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Electric truck feasibility for port drayage operations: Port houston case study

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ABSTRACT

Heavy-duty fleet electrification has the potential to reduce lifecycle operation costs, greenhouse gases, and criteria pollutant emissions. However, there are several obstacles to shifting from diesel fleets to full-electric fleets, such as range constraints and a lack of public charging infrastructure. This study developed an analytical feasibility framework for assessing the transition of an all-diesel heavy-duty fleet to a full-electric or a mixed electric and diesel fleet for drayage trucks operating at and around ports. The proposed framework devised a structured approach and multiple measures for determining the viability of heavy-duty fleet electrification, taking technological, operational, and economic aspects into account. The case study showed that, while battery electric trucks cannot replace entire diesel fleets yet, they are technologically and economically feasible for a portion of drayage operations. This practice will facilitate fleet electrification, particularly heavy-duty, by tackling major roadblocks and providing insight into the numerous unknown possibilities.

1. Introduction

In the US, the transportation sector is one of the largest energy consumers and a major contributor to greenhouse gas (GHG) emissions, including CO_2 and other emissions produced by the combustion of fossil fuels (US Energy Information Administration, 2024). In 2022, the sector produced 1,810 million tons of CO_{2e}, which accounted for 28 % of US GHG emissions and was an 18.7 % increase from 1990 (US Environmental Protection Agency, 2020, 2022). Medium- and heavy-duty trucks account for 23 % of GHG emissions from the transportation sector while being only 10 % of the vehicles on the road (US Environmental Protection Agency, 2022). Additionally, the high levels of particulates and nitrogen oxides from medium- and heavy-duty trucks can cause chronic disease and premature death, especially in urban areas and among environmentally impacted or disadvantaged communities (Badshah, Posada, & Muncrief, 2019). Decarbonizing medium- and heavy-duty fleets and replacing them with alternative fuel trucks, such as battery electric and hydrogen fuel cell trucks, will contribute to climate change mitigation as well as air quality and public health

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improvements. In 2023, a study estimated that the electrification of diesel heavy-duty drayage trucks operating at the Ports of Los Angeles and Long Beach in California would result in an 80 % reduction in premature death and an 87 % reduction in asthma attacks. The disadvantaged communities would receive over two-thirds of the benefits (Ramirez-Ibarra & Saphores, 2023).

Given that power generation in most nations is a mix of sources, the environmental benefits of an electric fleet are contingent on the amount of GHG emitted during electricity generation (Falcão, Teixeira, & Sodré, 2017; Mahmoud, Garnett, Ferguson, & Kanaroglou, 2016). Electrifying fleets may be the most effective way to reduce NO_x emissions, a significant precursor to air pollution (Chen et al., 2018). However, there is huge uncertainty related to the $PM_{2.5}$ concentrations of fleet electrification depending on the local specifications and electricity generation details (Soret, Guevara, & Baldasano, 2014). Light-duty electric vehicles combined with a higher percentage of renewable energy generation may result in increased energy efficiency and improved air quality, and a lower percentage of renewable sources in electricity generation may lead to environmental justice problems after transitioning to electric fleets (Huo, Zhang, Liu, & He, 2013; Ji et al., 2015). However, it is still a small proportion of the national production of particulate matter. To address the gap in climate change goals entirely through electric vehicles, the focus of fleet electrification should be shifted to more significant contributors of emissions, including commercial and heavy-duty fleets (Liu, Zhao, Liu, & Hao, 2018; Soret et al., 2014). Also, regardless of the power generation mix, electric trucks have zero emissions at the tailpipe and, therefore, can readily alleviate air pollution at the local community level.

In the long term, fleet electrification can be a key step toward regulatory conformity and environmental benefits, and environmental gains can be measured for creating incentives and loan programs. In the short term, heavy-duty fleet electrification can reduce major fleet expenses such as maintenance and fuel costs, especially for fleets with fixed routes and charging locations (Mihelic & Roeth, 2018). Electrifying long-haul trucking may remain a challenge for many years because of battery capacity (and mass) and the lack of public charging infrastructure. A 2021 study on the economic feasibility analysis of electrifying trucks indicated that long-haul heavy-duty truck electrification may be challenging and not reach economic parity with diesel trucks (Vijayagopal & Rousseau, 2021). However, regional short-haul and drayage operations are promising candidates for heavy-duty fleet electrification because of their low daily mileage, daily depot visits, and idling at the depot for charging opportunities (Lund & Roeth, 2020). Fleet operators at ports are logical early adopters of electrification, and multiple major ports in California have already prepared feasibility assessments of drayage truck electrification, and they have shown great potential for implementation (Di Filippo, Callahan, & Golestani, 2019; Port of Oakland, 2019; Tanvir, Un-Noor, Boriboonsomsin, & Gao, 2021; Tetra Tech & Gladstein, 2020).

While some of the electrification solutions from the light-duty sector can be adopted for heavy-duty fleet electrification, there are still many key differences in their specifications, including a lack of public fast-charging infrastructure, operational range limitations, and high capital costs. A recent interview with 28 fleet decision-makers identified the top six barriers as charging infrastructure, purchase cost, range, availability, weight, and charging time, highlighting the absence of a decision-making platform for heavy-duty fleet owners and regional planners that takes into account all technology, operational, and economic aspects of electrification (Sugihara, Hardman, & Kurani, 2023). The main objective of this research is to develop a structured approach and measures in the form of an analytical framework that assists fleet operators and other stakeholders when examining the practicality of heavy-duty fleet electrification at ports from technical, operational, and economic perspectives. The framework uses Port Houston drayage truck sample data as an early adopter of fleet electrification for a case study. The proposed feasibility assessment framework will integrate electric vehicles into the existing fleet operation, estimate detailed costs of electrifying the fleet, and examine potential solutions to key barriers to heavy-duty truck electrification. The study also outlines potential emissions benefits to address sustainable, inclusive, and innovative infrastructure and be in compliance with sustainable development goals (United Nations, 2021). The algorithms and detailed measures are intended to be easily transferable to other drayage fleets and understandable for regional planners and fleet owners considering electrifying heavy-duty fleets.

2. Background

A few studies have investigated the potential for heavy-duty drayage fleet electrification at ports and electrifying urban goods distribution trucks, and offered a series of transition plans for electric trucks that might begin in the near future and continue to grow. Battery electric heavy-duty trucks can offer better performance than diesel trucks but have range limitations. The Port of Oakland (2019) feasibility assessment found that electric trucks were not cost-effective or operationally feasible, and their potential market penetration rates were unclear at the time of the study. In addition to operational viability and cost efficiency, significant support, urban policies, routing solutions, and charging accessibility would also be essential for the successful adoption of electric trucks. Another 2019 study assessed the feasibility of drayage electrification at the Ports of Los Angeles and Long Beach, considering technology, operation, and economic aspects (Di Filippo et al., 2019; Tetra Tech & Gladstein, 2020). They underlined the importance of substantial incentives and grants to make commercially available battery electric heavy-duty trucks more economical than diesel trucks. A 2021 study on drayage electrification operational feasibility at the Ports of Los Angeles and Long Beach showed that 85 % of operations could be served by electric trucks considering charging at the depot (Tanvir et al., 2021). A National Renewable Energy Laboratory (NREL) study explored the viability of partial fleet electrification using existing technology and minimal operations adjustments at the Ports of New York and New Jersey, highlighting the range and charging infrastructure limitations for full electrification (Kotz, Kelly, Lustbader, Cary, & Oakleaf, 2022). Feasibility assessments of light-duty fleet electrification demonstrated that although the daily mobility needs of most fleets were within the driving range of the commercially available electric vehicles with no reliance on opportunity charging, the limited annual mileage prevented the economical acquisition of the electric fleet (Danielis, Scorrano, Giansoldati, & Alessandrini, 2020). Therefore, while the target fleet for electrification needs to meet certain daily mileage or charging windows, it also needs to justify a minimum annual mileage for economic purposes. This study is unique as it defined a decision-making method that includes reusable measures to investigate the feasibility of drayage electrification from technology, operational, and economic perspectives.

Ongoing battery advancement and global market growth may reduce electric vehicle costs over time. A 2021 study predicted that by 2025, 40 % of non-Postal Service federal fleet cars and 97 % of USPS vehicles may be replaced with electric vehicles at a cheaper total cost of ownership (TCO) than equivalent gas and diesel vehicles (Di Filippo, Nigro, & Satterfield, 2021). However, the uncertainty associated with future technology and costs is a primary challenge in fleet electrification (Danielis, Giansoldati, & Rotaris, 2018; Danielis et al., 2020). Since electric vehicles are a relatively new technology that is still evolving, significant technical uncertainty exists over battery degradation, which has consequences for both replacement prices and the vehicle's resale value. Additionally, the efficiency of electric vehicles in real-world traffic at various speeds, and their true maintenance and repair costs, are unknown. Technical uncertainty decreases as more experience with electric vehicles is gained. Economic uncertainty is associated with the future price of fuel and energy. Technology and economic uncertainty associated with future advancements and pricing can be examined through a feasibility framework such as the one in this study.

3. Framework formulation

For fleet electrification, the fleet operators need to (1) identify the right truck and charging technologies, (2) create an operational plan that fits their current business needs, and (3) evaluate the capital and operation costs of electrification. Additionally, the environmental assessment allows both regional planners and fleet owners to monetize emission savings for electrification grants.

3.1. Technology availability

This research evaluated the technology and commercial availability of battery electric heavy-duty trucks, batteries, charging stations, and charging methods for implementation and identified potential alternatives for electrifying and charging heavy-duty fleets.

3.1.1. Electric trucks

This research focused on trucks used in port drayage operations. Table 1 lists some of the commercially launched or available for launch battery electric heavy-duty trucks (class 8) in the US, as well as their specifications.

One stated technological problem with battery electric trucks is that the batteries are very heavy, which means the trucks can carry smaller loads before reaching the maximum allowable load (Gao, Lin, & Franzese, 2017; Sripad & Viswanathan, 2017). For short-haul trucks with lower battery capacity, studies indicated that the weight difference could be as low as 1,400 lb (Harvey et al., 2020), and the current 2,000-pound waiver policy for electric vehicles can cover the payload capacity difference (H.J.Res.31 - 116th Congress, 2019-2020). Additionally, weigh-in-motion data from fifteen states, including Texas, indicated that 90 % of on-road heavy-duty trucks in operation weigh less than 73,000 lb, showing that there are likely to be no payload capacity reductions for a battery electric heavy-duty trucks (Davis & Boundy, 2021).

3.1.2. Charging infrastructure

The battery pack must be recharged at charging sites before the batteries run out. Currently, the US has only one public charging station for battery electric heavy-duty vehicles, equipped with eight high-power chargers (Daimler Truck North America, 2021). As a result, fleet owners must rely entirely on their funded private charging infrastructure, which is ideally installed at fleet depots that they frequently visit. Plug-in charging is a time-tested stationary conductive charging approach that offers cheap capital costs per charge port and allows for overnight charging. The plug-in charging station for DC fast-charging can have a power output as high as 350 kW and cost more than 150,000 dollars (Gladstein, 2019). Staff and specific cable management logistics are required for each charging session.

While many personal battery electric vehicle owners may charge their vehicles using a standard wall socket in their garage or a

Table 1
Heavy-duty Truck Specifications.

Make & Model (Year)	Number of Tractor Axles	GCWR (lbs)	Maximum Power (HP.)	Battery Capacity (kWh)	Range (miles)	Suggested Charging Power (kW)
Freightliner eCascadia (2021)	3	82,000	360/500	315/475	250	250
Lion 8T (2021)	3	82,000	536/670	653	260	220
Peterbilt 579 EV (2021)	3	80,000	536	396	150	NA
Volvo VNR Electric 6X2 (2021)	3	82,000	455	264	120	150
BYD 8TT (2022)	3	105,000	483	435	124	NA
Kenworth T680E (2021)	3	82,000	450	396	150	120
Tesla Semi (2025)	3	80,000	1000	500	300—500	NA
Nikola motor Tre BEV (2022)	3	82,000	645	753	350	240

level 2 charger with a capacity of around 7 kW, heavy-duty trucks typically demand far greater power levels. With less time to charge, more power may be required. Fleets experiencing this kind of demand will almost certainly require DC fast-charging. Current battery electric heavy-duty truck manufacturers suggest a charging power between 120 and up to 250 kW for their trucks (see Table 1).

3.2. *Operational practicality*

Operational feasibility assessment determines how well electrification technologies fit into the current business operation and whether battery electric heavy-duty trucks can perform a full or partial proportion of their current trip scheduling without fleet reassignment. This research evaluated the state of charging of an electric fleet running on the current schedule.

3.2.1. *Tour identification*

A tour is a sequence of trips and stops operated by the same truck, starting and ending at depot parking. Fig. 1 illustrates the visual representation of a drayage tour.

Until recently, efforts to design tour-based truck operations have been limited because of the difficulties in gathering high-resolution truck movement data. The advantages of designing a tour-based model for fleets are truck operation consistency and delivery scheduling improvement. Also, tour-based modeling allows for scheduling overnight charging sessions at depots in a mixed electric fleet. Therefore, this research generated tours from sequential trips of each truck and considered a minimum time length at the depot before and after each tour for charging sessions.

3.2.2. *Energy consumption*

Battery electric heavy-duty trucks should be able to conduct entire operations between charging sessions. Therefore, all assigned tours to the truck should consume less energy than the usable battery capacity.

Standard 1. Maximum Energy Consumption.

$$\textit{Tour Energy Consumption} < \textit{Usable Battery Capacity}$$

To improve readability, this paper has identified tours with energy consumption lower than the usable battery capacity as short-haul or electrifiable tours. Trucks that complete only short-haul tours are referred to as short-haul trucks. Conversely, tours that require more energy than the battery capacity are classified as long-haul tours, and trucks that complete only long-haul tours are referred to as long-haul trucks. However, it is important to note that this does not necessarily mean that long-haul and short-haul operations should be separated, as some trucks may perform both types of tours.

3.2.3. *Fleet mix*

Given the battery capacity constraints, the long-haul tours should either have on-route charging feasibility or only be conducted by diesel trucks. Fleets may not transition to full-electric operation without sacrificing the long-haul part of their operations. As a result, it is essential to determine how many diesel trucks are required to support the long-haul part of the operation, and whether part of short-haul tours can also be scheduled to be done by diesel trucks, depending on their availability and long-haul tour scheduling. This section implements the one-pass greedy algorithm for interval scheduling and determining the minimum number of trucks required to perform only the long-haul part or all operations. It should be noted that the algorithm aims to maximize resource utilization and does not take charging feasibility into account. Additionally, it does not imply that long-haul and short-haul operations should be separated, and the findings serve as a jumping-off point for understanding fleet transition and operation assignment.

Given a set of tours where tour $i \in I$ starts at time s_i and ends at time f_i, the algorithm solves an interval scheduling problem and determines the minimum number of identical trucks required to accomplish tours in a way that no two tours are assigned to the same truck at the same time. Algorithm 1 details the algorithm for estimating the minimum number of trucks to run a given set of tours using a one-pass greedy technique (Kleinberg & Tardos, 2006).

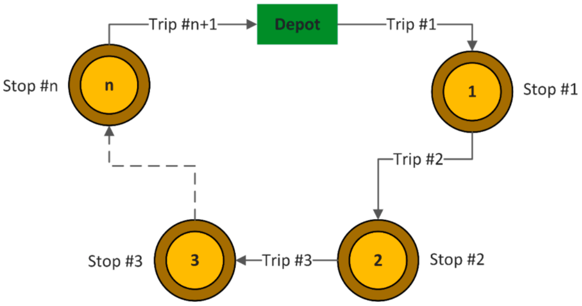

Fig. 1. Tour and Its Components.

Algorithm 1. (*Minimum Number of Trucks Calculation*)

```
Input = tours $i \in I$ with start times $s_i \in S$ and end time $f_i \in F$ for fleet $l \in L$
Output = depth value for fleet $l \in L$
1. For fleet $l$
  a. Set $M = \{s_i, f_i\}$ for all tours $i \in I$
  b. Sort $M$ in a non-decreasing order where $s_i$ is placed before $f_j$ if $s_i = f_j$ for any $i, j \in I$
  c. Set $n = 0$
  d. Set depth $= 0$
  e. For each $m \in M$
    i. If $m$ value is a start time, $m \in S$
      (1) Set $n = n + 1$
    ii. Else If $m$ value is an end time, $m \in F$
      (1) Set $n = n - 1$
    iii. If depth $< n$
      (1) Set depth $= n$
```

The fleet mix standard ensures the availability of a minimum number of diesel trucks for the completion of long-haul operations and determines whether they can complete short-haul operations as well. Assuming no additional budgets or grants are available, the proposed number of electric trucks and the required number of diesel trucks for long-haul operation should be less than the number of existing diesel trucks in the fleet. While it may seem like a basic standard, its strength lies in its simplicity in applying to existing fleets and assessing the electrification potential with no additional grants.

Standard 2. Fleet Mix Availability.

$$n^d + n^e \leq n^t$$

n^e = Proposed Number of Electric Trucks
n^d = Minimum Number of Required Trucks for Long-haul Operations
n^t = Minimum Number of Trucks Currently Required for All Operations

3.2.4. Charging requirements

The availability of a charging window and charging station during an average or worst-case scenario day (the day with maximum energy consumption) are two other measures for charging requirements and assuring operational practicality. The charging window availability (standard 3) measures the total time spent by the entire fleet on operations and charging within a 24-hour window and ensures that the overall duration of daily operations and required charging sessions can be completed in a single day. It should be highlighted that even if trucks use the same charger one after another, or multiple chargers simultaneously, their total charging time is combined and remains the same. This measure can be computed for each day and reported as the percentage of days on which the fleet has sufficient time to complete both operation and recharging. It should be noted that while driving durations for each driver may be limited, the priority for charging window availability is to calculate overall fleet utilization, considering all drivers and charging needs.

Standard 3. Charging Window Availability.

$$\frac{\frac{W}{P} + h}{n^e} < 24\ hours$$

Charging station availability (standard 4) estimates the number of charging stations needed to provide the required energy for all short-haul operations. This measure can be computed for each day and reported as the percentage of days on which the fleet can complete all short-haul operations with a specific number of charging stations.

Standard 4. Charging Station Availability.

$$n^c = \frac{\frac{W}{P}}{24}$$

Where,

W = Daily Short-haul Electricity Consumption of Fleet (kWh)
P = Charging Power (kW) = 100 kW
h = Operation Duration (hours)
n^e = Minimum Number of Required Trucks for Short-haul Operations
n^c = Number of Required Charging Stations

3.3. Economic analysis

This section explores the economics of electrification and performs a break-even analysis for future investments in battery electric heavy-duty trucks. The break-even point between a diesel heavy-duty truck and a battery electric heavy-duty truck shows the point that the TCO of a diesel truck equals the TCO of a battery electric heavy-duty truck.

3.3.1. Total cost of ownership

The TCO is a calculation of the costs of purchasing, installing, utilizing, maintaining, and retiring a product or piece of equipment. The TCO of truck fleets during their entire life span was estimated based on monetary values for local conditions and using the following equations. Equation (1) computes total capital cost and retail tax of truck fleet and refueling stations at year zero. Equation (2) computes the net present value of total annual truck registration fees (paid at the start of each year) at year zero. Equation (3) computes the net present value of annual operation and maintenance costs (assumed to be paid at the end of each year) at year zero. Equation (4) computes the net present value of fleet salvage value at the end of life. Equation (5) calculates the fleet TCO using net present values of capital cost, retail tax, registration fee, operation and maintenance cost, and salvage value.

$$C_I = \sum_{k\in\{D,E\}} \alpha_k(1+\tau_k) + n^c\alpha^c \tag{1}$$

$$C_F = \sum_{m=1}^{Y}\sum_{k\in\{D,E\}} \phi_k(1+r)^{1-m} \tag{2}$$

$$C_O = \sum_{m=1}^{Y}\sum_{k\in\{D,E\}} \Delta^k o_k(1+r)^{-m} + \sum_{m=1}^{Y}\sum_{k\in\{D,E\}} V^k \varepsilon^k_{avg}(1+\theta_k)^m \tag{3}$$

$$C_R = \sum_{k\in\{D,E\}} \frac{\alpha_k(1-\rho_k)^{Y-1}}{(1+r)^Y} \tag{4}$$

$$TCO = C_I + C_F + C_O - C_R \tag{5}$$

Where,

D = set of diesel trucks
E = set of battery electric trucks
Y = life duration
α_k = unit purchase cost of truck k (dollars)
τ_k = unit retail tax rate of truck k (dollars)
n^c = number of chargers at depot
α^c = unit purchase cost of charging station (dollars)
ϕ_k = unit registration fee of truck k (dollars)

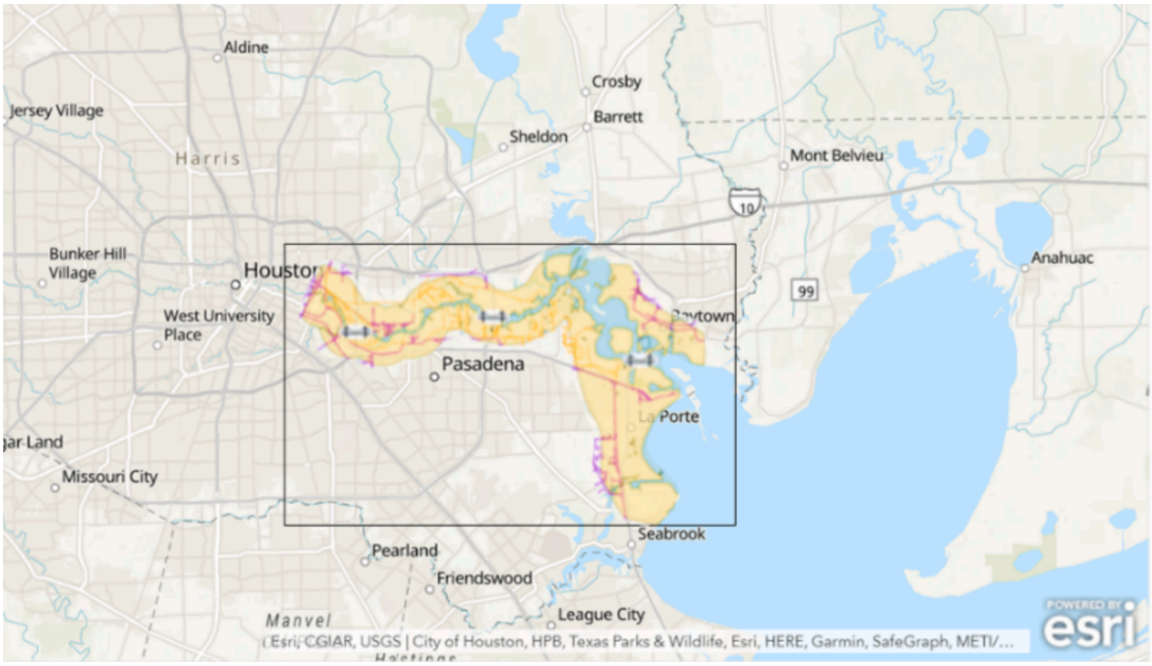

Fig. 2. Port Houston Location in Yellow (Port Houston, 2021b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Δ^k = annual mileage of truck k (miles)
o_k = unit O&M cost of truck k (dollar per mile)
V^k = annual energy consumption of truck k (kWh)
ε^k_{avg} = unit average fuel rate for truck k (dollar per kWh)
θ_k = fuel real growth rate for truck ka
ρ_k = depreciation rate for truck k
r = discount rate

Using equations (1) to (5), the TCO can be estimated for mixed diesel and electric fleets. The current calculation of the TCO did not include any potential rebates, insurance premiums, or downtime costs.

3.3.2. Electrification mileage

There is a break-even operation or annual mileage at which the operation and maintenance cost savings outweigh the higher purchase price of battery electric heavy-duty trucks. This break-even annual mileage may vary depending on the region and different fees. We will illustrate the calculation steps and reasonable assumptions in the Port Houston case study section. The following outlines the general standard:

Standard 5. Electrification Annual Mileage with Lower TCO.

Annual Mileage of Battery Electric Truck > *Breakeven Mileage*

4. Port Houston case study

Port Houston is the largest port on the Gulf Coast and the biggest port in Texas, including nearly 200 private and public terminals. About 2,500 trucks visit the largest container terminal, the Barbour's Cut terminal, each day. An estimated 247 million tons of cargo is being processed annually at Port Houston, leading to 339 billion dollars of total economic value or 20.6 % of the gross domestic product of Texas (Port Houston, 2021b). Fig. 2 shows the extent of Port Houston.

Port Houston is located in the Houston-Galveston-Brazoria area, which is designated as a severe ozone non-attainment area and requires additional measures to improve air quality (Texas Commission on Environmental Quality, 2021). Heavy-duty trucks at Port Houston are being operated by industry partners, and they are the third largest NO_x emission source. The largest NO_x emission source is the ocean-going vessels (58 % of NO_x emissions), and the second largest is cargo handling equipment (16 % of NO_x emissions) (Eastern

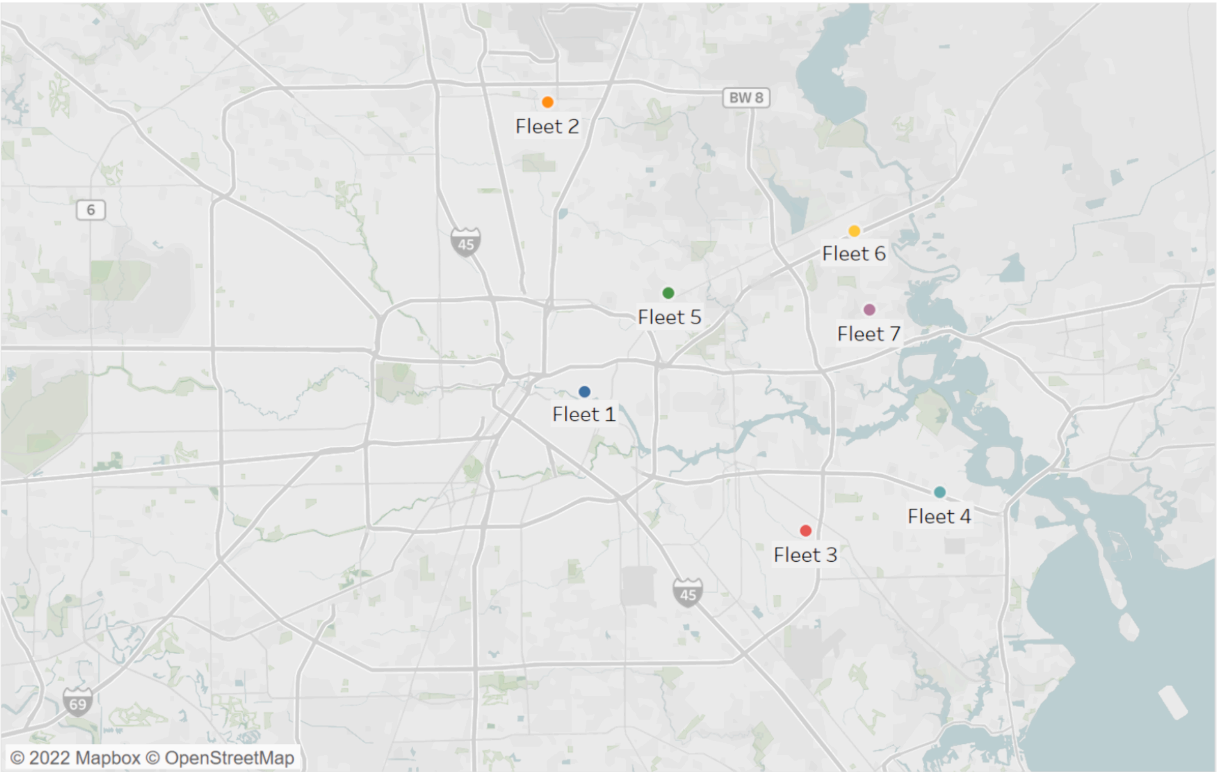

Fig. 3. Fleets Depot Locations.

Research Group, 2017). Heavy-duty trucks account for 15 % of total NO_x emissions and 17 % of total $PM_{2.5}$ emissions at Port Houston (Eastern Research Group, 2017). Therefore, the Clean Air Strategy Plan proposes collaboration with partners to reduce heavy-duty truck emissions by improving fuel efficiency, electrification, better scheduling, etc. (Port Houston, 2021a). One of the highest priorities is to investigate drayage truck electrification feasibility at Port Houston to help reach regional air quality goals, and the knowledge gained in this process can be used for drayage truck electrification and impact assessment elsewhere.

4.1. *Truck activity*

The study data focuses on a sample of 40 heavy-duty trucks from 7 fleet operators at Port Houston. While the existing sample may be a small percentage of the actual number of trucks operating, the data can be utilized as a case study for evaluating the performance of the designed framework and showcasing the strength of method. It was assumed that fleet electrification plans were only focusing on this part of the fleet, and there was no attempt in this study to scale up the findings to reflect the whole fleet.

The data collection process was conducted by the Texas A&M Transportation Institute (TTI) research team (Farzaneh, Johnson, Jaikumar, Ramani, & Zietsman, 2020). The vehicles were sampled by contacting fleets within the drayage loan program, a partnership for replacing old and polluting trucks, and they agreed to participate in the data collection process. The Portable Activity Measurement System (PAMS) was installed at a convenient time during daily truck operations. The PAMS was left on each truck for at least two weeks (up to 251 days for some fleets) and collected second-by-second vehicle operation data when the engine was turned on. From April 12, 2017, to April 26, 2018, over 81 million data points were collected, spanning over 23,300 h of operation and approximately 413,000 miles of travel. The second-by-second truck activity was aggregated into a trip-based dataset based on the times trucks were idling or off. Fig. 3 maps the fleet depot locations for truck parking (and potentially charging).

Despite the quality of the data collection device and the continuous efforts to monitor data collection, several minor data quality issues were addressed for generating trip-based truck activity data from second-by-second raw data (including removing duplicated trip record and engine-off data) (Sharifi, Xu, Meitiv, & Xu, 2021). Only 0.1 % of the data were removed in this process and should have negligible impacts on final operation and energy results. After data cleaning and speed processing, trip sequences were split by operation and idling (the vehicle is defined in idling if the speed is continuously less than 3 mph for more than 600 s), and records were aggregated into a trip-based truck activity. The travel time, travel distance, origin coordinates, destination coordinates, departure time, and arrival time were calculated for each operation or idling sequence. Overall, the operation data collected from the seven fleets represent a wide range of driving conditions, from short to long operation durations, and covers a wide range of operating speeds. Note that all calculations are based on the sampled data and not the entire fleet of trucks.

4.2. *Energy consumption and emission*

The operation data in this study came from conventional trucks, and it is assumed that the operation patterns remain unchanged if electrified. The trip-level energy consumption is estimated for each trip using conventional truck and battery electric truck specifications, respectively. This research adopted Fuel and Energy Calculator (FEC) to use second-by-second speed and operating mode bin to generate trip-level energy consumption for both conventional diesel trucks and battery electric trucks (Xu et al., 2018). The local inputs were prepared to run FEC and generate energy and emission estimations per trip, with few assumptions made to fill the gap. The major inputs in FEC have been summarized in Table 2 below. For emission estimation from electricity consumption, the emission factors from EPA eGRID database were used, together with Texas-specific electricity generation profile (US Environmental Protection Agency, 2014).

The major assumptions made in generating energy and emissions in this study include the following items:

Table 2
FEC Input Specification Summary.

Category	Variable	Value
Scenario settings	City and state	Houston, TX
	eGRID Subregion	Electric Reliability Council of Texas (ERCOT, with 20 % renewable)
	Season Scenario	Summer
	Inventory Year	2018
	Meteorology severity (1 – mild, 6 – severe)	2
Fleet information	MOVES source type	61
	Vehicle classification	Combination short-haul truck
	Vehicle age	0 (default)
	Baseline fuel type	Diesel
	Alternative fuel type	Battery electric
Vehicle operation	Duty cycle	Cleaned drayage truck speed profiles from GPS data
	Idle speed range (mph)	3
	Maximum vehicle gross weight (lbs)	80,000 (Texas Department of Motor Vehicles, 2020)
	Route length (mile) and hours of operation	Derived from speed profile
Electric powertrain	Battery size (kWh)	396 kWh (Peterbilt 579 EV, 2021)
	Motor power (kW)	400 kW (Peterbilt 579 EV, 2021)

- **Vehicle selection**: The vehicle specifications for conventional trucks were defined using EPA's MOtor Vehicle Emission Simulator (MOVES) diesel–fuel combination short-haul truck (source type = 61) to obtain the corresponding emission rates. The vehicle specifications for battery electric heavy-duty trucks were collected from a truck manufacturer, known as Peterbilt, based on their 579EV truck specifications (Peterbilt 579 EV, 2021).
- **Vehicle age**: Selected diesel and battery electric heavy-duty trucks for reassigning fleet operations are both assumed to be new. So, it does not have any bias toward a newer battery electric heavy-duty truck technology benefit considering the actual age of the current diesel trucks.
- **Truckload**: Due to the lack of truckload data, both conventional and battery electric heavy-duty trucks were assumed to carry the maximum load allowed in Texas (80,000 lbs). While the maximum payload capacity of a diesel versus a battery electric heavy-duty truck is debatable, this research makes a reasonable assumption that they have the same maximum payload capacity based on already available commercial diesel and battery electric heavy-duty trucks (Cascadia Evolution, 2017; Peterbilt 579 EV, 2021).
- **Truck idling**: due to the low quality of GPS signal during low-speed operations, the idling speed range was set as 3 mph (if speed $<=$ 3mph and vehicle is not decelerating, the truck is idling).

The energy estimation method for diesel and battery electric trucks is outlined below:

- Conventional diesel trucks: The scaled tractive power (STP) value was calculated using the second-by-second speed profile of trips and vehicle type information. Later, the second-by-second STP values, speed, and acceleration were used to generate the MOVES operating mode bins (OpMode bins) and obtain the mode bin distributions. Finally, the on-road energy use and emissions were computed by multiplying the operating mode distribution with corresponding MOVES emissions rates for the selected region, meteorology, and fuel type in Table 2. For trips with missing driving profiles but with average speeds, the energy and emission rates were imputed using the average energy and emissions rates of two other trips with the closest average speeds collected from the same truck. The energy and emissions for those trips were then computed by multiplying imputed rates and travel time (Sharifi et al., 2021).
- Battery electric trucks: The study developed and implemented a modeling approach to account for the energy recovery during regenerative braking and the second-by-second energy consumption rates. Using Equation (6) and Equation (7), the trip-level energy consumption for battery electric trucks was calculated by aggregating second-by-second energy use (Sharifi et al., 2021).

$$TractivePower(TP) = Av + Bv^2 + Cv^3 + M(a + gsin\theta)v \tag{6}$$

$$Energyrate(kW) = \begin{cases} TP/\eta_1\eta_2\eta_3(ifTP \geq 0) \\ TP^*\eta_r(ifTP < 0) \end{cases} \tag{7}$$

Where,

TP = vehicle tractive power (kW)
A, B, C = the road load coefficients
v = vehicle speed (m/s)
a = vehicle acceleration (m/s^2)
M = source mass for the source type (metric tons)
g = the acceleration due to gravity = 9.8 m/s^2
$sin\theta$ = the (fractional) road grade
η_1, η_2, η_3 = inverter efficiency (97 percent), motor efficiency (86 percent), and battery efficiency (90 percent) from the FEC (Xu et al., 2018)
η_r = regenerative braking energy recovery efficiency (Zhang, Yang, Zhang, & Ma, 2019)

The regenerative braking efficiency, or fraction of recovered energy among vehicle kinetic energy, was assumed to be 60 percent using measurement data from a previous study (Zhang et al., 2019). For emissions estimation from energy use, the emission factors from the EPA eGRID database were used, together with a Texas-specific electricity generation profile (US Environmental Protection

Table 3
Average Emissions per Mile from All Diesel Trucks or All Battery Electric Trucks.

Emissions		Fleet 1	Fleet 2	Fleet 3	Fleet 4	Fleet 5	Fleet 6	Fleet 7
Tailpipe Emissions for Diesel Trucks	CO_2e (kilograms per mile)	2.4	2.3	2.1	2.3	2.4	2.1	2.1
	VOC (grams per mile)	0.07	0.05	0.04	0.06	0.06	0.04	0.05
	NO_x (grams per mile)	1.3	1.2	1.1	1.2	1.3	1.1	1.1
	$PM_{2.5}$ (grams per mile)	0.02	0.01	0.01	0.02	0.02	0.01	0.01
Emissions from Electricity Generation for Battery Electric Trucks	CO_2e (kilograms per mile)	1.3	1.5	1.5	1.4	1.4	1.5	1.4
	NO_x (grams per mile)	0.72	0.78	0.78	0.74	0.75	0.79	0.72
	$PM_{2.5}$ (grams per mile)	0.07	0.08	0.08	0.07	0.07	0.08	0.07

Agency, 2014).

The individual truck daily energy use distributions for all the fleets were calculated. Due to the higher energy efficiency of electric vehicle powertrains (Zhang & Mi, 2011), the daily energy consumption of electric vehicles was about half of their conventional counterparts. Table 3 shows the average on-road emission rates per mile for each fleet, considering all trucks were new model year 2018 diesel trucks, and the average emissions from electricity generation total on-road emissions, considering all trucks were new model year 2018 battery electric trucks. By electrifying the fleet, the NO_X reduction can reach 1 – 1.2 g per mile from roadways, which could serve as a potential mitigation strategy for the Houston Ozone non-attainment area. In addition, electrifying the fleet has great potential in reducing the on-road $PM_{2.5}$, Volatile Organic Compound (VOC), and CO_{2e} emissions from the high-emitting diesel fleets by an average of 0.015 g per mile, 0.05 g per mile, and 2.2 kg per mile, respectively. CO_{2e} and NO_x emissions per mile from electricity generation were 1.4 kg per mile and 0.8 g per mile, respectively, while $PM_{2.5}$ emissions per mile from electricity generation is almost 4 to 6 times more than on-road $PM_{2.5}$.

4.3. Monetary values

Detailed costs were obtained from the TCO analysis framework developed by the Environmental Defense Fund (2019). The energy rates were confirmed with values from other references (US Energy Information Administration, 2023). The purchase prices were confirmed with values from another study, listing $279,000 and $150,0000 for battery electric and diesel trucks, respectively (Xie, Basma, & Rodrigues, 2023). The other study also listed the purchase prices as $296,000 and $122,000 for battery electric and diesel trucks, respectively (Vijayagopal & Rousseau, 2021). Also, Tesla Semi costs around $250,000 according to the Business Insider (2023). However, purchase prices may vary largely depending on the make and model. Therefore, the case study completed a sensitivity analysis for various battery electric pricing, as well as energy rates. Other fees and taxes were acquired from state rates (Texas Comptroller of Public, 2024; Texas Department of Motor Vehicles, 2020, 2024). The cost profiles in 2018 dollars adopted in this study for local conditions are summarized in Table 4. This research selected a medium fuel rate setting, as it is recommended when the user owns larger fleets (10 vehicles or more) and aims for higher charging power. Maintenance costs included those related to, but not limited to, propulsion, body and accessories, inspections, brakes and steering, suspension, HVAC, lighting, general air system repairs, axles, wheels, and tires.

Currently, there is no actual data on the depreciation rate of the battery electric heavy-duty trucks. However, Electrification Coalition (2010) suggests a residual value of between 8–25 % after 10 years. The assumption for this research was a depreciation rate of 14 % (equal to a residual value of 19 % after 12 years) for both diesel and battery electric heavy-duty trucks. The discount rate was 2 % per EDF suggestion (Environmental Defense Fund, 2019). Finally, diesel and electricity inflation rates were 1.4 % and 1.3 %, respectively, according to the US Energy Information Administration (2024).

4.4. Electrification feasibility assessment

A total of 4,875 tours were identified within all fleets in the case study (see Table 5 for details). The variation in values between fleets and within each fleet demonstrates the breadth of truck activities, the potential for electrification of short-haul tours, and the necessity of including diesel vehicles in long-haul operations.

If the maximum energy consumption of 396 kWh is considered based on the battery capacity (see Table 2), about 75 % of tours in

Table 4
Cost Profiles of Diesel Heavy-duty Trucks and Battery Electric Heavy-duty Trucks.

Cost Category	Item	Diesel Heavy-duty Truck	Battery Electric Heavy-duty Truck	Source
Capital Cost	vehicle purchase cost (dollar)	140,000	262,363	Environmental Defense Fund (2019)
	infrastructure cost (dollar)	Not applicable	60,000	Greater Bridgeport (2024)
	life span (year)	12	12	Environmental Defense Fund (2019)
Operation and Maintenance Cost	unit operation and maintenance cost (dollar per mile)	0.21	0.1025	Environmental Defense Fund (2023)
	fuel rate – low (dollar per kWh)	0.09	0.1	Environmental Defense Fund (2019)
	fuel rate – medium (dollar per kWh)	0.10	0.13	Environmental Defense Fund (2019)
	fuel rate – high (dollar per kWh)	0.11	0.16	Environmental Defense Fund (2019)
Other Costs	retail tax rate (percent)	6.25 %	6.25 %	Texas Comptroller of Public (2024)
	retail tax (dollar)	8,750	16,398	Calculated
	registration fee (70000–80000 lbs)	840	840	Texas Department of Motor Vehicles (2024)
	registration fee (Harris County surcharge)	11.5	11.5	Texas Department of Motor Vehicles (2024)

Table 5
Tour Statistics of Sampled Fleets.

Fleet ID	Total Number of Tours	Data Collection Duration in days	Number of Tours per Day		Tour Length (miles)		Tour Duration (hours)	
			Average	Maximum	Average	Maximum	Average	Maximum
Fleet 1	719	251	3.9	8	114	533	7.6	30.17
Fleet 2	490	185	3.7	10	164	2610	6.8	60.24
Fleet 3	60	43	2.0	4	181	787	6.6	15.77
Fleet 4	2506	96	26.4	56	48	659	3.0	24.10
Fleet 5	1013	167	8.4	16	94	607	5.3	25.65
Fleet 6	32	50	2.1	6	323	2584	10.0	78.73
Fleet 7	55	61	1.2	3	130	318	5.8	10.65
All	4875	NA	15.2	68	83	2610	4.7	78.73

the sampled truck activity can be operated by battery electric heavy-duty trucks. Fig. 4 shows this percentage is changing from 47 to 60 % for all fleets, except for sampled Fleet 4. More than 85 % of tour operations of sampled Fleet 4 have an energy consumption lower than 396 kWh, making sampled Fleet 4 have the highest percentage of electrifiable tours.

Table 6 displays the statistics for electrifiable tours (those requiring less than 396 kWh of battery energy) across the data collection period. As demonstrated, electrifying these tours can save an average of 35 % of the diesel energy consumed, or 1.25 million kWh over the period of data collection. Electrifying all these tours, however, may not be recommended for the following reasons:

- Replacing diesel trucks by battery electric trucks needs a substantial upfront investment; and
- Fleet mix standard may ensure availability of diesel trucks for completing part of short-haul operations.

Table 7 details the minimum number of trucks required to conduct short-haul tours (we define them as tours with energy consumption equal to or less than 396 kWh in this case study) and long-haul tours (with energy consumption of more than 396 kWh). There may be a changing proportion of long-haul and short-haul operations to all operations throughout each time interval. Therefore, the minimum number of trucks for long-haul and short-haul operations may not occur simultaneously, and their aggregate does not equal to the minimum number of trucks for all operations. For example, sampled Fleet 1 may handle all tour operations with 5 trucks, requiring at least 5 diesel trucks to handle long-haul operations. Sampled Fleets 1, 2, 6, and 7 cannot reduce their number of diesel trucks due to their long-haul operation needs. However, adding battery electric trucks may still be cost-effective if the operational cost saving outweighs the initial investment. Other than that, emission savings from electrified tours are beneficial. For example, 40 % of sampled Fleet 1 energy consumption comes from short-haul tours (see Table 6), which substantially impacts operational benefits and environmental advisability of fleet electrification. Sampled Fleets 3, 4, and 5 may reassign part of their operations and replace some diesel fleet operations with battery electric heavy-duty trucks.

Charging sessions are available on both average- and high-use days for all sampled fleets. Additionally, the majority of fleets only require a single charger at the depot. However, sampled Fleet 4 requires more than one charger on 38 % of days. It is worth noting that this part of the feasibility study does not account for time-of-use electricity pricing or optimal charging scheduling for future use. These two features could be assessed in future research.

Fig. 5 summarizes the TCO comparison between a fleet of all diesel heavy-duty trucks and a fleet of all battery electric heavy-duty trucks operating only electrifiable tours (see Table 6), and considering the minimum required number of trucks (see Table 7), to assess the financial benefits of replacing diesel trucks for short-haul operations. The basic conclusion is that electrifying all short-haul operations would result in higher TCO except for sampled Fleet 4. That is, electrifying short-haul tours requires a minimum operation and maintenance cost saving compared to diesel trucks to pay back the higher initial cost of battery electric trucks, which is a substantial portion of the TCO of heavy-duty trucks.

Fig. 6compares the TCO of a diesel truck with a battery electric heavy-duty truck over a range of annual mileages, assuming one charger per truck. With an annual mileage of 31,000 or more, battery electric heavy-duty trucks have a lower TCO than diesel heavy-

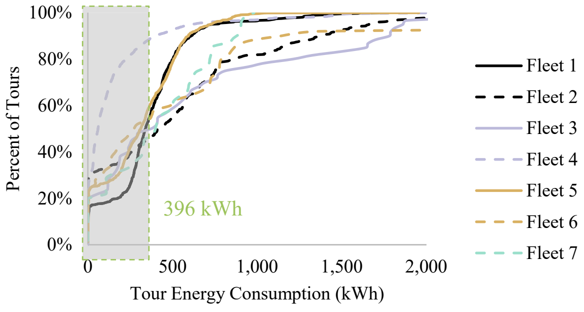

Fig. 4. Tour Energy Consumption Cumulative Distribution for Fleets.

Table 6
Feasible Electrifiable Tours within the Sample of Each Fleet.

Fleet ID	Total Electrifiable Miles (percent of total miles)	Total Electrifiable Hours (percent of total hours)	Consumed Electricity Energy (kWh)	Saved Diesel Energy (kWh) (percent of total diesel energy)
Fleet 1	29,736 (36 %)	2,697 (49 %)	94,460	289,345 (40 %)
Fleet 2	6,071 (8 %)	522 (16 %)	20,528	62,192 (9 %)
Fleet 3	988 (9 %)	94 (24 %)	3,526	10,506 (12 %)
Fleet 4	56,232 (47 %)	5,179 (69 %)	183,829	548,734 (53 %)
Fleet 5	31,212 (33 %)	2,698 (50 %)	105,959	323,099 (38 %)
Fleet 6	824 (8 %)	40 (12 %)	2,424	6,462 (8 %)
Fleet 7	1,228 (17 %)	73 (23 %)	3,893	10,350 (18 %)
All	126,291 (31 %)	11,303 (50 %)	414,619	1,250,688 (35 %)

Table 7
Minimum Number of Required Trucks for Sampled Fleets.

Fleet ID	Current number of diesel trucks	Minimum required number of trucks for all operation	Minimum required number of trucks for long-haul operations	Minimum required number of trucks for short-haul operations
Fleet 1	5	5	5	5
Fleet 2	5	5	5	4
Fleet 3	5	4	3	3
Fleet 4	15	14	8	13
Fleet 5	8	8	6	6
Fleet 6	1	1	1	1
Fleet 7	1	1	1	1

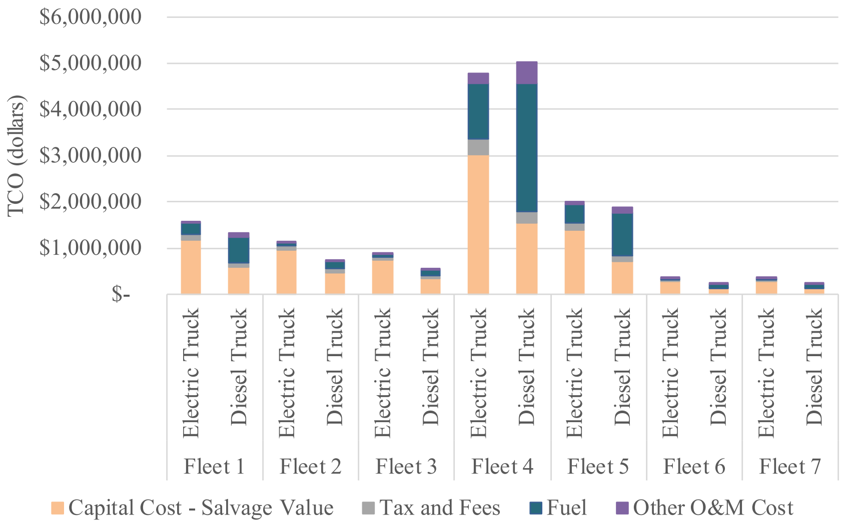

Fig. 5. TCO Comparison between Diesel Heavy-duty Trucks and Battery Electric Heavy-duty Trucks Performing Short-haul Operation.

duty trucks. Fig. 7 compares the TCO of a diesel truck with a battery electric heavy-duty truck over a range of annual mileages, not including the charging station cost. This scenario shows the second battery electric truck added to the fleet may have a lower TCO than a diesel truck with an annual mileage of 20,000 miles or more, considering the previously installed charging station is available.

Based on Table 6 electrifiable mileage and projected to the annual mileage, sampled Fleets 1, 4, and 5 operate sufficient annual mileage from electrifiable tours that it makes economic sense to include one or multiple battery electric heavy-duty trucks in the fleet.

Table 8 summarizes the feasibility measures for each sampled fleet in Port Houston, indicating that sampled Fleets 4 and 5 are the best prospects for electrification at the current price bracket.

The tailpipe emissions reduction and electricity emissions generation from electrifying short-haul tours were calculated and summarized in Table 9. Fleets can save between 13 and 557 tons of tailpipe CO_{2e} emissions per year, with the greatest savings occurring in sampled Fleet 4. In sampled Fleet 4, the tailpipe CO_{2e} emission reduction from electrifying electrifiable tours accounted for 53 % of total tailpipe emissions. The electricity required to charge electrifiable tours produced 297 tons of CO_{2e} emissions per year, contributing back 28 % of tailpipe emissions at the power plants. Additionally, electrifiable short-haul tours operated by sampled Fleet 4 may save up to 307 kg of NO_x and 4.3 kg of $PM_{2.5}$. However, electricity generation for charging short-haul tours may result in the

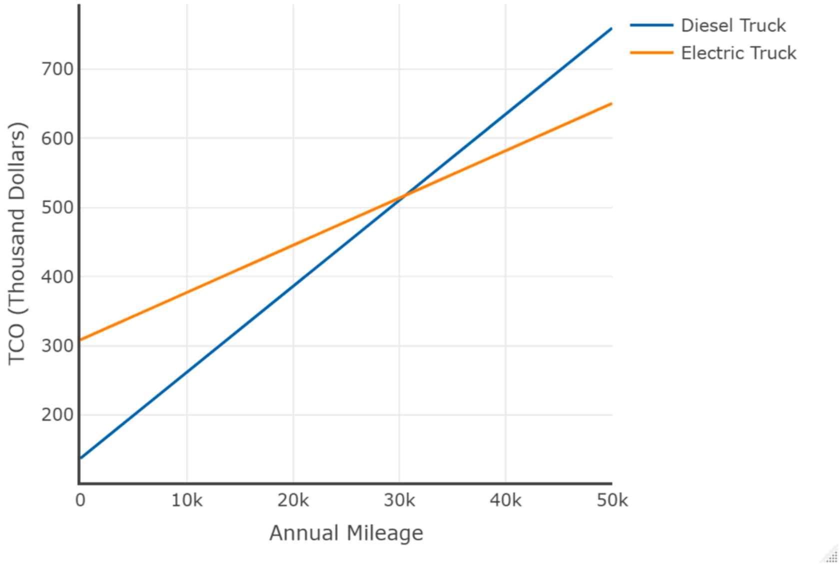

Fig. 6. Break-even Annual Mileage between a Diesel Heavy-duty Truck and a Battery Electric Heavy-duty Truck and One Charging Station.

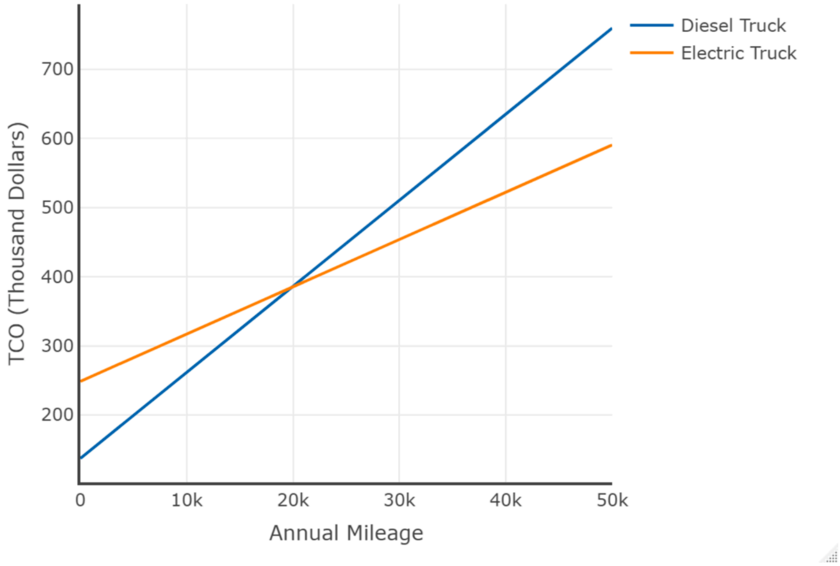

Fig. 7. Break-even Annual Mileage between a Diesel Heavy-duty Truck and a Battery Electric Heavy-duty Truck and No Charging Station.

emission of 15.9 kg of $PM_{2.5}$. Additionally, the tailpipe emissions savings can be weighed against the per dollar increase of TCO associated with electrifying short-haul tours. Only sampled Fleet 4 has a lower TCO for battery electric trucks than for diesel trucks (see Fig. 5) and electrifying its short-haul tours can save both emissions and costs. Most other fleets demonstrate a substantial potential for tailpipe CO_{2e}, NO_x, and $PM_{2.5}$ emissions savings per additional dollar spent on the electric fleet operation. These values can be checked versus the damage estimate of these emissions for regional electrification supports and grants, while the emissions from electricity generation can motivate studies on the public health impact of fleet electrification near power plants. Such grants may help toward low annual mileage or provide an opportunity for adding an extra battery electric truck, despite the availability of diesel trucks, especially in cases where the electrification of fleets may be identified as infeasible, according to this study.

With the advancement of battery electric heavy-duty trucks and charging technology, as well as the introduction of new truck models and increasing charging powers, running with limited battery capacity becomes increasingly viable, and the price disparity between diesel and battery electric heavy-duty trucks narrows (Xie et al., 2023). In other words, changes in the viability of technology will have operational and economic consequences. Federal and state rebates for electrification contribute to the price gap reduction as well. Fig. 8 shows that a 25 percent reduction in the purchase price (to approximately $195,000) can lead to a break-even annual

Table 8

Fleet Electrification Feasibility Standards Summary.

Standard	Parameter	Fleet 1	Fleet 2	Fleet 3	Fleet 4	Fleet 5	Fleet 6	Fleet 7
Maximum Energy Consumption	Electrifiable Mileage Percentage	36 %	8 %	9 %	47 %	33 %	8 %	17 %
Charging Window Availability	Electrifiable Truck Days Percentage	100 %	100 %	100 %	100 %	100 %	100 %	100 %
Charging Station Availability	Electrifiable Truck Days Percentage for one Charger	100 %	100 %	100 %	62 %	100 %	100 %	100 %
Fleet Mix Availability	Minimum Required Number of Trucks for all Operation	5	5	4	14	8	1	1
	Minimum Required Number of Trucks for Long-haul Operation	5	5	3	8	6	1	1
Electrification Annual Mileage with Lower TCO	Electrifiable Annual Mileage	43,242	11,977	8,389	213,798	68,218	6,013	7,345

Table 9

Changes in Tailpipe Emissions and Electricity Generation from Electrifiable Tours for Sampled Fleets.

Emissions			Fleet 1	Fleet 2	Fleet 3	Fleet 4	Fleet 5	Fleet 6	Fleet 7
Tailpipe Emissions Change	CO_{2e}	Annual Tons	−112	−33	−24	−557	−188	−13	−17
		Percent	−40 %	−9%	−12 %	−53 %	−38 %	−8%	−18 %
		Grams Saved per Dollar Cost	5,318	972	894	NA	17,728	1,173	1,633
	NO_x	Annual Kilograms	−62	−18	−13	−307	−104	−7	−9
		Percent	−41 %	−10 %	−13 %	−54 %	−39 %	−8%	−19 %
		Grams Saved per Dollar Cost	2.94	0.53	0.49	NA	9.74	0.64	0.88
	$PM_{2.5}$	Annual Kilograms	−0.9	−0.2	−0.2	−4.3	−1.5	−0.1	−0.1
		Percent	−43 %	−11 %	−16 %	−59 %	−41 %	−9%	−20 %
		Grams Saved per Dollar Cost	0.04	0.01	0.01	NA	0.14	0.01	0.01
Emissions Change from Electricity Generation	CO_{2e}	Annual Tons	58	17	13	297	98	8	10
		Percent	21 %	5 %	6 %	28 %	20 %	5 %	11 %
	NO_x	Annual Kilograms	31	9	7	159	53	4	5
		Percent	20 %	5 %	7 %	28 %	20 %	5 %	11 %
	$PM_{2.5}$	Annual Kilograms	3.1	0.9	0.7	15.9	5.3	0.4	0.5
		Percent	154 %	41 %	58 %	220 %	144 %	59 %	92 %
Net Change in Emissions	CO_{2e}	Annual Tons	−54	−16	−11	−260	−90	−5	−7
		Percent	−19 %	−4%	−6%	−25 %	−18 %	−3%	−7%
	NO_x	Annual Kilograms	−31	−9	−6	−148	−51	−3	−4
		Percent	−21 %	−5%	−6%	−26 %	−19 %	−3%	−8%
	$PM_{2.5}$	Annual Kilograms	2.2	0.7	0.5	11.6	3.8	0.3	0.4
		Percent	111 %	30 %	42 %	161 %	103 %	50 %	72 %

mileage of 20,000 miles. On the other hand, some battery electric trucks may be higher in price than the assumed price in Table 4. According to Fig. 8, a 25 percent increase in the purchase price (to approximately $320,000) can lead to a break-even annual mileage of 40,000 miles. Either of these scenarios may become possible considering rapid technology advancements and the variety of makes and models in the market.

The break-even annual mileage can also vary based on predicted annual price increases for electricity and diesel. Fig. 9 shows how different increase rates result in different break-even points, such that a 4.5 percent annual electricity increase rate may result in sampled Fleet 1 being rejected economically electrified.

5. Discussion

5.1. Findings and contributions

This feasibility assessment for heavy-duty port drayage fleet electrification evaluated the potential of shifting a heavy-duty fleet

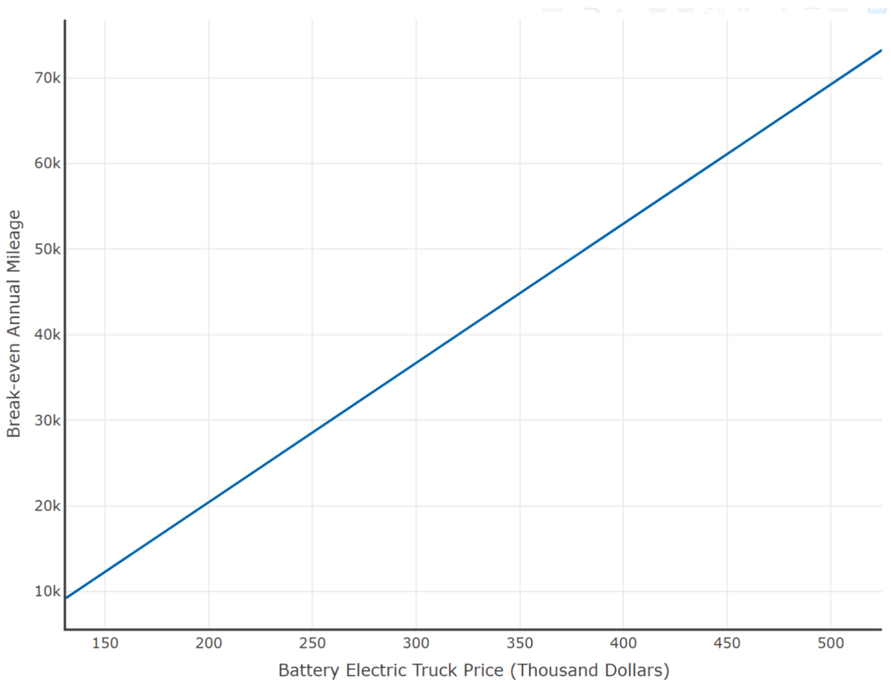

Fig. 8. Break-even Annual Mileage for Potential Changes in Battery Electric Heavy-duty Truck Purchase Price.

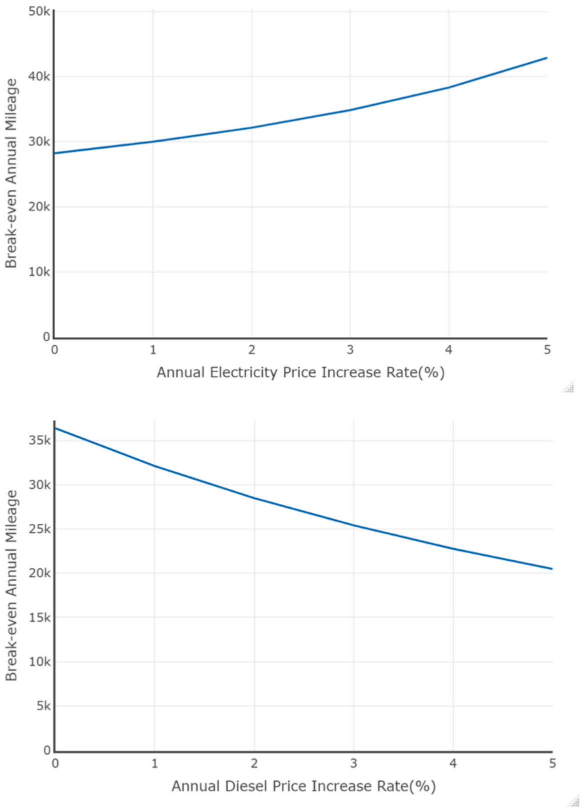

Fig. 9. Break-even Annual Mileage for Potential Changes in Diesel and Electricity Price Increase Rate.

from all-diesel to partially battery electric trucks. It included a thorough examination of the technological, operational, and economic elements, as well as consideration of environmental consequences, using a sample of the Port Houston fleets as a guide. Five measures, maximum energy consumption, fleet mix availability, charging window availability, charging station availability, and electrification annual mileage with lower TCO, were developed to create a feasibility framework, allowing fleets operating in ports to conduct their own initial assessment of fleet electrification. The procedure for generating and accessing data sources was detailed, and the techniques are easily transferable to other regions. The majority of data sources are accessible to fleet owners and regional planners for future practice in making sustainable transportation decisions.

The findings indicated that the feasibility of fleet electrification varies significantly depending on the operating pattern and fleet characteristics. With current battery electric truck technology and the assumption that charging is only accessible at the depot, up to 47 % of the mileage of sampled fleets at Port Houston may be electrified. If additional charging stations are added in addition to the charging stations at depots, the proportion of miles that can be electrified will grow. Given the current purchase prices of diesel and battery electric trucks and a 12-year life expectancy, a battery electric truck will have a lower TCO than a diesel truck if its annual mileage is greater than 31,000. Also, electrifying electrifiable tour operations of sampled fleets at Port Houston may save up to 54 % of tailpipe nitrogen oxide compared to new diesel trucks. Such emissions savings would continue to rise over time, as battery electric trucks continue to emit zero emissions from the exhaust, while diesel trucks age and become more polluting. The outcomes of this experiment demonstrate that while electric trucks are not currently capable of performing all functions of a drayage truck fleet, they are technologically and economically feasible for a large fraction of drayage operations in larger fleets. However, transitioning smaller or independent owner-operator fleets may be an operational and economic challenge due to their long-haul tours and low annual short-haul mileage.

5.2. *Research limitations*

There are more aspects to consider when determining the feasibility of a fleet electrification framework that the current study did not focus on those aspects, including legal, organizational, and scheduling feasibility. It is worth noting that, at the time of this study, the federal government expressed strong support for developing battery electric vehicles and charging infrastructure (H.R.3684 - 117th Congress, 2021-2022; US Environmental Protection Agency, 2010). Despite existing challenges for long-haul trucks, supportive policies can accelerate electrification across the board. Some studies have discussed the substantial impact of policies on facilitating the process of heavy-duty electrification, such as reducing the TCO gap for lower utilization through tax incentives (Fleming, Brown, Fulton, & Miller, 2021; Wang et al., 2023).

Additionally, this study is limited to the environmental impact of electric and diesel trucks during their use phase due to data limitations. The authors acknowledge the importance of a full life cycle assessment, including production and recycling phases, to provide a more comprehensive assessment. Some studies have specifically focused on life cycle assessments of electric cars and trucks, which can inform future improvements to the feasibility assessment framework (Sen, Ercan, & Tatari, 2017; Verma, Dwivedi, & Verma, 2022).

Battery electric truck technology is still in its infancy; there are not enough long-term studies to reliably predict a battery electric vehicle's lifespan or salvage value. Also, the lack of heavy-duty charging infrastructure in the network forced the proposed framework to focus on depot charging. Once such charging infrastructure becomes widely available, the model can be adapted to include other charging locations at stops. Also, long-haul tours may be electrified through battery swapping at idling times, regardless of the high capital cost. Additionally, the framework made simplifications by ignoring the impacts from the following areas: 1) battery degradation with vehicle age, 2) seasonal impact on air conditioning load, and 3) missing truck cargo load, causing overestimation of energy consumption.

The proposed feasibility method does not imply that by examining a sample of truck activity, we can draw conclusions about the entire fleet; rather, they demonstrate that the same procedure may be applied to the entire fleet. Fleet operators either have the entire fleet's truck activity (and they often have an operation timetable) and apply the methods to the entire fleet, or they can subset the fleet (depending on their business strategy, drivers operating trucks, and truck age) and apply the methods to that subset. While we acknowledge the potential benefits of a vehicle routing problem approach, a joint scheduling and charging algorithm, or a tour optimization for maximizing the utilization of electric trucks, the proposed framework is a first step toward identifying the possibilities and priorities for heavy-duty electrification, and the operation is assumed to exactly mimic the existing fleet schedule. An optimization model is required to prioritize and reallocate operations and develop a charging schedule that adheres to established technology, operation, and economic standards. Since capital costs associated with fleets are a significant portion of TCO, transitioning to a mixed electric fleet needs to meet the cost constraints and fulfill the required operation for the fleet owners. Therefore, cost-constrained operation electrification can be provided to fleet owners for selecting the optimal electrification case.

CRediT authorship contribution statement

Farinoush Sharifi: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mark Burris:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology. **Luca Quadrifoglio:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Nick Duffield:** Writing – review & editing, Supervision, Methodology. **Xiaodan Xu:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alexander Meitiv:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation. **Yanzhi Ann Xu:** Writing – review & editing, Project administration, Methodology, Investigation, Data

curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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