin-destination data. We use the SCAG model data to map truck activity. Combined with employment, distribution center locations, and intermodal facilities, the map identified three specific clusters of truck-related activity in the greater Los Angeles area.

6.1.1 Freight clusters

The 2016 SCAG trip simulation data provided the basis to identify potential markets for electric trucks in Los Angeles, based on the truck trip density in each Travel Analysis Zone (TAZ). Truck trip density is defined as the total number of heavy-duty-vehicle trips generated per square mile. We assume that areas with a high concentration of truck trips, employment in transportation and warehousing, as well as warehousing facilities would be a potential market, because of the high concentration of air toxics and the potential economies of locating charging stations where demand is highest. Given this assumption, we utilized several spatial analysis tools in ArcGIS to identify places with high concentrations in all these three aspects:

Step 1: Mapped the spatial distribution of - (1) Truck trip intensity, (2) Employment in transportation and warehousing, as well as (3) Warehousing facilities, as three individual layers

Step 2: Conducted Hotspot Analysis respectively for each layer resulted from Step 1

Step 3: Intersected the significant hotspot areas of three layers to identify the overlapped hotspot areas with high concentration of truck trips, employment in transportation and warehousing, as well as warehouses. These areas could have the highest potential.

Step 4: Identified spatial clusters and the corresponding centers. Used 5-mile buffer zone to cover the hotspot TAZs in each cluster. Figure 15 shows the result of this analysis, in which three 5-mile-radius clusters in Los Angeles can be identified as the areas with greatest potential as markets for electric trucks (light yellow circles). They are named by location:

- Los Angeles (LA) cluster: located in downtown LA, near Union Station
- Long Beach (LB) cluster: located around the Long Beach Port
- Ontario (ONT) cluster: located near the Ontario Airport

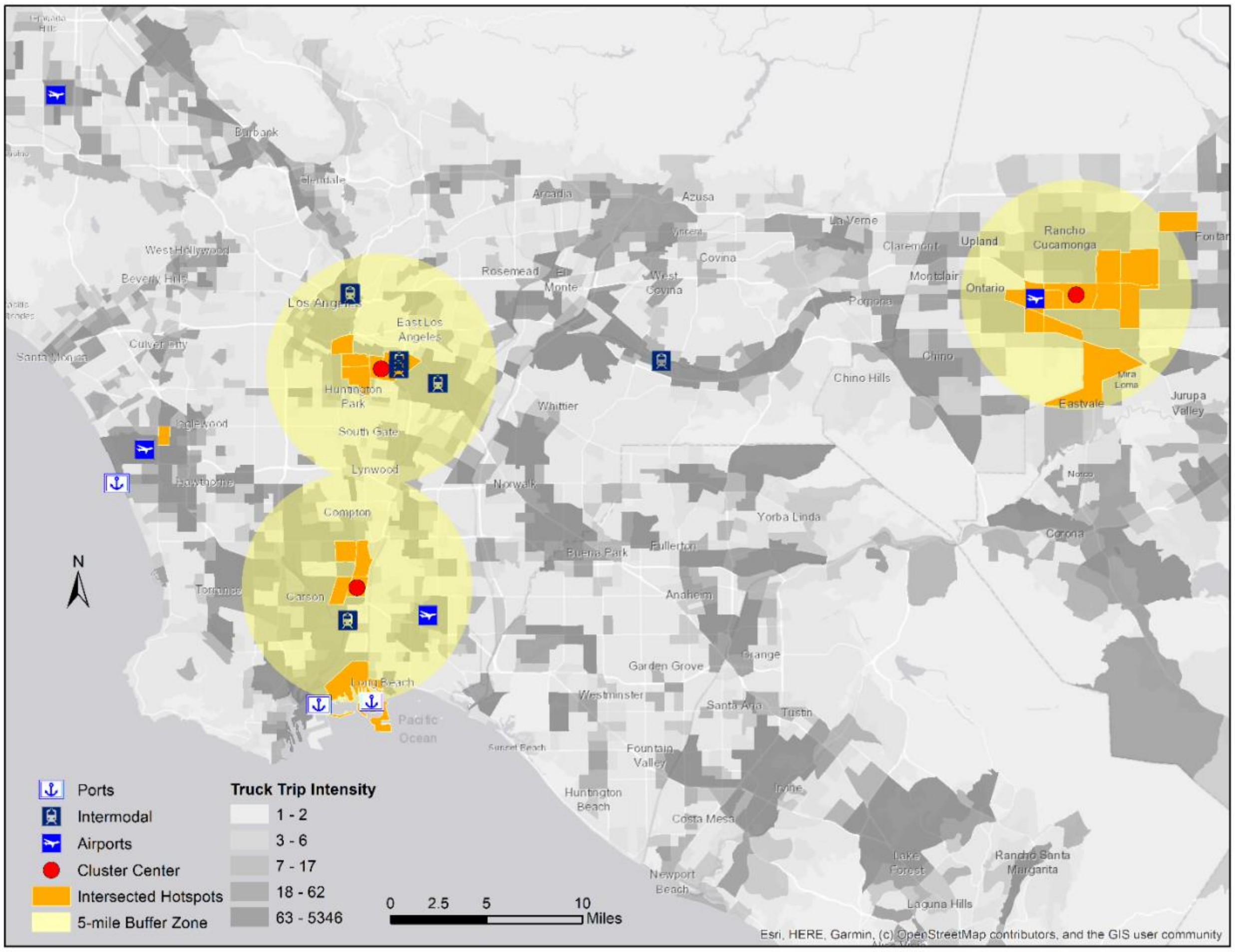

Figure 15. Mapping truck trip intensity and identifying clusters

The map shows the location of the three clusters identified (light yellow shades), together with the distribution of: truck trips (in grey shades), intersected hotspots (in orange shades), ports, airports, and intermodal facilities. Given our knowledge of regional distribution activity, the cluster locations are as expected. In general, truck trips are more concentrated along major highways and near intermodal centers such as airports, ports, and regional railroad facilities. Employment related to transportation and warehousing are also distributed closer to places with high truck trip intensity. Locations close to goods movement infrastructure with high truck trip intensity would be potential market areas for electric trucks given the magnitude of trucking demand.

6.1.2 Industry mix and trip distance

Concentration of truck activity may be one indicator of potential market, but more important in the short and medium term is trip distance and load weight. We used the SCAG heavy truck O-D data to generate trip distance distributions for each cluster. We used Google Maps to zoom in and identify the types of business in each cluster. Business type is a rough proxy for potential weight and trip distance. Figure 16 through 18 show the trip distance distribution for each cluster, and Table 44 through 46 show the most common businesses located in each zone (TAZ) making up the cluster.

Cluster LA information is shown in Figure 16 and Table 44. It has the largest number of total trips, about 10,000. Cluster LA includes the BNSF intermodal facility. It is a major destination for import cargo arriving at the ports. It is a heavy industrial area, with high concentration of transport-related industries and heavy industries. It also includes LA's apparel manufacturing center. Cluster LA has a high concentration of short trips; 70% are within 20 miles; this is likely explained by the drayage traffic. Cluster LA has promise because of the large number of short trips, but loads are likely to be at or near the legal weight limit, making use of BEHDTs less promising. However, it is possible that apparel and food activities could constitute a promising market.

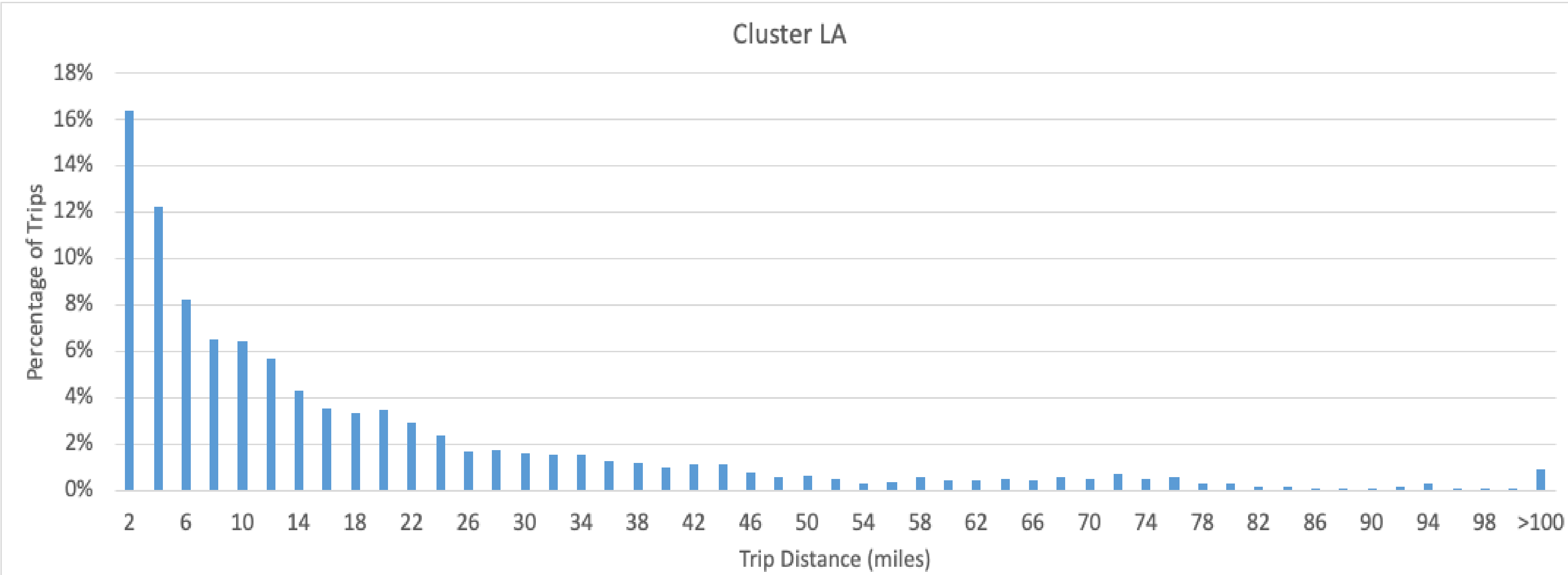

Figure 16. Cluster LA trip distance distribution

Table 44. Top 25% of TAZs in Cluster LA with Business Types

TAZ	HDT trips	Business Type
1675	1751	Motor body, Food
2539	1649	BNSF Rail
2525	1285	Food
1682	1217	Metro, Motor body, Rail & Truck Yard
2518	1155	Furniture, Food, Metal
1676	1036	Chemical, Print, Concrete, Food
1670	905	Food, Print, Textile, Pump, Apparel
2175	555	Apparel, Food, Electronics, Textile
1689	500	Rail, Food, Beverage
Cluster LA Total:		14662 trips

Figure 17 and Table 45 give the same information for Cluster LB. Cluster LB includes the I-710 corridor, which is the main freeway between the ports and the intermodal facilities in Los Angeles. It is an industrial corridor with high concentration of warehouse and distribution. Closer to the ports is a zone of petrochemicals. The cluster also includes downtown Long Beach. The trip distance distribution is skewed towards shorter trips with 78% within 20 miles, but again load weight is likely high. Trucking companies might have to adjust their operations in order to avoid overweight problems.

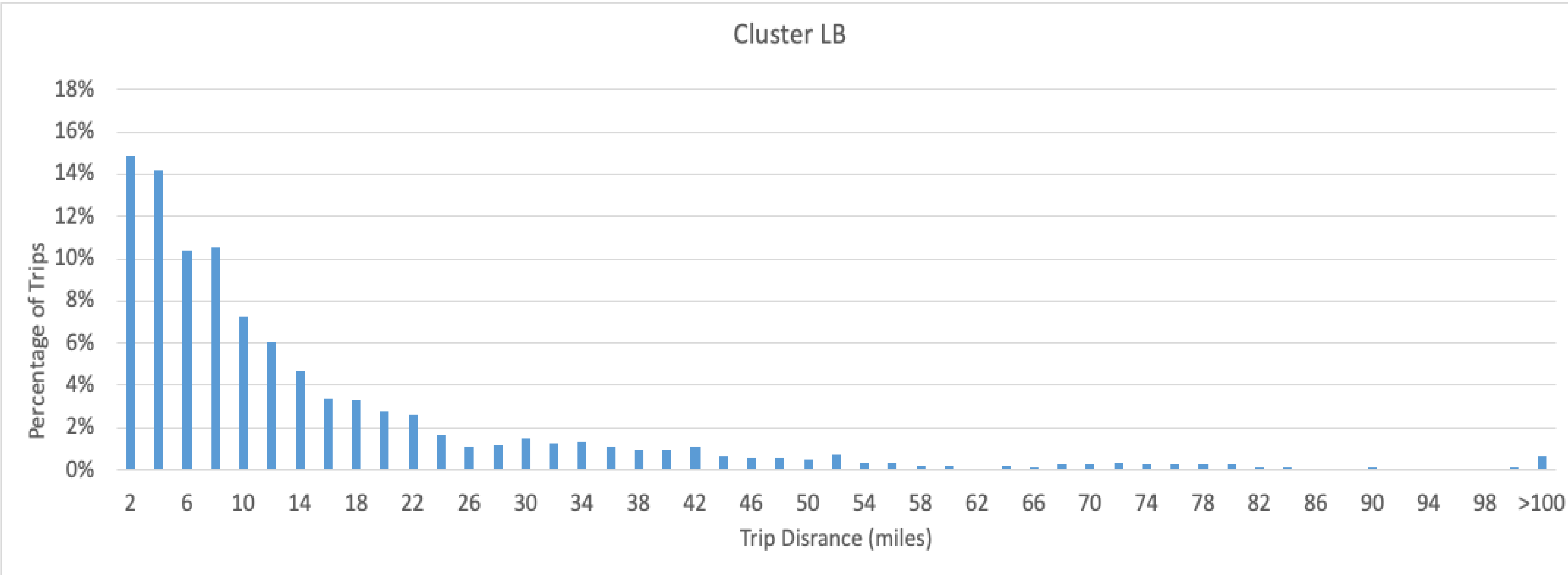

Figure 17. Cluster LB trip distance distribution

Table 45. Top 25% of TAZs in Cluster LB with Business Type

TAZ	HDT trips	Business Type
1576	920	Textile, Apparel, Food, Marine Equipment, Medical Equipment, Furniture, Motor Vehicle Parts, Paper Mill, Industrial, 3PLs
1459	882	Downtown Long Beach: Hotels, Restaurants, Office
1977	668	Oil Refinery, 3PL
1518	664	Electronics, Plastics, Steel, Petroleum, Storage
1520	561	Oil Refinery, Chemicals, Food, 3PLs, Fabricated Metal, Paper Mill
1989	514	Machine Shops, Household Goods, Food, Retail, Electronics, Motor Vehicle Parts
1577	501	Transloading, Apparel, Chemicals, Wholesale, Movie Studio, Furniture, Textile
2009	483	FedEx, Apparel, Aerospace, Temperature Control, Motor Vehicle
Cluster LB Total:		11009 trips

Cluster ONT is located around the Ontario Airport industrial zone. The area is one of the region's major distribution hubs as well as a manufacturing zone. See Table 46. The trip distance distribution is much more even, with 55% of trips within 20 miles. See Figure 18. With long average trips distances, this cluster is not promising for BEHDTs. However, as a courier hub the airport may be a potential market for medium duty BETs.

We note that this spatial market analysis is limited, because we cannot link specific trips to specific industry segments. It is quite possible that there are niche markets in each of these clusters that would have good potential for heavy duty BEHDTs. More research on the freight operational characteristics of different industries is necessary to better understand potential markets.

Table 46. Top 25% of TAZs in Cluster ONT with Business Type

TAZ	HDT trips	Business Type
3512	1157	Plastic, Motor, Chemical, Computer, Furniture, Food
1192	1046	(Ontario Airport) Food, Couriers (USPS, FedEx), Motor Vehicle
402	903	Metal (Copper), Concrete, Paper, Motor Vehicle, Cosmetics, Apparel, Pharma, Electronics, Plastics, Truck Freight
3518	594	Furniture, Pipeline, Electronics, Beverage (Water, Wine), Food
3520	479	Furniture, Electronics, Electrical, Plastics, Construction, Equipment (Safety, Power), Motor Vehicle, Beverage, Food
3513	478	Package Supply, Food, Pharma, Concrete, Paper
Cluster ONT Total:		9823 trips

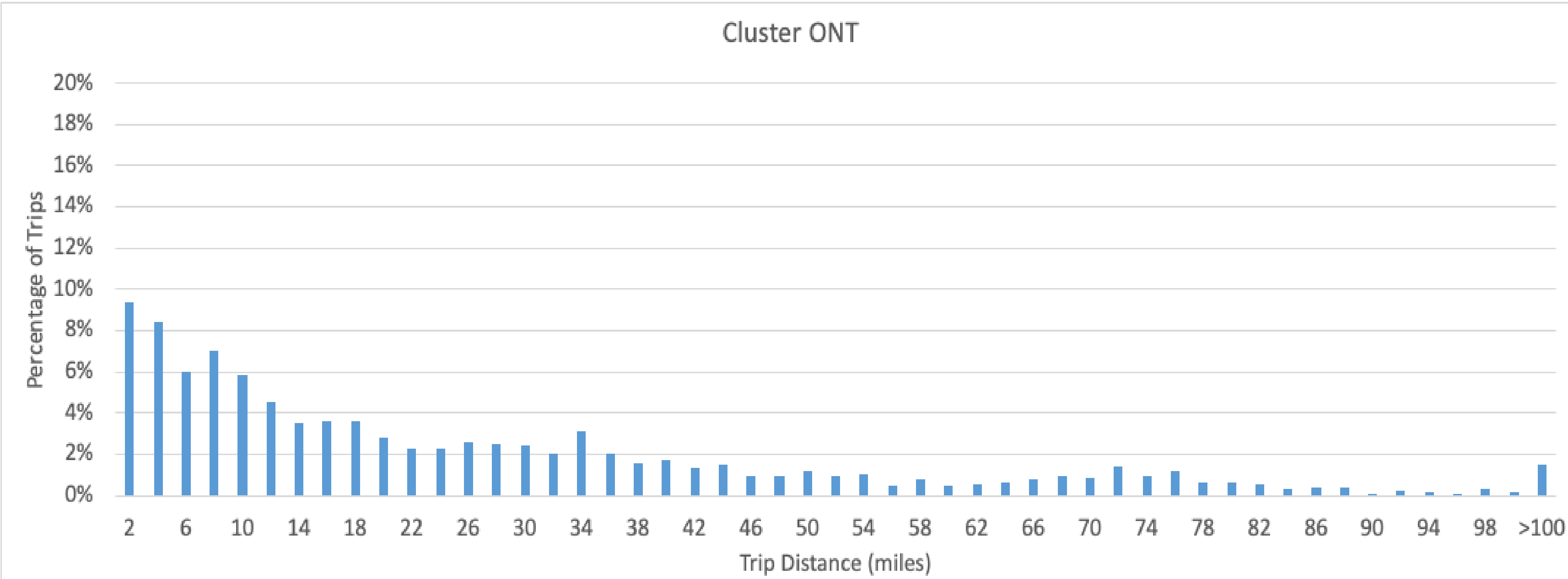

Figure 18. Cluster ONT trip distance distribution

6.2 Findings on potential markets

This section synthesizes the results presented in the previous chapters and summarizes our findings.

Finding 1: At the current state of BEV technology, BEHDTs have limited application in the short haul heavy truck market

BEHDTs are not yet feasible substitutes for conventional diesel due to limited range, required charging time, and the impacts these limitations have on freight operations. Our simulations showed that in order to use a significant number of BEHDTs, the total number of vehicles required increases. More vehicles add to total costs, generating a high price per ton for CO2 emissions removed.

Our simulations did not take weight limits into account, and assumed a single shift operation. Our case studies and interviews revealed that many drayage firms use vehicles for multiple shifts per day, making it difficult to use trucks that must remain out of service for hours in order to refuel. Our case studies also revealed that most loads are close to the maximum allowable. This makes sense; it optimizes use of the truck. At about 5,000 pounds, battery weight would cause widespread overweight trips, or would require breaking up loads to meet the limit. Breaking up loads requires more trips, more vehicles, and more VMT. The other option, increasing the maximum weight limit, would have implications for safety and road damage.

Our interviews revealed other issues that further constrain use of BEHDTs. Real world operating conditions are more energy intensive than the OEM's advertised range suggests, hence actual range is less than expected. Grades are a particular problem. Range anxiety further shortens operating distances; most demonstration vehicles are being used for very short trips. It appears that range will have to increase substantially if significant market penetration is to be achieved.

The lack of charging infrastructure is another problem for drayage firms. Drayage is a low margin business, and the additional costs for building charging facilities may be prohibitive. Furthermore, lack of charging facilities restricts the routes that can be assigned to those that assure arrival back to the home location within the range limit.

Finding 2: Natural gas hybrid near zero vehicles are preferred in the short term

Our simulations suggest that at present, hybrid-electric trucks are a more feasible option. Because hybrid trucks have comparable range to conventional diesel, using hybrids does not impact freight operations. The substitution of vehicles is one to one, substantially reducing capital costs relative to ZE. The all hybrid option dominates our midpoint ZE option, because increasing the share of BEHDTs requires increasing the total number of vehicles.

In the out years, performance of the all hybrid alternative depends on what costs are counted. When considering full costs, hybrid is preferred for NOX, but not for PM 2.5 or CO2. When we consider only incremental costs, the all hybrid option is preferred for all emissions and all target years.

Our interviews revealed that fleet operators preferred NG hybrids to BEHDTs. While NG hybrids also have a fueling problem, they do not have the range or weight restriction problems of BEHDTs. Thus, hybrids can more easily be integrated into freight operations.

Finding 3: The medium term market is promising and depends critically on the rate of improvement of battery technology and rate of decline in vehicle price

Our simulations and case studies show that potential market penetration is much greater in 2025 and 2030 due to the assumed improvements in battery technology and assumed reduction in the price of BEHDTs. These assumptions are based on the best available projections. The difference in our results between 2020 and 2025 are particularly dramatic, because we used actual performance data for 2020. If the projections do not take into account grades, driver behavior, and load factors, they are likely to be optimistic. We note in particular the assumed drop in ZE price from $300,000 in 2020 to $165,000 in 2025, a decline of almost half. From 2015 to the present, prices have stayed in the low $300,000 range. It is therefore possible that the projected price reductions are also optimistic.

Our estimate of costs and benefits shows that performance of the ZE alternatives depends on how costs are counted. When considering only incremental costs relative to diesel, the hybrid alternative is preferred even in the out years. These results would change if BEHDTs became more efficient.

Finding 4: The medium term market depends on charging infrastructure and energy availability

Our simulations and case studies made assumptions about charging infrastructure location and did not consider any costs. The cost of construction of charging stations is substantial, and if firms are expected to build their own charging stations, this would be an additional upfront cost for investing in BEHDTs. If there is no or limited availability of public charging stations, BEHDTs would always be limited by the requirement of having to return to base for refueling, eliminating potential for future longer distance markets.

Fleet operators identified the lack of charging stations as a significant barrier to their willingness to use BEHDTs. Not only would building their own station add to initial costs, it would not help range anxiety. If the only place one can charge is at the home base, operators will be very conservative in routing BEHDTs to avoid a truck being stranded. A private, for-profit model of charging stations is unlikely in the near term given the expected limited penetration of BEHDTs in the next 5-10 years. Thus, it appears that charging stations will need to be publicly provided.

Fleet operators also had concerns about the capacity of the electric grid. They questioned the feasibility of charging large numbers of trucks at the same time in areas where drayage and warehousing operations are concentrated.

Finding 5: The medium term market depends on subsidies

At present the only heavy duty BEHDTs in service are those in demonstration or given to operators by OEMs interested in having their vehicles tested. There is no willingness to pay for a vehicle that costs nearly three times more than a new diesel truck and has inferior operating characteristics. While the capital cost differential is expected to shrink considerably between now and 2030, the range, load capacity and charging constraints will be slower to disappear.

Our stated preference survey showed that even with vehicle alternatives that were comparable, respondents chose the diesel alternative 86% of the time. These results suggest both attitudinal factors and operational considerations may play a role. Our interviews with fleet operators revealed a general distrust of the technology and negative perceptions of what they considered aggressive regulatory efforts to force the technology on the industry. At the same time, our case studies showed how complex short haul operations can be. Fleet operators have a detailed understanding of all the changes that would be required to introduce ZEHDTs into the fleet (e.g., new maintenance procedures, driver training, new constraints on routing), and these details are generally not reflected in studies of heavy duty ZEHDTs.

Finding 6: Institutional and organizational issues are a consideration

Our research revealed many organizational and institutional issues that merit consideration. First, there are varied models of employment and vehicles. Owner-operators continue to make up a sizeable share of all operations in the short haul market. Some firms own their own vehicles and have their own employees; others lease vehicles and use employee drivers, some use owner operators exclusively, and still others use a mix. Introducing ZEHDTs has different implications for different business models. Owner operators are very unlikely to consider ZE because such a vehicle would severely restrict job opportunities. Those who lease vehicles may be more inclined to use ZEHDTs as long as the price is right and the vehicle is able to do the job. Those who own their own fleets may consider ZE when a vehicle is due for replacement, but would be averse to shedding vehicles otherwise due to the costs involved.

Although we were able to conduct only two case studies, our firms could not have been more different. They illustrate the great variation in products hauled, delivery patterns, and operational constraints that exists even within a small submarket. Any comprehensive ZE program would need to take this variation into account.

Our research also showed that current state maximum gross vehicle weight limits presents an additional problem for BEHDTs. Batteries weigh in excess of 5,000 lbs. The maximum load for diesel trucks is about 44,000 lbs., the difference between the maximum gross vehicle weight of 80,000 lbs. and the usual weight of truck and chassis. Maintaining the gross limit with a ZE means a reduction of over 10% in load capacity. While increasing the allowable gross weight for BEHDTs to 85,000 would solve the problem for BEHDTs, it would lead to more pavement damage and possible safety problems.

An additional observation from the research is that larger firms are more likely to be able to successfully integrate ZEHDTs into their operations. This is a matter of proportions: one ZE truck in a fleet of 100 vehicles will not greatly impact operations; one ZE truck in a fleet of 10 would be critical. Larger firms have more options for routing and trip assignments, all else equal. While demonstrations have focused on the larger drayage firms, the industry itself is made up mostly of smaller firms. According to the May 2020 Clean Truck Program monthly report data from the Port of Los Angeles, about two thirds of the firms serving the ports have less than 20 vehicles.

Finally, our interviews revealed that there was little awareness or understanding of the incentive programs available for ZEHDTs. Subsidies for purchase were seen as difficult and confusing to pursue. We were also informed that a subsidy would be treated as additional income to the firm, increasing tax liability. There was almost no awareness of the fuel credits available under the Low Carbon Fuel Standard. In fact, a new business is emerging to guide firms through the labyrinth of available subsidy programs.

Finding 7: More data is required to better understand freight operations and identify potential markets

Our interviews revealed that real world operations are complicated, and even within the drayage short haul industry there is enormous diversity in how companies are structured, the size of the operation, what is carried, how shipments are organized, how drivers and vehicles are assigned, and how strictly the shipper must conform to customer requirements. All else equal, it should be easier for large firms to use ZEHDTs, because 1) there should be a sufficient number of short enough trips, 2) in case of mechanical problems, it should be easier to find a substitute vehicle; 3) large firms are likely to be more aware of government subsidy programs.

Chapter 7. Policy strategies and recommendations

Our final chapter presents policy strategies and recommendations. The first section of this chapter provides an overview of policy strategies currently in place to achieve the state and regional emissions reductions targets. It also considers other policies that could enhance current efforts. The second section provides policy recommendations. Our recommendations are based on the findings presented in Chapter 6. The chapter ends with some conclusions on the entire report.

7.1 Policy strategies

Governments play an important role in setting policies and standards. For the adoption of new technology like electric trucks, local, state, and federal governments can fund research development, provide seed money for technology development and demonstrations, and provide incentives for accelerating adoption. For ZE trucks specifically, first adopters need government support for vehicles and charging systems because of the initial high cost of first-generation products.

The case for zero and near zero heavy duty vehicles is twofold; heavy duty trucks are now the largest single mobile source of NOX and a major source of PM 2.5. ("Cleaner Trucks Initiative: Regulations for Emissions from Vehicles and Engines ," n.d.) The health effects of these air toxics warrant further controls on emissions. Secondly, heavy duty trucks are a major contributor of GHGs (Greene, 2017) Reaching California's ambitious GHG reduction targets will require GHG reductions in the transport sector.

This section summarizes California's regulatory programs, describes the major local programs applying to heavy duty trucks, and presents some additional policies for reducing emissions and their impacts.

7.1.1 Summary of California air toxic reduction measures

California is widely recognized as the U.S. leader in both air toxic and GHG reductions, California led the nation with the first tailpipe emission standards established in 1966. Having established air quality standards before the federal government, California was granted permission to establish standards above those of the federal government. California followed with regulation for nitrogen oxide (NOX) in 1971 and for particulates in 1982. ("History California Air Resources Board," n.d.) GHG regulation began with AB 1493 (Pavley) in 2002, which established a vehicle GHG reduction program to begin with the 2009 model year. (AB-1493 Vehicular emissions: greenhouse gases., 2002) Today California's GHG reduction target is a 40% reduction from 2020 by 2030. (SB-32 California Global Warming Solutions Act of 2006: emissions limit., 2016) The state has implemented a massive program across all sectors of the economy to achieve this target. We focus on the heavy duty truck sector.

There is a broad array of air pollution and GHG reduction policies currently in place that apply to the heavy-duty truck sector. These are summarized in Table 47 and briefly described below.

Table 47. Summary of current policies applied to or affecting the heavy-duty truck sector

Policy/regulation/programs	Description
Cap-and-trade 2006 AB 32 2016 SB 32	• Establishes a "cap" on overall emissions from large emitters by issuing a limited number of permits • Permits to be bought and sold (traded) • Create a market price for carbon per ton and incentives to reduce emission output
Low Carbon Fuel Standard	Requires transportation fuel suppliers reduce carbon intensity of fuels
Freight efficiency, ZE target 2016 California Sustainable Freight Action Plan	• Enhance system efficiency (value of goods relative to emissions) by 25 percent by 2030 • 100,000 ZE heavy duty vehicles in operation by 2030
Vehicle-Related Programs 2019 SB 44	• Incentives to develop and deploy truck technology (incl. demonstrations), specifically electric • Incentives for early commercial deployment
Vehicle emissions standards	• Graduated emissions standards to promote use of cleaner vehicles
Advanced Clean Truck Program 2020	• Requires new ZE trucks sold to reach target market shares by 2035; targets by class of truck
Executive Order N-79-20	• All medium and heavy duty trucks sold to be ZE by 2045, drayage by 2035

Source: Adapted from Taylor, 2018 (Taylor, 2018)

7.1.1.1 Cap and Trade

In the Global Warming Solution Act of 2006 - more commonly known as Assembly Bill (AB) 32 - California introduced a law to fight global warming from all sources in the state. AB32 introduced a cap-and-trade program to reduce in-state GHG at least 20%. The cap, which was initially set about 2% below the 2012 GHG emission level, is designed to gradually decline by 3% a year from 2015 until 2020. (*Overview of ARB Emissions Trading Program*, 2015) Further refinements are being discussed to carry this forward. Through a combination of increasing emission caps (year-over-year) and trading mechanisms, large electric power plants, large industrial plants, and fuel distributors are incentivized to reduce GHGs below allowable levels through investments in clean technologies. The first auction of allowance was made in 2012 and over the years, the program expanded to cover about 450 entities in California. (*Overview of ARB Emissions Trading Program*, 2015). By its design, cap-and-trade (CAT) is aimed more at tackling stationary fixed source emitters, such as electricity producers and distributors as well as large industrial emitters within California.

The heavy duty truck sector is indirectly affected by CAT, as the costs of purchasing emissions credits gets passed down the production chain. Perhaps the most significant impact is the CAT revenue, which is used in part to fund incentives for truck deployments like the project for

Anheuser-Busch (21 BYD class 8 electric trucks). ("Anheuser-Busch to Deploy 21 BYD Electric Trucks as Part of State-Wide Commitment to Sustainable Logistics - BYD USA," 2019)

7.1.1.2 Low Carbon Fuel Standards

Another carbon trading scheme that will lower GHG and impact heavy-duty trucks is the low carbon fuel standards (LCFS) program. Per CARB, this program under AB 32 is:

> "designed to encourage the use of cleaner low-carbon transportation fuels in California, encourage the production of those fuels, and therefore, reduce GHG emissions and decrease petroleum dependence in the transportation sector." ("Low Carbon Fuel Standard | California Air Resources Board," n.d.)

The LCFS standards are based on life cycle GHG emissions and are measured in terms of the "carbon intensity" (CI) of gasoline and diesel fuel and their respective substitutes. ("Low Carbon Fuel Standard | California Air Resources Board," n.d.). The LCFS is another form of trading system. Clean fuel operations (e.g., operators of EVs, EV charging station owners) generate credits, and gasoline and diesel fuel consumption must be offset with credits. ("SRECTrade | LCFS Markets | California | CA," n.d.) Credits were trading at approximately $219/ton before the COVID-19 pandemic. SRECTrade estimates that net income of approximately $13,700/year can be earned from charging a class 4 or higher ZE HD truck on the normal California grid, while approximately $16,000/year can be earned per truck from zero-carbon electricity sources. The credits are linear; each subsequent truck will return a similar return based on the kWh charged. In this manner, fleets can recoup the high cost of charging infrastructure over time. (Faruq, 2020)

7.1.1.3 California Sustainable Freight Action Plan

The CSFAP was established to develop a comprehensive statewide program to increase the efficiency sustainability of the freight sector. (California Air Resources Board P, 2016) It has three goals: increase efficiency of the freight system, transition to zero emission vehicles, and increase the competitiveness and economic growth of the freight sector. Efficiency is defined as output relative to carbon emissions. The CSFAP establishes new criteria for public investments, proposes three large pilot programs, and sets out a process for developing economic competitiveness targets. The pilots include an Advanced Technology for Truck Corridors pilot in Southern California. The CSFAP has no specific funding, hence most CSFAP activities have been through coordination with other programs. A notable example is the $20 million CARB program to pilot zero and near zero HDTs in 2018. (*Envisioning a path to zero emission trucks in California*, 2019)

7.1.1.4 Vehicle related programs

California has a large number of programs intended to promote the development and use of zero and near zero emissions trucks.

Purchase subsidies:

CARB in partnership with CALSTART provides point-of-sale vouchers for ZE trucks and buses. The Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) offsets the higher costs of the technology. California's HVIP incentives vary by technology and vehicle type/weight and is higher for those vehicles operating within a disadvantaged community. The process has been streamlined recently to make it easier for firms and owner operators to obtain vouchers. By all accounts this program is successful, because demand has exceeded supply; last year voucher requests were waitlisted after the $142M budget was exhausted. ("Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) and Low NOx Engine Incentives in 2009 to accelerate the purchase of cleaner, more efficient trucks and buses in California. | California HVIP," n.d.) Other incentive programs for medium and heavy-duty alternative fuel vehicles and infrastructure programs in California can be found at https://fundingfindertool.org/.

Demonstration projects:

The State of California is currently funding numerous demonstration projects with earmarked monies. Fleets are provided with alternative fuel trucks at little to no cost to try out the technology in their operations. Data gathering on use, limitations, and the best markets for the technology will help to pinpoint future areas for improvement. For a complete discussion on these demonstration projects and incentive funding, see Chapter 3.

7.1.1.5 Advanced Clean Truck Program

The Advanced Clean Truck program follows in the footsteps of the passenger vehicle ZE mandate introduced in 1990. The ZE mandate is an example of technology forcing regulation. By setting standards that cannot be achieved with current technology, the standard is intended to spur technology development to meet the standard. The passenger ZE mandate was revised many times as the standards proved to be difficult to achieve, and eventually became part of the Advanced Clean Cars program in 2012.

Since 2017, in recognition of an increasingly number of manufacturers offering commercially available Class 3–8 electric trucks and vans, as well as the need to accelerate large-scale transition to zero-emission technology and foster a self-sustaining zero-emission truck market, CARB has developed new rules that specifically target the freight fleet. The Advanced Clean Trucks (ACT) program targets medium and heavy-duty vehicles from Class 2B to Class 8 and will be put into effect from the 2024 model year. The ACT was approved by CARB in June 2020 and includes the following mandates:

a) Zero-emission truck sales: Zero-emission truck sales: Manufacturers who certify Class 2b-8 chassis or complete vehicles with combustion engines will be required to sell zero-emission trucks as an increasing percentage of their annual California sales from 2024 to 2035. By 2035, zero-emission truck/chassis sales would need to be 55% of Class 2b–3 truck sales, 75% of Class 4–8 straight truck sales, and 40% of truck tractor sales.

b) Company and fleet reporting: Large employers including retailers, manufacturers, brokers and others would be required to report information about shipments and shuttle services. Fleet owners with 100 or more trucks would be required to report about their existing fleet operations. This information would help identify future strategies to ensure that fleets purchase available zero-emission trucks and place them in service where suitable to meet their needs. ("Advanced Clean Trucks | California Air Resources Board," n.d.)

A second part of the ACT Program is in progress. This part will set targets for purchase of ZE trucks by companies that perform trucking services.

7.1.1.6 Executive Order N-79-20

Most recently Gov. Newsom issued an executive order to further accelerate the shift to ZE vehicles. By 2035 all new passenger cars and trucks sold in California must be zero emission. Medium and heavy duty truck operations are to be 100% zero emission by 2045 where feasible. The 100% mandate for drayage trucks is to be accomplished by 2035 (Newsom, 2020).

7.1.1.7 Vehicle emissions standards

Issued in 2006, California's On-Road Heavy-Duty Diesel Vehicles (In-Use) Regulation requires that older polluting diesel truck engines be retired. Currently in the State, model year 2006 and older are prohibited and, by 2023, all trucks must be 2010 model compliant. (SB-44 Medium- and heavy-duty vehicles: comprehensive strategy, 2019; *Truck and Bus Regulation Compliance Requirement Overview*, 2019) Additional regulations under the California Sustainable Freight Action Plan through 2050 is due by January 2021.

Table 48. Drayage Truck Regulation Requirements by model year

Drayage Compliance Schedule (GVWR 26,001 lbs. or more)	Truck Engine Model Year Emission Requirements
2006 and older	Not allowed
2007-2009	Compliant through 2022
2010 and newer	Fully compliant

(*Truck and Bus Regulation Compliance Requirement Overview*, 2019)

Graduated performance requirements force turnover of older polluting trucks California. This is key because these assets typically have a life span of 12-15 years.

7.1.2 Local Policies

7.1.2.1 Vehicle surcharges at the ports

The Joint Harbor Commission of the Los Angeles and Long Beach ports recently voted on a surcharge for certain non-zero emission diesel powered trucks. Called the Clean Truck Fund, it is under the port's Clean Air Action Plan. Trucks meeting the criteria will be charged $20 per loaded 40-foot equivalent unit. Some believe this fee too small to entice companies to make the switch to zero-emission models. Per year, the fees are expected to fund the purchase of 600 cleaner trucks. ("Clean Truck Fund Rate Joint Harbor Commission Meeting March 9," n.d.)

7.1.2.2 PierPass

The Los Angeles/Long Beach port PierPass program was implemented as result of pressure from government regulators to address air quality and congestion at the port complex. Launched in 2005, PierPass charged a per container fee for any import pickup conducted during the day (7 AM to 6 PM). Its purpose was to switch drayage trucks to off-peak shifts. PierPass was very successful in shifting traffic from days to nights; per the Journal of Commerce, approximately a 50-50 split between peak and off-peak truck traffic resulted from the program. (Giuliano & O'Brien, 2008; Mongulluzzo, 2019) However, in November 2018, PierPass was converted to a flat fee, eliminating the incentive to use night deliveries. The revised fee system was implemented with a ports-wide gate appointments system. Results of the new fee structure are unknown.

7.1.2.3 Clean Air Action Plans

The Los Angeles and Long Beach ports made history in 2006 by adopting a joint Clean Air Action Plan. The CAAP was intended to reduce air pollution problems at and near the port complex. The single largest and most ambitious part of the CAAP was the Clean Trucks Program. It required all drayage trucks operating at the port to have 2014+ model year engines by October 2018 (Giuliano and Linder, 2013). The most recent revision of the program requires the ports to operate with all zero-emission equipment by 2035, which includes drayage trucks. Emission changes to date from these efforts have been significant and resulted in reductions of 97% in PM10, PM2.5, and diesel PM even with increases in port traffic (2005 to 2016). (Starcrest Consulting Group, 2017)

7.1.3 Some potential policies

7.1.3.1 Low emissions zones for trucks

To address air quality in major urban centers, some cities are implementing "eco-zoning" – low or zero emission zones (LEZs) for cars and trucks. Only vehicles meeting the standard may enter the designated zone. Many cities in Europe have some form of LEZ, including London, Stuttgart, Milan, Brussels, Antwerp, and Stockholm. There are no US examples, but both New York City and Los Angeles are considering LEZs. The concept of LEZ could be applied to high impact areas, for example the warehouse and distribution clusters along the I-710 corridor. Geofencing could be used to operate hybrid vehicles on battery while traveling in or through high impact areas. LEZs could also be established by time day; only low emissions vehicles may enter the zone during daytime hours. In the case of London, the LEZ is combined with the cordon toll, and low emission vehicles receive a discounted toll (Provonsha & Sifuentes, 2018).

7.1.3.2 Truck bans

Complete bans on truck traffic is becoming more popular to address both congestion and pollution concerns. For example, Prague will not allow vehicles over 3.5 tons during normal business hours without a special permit from the city. Seoul also limits trucks over 3.5 tons during peak hours. In Paris, trucks with certain dimensions are excluded during certain hours on the city streets. (*Delivering the Goods: 21st Century Challenges to Urban Goods Transport*, 2003). Banning of heavy trucks however has a cost, as more total truck trips result from using smaller vehicles. In addition, staging areas outside of the zone must be set up to transfer cargo from larger to smaller vehicles.

7.1.3.3 Emissions tax/carbon tax

The most straightforward policy for reducing emissions is to directly tax them. The concept of Pigouvian tax is that firms are charged for the social costs generated by their actions. The tax increases the cost of doing business, and hence provides an incentive to reduce the social cost, in this case generated from use of carbon-based fuels. Firms who invest in innovation (and reduce emissions) can avoid taxes. Highly polluting industries will pass along these additional costs to consumers reflecting both marginal private and marginal external costs. The rules of supply and demand indicate that fewer units will be sold at a price that reflects the marginal social cost of production, thereby adjusting the market to the negative externality. (Hackett, 2011).

In theory a carbon tax and cap and trade should be equally efficient and lead to the same outcomes. However, California is discovering that the market price of carbon is much below what would be needed to achieve the 2030 target. Many regulatory programs are aimed at forcing carbon reductions beyond those occurring in response to cap and trade. A tax on emissions, e.g., NOX or PM 2.5, could help to reduce these air toxics in the near term.

7.1.3.4 ZE truck priority for time savings

In the trucking industry, time is money. Time lost in congestion or waiting for pickups or deliveries adds to trucking costs. As we showed in our stated preference survey, fleet managers are willing to consider time savings to offset higher vehicle costs. Priority gates at ports and airports, preferential gate appointments at terminals, and priority truck lanes are examples of how time savings could be offered for zero and near zero trucks.

7.2 Policy recommendations

Our last task in this research is to provide policy recommendations for increasing the market share of heavy duty ZEHDTs and near ZEHDTs within the short haul market. Our recommendations are tied to the findings presented in Chapter 6.

Finding 1: At the current state of BEV technology, BEHDTs have limited application in the short haul heavy truck market

Recommendation: State and local policy should take into account the full impacts of BEHDTs on freight operations and costs

Our research suggests that the current state of BEV technology creates many challenges for using them even in the short haul market. BEHTDs cannot be substituted one for one into freight operations due to their performance characteristics. The lack of charging infrastructure adds to the challenges. We are unaware of prior research that has taken full impacts into account. More research should be conducted to more fully understand the impacts of BEHDTs, and these impacts should be considered in future regulations and ZE targets.

Finding 2: Natural gas hybrid near zero vehicles are preferred in the short term

Recommendation: State and local policy should be more flexible and consider hybrid technologies as viable near and middle term options for GHG and other emissions reductions

State and local policy is focused heavily on moving to ZE. At this time, the only type of ZE on the market is the BEHDT, which suffers from high cost, limited range, lack of fueling facilities, and lengthy charge times relative to diesel. This limits feasible market penetration, and hence takes few diesel trucks off the road. Our midpoint ZE scenario clearly shows that a mixed fleet with large numbers of BEHDTs but also large numbers of diesels is the least cost effective option. In contrast, hybrid trucks are near zero and could be regulated to use battery power in sensitive areas. Hydrogen fuel cell trucks are in early testing. They do not have the range or charge time problems of BEHDTs and thus may become a viable option post 2025-2030. By focusing almost exclusively on BEHDTs, near term reductions in emissions are likely to be small. In addition, the focus on BEHDTs may crowd out research on fuel cells or other potentially more effective technologies.

Finding 3: The medium term market is promising and depends critically on the rate of improvement of battery technology and rate of decline in vehicle price

Recommendation: Continue to promote and invest in battery technology improvements

The DOE has a massive battery research program that state and local policy makers should continue to support. California is supporting R&D through its many demonstration programs. The process could be improved by testing and reporting performance in the field so that prospective purchasers have a better idea of the actual performance to be expected from the vehicles.

Finding 4: The medium term market depends on charging infrastructure and energy availability

Recommendation: Develop a comprehensive investment plan for public charging stations and identify a funding source

Charging stations add to the cost of using BEHDTs. Our research suggests that trucking firms are unlikely to have the means or willingness to invest in their own charging stations. In order to justify the costs of a charging station, only firms that could use a large enough number of BEHDTs would invest in them. In addition, a system of home base charging stations would limit BEHDTs to round trips within the charge range of the vehicle. Public charging stations located along major truck routes would allow for longer tours and address range anxiety. A public charging station would allow a quick charge if the energy reserve is running low. Public charging stations would be open to all firms and owner operators, better leveraging the investment and incentivizing use of BEHDTs across firms.

Finding 5: The medium term market depends on subsidies

Recommendation: Develop a comprehensive subsidy and incentive program to promote ZE and near-ZE purchase and use, and fund at a sufficiently high level

Although there are subsidies available for purchase of ZEHDTs, they are limited and reportedly difficult to get. Given the upfront cost of a ZE, subsidies are necessary to offset these costs. Although operating costs of ZEHDTs are lower than diesel, these savings will be offset by losses of productivity due to the inferior performance of ZEHDTs. Thus, as a rough rule of thumb, the subsidy should at least offset the difference in purchase price between ZE and diesel, net of any taxes.

There are a number of subsidies and incentives on offer for purchase and use of ZEHDTs, but there is no comprehensive program. As far as we know, there is no one stop website where a fleet operator could go to find out what subsidies are available and how to apply and receive them. A one-stop website could also include an app that would evaluate the type of freight operation and provide information similar to our case studies. This would give the fleet operator guidance in the extent to which his/her operation is amenable to using ZEHDTs.

Incentives related to the California cap and trade and LCFS programs should be more effectively marketed as part of the package for ZE or hybrid purchase. There are also incentives in the form of time savings, such as proposals for ZEHDTs or hybrids to “jump the queue” at terminal gates. Other incentives could include waiver of the PierPass fee at the ports, discounted electricity prices, or tax credits.

There are many policy instruments that can be used to encourage use. Low emission zones with costly entrance fees and low or no costs for electric vehicles will encourage businesses to adopt the technology for operational efficiency. The ability to trade carbon credits from charging trucks using firm owned equipment will be attractive to firms wishing to lower operations costs. However, with all these programs, making them straightforward and simple to understand and use will be key. Our conclusion is that a suite of incentives that can be customized to the particular needs of highly diverse firms would be most effective.

Finding 6: Institutional and organizational issues are a consideration

Recommendation: Regulatory policies should be flexible enough to accommodate the diversity of the short haul sector

Regulatory policies tend to be rigid; a target is established that all firms must reach, such as CAFÉ standards for new vehicles. The Advanced Clean Truck Program is similarly rigid. OEMs will be required to sell a given number of ZEHDTs as a percentage of their total sales. A later phase of rulemaking will require fleet owner to purchase a given percentage of vehicles. The diversity of short haul operations makes it easier for some firms and harder for others to meet such requirements. It is possible that a credit exchange will be established, allowing firms to trade with each other. This adds another layer of cost to the firms involved.

Flexibility is needed in policy making over the next 10 years. Like light-duty cars and trucks, as "ZEHDTs reach cost parity and become mainstream, incentives and consumer awareness programs can evolve with a changing market, while infrastructure costs continue through the transition." (Slowik, Hall, Lutsey, Nicholas, & Wappelhorst, 2019) The transition to fund battery electric trucks will shift from governments to the private sector through the 2020-2030 period as policies and adoption evolve. As these government incentives diminish, pollution-indexed taxation would most likely replace them as a mean to discourage use of high polluting diesel engines.

The earlier 1990 ZE mandate for passenger cars may serve as a model. Over the years the mandate was extended and reworked, including more types of alternative fuel vehicles and moving away from specific targets. It became part of the Advanced Clean Car program in 2012. The ACC is an integrated program of incentives and rules aimed at achieving the state's air pollution and GHG reduction goals. Notably the program includes low emission vehicles.

Finding 7: More data is required to better understand freight operations and identify potential markets

Recommendation: State and local policy makers should support a freight research program to analyze short haul submarkets and recommend strategies for best serving specific submarkets

Our research was limited by lack of data. The data anticipated from the second generation demonstrations was not available due to delays in program implementation. As the data from the demonstrations comes in, it should be made broadly available to the research community. A policy to make data accessible to researchers could be incorporated into demonstration agreements.

There is no publicly available source for detailed information on freight operations and costs. The trucking industry is reticent to share data with regulators. Consequently, policy decisions are being made without sufficient information. A freight research program conducted at arms length from both the industry and the regulators could provide valuable information to inform future policy decisions.

7.2.1 Conclusions on policies

ZE heavy duty trucks are not yet suitable substitutes for conventional diesel. Although BEHDTs have the most potential for reducing air toxics, they add substantial costs to short haul goods movement. In the short run, using BEHDTs would require significant increases in the heavy duty truck fleet, putting more trucks on the road and increasing congestion. Our analysis did not consider these indirect effects. Using BEHDTs affects fleet operations and reduces productivity. Nor is the charging infrastructure in place to support widespread use of BEHDTs.

Our policy recommendations are aimed at managing the next 10 years as effectively as possible. This means being flexible in terms of preferred technology, considering the diversity of the short haul segment, investing in alternative fuels infrastructure, and structuring a large subsidy and incentive program.

7.3 Report conclusions

This report reviewed the literature on alternative fuel heavy duty trucks and described the California demonstration programs. We conducted simulations and case studies to examine the impacts of using BEHDTs on freight operations. Our simulations and case studies revealed challenges to using BEHDTs that prior studies have not considered, namely the need for more vehicles to perform the same amount work due to range limits, charging time requirements, and weight limits. Our assessment of costs and benefits revealed hybrids as the most cost effective alternative through 2030. We conducted two rounds of stakeholder interviews and one stated preference survey to elicit information on industry perspectives. We found that there are important concerns regarding BEHDTs, including price, range, charging time, availability of charging stations, and impacts on operations. We examined the potential market for BEHDTs in the Southern California region. While there are large clusters of freight activity and a substantial share of trips that are short enough to be operated by ZE, our case studies revealed the complexities of using BEHDTs in specific firms.

Over time the market for BEHDTs will grow as BEHDTs achieve a 300-mile range and short charge times—meaning as BEHDTs achieve the same performance attributes of diesel or hybrid. However, the weight constraint will have to be resolved, and BEHDTs will have to be shown capable of running almost continuously across multiple shifts. There is promise for significant ZE market share by 2030. Achieving that share will require public investment in charging infrastructure and a broad set of incentives to promote ZE use.

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Data Management

Products of Research

The following is a description of the data that were collected and used.

1. Drayage origin-destination survey data, 2010-2012, provided by Port of Los Angeles and Port of Long Beach
2. Operational data for selected months from two drayage firms
3. Vehicle costs, emissions data from San Pedro Bay Ports, CARB, UC Davis
4. Round 1 interview data, 2018, two vehicle manufacturers, three fleet operators
5. Round 2 interview data, 2019, nine fleet managers
6. Stated preference survey, 2019, 14 fleet managers

Data Format and Content

The following is a description of the format, of the data, and the contents of each file.

1. Drayage origin-destination survey data, 2010-2012:
   a. **Data format**: Excel file (XLSX)
   b. **File contents**: detailed information about how many containers are transferred between two ports and the destination areas. Information includes addresses, number of containers, locations and type of containers, etc.
2. Operational data from two drayage firms:
   a. **Data format**: the original operational data from two drayage firms were stored as spreadsheets in either CSV or XLSX format. Data were then cleaned in Microsoft Excel and then stored as XLSX in uniformed structure.
   b. **File contents**: the original operational data collected from each firm is very similar. Data included: *Truck ID, Drive ID, Date/Time, Geographic Coordinates for Each Stop, Load Weight, and Trip Distance* (the distance between two stops). Two months of data was provided by Firm 1 (October and March), and one month of data for Firm 2 (March). After cleaning the data, trips and tours by specific trucks were constructed based on movement throughout the day. A trip refers to an origin-destination pair without any stops, with the same load weight. A tour is the combination of multiple trips starting or ending at a firm location, in one or more days.
3. Vehicle costs, emissions data from San Pedro Bay Ports, CARB, UC Davis: tables provided in the final report.
4. Round 1 interview data:
   a. **Data format**: Word file transcribed from verbal interviews and written notes.
   b. **File contents**: the data comprise responses to interviews of two ZEV manufacturers and three trucking firms using ZEV demonstration trucks in 2018.

Data includes the demonstration truck type, quantity, operational use, and perceptions of performance for operations.

5. Round 2 interview data:
    a. **Data format**: Excel file XLSX transcribed from verbal interviews and written notes.
    b. **File contents**: the data comprise responses to 17 multiple-choice and open-ended questions about firm operations and opinions on alternative fuel vehicles. The survey instrument is included in Appendix B, Round Two Interview Questionnaire of the report.
6. Stated preference survey, 2019, 14 fleet managers:
    a. **Data format**: the responses to the Stated Preference Survey are stored online in the California State University, Long Beach's password-protected Qualtrics account. With the appropriate permissions and confidentiality agreements in place, the data may be retrieved and converted to a variety of file formats, including text, comma-separated values, and Microsoft Excel. The survey instrument can be viewed here: https://csulb.qualtrics.com/jfe/form/SV_4Vmyp5vC3kN0vNH
    b. **File contents**: the data comprise responses to several free-response and multiple-choice questions about the nature of the respondents' operations, their knowledge of and attitudes toward battery-electric trucks, and responses to several scenarios in which fleet managers are asked to choose between conventional diesel trucks and battery-electric trucks, based on vehicle pricing and operating characteristics.

Data Access and Sharing

The following is a description of how the general public can access the data.

1. Drayage origin-destination survey: available from the ports by request.
2. Operational data from two drayage firms: proprietary data; cannot be made available to general public.
3. Vehicle costs, emissions data: available from the sources cited in the report.
4. Round 1 interview data: proprietary data; cannot be made available to general public.
5. Round 2 interview data: proprietary data; cannot be made available to general public.
6. Stated preference survey: the survey instrument was deployed with Institutional Review Board approval, and in strict compliance with confidentiality requirements. Accordingly, the data will not be made available to the general public. They may, however, be obtained for academic purposes with appropriate permissions and confidentiality agreements in place.

Reuse and Redistribution

Unrestricted data can be reused and redistributed with proper citation given to the researchers.

Appendix A. Solution Algorithms

a. The Minimum Cost Circulation Problem

First, we list the notation we use for this sub-problem.

V: the set of vertices, each v_i stands for a location and v_0 is the port
V': a copy of V where v_i' stands for a location and v_0' stands for the port
E: the set of edges, each edge is denoted by uv or (u, v) with $u, v \in V \cup V'$
d_{uv}: the demand from u to v
c_{uv}: the cost for edge uv
f_{uv}: the flow (demand) for edge uv

Figure 19 illustrates the network that is constructed. Originally, we have the set of vertices V representing the port and the locations. An edge exists between v_0 and v_i if v_i has container demands from the port. Then we make a copy of V, which is V'. An edge exists between v_i' and v_0' if v_i' delivers containers to the port. After that, we link all the edges between $\{v_i\}_{i=1}^{n}$ and $\{v_i'\}_{i=1}^{n}$ such that they form a complete bipartite graph. Finally, we link edge $v_0'v_0$ to make the network a circulation network.

The capacity of the edges between $\{v_i\}_{i=1}^{n}$ and $\{v_i'\}_{i=1}^{n}$ as well as $l_{v_0'v_0}$ are set to infinity. And the edges between the port and the locations, $l_{v_0\ v_i}$ and $l_{v_i'v_0'}$, are set to $max(d_{v_0v_i}, d_{v_iv_0})$ for all $i = 1, \ldots, n$. Each $max(d_{v_0v_i}, d_{v_iv_0})$ represents the maximal one-direction demand between the port and the location v_i. The cost for any edge $uv \in E$ is actually the distance (in miles) between location u and location v. Notice that $c_{v_i\ v_i'}$ is 0 for all $i = 1, \ldots, n$ because v_i' and v_i represent the same location.

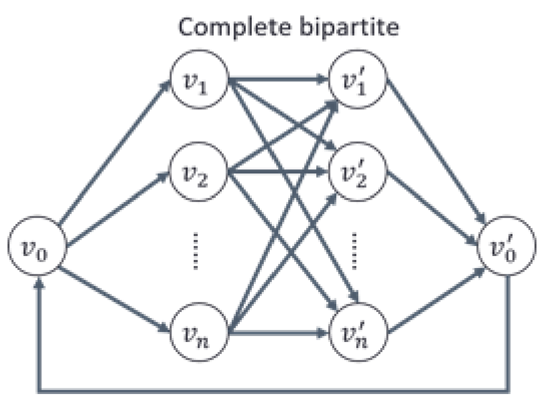

Figure 19. The Constructed Network

Based on the network above, we develop the following mathematical model. Notice that f_{uv} are the decision variables.

$$\min \sum_{uv \in E} c_{uv} f_{uv}$$

$$s.t. \quad \sum_{v \in V \cup V'} f_{uv} = \sum_{v \in V \cup V'} f_{vu}\,, \forall u \in V \cup V'$$

$$f_{v_0 v_i} \geq d_{v_0 v_i} \ \forall i = 1, \dots, n$$

$$\sum_{j=1}^{n} f_{v_j v_i'} \geq d_{{v_i'}_i v_0} \ \forall i = 1, \dots, n$$

$$f_{uv} \geq 0, \forall uv \in E$$

The first set of constraints are the flow conservation constraints and the second set of constraints ensures that demand is met. We use the Gurobi software to solve our linear program model.

b. The Bin-packing Problem

Recall that the output for the minimum cost circulation problem is a set of optimized vehicle trips. We want to assign the trips to trucks such that the number of trucks is minimized. This is exactly the same as the bin-packing problem where items (trips) are packed (assigned) into bins (trucks) and the objective is to use as few bins (trucks) as possible. Figure 20 illustrates how minimizing the fleet size is actually a bin-packing problem. The slight deviation from the standard bin-packing problem is that the refueling process needs to be also inserted during the day. Although we assume all trucks are full of fuel (diesel trucks) or fully charged (BEHDT) at the beginning of the day, refueling occurs during the day if the usage from the assigned trips is greater than the truck's fuel range.

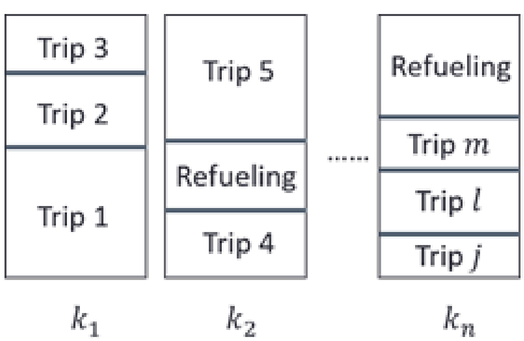

Figure 20. The Bin-packing Illustration

Suppose there are in total n trucks and j trips. The notation we use for this problem is listed below.

r_i: the range for truck i in terms of travel time
t_j: the operation time required for trip j
T: the working hours limit for each truck
h_i: the refueling time for truck i

k_i: $k_i = 1$ if truck i is used, and 0 otherwise

x_{ij}: the indicator of whether truck i is assigned to trip j

We can formulate this problem into a mixed integer linear programming problem (MILP) as shown below. Notice that k_i and x_{ij} are the decision variables. In presenting the formulation, we treat the refueling (h_i) as a constant for ease of understanding of the model. However, in actuality, the refueling time depends on the day's usage and especially for BEHDT cannot be treated as a constant time. Thus, our solution procedure takes these factors in account in determining the refueling time and we discuss this computation after presenting the formulation.

$$\min \sum_{i=1}^{n} k_i$$

$$s.t.\ h_i + \sum_{j=1}^{m} t_j x_{ij} \leq T k_i, \forall i = 1,2,\dots,n$$

$$t_j x_{ij} \leq r_i, \forall i = 1,2,\dots,n\ \ \forall j = 1,2,\dots,m$$

$$\sum_{i=1}^{n} x_{ij} = 1, \forall j = 1,2,\dots,m$$

$$k_i = 0\ or\ 1, \forall i = 1,2,\dots,n$$

$$x_{ij} = 0\ or\ 1, \forall i = 1,2,\dots,n\ \forall j = 1,2,\dots,m$$

The objective of the formulation is to minimize the total number of trucks needed to serve the demand. The first set of constraints ensures that the operating time for each truck does not exceed the working time limit. The second set of constraints ensures that every trip assigned to the truck does not exceed its corresponding range. The third set of constraints ensures that every trip is served by one truck.

To solve this problem, we adapt a base algorithm developed by Pisinger and Toth (1998). The idea of this base algorithm is to pick trips such that the summation of their travel times is maximized and fits the time constraint of a truck. We augment this algorithm by considering refueling between trips. After the assignment of a trip to a truck and if the remaining fuel level is less than the range of this assigned trip, then the refueling time is added to this truck. The computation of the refueling time is described in the next section. Since the battery depletion rate depends on whether the truck is loaded or not, the amount of time required to recharge the battery also depends on the nature of the trips.

Appendix B. Round 2 Interview Questionnaire

1. Are you a?

- *a. Owner-Operator. If yes: How many trucks do you own?*
- *b. Fleet Manager. If yes: How many trucks do you operate?*
- *c. Trucking Company Owner/Principle. If yes: How many trucks do you operate?*
- *d. Other ___________ If yes: How many trucks do you operate?*

2. What do you mostly use your truck for?

- *a. Drayage (port only)*
- *b. Short-Haul*
- *c. Long-Haul*

3. Where is operation located (city/cities)? Do you have more than one "home-base?"

4. What type of goods do you transport? (choose all that apply)

- *a. Perishables*
- *b. Non-perishables*
- *c. Clothing*
- *d. Food*
- *e. Bulk*
- *f. Parcel*
- *g. Non-alcoholic beverages*
- *h. Alcoholic beverages*
- *i. Grocery*
- *j. Furniture*
- *k. Electronics*
- *l. Office Supplies*
- *m. Chemicals*
- *n. Other (specify) _________*

5. Which of those goods do you transport most often? (specify a-n above)

6. On a typical day, how many shifts do you operate each truck? (1,2,3)

7. Do you operate on weekends? (Y/N)

8. On average, how many customers do you serve on a tour? What type of drivers do you use? (employees, independent operators, mix) Number of drivers?

9. During your most common type of shift, how many miles is the truck driven?

- *a. 0-40*
- *b. 40-80*
- *c. 80-120*
- *d. 120 or more*

10. How many turns per shift are typically completed?

11. Who plans the routes and sequences of stops for each shift?

a. Driver
b. Dispatcher
c. Other ______________

12. Other open-ended questions to understand more about their operation:

a. Are trucks assigned to a specific driver? (Y/N) Slip-seated to keep them on the road? (Y/N)
b. When is vehicle maintenance performed? Where? Do you employ people for maintenance?
c. When do you refuel? Where?
d. Is there anything like a "regular" route that some trucks take on a routine basis? For example, are trips like clockwork or is everyday a blank page?
e. What type of concerns do your customers have about their shipments?
f. How much of the trip time is spent waiting (at the port, at a customer, in traffic)?
g. Did you use PierPass off-peak prior to Nov 2018? Why/why not? Has the change in cost impacted your decision to keep this schedule? Why/why not?

BEV and truck purchases

13. How much do you know about each of the following? (scale 0 to 3: nothing/a bit/more than most/a great deal)

a. Battery electric trucks
b. Hydrogen fuel cell trucks
c. Compressed Natural Gas (CNG) trucks
d. Liquefied Natural Gas (LNG) trucks
e. Hybrid trucks

14. When did you last purchase a truck?

a. Was it new or used?

15. What is the average age of your trucks?

16. What concerns, if any, do you have about these new vehicle technologies? (please choose all that apply)

a. Truck cost
b. Fuel cost
c. Maintenance cost
d. Charging equipment cost (for electric vehicles)
e. Fueling or charging location
f. Fueling or charging time
g. Range
h. Performance

i. *Other (please specify) __________________*

17. *Other open-ended questions to understand more about BEV knowledge/perceptions:*
    a. *Have you ever purchased a vehicle using incentives? If yes, did you have problems?*
    b. *Do you know about the current CA incentives for alternative fuel trucks?*
    c. *Do you know other firms who have been involved in demonstrations of new tech? What have you heard?*
    d. *Have you been approached by manufacturers of alternative fuel vehicles? Which ones? Were you interested in what they had to say? Why/why not? What was their pitch?*
    e. *Would you consider purchasing an alternative fuel vehicle now, in 5 years, in 10 years? Why did you answer the way you did?*
    f. *Who do you rely on for information on which truck to purchase?*
    g. *If you could use BEVs for a certain amount of your routes, would you? What % is that threshold? (e.g., would you need the flexibility to use for any/all routes – 100%?)*
    h. *If a BEV fully loaded could only go 80 miles today between charges (without any range anxiety) even if this vehicle could be very inexpensive to get into, would you consider buying?*
    i. *If a BEV fully loaded could only go 120 miles today……*
        i. *What is the range you would need a BEV to go?*
        ii. *Fueling: if cost is not an issue, would you install charging at your site? Would you spend time in the middle of day for a quick charge? (full charge 4-6 hrs., fast charge with only 80% in 30 minutes, but decreases battery life) Do you have reservations do you have with electricity prices?*
    j. *Do you consider "greener" operations as a competitive edge/marketing tool? Does your company have sustainability goals as part of their strategic plan? What are you doing to reduce your carbon footprint in transportation?*