# DRAYAGE TRUCK ELECTRIFICATION FEASIBILITY AND BENEFIT ANALYSIS

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16. Abstract

Port Houston (POH), as the Gulf Coast's largest port, has a great opportunity for fleet electrification due to its high trucking activity. This initial feasibility assessment of electrifying drayage truck fleets operating in and near POH comprised a comprehensive examination of technological, operational, and economic factors, as well as detailed computation of diesel and battery electric trucks. The study discovered that electrification would result in significant emissions savings and is technologically, operationally, and economically feasible to a substantial extent, based on data collected from 40 drayage trucks in the Houston area from 2017 to 2018. With current electric truck and charger technologies, up to 42% of a fleet mileage might be electric, assuming trucks charge only at the depot. With a 12-year life expectancy and 27,000 annual miles, the total cost of ownership of a battery electric truck becomes cheaper than the total cost of ownership of a diesel truck. The greater the distance traveled by a truck, the shorter the payback period. Also, an electric truck would save almost 1 gram of nitrogen oxide per mile at the tailpipe. Such emissions savings would continue to grow over time, as electric vehicles continue to emit zero emissions from the exhaust, while diesel trucks age and become more polluting.

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# Executive Summary

Fleet electrification plays an important role in achieving regional climate and air quality goals. As the largest port on the Gulf Coast, Port Houston (POH) provides the greatest potential of fleet electrification due to its high truck volume. The goal of this study was to assess the feasibility of drayage truck electrification of fleets operating at and around POH. The feasibility assessment includes the commercial availability of the technology, the practicality of truck operations considering range and charging, and the economics of transitioning to an electric fleet.

Using data collected from 40 drayage trucks in the Houston area from 2017 to 2018, the project found that electrification would offer sizable emissions benefits and is technologically, operationally, and economically feasible to a large extent. Regarding emission benefits, an electric truck would eliminate more than 1 gram per mile of tailpipe nitrogen oxide emissions from a new model year 2018 diesel truck, and the size of the emission reduction would grow as vehicles age. Regarding feasibility, up to 42 percent of a fleet's mileage could be electric, given the prevailing electric truck and charger technology, if trucks only charge at the depot. The percentage of miles that can be fulfilled by an electric truck increases if the charging speed is faster or if there are options to charge en route. Considering a 12-year life span, the break-even point of an electric truck is around 27,000 annual mileage. The more a truck travels, the faster the payback time.

Challenges remain to implement electric trucks regarding optimized operational schedules and improved return on investment. Nonetheless, this project has demonstrated that electric trucks are feasible for drayage operations and electric trucks provide net emissions benefits for the surrounding communities.

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# Chapter 1: Project Overview

## Background

In 2014, the City of Houston emitted 34,316,303 metric tons of carbon dioxide equivalent ($CO_2e$), with 47 percent of emissions from transportation fuel sources [1]. About 20 percent of on-road emissions came from commercial hauling and freight vehicles [1]. To comply with the Paris Climate Agreement and achieve carbon neutrality by 2050, the City of Houston proposed to reduce 40 percent of $CO_2e$ by 2030 [1], with reducing emissions from transportation sectors among the top priorities. Also, the Houston–Galveston–Brazoria area was designated as a serious ozone non-attainment area [2], which requires additional measures to improve air quality. In the transportation sector, fleet electrification is a viable approach to achieve climate goals and improve regional air quality. In the short term, fleet electrification can reduce major fleet expenses such as maintenance and fueling costs, especially for medium- and heavy-duty fleets with fixed routes and charging locations. In the long term, fleet electrification can be an important step toward creating legislative compliance and delivering environmental benefits [3]. Therefore, it is important to develop a fleet electrification use case in Houston to support the city's climate goals and air quality improvement efforts.

Port Houston (POH) is the largest port on the Gulf Coast and the biggest port in Texas, containing nearly 200 private and public industrial terminals and processing 247 million tons of cargo annually [4]. The largest container terminal (the Barbours Cut Terminal) records about 2,500 truck visits each day [5]. Due to the large vehicle volumes at the port and great variety of fleet operations, the on-road and non-road fleets operating within POH can be great candidates for fleet electrification. The on-road fleet is mostly composed of drayage trucks that operate within the urban area near the port and long-haul trucks that make long-distance shipments [5]. The electrifiable non-road equipment is mostly composed of cargo-handling equipment, such as cranes and yard tractors [6]. In the near term, the range of battery-electric trucks (BETs) is suitable for many drayage service needs, and drayage truck electrification has reached the early commercialization stage with the BYD® BETs [7]. The feasibility of drayage trucks has been assessed at multiple major ports in California and shows promising implementation potential [7]–[9]. It is worth investigating the feasibility of drayage truck electrification to reach regional climate and air quality goals, and the knowledge gained in this process can be used to expand the electrification to other trucks and non-road equipment.

So far, fleet electrification remains at the early stage due to the following challenges [9]:

- Infrastructure constraint: The charging infrastructure needs to be planned to meet needs in terms of charger type, charging speed, and cost and is constrained by existing space and budget [3]. Depending on budget, charging needs, and available land, a feasible charging solution may not always be available to support the fleet.
- High cost: BETs have substantially higher up-front capital costs than their conventional counterpart and require large infrastructure investments [10].
- Limited vendors: By 2018, there was only one Class 8 electric truck model provided by a single company, BYD [10].
- Limited range: Early-stage BETs will provide driving ranges of 125 to 300 miles [7], which may not be sufficient to support long-distance shipments without recharging during operation.
- Heavy batteries and axle loads: The combined tractor weight plus cargo payload of electric trucks may be higher than the 80,000-lb overall gross weight allowed [9].

Besides, POH may face additional challenges for truck electrification that are not yet explored in existing studies, such as local funding support, the condition of existing infrastructure, and seasonal severe weather. The feasibility of electrification at POH needs to be analyzed under the local context and constraint. The value of this study is in the answering of the key implementation questions related to fleet electrification in the context of POH and effectively delivering the results to various stakeholders.

## Research Goals

The major objective of this study was to investigate the feasibility of electrifying drayage trucks operating at and around POH based on real-world truck operations. In general, the feasibility assessment of drayage truck electrification included two aspects: assess the major barriers in vehicle electrification and evaluate the potential benefits under the plausible truck electrification scenarios. This study evaluated the potential barriers to battery-electric adoption:

- Vendor barrier: If electric models are available to replace the current on-road vehicles and equipment.
- Operational barrier: If the alternative electric models can perform the duty cycles of the fleet at POH, especially meeting the range required by the current and future fleet.
- Infrastructure barrier: If charging at depots is sufficient for fleet electrification.

Also, this study analyzed the potential benefits of drayage truck electrification to support the Center for Advancing Research in Transportation Emissions, Energy, and Health sustainable, multimodal, accessible, resilient, and technological goals:

- Sustainable: If the fleet electrification can yield meaningful climate, air quality, and health benefits while maintaining financial feasibility.
- Multimodal: If the fleet electrification can be expanded to serve several modes and to improve supply chains.
- Accessible: If the fleet electrification is feasible for different sizes of businesses.
- Resilient: If the fleet electrification can sustain a stressful situation, such as spikes in electricity demand and natural disasters.
- Technological: If the fleet electrification will include emerging transportation technologies, such as truck technologies in the research and development stage.

With limited time and budget, it was practically infeasible to electrify the entire fleet at POH. In this case, the goal of this study was to assess the potential of electrification based on current fleet operation and prioritize fleets with higher benefits if electrified and no significant barriers during implementation. Practically, this goal can be broken down into the following technical objectives:

1. Constraint analysis: Identify the suitable vehicle and infrastructure that can serve the current and future system need and satisfies the constraints listed previously.
2. Cost-benefit assessment: Assess the cost and benefits of fleet electrification, compare them to current practices, and follow the benefits listed previously.
3. Result communication and analysis: Develop an interactive dashboard for summarizing findings, highlighting fleets with higher electrification potentials, and listing suggestions for implementation.

## Organization of Report

This report is organized as follows. Chapter 2 provides an overview of real-world truck operation characteristics at POH, and detailed data processing methods for data cleaning and visualization. Chapter 3 presents the energy consumption patterns of conventional and electric trucks under real-world operations and the potential emission reductions by choosing electric trucks over conventional trucks. Chapter 4 analyzes the technological, operational, and economic feasibility of electrifying the fleets in this study. The major findings and outcomes are summarized in Chapter 5, as are potential future directions and research needs.

# Chapter 2: Truck Operation Patterns

This study used combination truck operation data collected from 2017 to 2018 from Class 8 trucks, which were participating in a drayage loan program managed by the Houston–Galveston Area Council [11]. A total of 40 trucks from 7 fleets (including 2 owner operators) was recruited, and second-by-second vehicle operation, location, and engine data were collected by the Texas A&M Transportation Institute (TTI) using the Portable Activity Measurement System (PAMS). This was a very small sample in the context of truck operations at POH, which observed close to 49,000 trucks from January 2009 to April 2010 in the largest two terminals—Barbours Cut and Bayport [12]. Nonetheless, this dataset provided valuable longitudinal information about truck operation patterns and allows for energy consumption estimation and electrification feasibility analysis. As shown in later sections, the operation patterns revealed through this dataset corroborate with the patterns observed in previous studies [12], in that drayage trucks are used in a wide range of operations. This section provides an overview of the dataset, presents the major steps adopted to clean the data and generate trip attributes, and visualizes the operation patterns of truck fleets.

## Data Overview

This section provides a brief overview of the data sources used in this analysis. The vehicle and fleet information are summarized in Table 1. During the data collection period, the PAMS was installed at a convenient time during daily truck operations. The PAMS was left on each truck for at least two weeks (maximum 251 days) and collected vehicle operation data at 1 Hz when the engine was turned on. The data were automatically transmitted to the TTI server via cellular service during the data collection period to monitor the progress and ensure the functionality of the system. The number-of-days attribute indicates the total number of days the PAMS was installed on each vehicle, and the active-days attribute in this table indicates the number of days with vehicle operation data (vehicle on duty). For the fuel type of the vehicles, most of the trucks used diesel as their primary fuel, while four trucks used compressed natural gas (CNG). Due to the lack of CNG emission rates from the U.S. Environmental Protection Agency's (EPA's) current Motor Vehicle Emission Simulator (MOVES) model [13], the energy consumption of CNG trucks was estimated using diesel rates.

**Table 1. Summary of Vehicle and Fleet Information**

| Vehicle ID | Fleet ID | Fuel | Model Year | Number of Days | Active Days |
|---|---|---|---|---|---|
| L118 | 1 | Diesel | 2012 | 213 | 102 |
| L119 | 1 | Diesel | 2012 | 251 | 139 |
| L120 | 1 | Diesel | 2012 | 251 | 168 |
| L121 | 1 | Diesel | 2012 | 242 | 129 |
| L122 | 1 | Diesel | 2013 | 250 | 154 |
| 420 | 2 | Diesel | 2011 | 146 | 85 |
| 438 | 2 | Diesel | 2015 | 173 | 119 |
| 439 | 2 | Diesel | 2015 | 169 | 107 |
| 445 | 2 | Diesel | 2016 | 55 | 25 |
| 447 | 2 | Diesel | 2016 | 154 | 83 |
| 072 | 3 | Diesel | 2011 | 30 | 13 |
| 074 | 3 | Diesel | 2011 | 43 | 29 |
| 078 | 3 | Diesel | 2011 | 35 | 15 |
| 080 | 3 | Diesel | 2010 | 16 | 7 |
| 093 | 3 | Diesel | 2015 | 27 | 19 |
| 036 | 4 | Diesel | 2014 | 80 | 56 |
| 816 | 4 | Diesel | 2012 | 80 | 55 |
| 822 | 4 | Diesel | 2012 | 94 | 78 |
| 824 | 4 | Diesel | 2012 | 91 | 71 |

| Vehicle ID | Fleet ID | Fuel | Model Year | Number of Days | Active Days |
|---|---|---|---|---|---|
| 826 | 4 | Diesel | 2012 | 93 | 74 |
| 832 | 4 | Diesel | 2013 | 94 | 79 |
| 834 | 4 | Diesel | 2013 | 91 | 81 |
| 837 | 4 | Diesel | 2013 | 88 | 70 |
| 838 | 4 | Diesel | 2012 | 88 | 67 |
| 839 | 4 | Diesel | 2013 | 91 | 80 |
| 840 | 4 | Diesel | 2013 | 91 | 63 |
| 841 | 4 | Diesel | 2013 | 31 | 30 |
| 861 | 4 | Diesel | 2014 | 93 | 76 |
| 863 | 4 | Diesel | 2014 | 91 | 75 |
| 867 | 4 | Diesel | 2014 | 91 | 80 |
| 1500042D | 5 | Diesel | 2015 | 167 | 107 |
| 1503022C | 5 | CNG | 2015 | 167 | 111 |
| 1503132C | 5 | CNG | 2015 | 107 | 65 |
| 1600942D | 5 | Diesel | 2016 | 132 | 87 |
| 1600952D | 5 | Diesel | 2016 | 167 | 109 |
| 1600992D | 5 | Diesel | 2016 | 167 | 104 |
| 1603652C | 5 | CNG | 2017 | 167 | 88 |
| 1603892C | 5 | CNG | 2017 | 167 | 99 |
| 001 | 6 | Diesel | 2018 | 50 | 55 |
| 002 | 7 | Diesel | 2018 | 61 | 50 |

## Data Cleaning and Processing

Despite the quality of the data collection device and the continuous efforts to monitor data collection, several minor data quality issues needed to be addressed. The major data issues are:

- Duplicated data records: In the raw data file, duplicated data records appeared under the same time, potentially due to multiple read/write activities on the server side. The duplicated data records were removed.
- Missing time stamp data: In some cases, the time-stamp attribute was missing in the raw data files, which caused incomplete trip information and was impossible to process. In this case, those data were removed.
- Missing vehicle speed data: The vehicle speed was imputed from the wheel-based speed and filled with the global positioning system (GPS) speed if the wheel-based speed was missing or invalid (e.g., the GPS coordinates suggested vehicle idling while wheel-based speed was non-zero). When the speed data remained missing after the imputation, they were estimated with the cubic spline method [14] with second-by-second speed data before and after the missing values as inputs.
- Random errors in speed data: The speed profiles collected by GPS and onboard diagnostics readers included random errors such as jumping speed (high acceleration). The speed data were smoothed to reflect reasonable driving behaviors using a Kalman filter [15].
- Incorrect time series issues: In some cases, the time stamp did not have second-level information, and it was not possible to extract second-by-second driving profiles. Those trip sequences were kept but separated from other data (corresponding to break trips at time gap in Figure 1). The energy use was imputed for those trip sequences, and the detailed methodology is introduced in “Conventional Vehicle Energy and Emission Calculation” in Chapter 3.

The total hours-of-operation data before and after cleaning were 23,354.7 hours and 23,331.4 hours, respectively. Only 0.1 percent of the data were removed in this process and had negligible impacts on final operation and energy results.

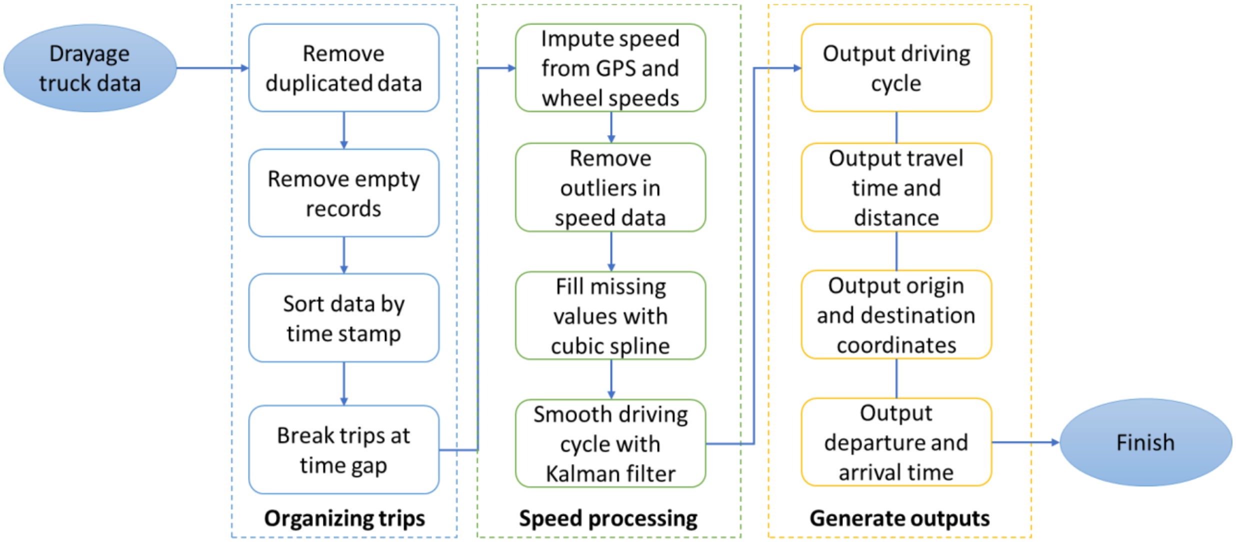


**Figure 1. Data cleaning and processing workflow.**

## Drayage Truck Operation Characteristics

After processing the vehicle operation data, the distributions of daily operation patterns of each fleet were summarized using box plots. The distribution of daily travel distances of individual vehicles in each fleet is illustrated in Figure 2. Fleet 3 and Fleet 6 generally operated longer distances than other fleets, with the average daily travel distance greater than 200 miles (represented by the cross mark in the graph).

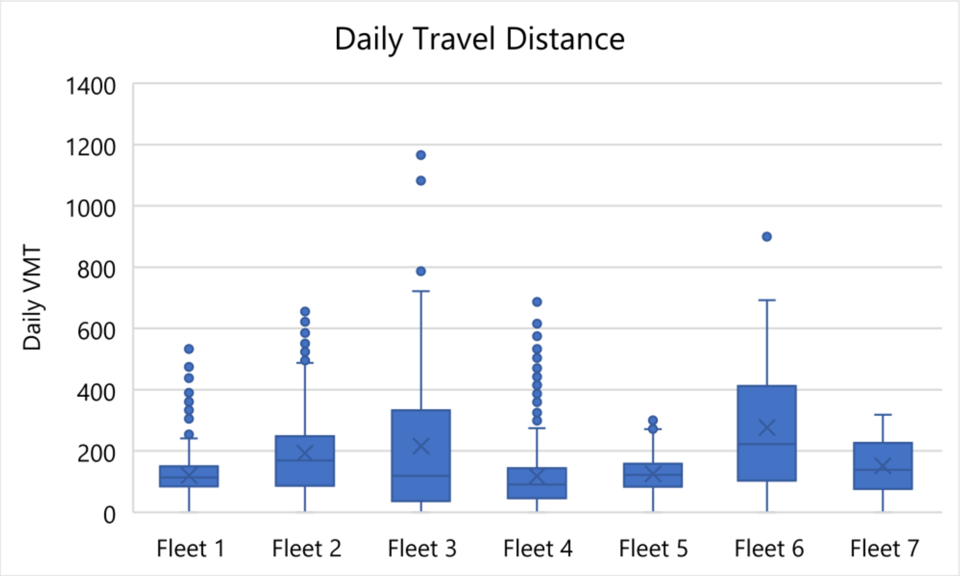


**Figure 2. Distribution of daily travel distance per vehicle.**

The distribution of daily travel speeds of individual vehicles in each fleet is illustrated in Figure 3. The daily average speeds (represented by cross marks) of all the fleets ranged between 15 mph and 25 mph, with maximum daily average speed around 60 mph observed for certain trucks in Fleet 3. Overall, the operation data collected from the seven fleets represented a wide range of driving conditions, from short to long operation durations, and covered a wide range of operation speeds. The feasibility analysis in the upcoming sections using this dataset can demonstrate the truck electrification potential under a variety of operating conditions.

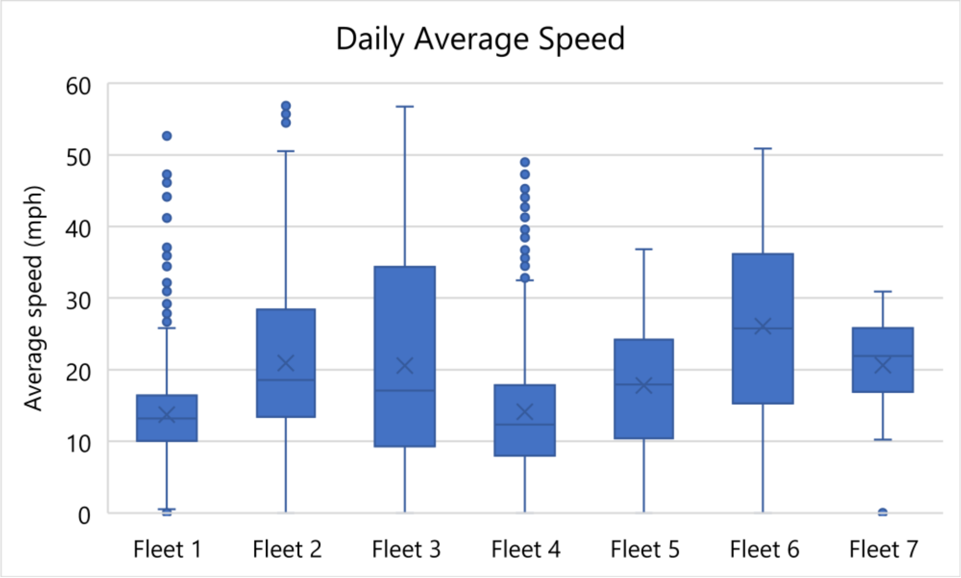


**Figure 3. Distribution of daily travel speed per vehicle.**

## Chapter 3: Truck Energy and Emissions Analysis

In this section, the energy use of trucks was estimated using the cleaned operation data documented in "Data Cleaning and Processing" in Chapter 2. The operation data collected in this study came from conventional trucks, and it was assumed that the operation patterns remained unchanged if electrified. The trip-level energy consumption was estimated for each trip using conventional truck and electric truck specifications. This chapter introduces the methodology of energy modeling and presents the results.

### Methodology Overview

The Fuel and Emissions Calculator (FEC) is an operating-mode-based, life-cycle energy and emissions modeling tool developed by Georgia Institute of Technology researchers [16]. The FEC can compare the performance of multiple alternative fuels and powertrains across a range of operational characteristics and environmental conditions. In this project, the FEC was adopted to estimate trip-level energy consumption for both conventional diesel trucks and electric trucks. The major advantages of using the FEC in this study are as follows:

- Reflect the impact of local operating conditions: The FEC's modeling approach estimated energy use and emissions as a function of engine load, which in turn was a function of vehicle operating parameters. The FEC allowed modelers to account for local on-road operating mode conditions as model inputs.
- Account for auxiliary load under specific meteorology: The FEC can model vehicle auxiliary load as a function of a range of different temperature and humidity combinations and captures the impact of the ambient environment.
- Use emission rates from regulatory tools: The FEC incorporated energy consumption and emission rates from the United States. EPA's MOVES2014 model and the emission results were comparable to MOVES project-level outputs.

In this study, the Python version of the FEC was adopted to rapidly process drayage truck operation data. The Python version enhanced model performance and provided functionality for advanced users who may wish to link the FEC with other modeling tools.

### Input Preparation and Model Setup

In this study, the local inputs were prepared to run the FEC and generate energy and emission estimations per trip, with few assumptions made to fill the gap. The major inputs in the FEC are summarized in Table 2.

**Table 2. FEC Input Specification Summary**

| Category | Variable | Value |
|---|---|---|
| Scenario settings | City and state | Houston, Texas |
| | 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 |
| | Baseline fuel type | Diesel |
| | Alternative fuel type | Battery electric |
| Vehicle operation | Duty cycle | Cleaned drayage truck speed profiles |
| | Idle speed range (mph) | 3 |
| | Maximum vehicle gross weight (lb) | 80,000 [17] |
| | Route length (mile) and hours of operation | Derived from speed profile |
| Electric powertrain | Battery size (kWh) | 396 kWh [18] |
| | Motor power (kW) | 400 kW [18] |

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

- Vehicle selection: The vehicle specifications for conventional trucks were defined using a MOVES diesel-fuel combination short-haul truck (a source type of 61) to obtain the corresponding emission rates. The vehicle specifications for electric trucks were collected from an electric truck manufacturer, known as Peterbilt, based on their 579EV truck specifications [18].
- Vehicle age: For the purpose of reassigning fleet operations, selected diesel and battery electric trucks are assumed to be new. Thus, the energy consumption comparison between a fully diesel fleet and a mixed-electric fleet is more precise and does not include any bias toward the benefits of newer battery electric truck technology, given the true age of contemporary diesel trucks.
- Truck load: In this analysis, due to the lack of truck load data, both conventional and electric trucks were assumed to carry the maximum load allowed in Texas (80,000 lb). While the maximum payload capacity of a diesel versus a battery electric truck is debatable, the current study makes a reasonable assumption that they can carry the same cargo load based on already available commercial diesel and battery electric trucks [19] [20]. Furthermore, weigh-in-motion data from 15 states, including Texas, revealed that 90 percent of on-road heavy-duty trucks in operation weigh less than 73,000 pounds, implying that a diesel or battery electric truck is unlikely to reach payload capacity [21].
- 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 is greater or equal to 3 mph and the vehicle was not decelerating, the truck was idling). In addition, the continuous idling period greater than 10 minutes was labeled as a potential charging window in the output.

Using the inputs and assumptions introduced, the energy consumptions was estimated for conventional and electric trucks, and on-road emissions were computed for conventional trucks. The detailed methodology for estimating conventional vehicle and electric vehicle results is introduced in the following sections.

## Conventional Vehicle Energy and Emission Calculations

The energy and emission calculations for conventional vehicles in the FEC adopted the MOVES project-level model [16], [22]. Three preliminary steps were taken to generate the energy and emission estimations for each truck trip:

1. Calculate second-by-second scaled tractive power (STP): The second-by-second speed profile of each truck trip and vehicle type information were used to calculate the STP value for each second.
2. Compute operating mode bin distribution: At each second, the STP values, together with speed and acceleration information, were used to generate the MOVES operating mode bins (OpMode bins). The operating mode bins were aggregated to obtain the mode bin distributions.
3. Generate on-road energy and emissions: The on-road energy use and emissions were generated by multiplying the operating mode distribution with corresponding MOVES emission rates for the selected region, meteorology, and fuel type.

The trip-level energy use and emissions were generated for all 7 fleets and 40 trucks. For trips with missing driving profiles but with average speeds, the energy and emission rates were imputed using the average energy and emission rates of two other trips with closest average speeds collected from the same vehicle. The energy and emissions for those trips were then computed by multiplying imputed rates and travel time. The results of conventional vehicle energy and emissions are provided in “Results Summary.”

## Electric Vehicle Energy and Range Calculation

This study only compared on-road energy use and emissions of conventional and electric vehicles. Because no fuel was used and no combustion was involved, battery-electric vehicles (BEVs) generated zero exhaust emissions at the point of use [23]. Therefore, only the energy consumption of BEVs needed to be generated in this analysis. A modified modeling approach was implemented in the FEC to account for the energy recovery during regenerative braking, and the second-by-second energy consumption rates were estimated using the following equations:

$$Tractive\ Power\ (TP) = Av + Bv^2 + Cv^3 + M(a + gsin\theta)v \tag{1}$$

$$Energy\ rate\ (kW) = \begin{cases} TP/\eta_1\eta_2\eta_3\ (if\ TP \geq 0) \\ TP * \eta_r\ (if\ TP < 0) \end{cases} \tag{2}$$

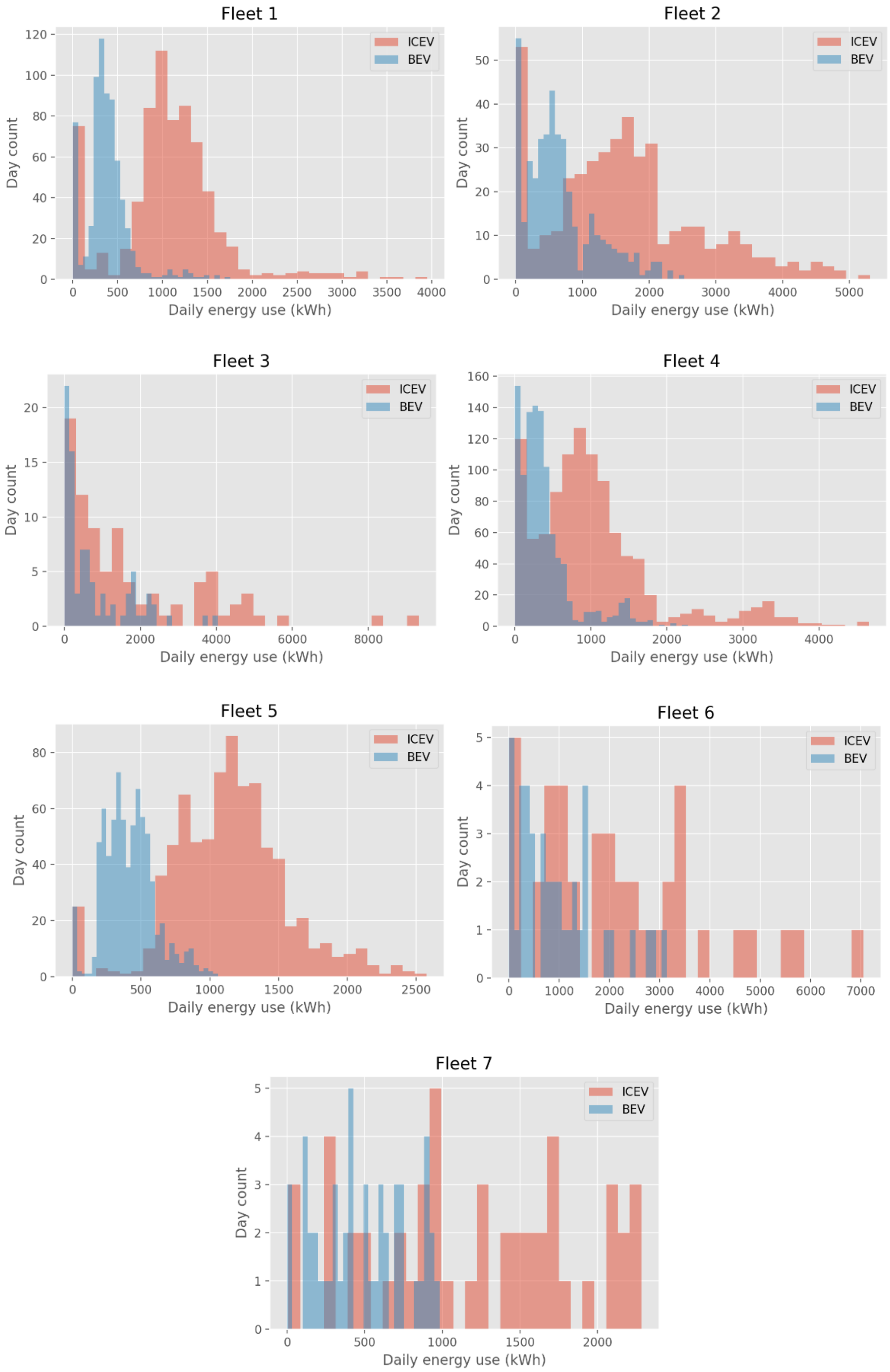
Where:

- $TP$ = vehicle tractive power in kW.
- $A, B, C$ = the road load coefficients.
- $v$ = vehicle speed in m/s.
- $a$ = vehicle acceleration in m/s$^2$.
- $M$ = source mass for the source type in metric tons.
- $g$ = the acceleration due to gravity = 9.8 m/s$^2$.
- $sin\theta$ = the (fractional) road grade.
- $\eta_{1,} \eta_2, \eta_3$ = inverter efficiency (97 percent), motor efficiency (86 percent), and battery efficiency (90 percent) from the FEC [16].
- $\eta_r =$ regenerative braking energy recovery efficiency [24].

The regenerative braking efficiency (fraction of recovered energy among vehicle kinetic energy) was assumed to be 60 percent using measurement data from a previous study [24]. Using Equations 1 and 2, researchers estimated the trip-level energy consumption for electric trucks by summing up instantaneous energy use from each second. The results of electric vehicle energy and emissions are provided in “Results Summary.”

## Results Summary

Using the methodology introduced above, researchers generated the energy use profiles for the seven fleets, for conventional vehicles and electric vehicles. The individual truck daily energy use distributions for all fleets are illustrated in Figure 4.



Note: ICEV refers to an internal combustion vehicle.

**Figure 4. Daily energy consumption per vehicle distribution by fleet.**

Due to the higher vehicle energy efficiency of electric vehicle powertrains [25], the daily energy consumption of electric vehicles was about half of their conventional counterparts. Furthermore, given 396 kWh of battery capacity, a significant portion of daily operations can be served within this capacity if electrified, which means that most shifts can be performed with a fully charged electric truck without recharge during operations. Fleet 1 and Fleet 5 had higher fractions of daily operations that can be electrified due to shorter daily operations. A more comprehensive feasibility analysis of fleet electrification is performed in Chapter 4, using the energy consumption results from the current chapter.

The FEC also provided the on-road emission results for conventional trucks to assess the environmental benefits of fleet electrification. The average emission rates per mile for each fleet are shown in Figure 5. By electrifying the fleet, the nitrogen oxide reduction can reach 1–1.2 grams/mile, which could serve as a potential mitigation strategy for the Houston ozone non-attainment area [2]. In addition, electrifying the fleet has great potential in reducing the particulate matter ($PM_{2.5}$), volatile organic compound, and greenhouse gas emissions from the high-emitting diesel fleets.

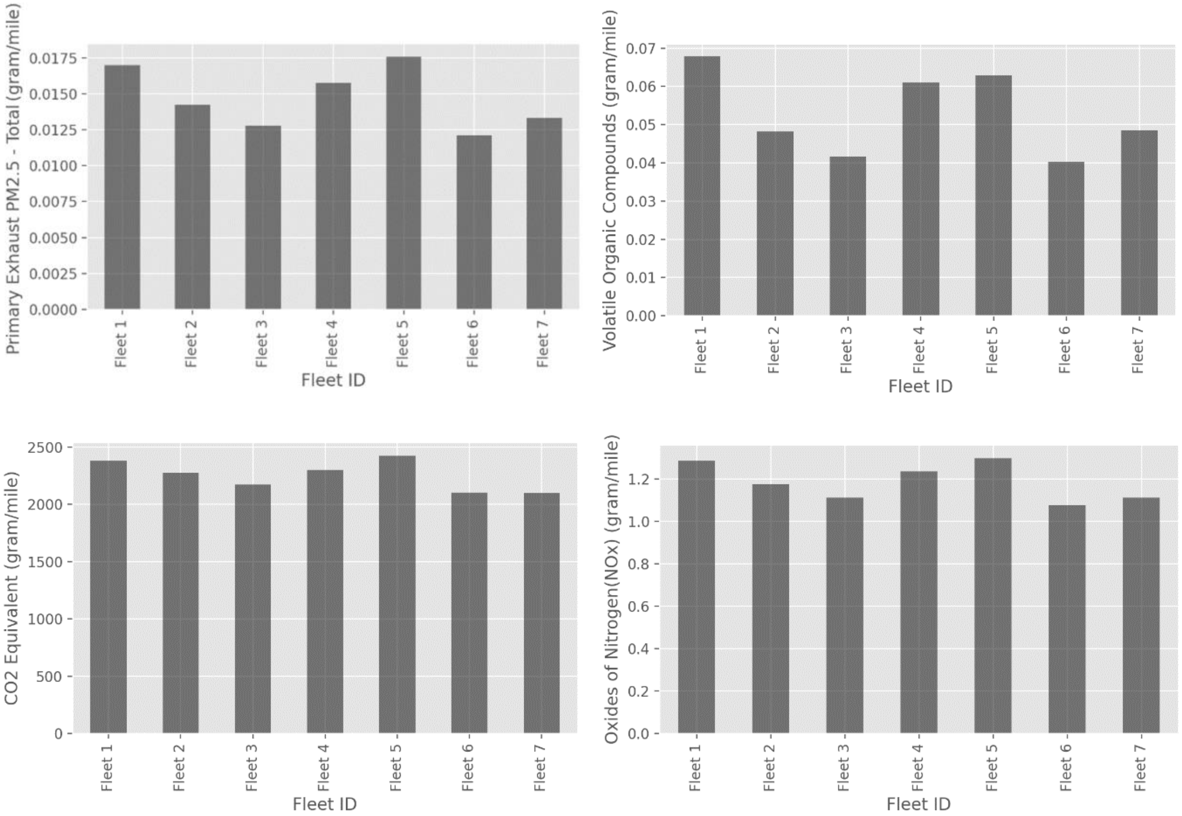


**Figure 5. Average emission rates per mile by fleet if all vehicles were new model year 2018 diesel trucks.**

# Chapter 4: Truck Electrification Feasibility Analysis

Fleet electrification requires technology availability, operational practicality, and economic workability for implementation. The three columns of feasibility assessment led to multiple criteria for fleet electrification viability, and the criteria were used to design electrification scenarios (see Figure 6). Each column is fully explained, and the relative criteria are defined in the following sections.

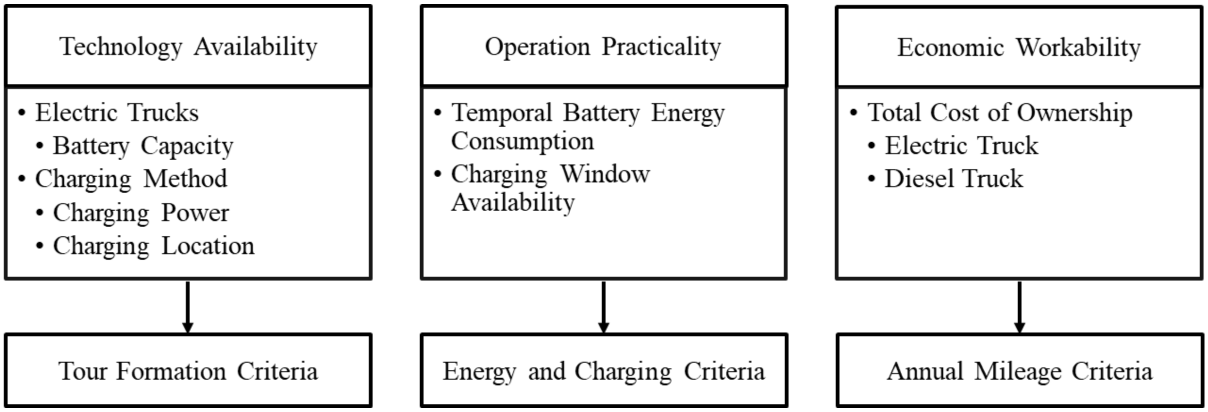


**Figure 6. Feasibility criteria.**

## Technological Feasibility

The feasibility assessment of the technology details the availability of the vehicles and charging infrastructure based on the required specifications.

### Battery-Electric Trucks

The current study focused on heavy-duty trucks and investigated commercially available BETs. Table 3 lists some of the currently operational heavy-duty BETs and their specifications. Their battery capacity ranged from 120 to 550 kWh, and the BETs had a mileage range from 120 to 170 miles.

**Table 3. Heavy-Duty Truck Specifications**

| Model | Gross Combined Weight Rating (lb) | Maximum Power (HP) | Battery Capacity (kWh) | Range (Miles) |
|---|---|---|---|---|
| Freightliner® eCascadia | 80,000 | 730 | 550 | 250 |
| Lion8® | 60,000 | 470 | 336 | 170 |
| Peterbilt® 579EV | 80,000 | 490 | 350–440 | 150 |
| Volvo® VNR Electric | 82,000 | 455 | 264 | 150 |
| BYD® 8TT | 105,000 | 483 | 435 | 124–167 |
| Kenworth® T680 | 80,000 | 450 | 396 | 150 |

### Charging Method

There is a wide range of charging methods for electric vehicles, stationary or dynamic, conductive or inductive. The plug-in station power for a direct-current fast charging can get as high as 350 kW [26]. The plug-in method is a proven solution for a low capital cost per charge port and overnight charging. However, the plug-in method requires personnel and some cable management logistics. Other charging methods include battery swap, catenary, and wireless charging.

## Operational Feasibility

The operational feasibility assessment investigated whether an electric truck can conduct current trips under battery capacity and range constraints.

### Tour Identification

A tour is a chain of trips conducted by the same truck starting and ending at the depot parking. The advantages of tour identification for fleet electrification are:

- Drayage operation consistency for scheduled delivery.
- Scheduling overnight charging at depot parking.

Therefore, this study developed the following algorithm for tour identifications for each truck:

1. Order trips based on the start time of the trip.
2. Set k = 0.
3. For each trip:
    a. If the trip start point is within 1 mile of the depot and there is a minimum engine-off duration of 30 minutes before trip start:
        i. Set k = k+1.
    b. Assign tour_id = k.

Table 4 summarizes the characteristics of identified tours from the dataset. The range of the number of tours per day, tour length, and tour duration showed a wide variety of tours happening from short haul to long haul.

**Table 4. Tour Characteristics**

| Metric | Average | Range |
|---|---|---|
| Number of tours per day | 15 | 1–69 |
| Length of tour (miles) | 83 | 0–2,610 |
| Duration of tour (hours) | 0.41 | 0.00–60.24 |

Figure 7 shows that a high percentage of tours are short haul and have the potential to be conducted by electric trucks. The study defined electrification energy criteria to better divide the tours that can be conducted by electric trucks from the rest.

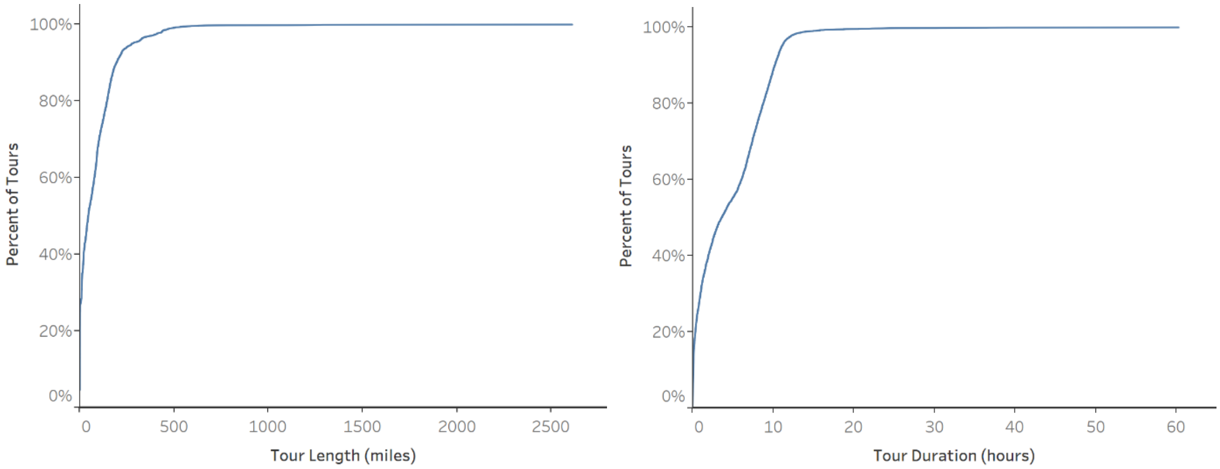


**Figure 7. Tour length and duration cumulative distribution.**

## Electrification Energy Criteria

Electric trucks should be able to conduct the tour operation within the battery capacity, and they can charge at a depot after the tour for their next tours. Therefore, the electrification energy criterion is that all tours assigned to the electric truck consume less energy than battery capacity.

If considering the maximum energy consumption of 360 kWh based on the battery capacity and a 10 percent energy reserve as a buffer, Figure 8 shows 72 percent of tours in the dataset can be conducted by electric trucks. Figure 9 shows this percentage varies from 45 to 87 percent for different fleets.

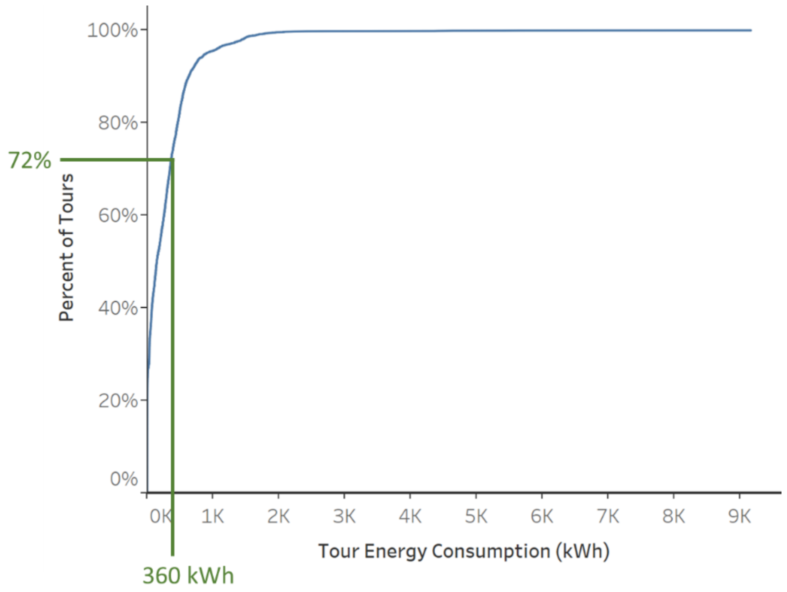


**Figure 8. Tour energy consumption cumulative distribution.**

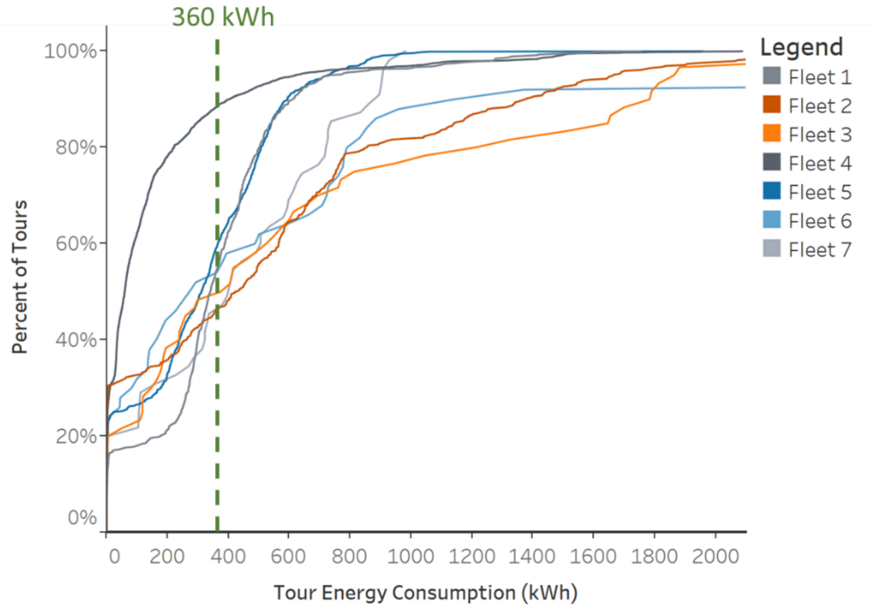


**Figure 9. Tour energy consumption cumulative distribution for fleets.**

Table 5 shows that potential tours for electrification under the energy criteria can save up to 49 percent of the diesel energy consumes or about 508,000 kWh over the data collection period.

**Table 5. Feasible Electrified Tours Characteristics**

| Attribute | Fleet 1 | Fleet 2 | Fleet 3 | Fleet 4 | Fleet 5 | Fleet 6 | Fleet 7 |
|---|---|---|---|---|---|---|---|
| Total miles traveled | 82,985 | 80,784 | 18,312 | 121,845 | 96,380 | 11,348 | 7,575 |
| Miles feasible to be electrified | 23,511 | 5,045 | 875 | 51,512 | 25,807 | 750 | 975 |
| Percent of miles feasible to be electrified | 28% | 6% | 5% | 42% | 27% | 7% | 13% |

Therefore, the next section explores the economy of electrification and identifies break-even criteria for future investment in electric trucks.

## Economic Feasibility

The break-even point in economics is where the costs and benefits of an investment become equal. In other words, the break-even criteria for electric truck investment show where the associated cost of electric trucks becomes equal to the cost of diesel trucks.

This section focuses on the development of break-even financial models based on the associated costs of truck electrification. First, the costs associated with diesel and electric trucks were explored. Then, the cost of replacing or adding an electric truck to the fleet was assessed.

### Total Cost of Ownership

The total cost of ownership (TCO) of truck fleets during entire life span was estimated based on the TCO cost analysis framework developed by the Environmental Defense Fund (EDF) [27]. The TCO cost analysis framework is a spreadsheet-based tool for estimating life-cycle costs for both medium- and heavy-duty fleets across multiple vehicle fuel types. The EDF tool adopts the latest data sources for major cost elements, such as vehicle cost, infrastructure cost, operation and maintenance (O&M) cost, and taxes. Specifically, the EDF tool includes detailed cost profiles for diesel and electric combination trucks, which makes it the best tool available for the cost analysis.

Due to the difficulty of incorporating an Excel spreadsheet into a feasibility analysis framework established in R, the EDF results were post-processed with modifications made to reflect local conditions. The cost profiles in 2018 dollars adopted in this study are summarized in Table 6.

**Table 6. Cost Profiles of Diesel Trucks and Electric Trucks (in 2018 Dollars)**

| Category | Item | Diesel Truck | Electric Truck | Source | Reference |
|---|---|---|---|---|---|
| Capital cost | Vehicle purchase cost ($/veh) | 140,000 | 262,363 | EDF | [27] |
| | Infrastructure cost ($/station) | N/A | 60,000 | Proterra 125 kW Electric Bus Chargers | [28] |
| | Life span (year) | 12 | 12 | EDF | [27] |
| O&M cost | Unit O&M cost ($/mile) | 0.21 | 0.1025 | EDF | [27] |
| | Fuel price—low ($/kWh) | 0.09 | 0.1 | EDF | [27] |
| | Fuel price—medium ($/kWh) | 0.10 | 0.13 | EDF | [27] |
| | Fuel price—high ($/kWh) | 0.11 | 0.16 | EDF | [27] |
| Other cost | Retail tax rate (%) | 6.25% | 6.25% | Texas Comptroller of Public Accounts | [29] |
| | Retail tax ($) | 8,750 | 16,398 | Calculated | |
| | Registration fee (70,000–80,000 lb) | 840 | 840 | Texas Department of Motor Vehicles | [30] |
| | Registration fee (Harris County surcharge) | 11.5 | 11.5 | Texas Department of Motor Vehicles | [30] |

The life cycle TCO of the entire fleet (diesel or electric) was estimated using the following equations:

$$\begin{aligned}&\mathit{Total\ capital\ cost\ at\ year\ zero} = \\ &(\mathit{number\ of\ electric\ trucks} * \mathit{electric\ truck\ purchase\ cost}) + (\mathit{number\ of\ charging\ units} * \\ &\mathit{unit\ charger\ cost}) + (\mathit{number\ of\ diesel\ trucks} * \mathit{diesel\ truck\ purchase\ cost})\end{aligned} \tag{3}$$

$$\begin{aligned}&\mathit{Total\ retail\ tax\ at\ year\ zero} = \\ &(\mathit{number\ of\ electric\ trucks} * \mathit{electric\ truck\ retail\ tax}) + (\mathit{number\ of\ diesel\ trucks} * \\ &\mathit{diesel\ truck\ retail\ tax})\end{aligned} \tag{4}$$

$$\begin{aligned}&\mathit{Total\ annual\ fees\ paid\ at\ the\ start\ year\ m} = \\ &(\mathit{number\ of\ electric\ trucks} * \mathit{electric\ truck\ registration\ fee}) + (\mathit{number\ of\ diesel\ trucks} * \\ &\mathit{diesel\ truck\ registration\ fee})\end{aligned} \tag{5}$$

$$\begin{aligned}&\mathit{Total\ annual\ O\&M\ cost\ paid\ at\ the\ end\ year\ m} = \\ &\mathit{annual\ electric\ mileage} * \mathit{electric\ truck\ unit\ O\&M\ cost} * (1 + re_e)^m + \\ &\mathit{annual\ electric\ energy\ use} * \mathit{electric\ truck\ fuel\ rate} * (1 + rf_e)^m + \mathit{annual\ diesel\ mileage} * \\ &\mathit{diesel\ truck\ unit\ O\&M\ cost} * (1 + re_d)^m + \mathit{annual\ diesel\ energy\ use} * \mathit{diesel\ truck\ fuel\ rate} * \\ &(1 + rf_d)^m\end{aligned} \tag{6}$$

$$\begin{aligned}&\mathit{TCO}\ (\mathit{net\ present\ value\ at\ year\ zero}) = \\ &\mathit{Total\ capital\ cost\ at\ year\ zero} + \mathit{Total\ retail\ tax\ at\ year\ zero} + \\ &\sum_{m=1}^{\mathit{life\ span}} \frac{\mathit{Total\ annual\ fees\ paid\ at\ the\ start\ year\ m}}{(1+r)^{m-1}} + \\ &\textstyle\sum_{m=1}^{\mathit{life\ span}} \frac{\mathit{Total\ annual\ O\&M\ cost\ paid\ at\ the\ end\ year\ m}}{(1+r)^m}\end{aligned} \tag{7}$$

Where:

$re_e$ = inflation rate for electric trucks equipment
$rf_e$ = inflation rate for electric trucks fuel
$re_d$ = inflation rate for diesel trucks equipment

$rf_d$ = inflation rate for diesel trucks fuel
$r$ = discount or return rate

The assumption for these values considering the EDF tool and current trends[1] is:

$$re_e = 0.065;\ rf_e = 0.05;\ re_d = 0.065;\ rf_d = 0.06;\ r = 0.03$$

To compute the fleet TCO, the users provided the number and specifications of diesel and electric trucks. The users also specified the fuel cost scenarios (low, medium, and high) to account for different fuel price scenarios. With Equations 3–7, the TCO was estimated for mixed diesel and electric trucks. The current calculation of the TCO did not include any rebates, insurance premiums, downtime cost, and salvage values.

## Electrification Mileage Criteria

As demonstrated in Chapter 3, electric trucks have a lower O&M cost than diesel trucks, mostly because of the lower energy consumption of electric trucks compared to their diesel counterparts. The energy consumption rates can be well approximated by a linear relationship with mileage:

- Diesel truck energy consumption (kWh) = 7.78 × diesel mileage + 78.
- Electric truck energy consumption (kWh) = 3.39 × electric mileage − 8.4.

Therefore, there is a break-even mileage at which the cost saving from O&M overcomes the higher purchase price. Figure 10 shows the TCO of diesel and electric trucks over different annual mileages. An annual mileage of about 27,000 or higher makes the TCO of electric trucks smaller than that of diesel trucks and more economically beneficial to the fleet owner. Therefore, if the fleet owner knows the truck is going to operate more than 27,000 miles per year, then electric truck is a more economical option.

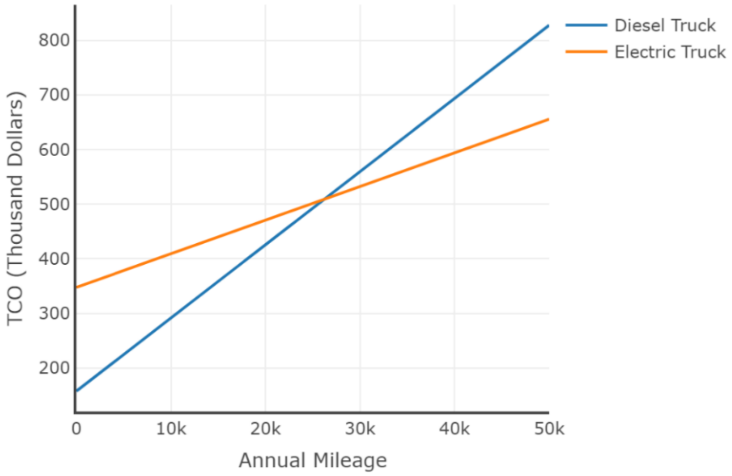


**Figure 10. TCO for diesel truck versus electric truck and the break-even annual mileage.**

With the technology becoming more available and more truck models joining the market, the price gap between diesel and electric trucks will decrease. Federal and state rebates for electrification contribute to the price gap reduction as well. Figure 11 shows that a 50 percent reduction in the purchase price (about $130,000) can lead to a

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[1] The U.S. Bureau of Labor Statistics provided more information at https://www.bls.gov/cpi/factsheets/motor-fuel.htm.

break-even annual mileage of 5,000 miles. This scenario may become a reality according to several recent announcements.[2]

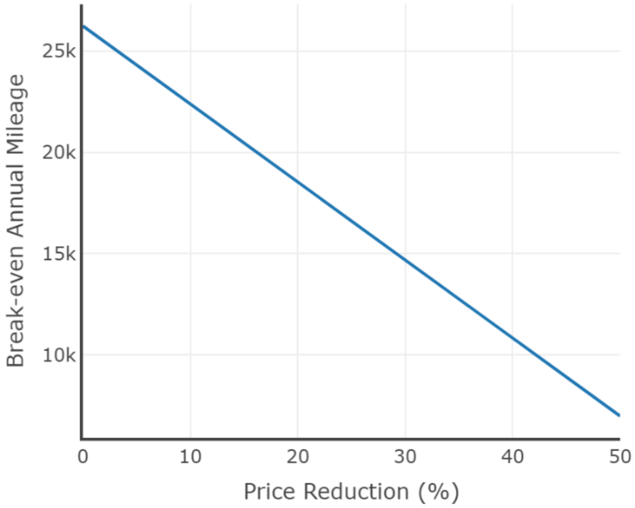

**Figure 11. Break-even annual mileage for potential reductions in purchase price.**

Also, the break-even annual mileage can vary based on electricity and diesel growth rate. Figure 12 shows how different growth rates result in different break-even points.

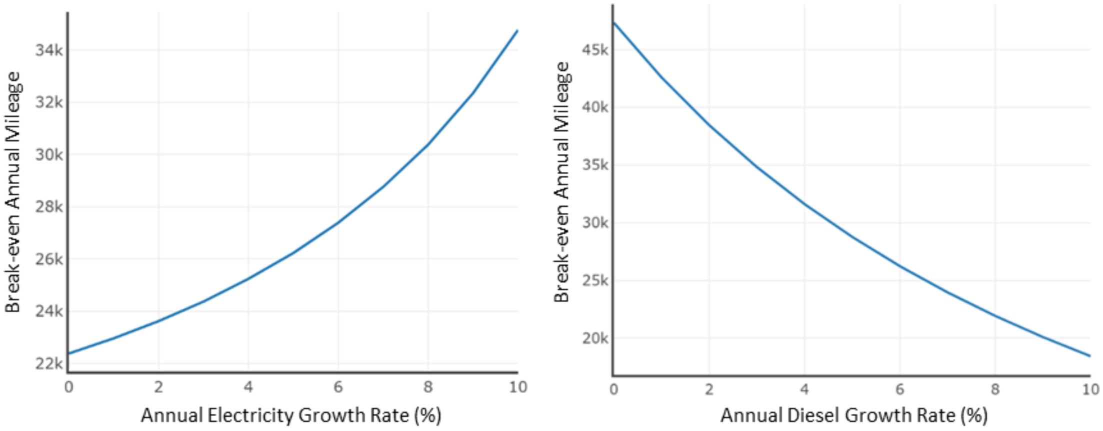

**Figure 12. Break-even annual mileage for the electricity and diesel price growth rate.**

The other question in economic assessment is whether it is beneficial for the fleet owner to purchase an electric truck as an addition to the diesel truck fleet and assign the energy-feasible tours to the electric truck. In other words, when is it economical for fleet owner to purchase an additional electric truck? Figure 13 shows that at an annual mileage of about 48,000 miles for the electric truck, an additional electric truck can lower the TCO. Again, the break-even mileage may be reduced to about 28,000 miles per year by a 50 percent reduction in purchase price.

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[2] Tesla provides more information at https://www.tesla.com/semi.

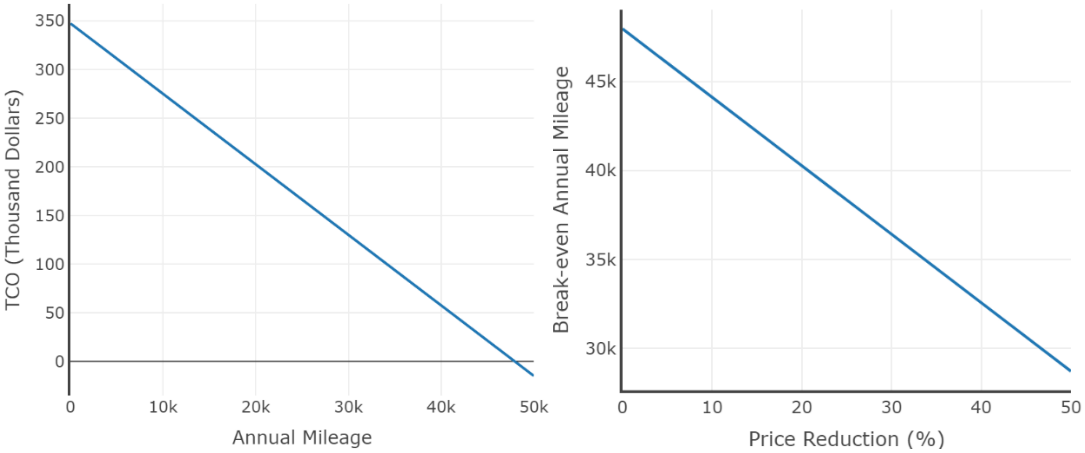

**Figure 13. Break-even annual mileage for purchase of an additional electric truck.**

# Chapter 5: Conclusions and Future Work

## Key Findings

This study assessed the feasibility of electrifying heavy-duty trucks based on real-world operation data collected from drayage trucks in the Houston region. To achieve this goal, the energy use and emissions of current truck operations were estimated using the FEC. Then, a feasibility analysis framework was proposed to account for the technological, operational, and economic viability of electrifying the truck fleet.

The results demonstrated that the feasibility of fleet electrification can vary greatly under different operation patterns and fleet characteristics. Up to 42 percent of a fleet's mileage can be electrified with current electric truck technology and the assumption that charging is only available at the depot. The percentage of miles that can be electrified will increase if additional charging opportunities exist beyond the depots. Given the current purchase price of diesel and electric trucks and an assumption of a 12-year life span, the break-even point for an electric truck is around 27,000 annual mileage. Compared to a new diesel truck, an electric truck would offer more than 1 gram per mile of nitrogen oxide emission saving from the tailpipe. Such emissions benefits would only grow with time because electric trucks will continue to have zero emissions from the tailpipe, but diesel trucks will become more polluting as they age.

## Discussions

The findings from this project indicate that electric trucks are not yet able to fulfill all operations of a drayage truck fleet, but it is feasible for a sizable portion of drayage operations both technologically and economically. Challenges remain to deploy electric trucks in three aspects. First, assigning the shorter tours that would fit the range constraints to one or more electric trucks will mean operational and scheduling changes for the fleet operator. Such assignment changes may be computationally complex, too. Second, the dwelling time required to charge further complicates the difficulty in scheduling tours. Some preliminary optimization experiments the project team has conducted indicate that fleets would need powerful fast chargers (greater than 125 kW) to shorten the required charging time and electrify more trucks.[3] Third, charging opportunities outside the depots, such as frequently visited locations (e.g., the port) and along major roadway corridors, could expand the feasible region of electric operations. Intelligently placing these chargers is another operations research challenge.

Despite these challenges, electric trucks bring measurable emissions benefits to communities near the roadways and the port. When these emissions can be monetized through public incentives, the economic attractiveness of electric trucks increases substantially. The analysis from this project has shown that an incentive of $130,000 would bring the break-even annual mileage point of an electric truck to 5,000 miles, making an electric truck an attractive choice over diesel trucks. Such incentives should be further considered by policy makers as they contemplate ways to improve air quality and public health.

## Future Work

The current study can be further expanded in the following aspects:

- By scaling up the results to more truck fleets, the economic and environmental benefits can be assessed at the regional level.
- Rigorous optimization algorithms should be developed to include multiple decision variables, such as the type of charging facility, dynamic electricity cost, and corridor charging for long-distance travels to facilitate the deployment and implementation of electric trucks.
- The charging load from this study can also be applied to investigate the grid impact of heavy-duty truck-charging behavior.

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[3] The optimization algorithms are outside the scope of this study and will be reported in a separate publication.

- The environmental benefits from this study might be relevant to the health condition of surrounding neighborhoods. The findings from this study could be beneficial for health impact study near the port.

## References

[1] City of Houston Office of Sustainability, *Houston Climate Action Plan,* Houston, Texas, 2020. http://greenhoustontx.gov/climateactionplan/CAP-April2020-Spreadsheet.pdf

[2] Texas Commission on Environmental Quality, *Understanding General Conformity in Texas*, 2020.

[3] PG&E, *A Guidebook to Fleet Electrification and Infrastructure,* 2019.

[4] Port of Houston Authority, *Port of Houston Overview,* 2020.

[5] Texas Transportation Institute, *Implementation of Idle Reduction Technologies at Ports—Case Study Evaluation for the Port of Houston,* College Station, Texas, 2009.

[6] AECOM, *Zero-Emission Cargo-Handling Equipment Feasibility Assessment,* 2019.

[7] J. Filippo, C. Callahan, and N. Golestani, *Zero-Emission Drayage Trucks—Challenges and Opportunities for the San Pedro Bay Ports,* 2019.

[8] H. Ambrose and M. Jaller, *Electrification of Drayage Trucks: On Track for a Sustainable Freight Path,* 2016.

[9] Port of Oakland, *Zero-Emissions Drayage Truck Feasibility Study,* 2019.

[10] Tetra Tech, *2018 Feasibility Assessment for Drayage Trucks,* 2019.

[11] R. Farzaneh, J. Johnson, T. Ramani, R. Jaikumar, A. Meyer, and J. Zietsman, *Collection and Analysis of Vehicle Activity Data to Improve Transportation and Air Quality Planning*, 2018. Available online at https://www.h-gac.com/getmedia/12a1530d-ad4f-4705-8e8b-68ccd2f29787/Vehicle-Activity-Data-09192018.

[12] A. Standard, C. Fulper, S. Kishan, and M. Sabisch, "Measurement and Analysis of the Operations of Drayage Trucks in the Houston Area in Terms of Activities and Exhaust Emissions," *SAE International Journal of Commercial Vehicles*, 11(2): 77–92, 2018. Available online at https://doi.org/10.4271/02-11-02-0007.

[13] U.S. Environmental Protection Agency, *MOVES2014, MOVES2014a, and MOVES2014b Technical Guidance: Using MOVES to Prepare Emission Inventories for State Implementation Plans and Transportation Conformity*, 2018.

[14] Q. Kong, T. Siauw, and A. Bayen, "Chapter 17—Interpolation." In Q. Kong, T. Siauw, and A. Bayen (Ed.), *Python Programming and Numerical Methods*, Academic Press, 295–313, 2021. Available online at https://doi.org/10.1016/B978-0-12-819549-9.00027-0.

[15] J. Jun, R. Guensler, and J. H. Ogle, "Smoothing Methods to Minimize Impact of Global Positioning System Random Error on Travel Distance, Speed, and Acceleration Profile Estimates," *Transportation Research Record: Journal of the Transportation Research Board*, 1972(1): 141–150, Jan. 2006. Available online at https://doi.org/10.1177/0361198106197200117.

[16] X. Xu, H. Liu, R. Passmore, T. Patrick, F. Gbologah, M. Rodgers, and R. Guensler, *Fuel and Emissions Calculator (FEC), Version 3.0, Summary Report,* 2018. Available online at https://escholarship.org/uc/item/59z12905.

[17] Texas Department of Motor Vehicles, *Texas Size/Weight Limits*, 2020.

[18] Peterbilt, “Model 579 EV Sales Sheet,” 2020. Available online at https://www.peterbilt.com/download/file/9196

[19] Penske Corporation, *2011 Freightliner Cascadia 113,* 2011.

[20] PG&E, *Summary of Zero Emission Vehicles and Equipment for Distribution and Delivery Fleets,* 2020.

[21] S. Davis, and R. Boundy, *Transportation Energy Data Book: Edition 39,* 2021.

[22] Y. Xu, F. E. Gbologah, D.-Y. Lee, H. Liu, M. O. Rodgers, and R. L. Guensler, “Assessment of Alternative Fuel and Powertrain Transit Bus Options Using Real-World Operations Data: Life-Cycle Fuel and Emissions Modeling,” *Applied Energy*, 154: 143–159, Sept. 2015. Available online at https://doi.org/10.1016/j.apenergy.2015.04.112.

[23] T. Murrells and Y. Pang, *Emission Factors for Alternative Vehicle Technologies,* 2013.

[24] W. Zhang, J. Yang, W. Zhang, and F. Ma, “Research on Regenerative Braking of Pure Electric Mining Dump Truck,” *World Electric Vehicle Journal*, 10(2): 39, June 2019. Available online at https://doi.org/10.3390/wevj10020039.

[25] X. Zhang and C. Mi, *Vehicle Power Management*, Spring London, 2011.

[26] C. Michelbacher, S. Ahmed, I. Bloom, A. Burnham, B. Carlson, F. Dias, E. J. Dufek, A. N. Jansen, M. Keyser, A. Markel, A. Meintz, M. Mohanpurkar, A. Pesaran, D. Scoffield, M. Shirk, T. Stephens, T. Tanim, R. Vijayagopal, and J. Zhang, “Enabling Fast Charging—Introduction and Overview,” *Journal of Power Sources*, 367: 214–215, no. NREL/JA-5400-69053; INL/JOU-18-45158-Rev000, 2017.

[27] Environmental Defense Fund, *Guide to the EDF Total Cost of Ownership Model for Transit Fleeting Planning,* 2019.

[28] Greater Bridgeport Transit, *Zero Emission Electric Buses 2020,* 2020.

[29] Texas Comptroller of Public Accounts, *Motor Vehicle—Sales and Use Tax,* 2021.

[30] Texas Department of Motor Vehicles, *Texas Registration Fees,* 2021.