WORKING PAPER

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Preparing for electric drayage trucks: Analysis of real-world operations in the Seattle-Tacoma port region

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SUMMARY

This study analyzes the operations of a population of drayage trucks in the Seattle-Tacoma region to provide insights on fleet electrification planning. Through analysis of telematics data from 10 vehicles over 22 months, combined with driver surveys from 31 operators and terminal gate data from five major ports, the study establishes operational patterns and develops representative drive cycles for vehicle simulation. The analysis reveals three distinct operational categories—local, short-haul, and regional—with substantially different daily distance requirements and infrastructure needs. Unlike broader studies that examine drayage operations at a high level, this analysis focuses on detailed operational patterns in a specific port region to capture the nuanced daily realities of drayage operations. These foundational insights provide concrete, actionable data for policymakers, fleet operators, and infrastructure planners working to accelerate electric drayage vehicle adoption. This study is the first part of a planned three-part series examining drayage truck electrification in the Seattle-Tacoma port region.

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INTRODUCTION

Medium- and heavy-duty vehicles (MHDVs) are significant contributors to transportation sector emissions, accounting for approximately 21% of greenhouse gas (GHG) emissions from on-road vehicles in the United States despite representing only 5% of the vehicle fleet (Ledna, et al., 2024). Class 7-8 vehicles with a gross vehicle weight greater than 26,000 lb comprise 22% of the MHDV fleet while accounting for 66% of MHDV GHG emissions (U.S. Department of Energy, 2024). With the adoption of several federal and state policies and private industry efforts, there is increasing focus on eliminating tailpipe emissions from diesel trucks.

Drayage trucks, which transport goods between ports, rail yards, and warehouses, are critical to the global supply chain. However, the reliance on trucks powered by diesel and natural gas negatively impacts environmental and public health, particularly in port-adjacent communities (U.S. Environmental Protection Agency, 2022). Transitioning drayage fleets to zero-emission vehicles (ZEVs) could address these challenges while potentially reducing operational costs (Basma, Buysse, Zhou, & Rodriguez, 2023).

Washington State has implemented a variety of policies to support the transition to zero-emission trucks. In 2021, Washington adopted California's Advanced Clean Trucks rule, which requires manufacturers to sell an increasing percentage of zero-emission trucks (Washington State Legislature, 2023). Several incentive programs for MHDV electrification are offered, such as grants for diesel vehicle replacement, tax credits, and point-of-sale vouchers (U.S. Department of Energy, 2023). The Northwest Seaport Alliance (NWSA) has established a Clean Air Strategy and a plan to phase out port-related drayage truck emissions (Puget Sound Zero-Emission Truck Collaborative, 2025). These efforts are supported by comprehensive planning initiatives like Seattle City Light's Medium and Heavy-Duty Charging Infrastructure Strategy, which outlines charging infrastructure needs and optimal deployment locations to support fleet electrification in the region (Steimer, Allcock, Minjares, Brito, & Buysse, 2024).

This study presents a comprehensive analysis of raw telematics data from 10 drayage trucks to evaluate the potential for drayage truck electrification in the Seattle and Tacoma port region.[1] The analysis identifies characteristic operational patterns and develops representative drive cycles that capture the diverse duty cycles of drayage operations. By examining real-world operational data from a key port region, we can better understand the practical requirements and challenges for electrification in similar port environments. These insights can serve as a resource for policymakers, fleet operators, and other stakeholders working to accelerate the adoption of electric drayage vehicles.

DATA COLLECTION

To support the assessment of zero-emission technologies in drayage trucking in the Puget Sound region, a comprehensive data collection effort was undertaken through a partnership between the International Council on Clean Transportation (ICCT), the African Chamber of Commerce of the Pacific Northwest (ACCPNW), and NWSA.

1 This study is the first in a planned three-part series examining drayage truck electrification. Additional information on an upcoming technical feasibility study and an economic analysis can be found in the appendix.

This study combines three complementary data sources:

» An anonymous survey of 31 drayage truck operators from the ACCPNW to understand operational patterns and constraints.

» Radio-frequency identification (RFID) gate data from five major terminals in the Ports of Seattle and Tacoma provided by NWSA to analyze port terminal operations.

» Detailed telematics data from a sample of 10 drayage trucks to capture real-world driving patterns.

Together, these data sources provide a comprehensive view of drayage operations in the region, with particular focus on small fleets and independent owner-operators. The following sections describe the driver survey, port operations analysis, and telematics data collection, along with relevant insights.

DRIVER INSIGHTS

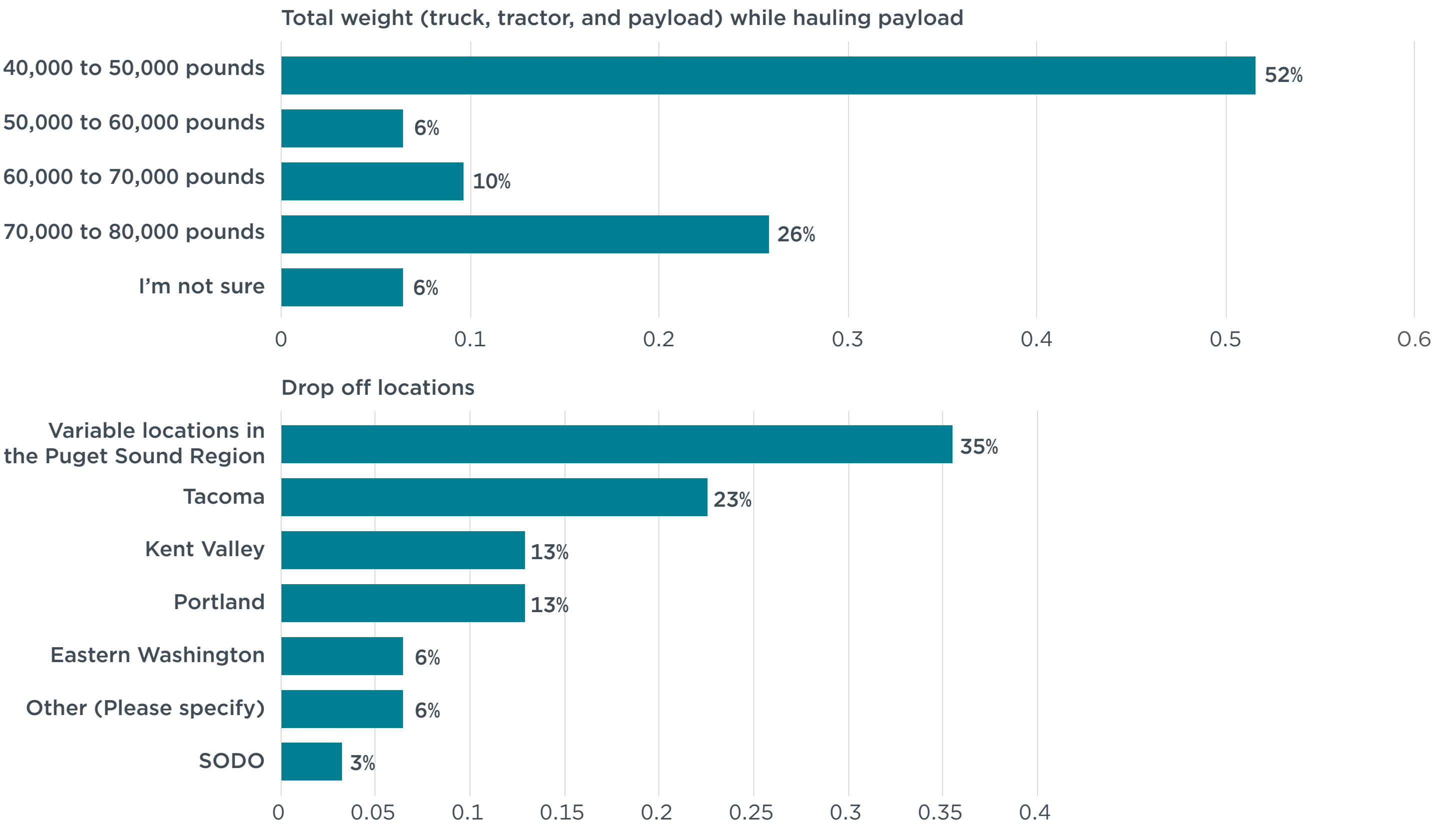
To understand the operational and financial considerations that may affect the transition to zero-emission vehicles, an anonymous survey was conducted in collaboration with ACCPNW. This survey, which gathered responses from 31 drayage truck operators, was part of a broader outreach project which included webinars and focus group discussions between June and October 2021. While this sample provides insights into the local drayage community, it represents a subset of the broader drayage operation in the Seattle-Tacoma port region, which includes more than 3,500 unique trucks according to RFID gate data from the ports. For this reason, it is not known to what extent it represents the views of drivers whose vehicles were equipped with telematics devices.

Operational considerations

Analysis of load weights showed that most drayage operations involve light to moderate loads, with only 26% of trips utilizing full vehicle capacity. The geographic distribution of deliveries demonstrated a strong local focus, with the highest concentration of drop-offs in Tacoma (23%) and various locations throughout the Puget Sound region (35%) (Figure 1).

Figure 1

Total vehicle weight carried by the respondents and drop-off location distribution



Note: Total weight includes the truck, trailer, and payload. N=31 respondents.
Source: ACCPNW Drayage Operator Survey (June–October 2021).

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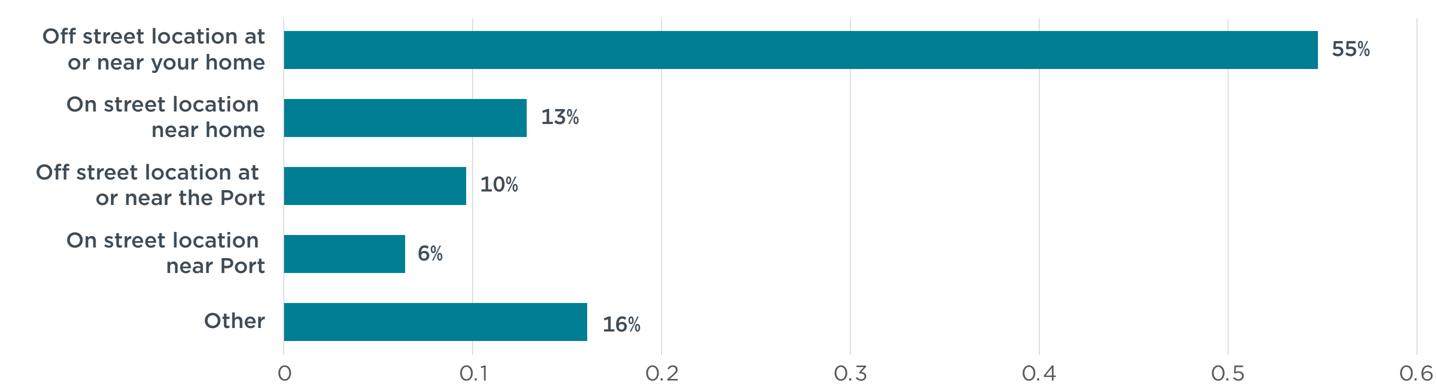
Daily operations face several challenges, particularly regarding parking and port efficiency. Most drivers (55%) park their trucks off-street near their homes (Figure 2), with 48% paying for parking. These parking patterns have important implications for overnight charging strategy development, provided the parking locations are consistent.

Figure 2

Parking locations of respondents' trucks at the end of day



Source: ACCPNW Drayage Operator Survey (June–October 2021). N=31 respondents.

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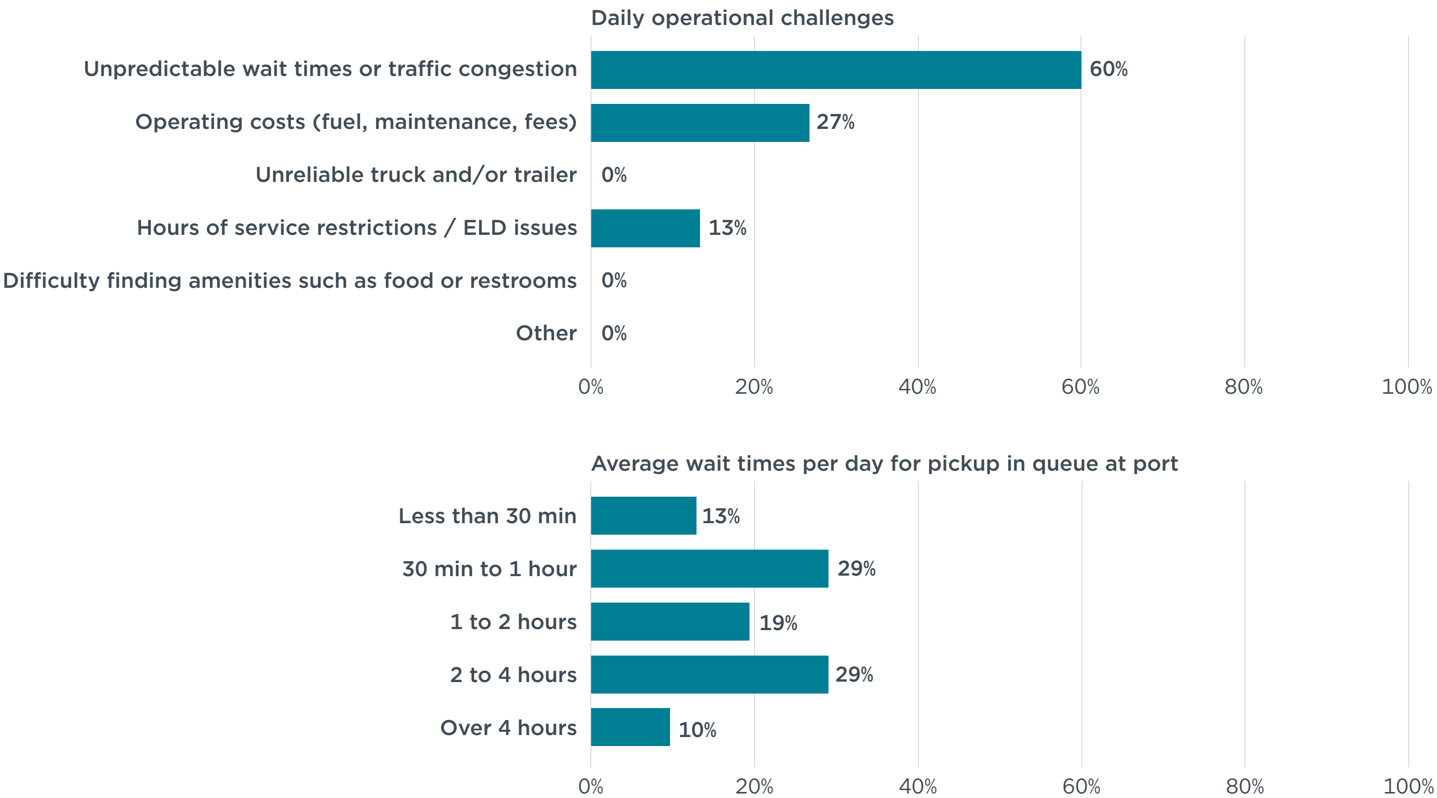
A serious operational challenge emerged from the survey results: unpredictable wait times at ports, cited by 60% of respondents as their primary concern. Time spent waiting at ports also emerged as an important issue, with 77% of drivers reporting wait times between 30 minutes to 4 hours per day (Figure 3); the extent and duration of wait times varied through the day. These inefficiencies can affect operational planning and contribute to increased emissions from idling vehicles. However, given that most drivers operate only on weekdays, with trucks typically parked on weekends, there are potential opportunities for regular, low-power, and inexpensive charging of zero-emission trucks.

Figure 3

Biggest challenge for respondents' daily operations and wait times for pickup at port



Source: ACCPNW Drayage Operator Survey (June–October 2021). N=31 respondents.

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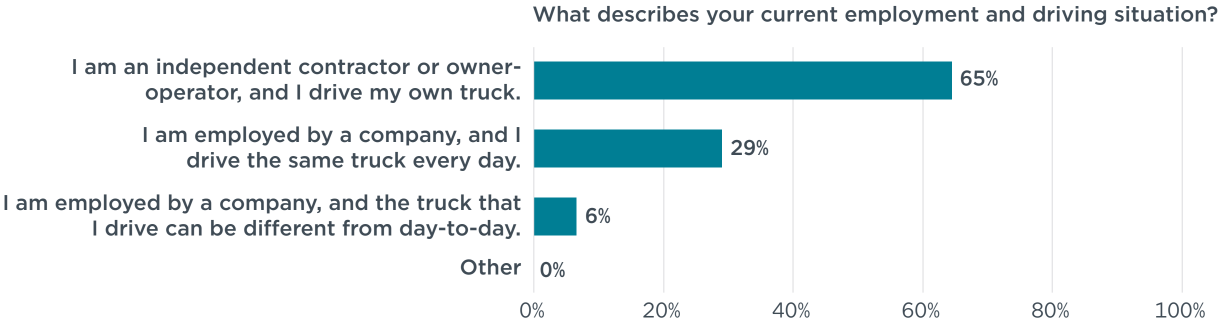
Financial considerations

The survey also revealed important financial and ownership patterns that could influence electrification strategies. The majority (65%) of respondents were independent contractors or owner-operators driving their own trucks, while 29% were company employees driving the same truck daily (Figure 4).

Figure 4
Employment and driving situation of respondents



Source: ACCPNW Drayage Operator Survey (June–October 2021). N=31 respondents.
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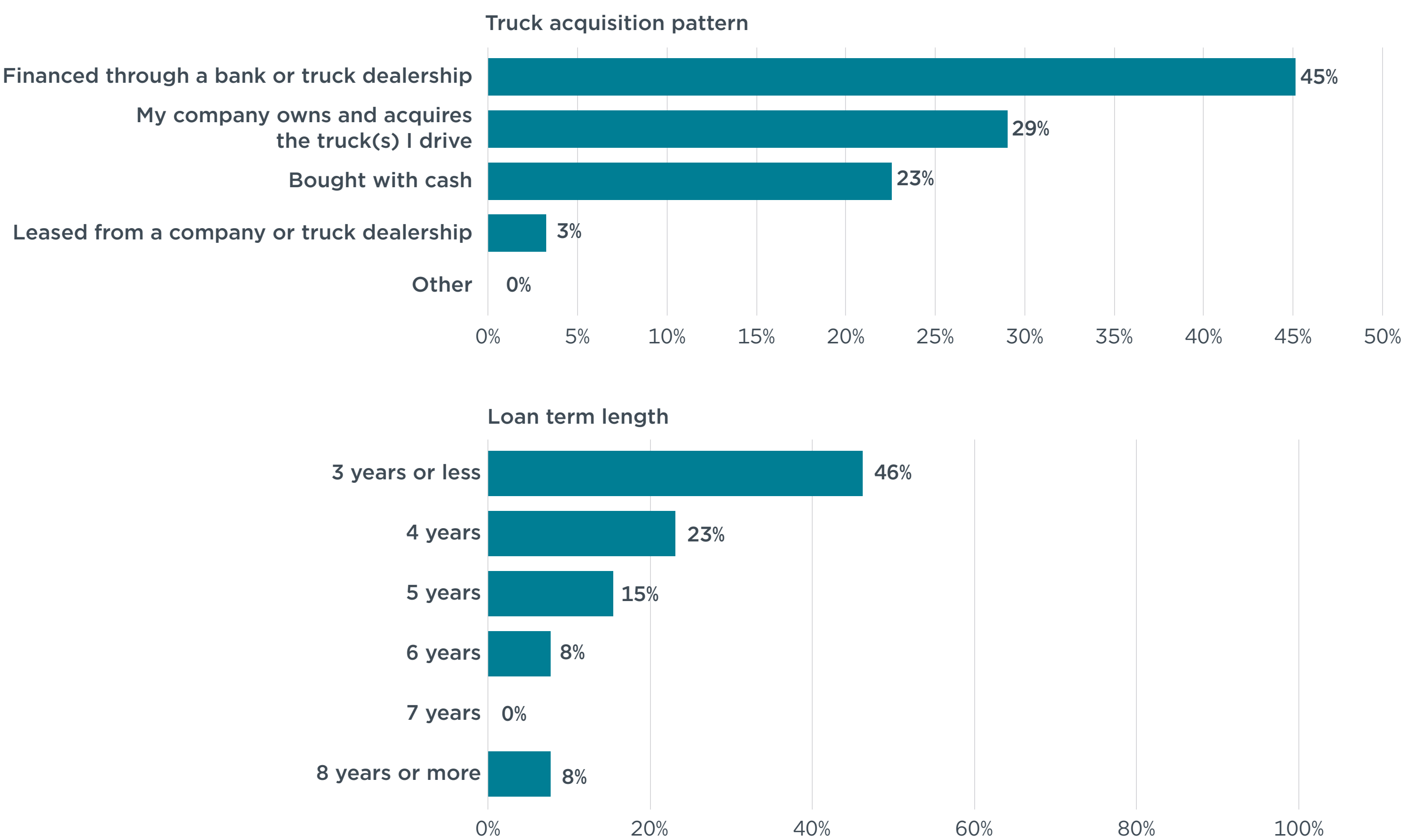
This ownership structure is reflected in vehicle acquisition patterns, where 45% of trucks were financed through banks or dealerships, 23% were purchased with cash, and 29% were company-owned (Figure 5). Among those who financed their vehicles, 46% had loan terms of 3 years or less, and 93% of respondents reported carrying current loan payments.

Figure 5
Truck acquisition method and loan term, if applicable



Source: ACCPNW Drayage Operator Survey (June–October 2021). N=31 respondents.
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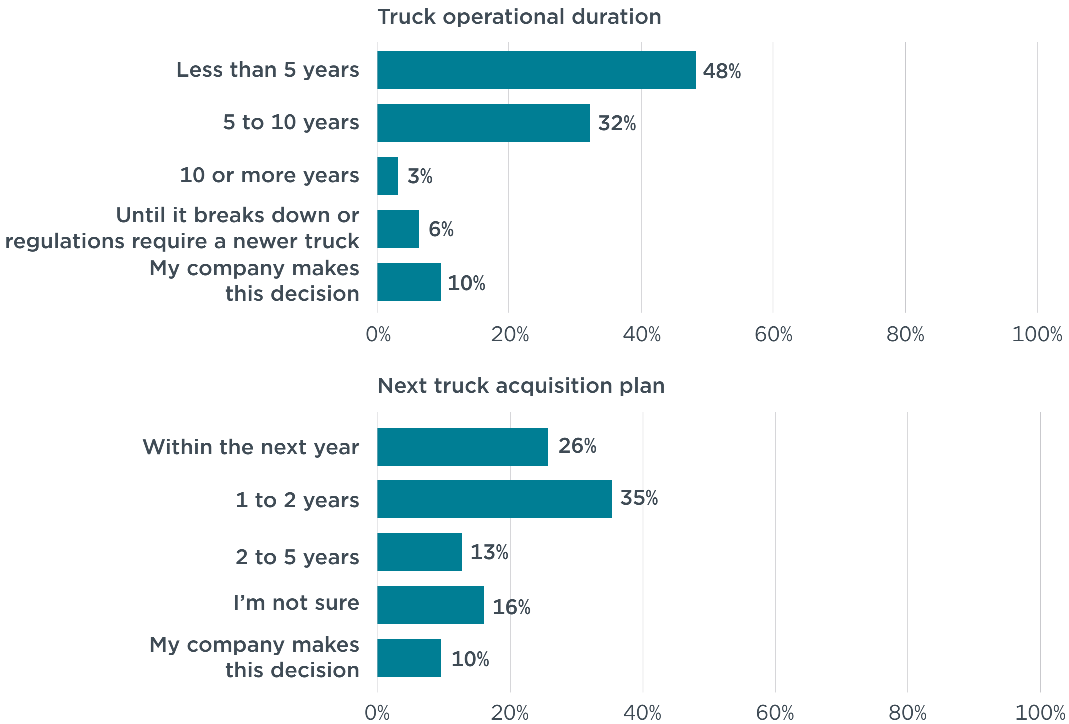
The survey also revealed patterns in fleet turnover and financing. Nearly half of respondents plan to operate their trucks for only 5 years (Figure 6), and approximately 60% intend to acquire a new or used truck within 2 years.

Figure 6

Duration of operation and next vehicle acquisition plan for respondents' trucks



Source: ACCPNW Drayage Operator Survey (June–October 2021). N=31 respondents.

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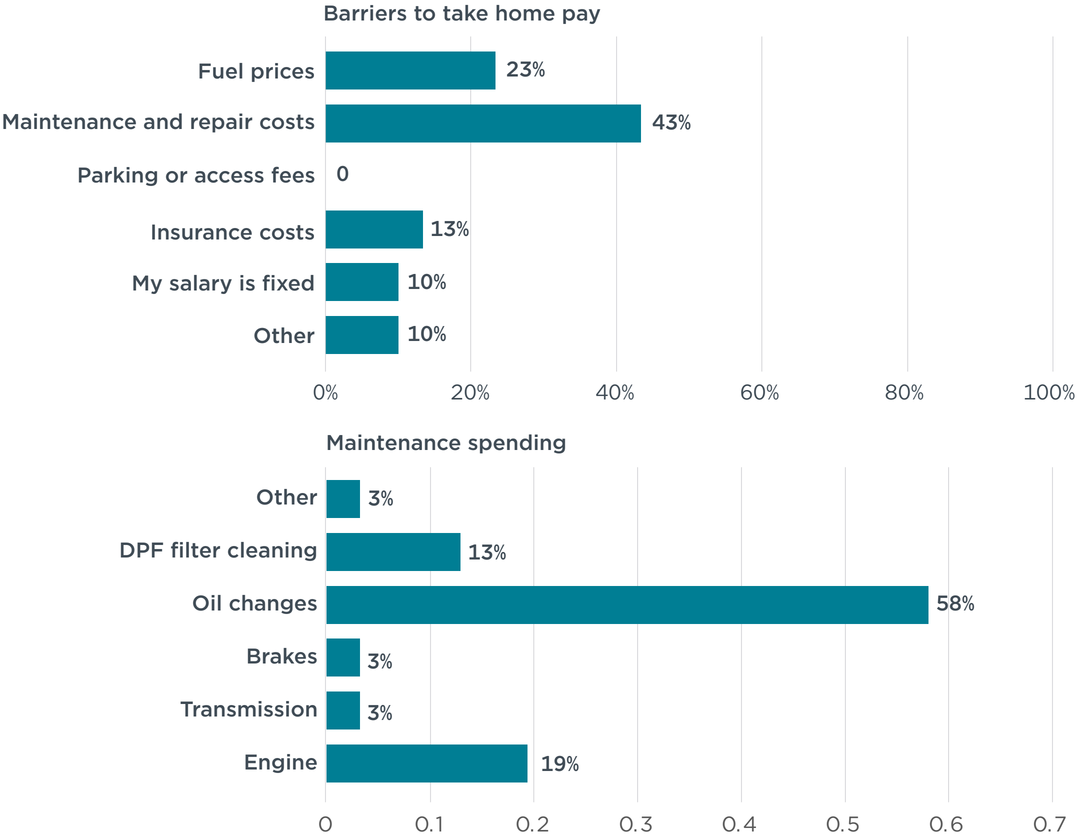
High operating costs such as fuel and maintenance were cited by 27% of respondents as their primary concern (Figure 3), with 43% indicating that maintenance and repair costs were the biggest barrier to increasing their take-home pay (Figure 7). Many drivers reported spending over $100 monthly just for truck parking. Oil changes represented one of the highest maintenance costs, highlighting a potential cost advantage for electric vehicles.

Figure 7

Barriers to take home pay and maintenance spending for respondents



Source: ACCPNW Drayage Operator Survey (June–October 2021). N=31 respondents.

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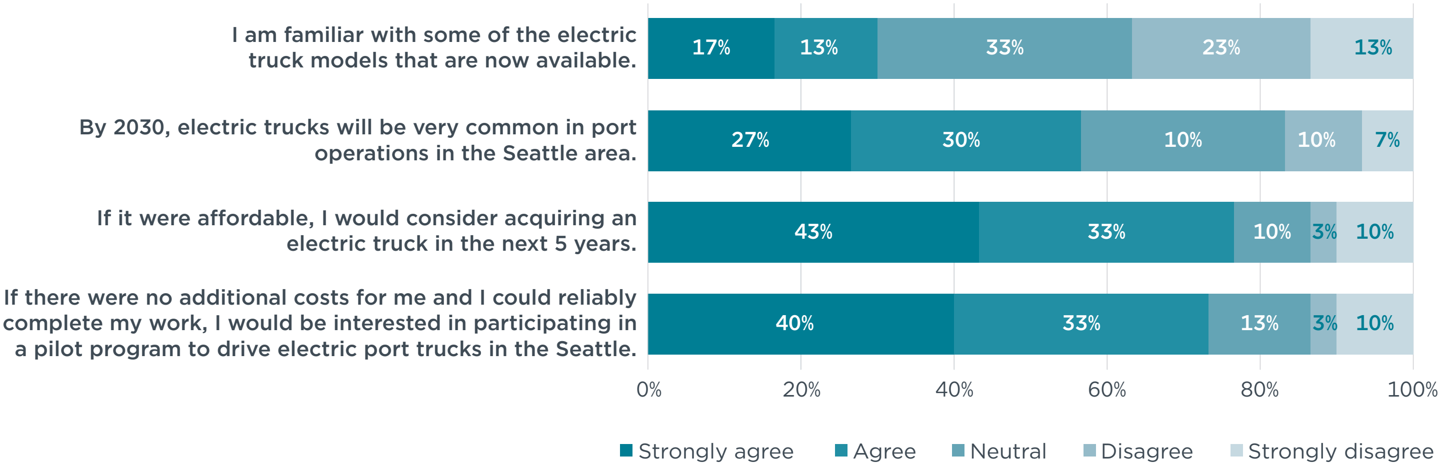
One concerning economic indicator emerged from the data: 42% of the surveyed drivers (13 out of 31) also work for ridesharing or delivery services, suggesting that drayage trucking alone may not provide sufficient income for these operators. This financial pressure could affect drivers' ability to invest in new vehicle technologies and should be considered in developing support mechanisms for fleet electrification.

Regarding future electrification, while 76% of respondents stated they would consider acquiring an electric truck if affordable (43% strongly agree, 33% agree), only 30% were familiar with currently available models. Additionally, 73% expressed interest in participating in pilot programs for electric port trucks (Figure 8), suggesting openness to new technology adoption despite current uncertainties.

Figure 8
Comments about electric trucks by respondents



Source: ACCPNW Drayage Operator Survey (June–October 2021). N=30 respondents.

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These survey findings provide insights into the existing operational constraints faced by drayage drivers which can inform electrification planning efforts. Patterns of vehicle usage, parking locations, port wait times, and geographical coverage highlight specific operational challenges that could be considered in the transition to zero-emission vehicles. For example, overnight parking locations will influence charging infrastructure placement, while port wait times might present both challenges (unpredictable schedules) and opportunities (potential charging during extended waits) for electrification. These operational realities could be incorporated into technical planning for vehicle specifications and charging networks.

Beyond operational insights, the survey reveals financial considerations that could influence the pace and feasibility of adoption. The predominance of independent owner-operators with varied financial constraints, the aging fleet profile, and the fact that some drivers seek supplemental income all represent important context for developing effective incentive programs and financing mechanisms.

A complete understanding of drayage operations requires examining not just driver activities but also the port terminal operations that impact vehicle utilization patterns. While drivers reported wait times at ports as a key operational challenge, quantifying these patterns requires additional data. The following section combines insights from the driver survey with RFID data collected from five major terminal gates, provided by NWSA, to create a more complete picture of port-related operational constraints that could influence electrification strategies.[2]

PORT OPERATION CONSIDERATIONS

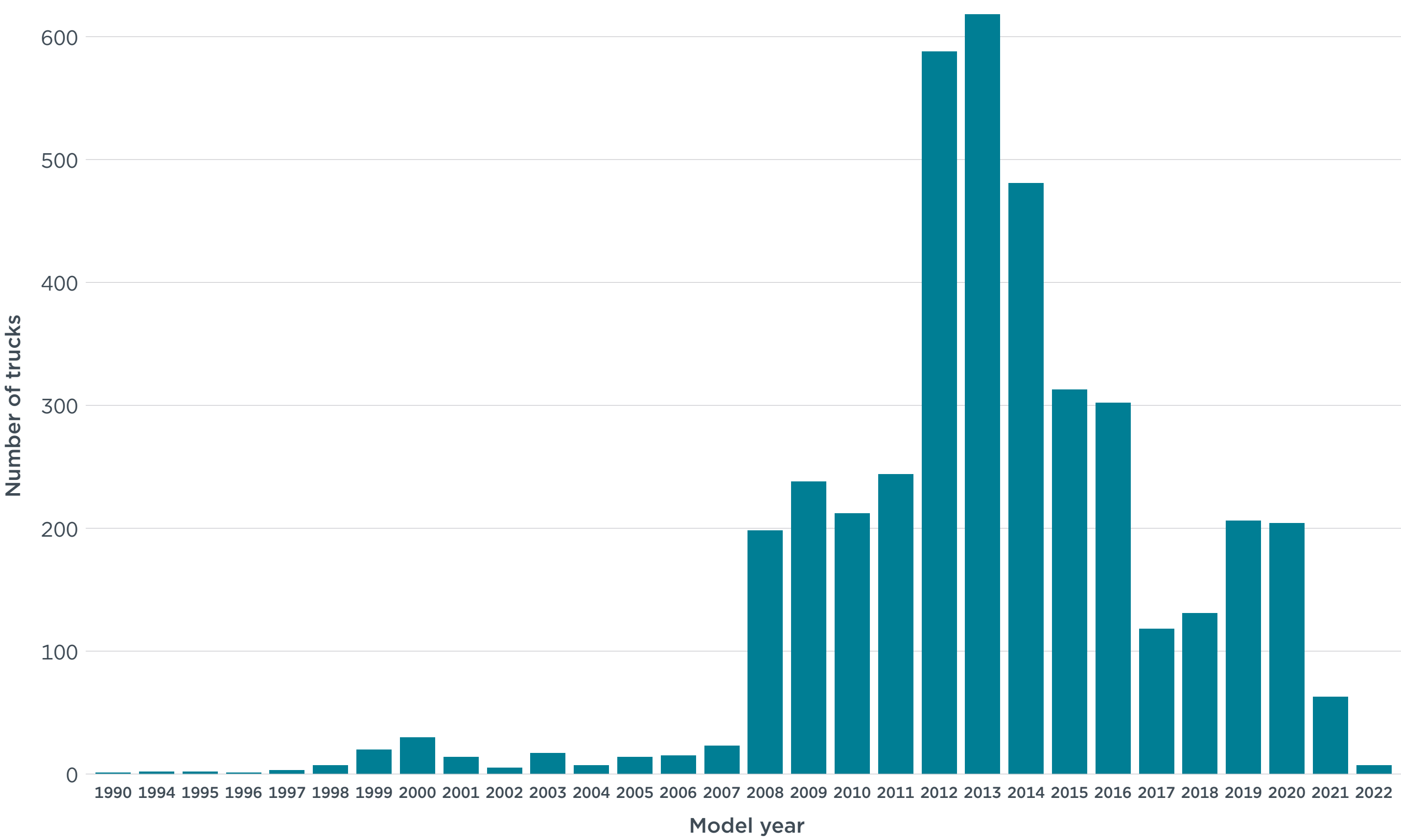
Analysis of port operations through both driver surveys and terminal data reveals challenges that could affect electrification planning. The survey showed that drivers

2 The RFID data provided by NWSA included 465,739 terminal visits recorded between January 3 and May 16, 2021, from five major terminals in the Ports of Seattle (Terminals 18 and 30) and Tacoma (Husky Terminal, Pierce County Terminal, and Washington United Terminals).

serve both major harbors in the region, with 35% primarily serving the North Harbor (Seattle), 13% focusing on the South Harbor (Tacoma), and 52% operating across both harbors equally.

The fleet serving these ports includes many older vehicles, with model years ranging from 1990 to 2022 (Figure 9). Since January 1, 2019, all trucks serving NWSA international container terminals were required to have a 2007 or newer engine which could explain the sudden jump in the number of trucks between 2007 and 2008. This aging fleet profile suggests an opportunity for modernization through electrification, particularly as maintenance costs for older vehicles continue to rise. Starting January1, 2026, the above requirement will extend to all trucks serving NWSA domestic container terminals too (Northwest Seaport Alliance, n.d.).

Figure 9
Truck model years serving the five terminals in Tacoma and Seattle



Source: Analysis based on RFID gate data

Note: 4,084 total unique trucks

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Port efficiency emerged as a critical concern in the driver survey. Drivers reported operational inefficiencies, particularly regarding employee break schedules and limited operational hours. These qualitative observations are corroborated by the quantitative data from RFID systems collected at five major terminals.

Analysis of terminal turn times, defined as the duration between first inbound and last outbound timestamp within the port, showed significant variation in operational patterns (Table 1). While the median turn time was 60 minutes, the mean of 81 minutes with a standard deviation of 72 minutes indicates a right-skewed distribution with a substantial number of longer delays. About 75% of all turns were completed within 114 minutes, though 10% extended beyond 176 minutes. Notably, only 3.4% of turns exceeded 4 hours, suggesting that extreme delays, while impactful, are relatively rare. Based on the data from 465,739 terminal visits over a 4-month period, this distribution of turn times has implications for charging strategy development. While most turns are brief enough to limit charging opportunities, the occurrence of longer turns might offer windows for opportunity charging, particularly at terminal locations.

Table 1

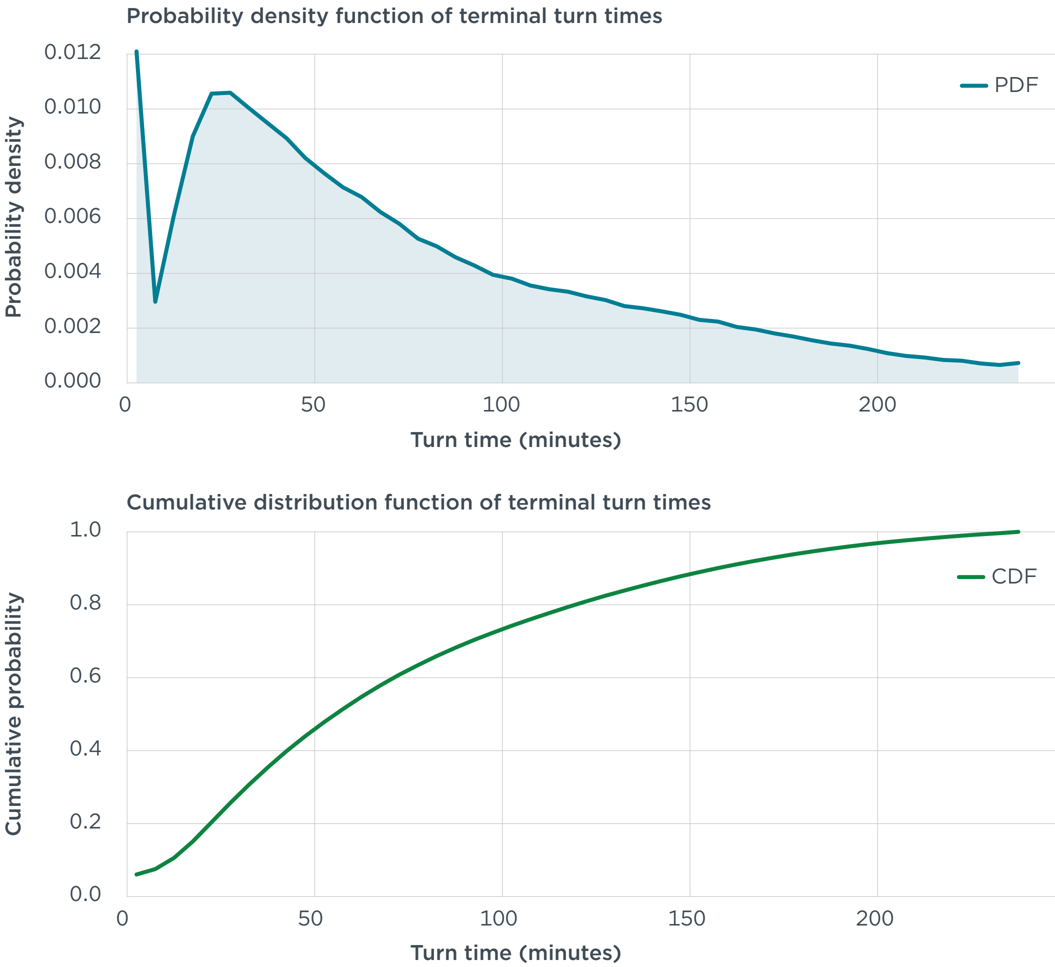
Terminal turn time statistics summary, January–May 2021

Metric	Value
Median turn time	60 minutes
Mean turn time	81 minutes
Standard deviation	71.6 minutes
25th percentile	30 minutes
75th percentile	114 minutes
90th percentile	176 minutes
Turns exceeding 4 hours	3.44%

Note: Analysis based on RFID gate data.

The probability density function reveals that half of all turn times fall between the 25th and 75th percentiles (i.e., between 30 and 114 minutes), with a long tail extending toward longer durations (Figure 10). The cumulative distribution function shows a steep initial rise, indicating that a large proportion of turns are completed within the first 2 hours, followed by a more gradual increase for longer durations.

Figure 10
Probability and cumulative distribution of turn times



Source: Analysis based on RFID gate data

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Drivers noted that port employees' break schedules create extended wait times, with some reporting that the port operates efficiently for only about 3.5 hours per day. These delays not only affect operational efficiency but also contribute to increased emissions from idling vehicles.

To complement the insights from the driver survey and RFID terminal data from ports, and to better understand the detailed operational requirements of drayage vehicles, the next section presents an analysis of high-resolution telematics data collected from a sample of trucks serving the ports.

TELEMATICS DATA COLLECTION AND FLEET CHARACTERISTICS

The ICCT subcontracted the ACC to install Geotab GO9 telematics devices on a sample of 10 drayage trucks (Table 2) making trips to and from the Ports of Seattle and Tacoma. These Geotab GO9 telematics devices used a combination of sensors such as accelerometers and gyroscopes, algorithms, and satellite communication to track and analyze vehicle movement to collect detailed operational data on their position and performance in real time. The device logged data based on a ‘curve logic’ algorithm which means it only recorded data when there is a substantial change in vehicle parameters, resulting in a variable logging frequency that is not strictly set to a specific time interval. Hence, there was a need for cleaning and processing of the raw data before analysis, which is discussed in a later section.

Table 2
Telematics fleet characteristics

Truck ID	Truck make and model	Model year	Activity period
Truck 1	Freightliner Cascadia	2010	July 30, 2022 to April 29, 2023
Truck 2	Freightliner Cascadia	2015	July 30, 2022 to August 12, 2023
Truck 3	Freightliner Cascadia	2013	August 12, 2023 to May 12, 2024
Truck 4	–	–	August 12, 2023 to May 23, 2024
Truck 5	–	–	August 12 2023 to May 12, 2024
Truck 6	Freightliner Cascadia	2012	August 12, 2023 to May 12, 2024
Truck 7	Freightliner Cascadia	2012	March 18, 2023 to August 12, 2023
Truck 8	International LF687	2013	August 12, 2023 to August 17, 2023
Truck 9	Freightliner Cascadia	2013	March 18, 2023 to August 12, 2023
Truck 10	Freightliner Cascadia	2015	March 18, 2023 to April 29, 2023

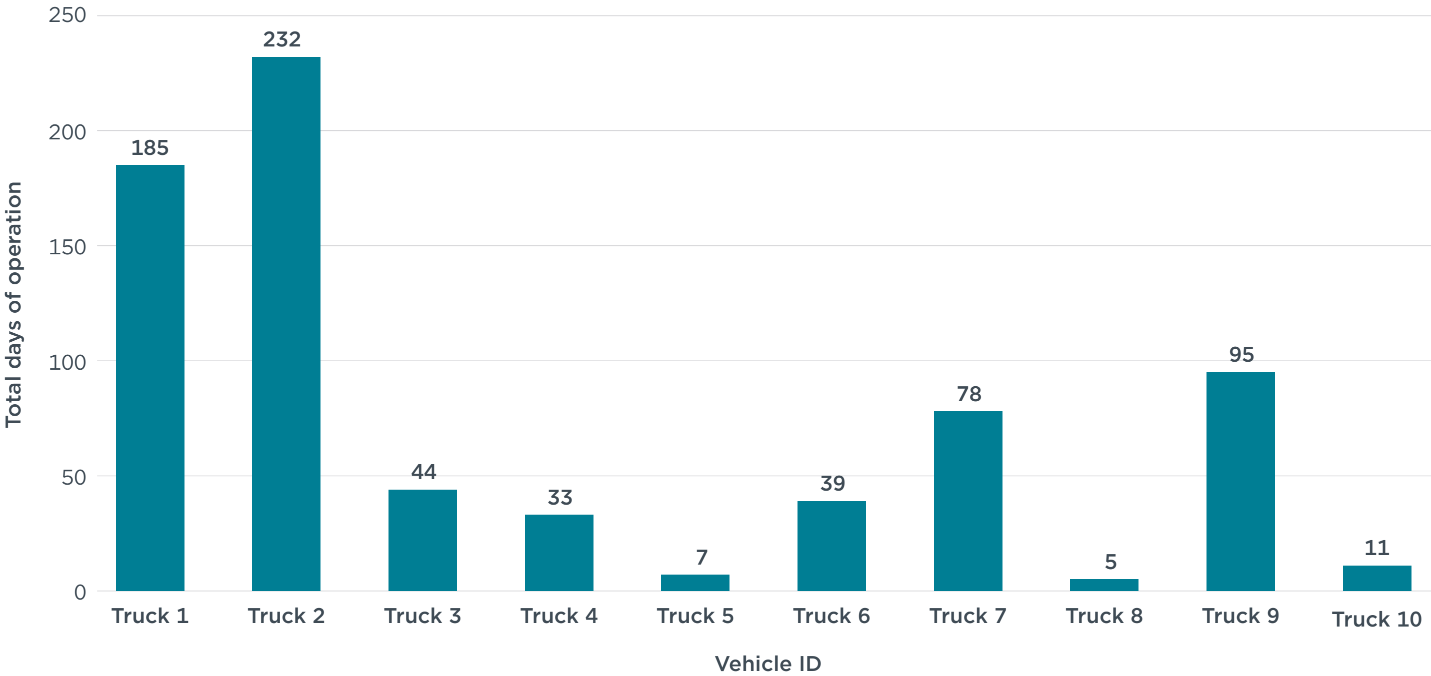
Note: Vehicle information for devices Truck 4 and Truck 5 was not available at the time of analysis due to incomplete documentation during the initial data collection phase. This missing information does not affect the operational data collected from these vehicles, which remains valid for analysis purposes.

The telematics devices captured operational parameters, including real-time vehicle speed, GPS coordinates, and engine ignition status, and detailed trip data such as trip start and stop times; driving, idling, and stop durations; distance; and average and maximum speeds. Subsequent data validation processes were implemented to verify device-vehicle associations for quality assurance purposes.

The data collection period yielded varying levels of operational coverage across vehicles, with individual vehicles recording between 1 and 232 operational days (Figure 11). This variation reflects both the real-world operational patterns and the phased deployment of telematics devices. The cumulative distance covered during the study period exceeded 86,500 miles, providing extensive quantitative data about vehicle operations (Figure 12).

Figure 11

Total days of operation by vehicle



Notes: A day of operation is defined as a unique calendar day in which the vehicle recorded at least one complete trip, where a trip is defined as starting when the vehicle starts and begins being driven. The trip continues after the vehicle has been stopped and ends at the time the vehicle restarts and begins being driven again, which then starts the next trip.

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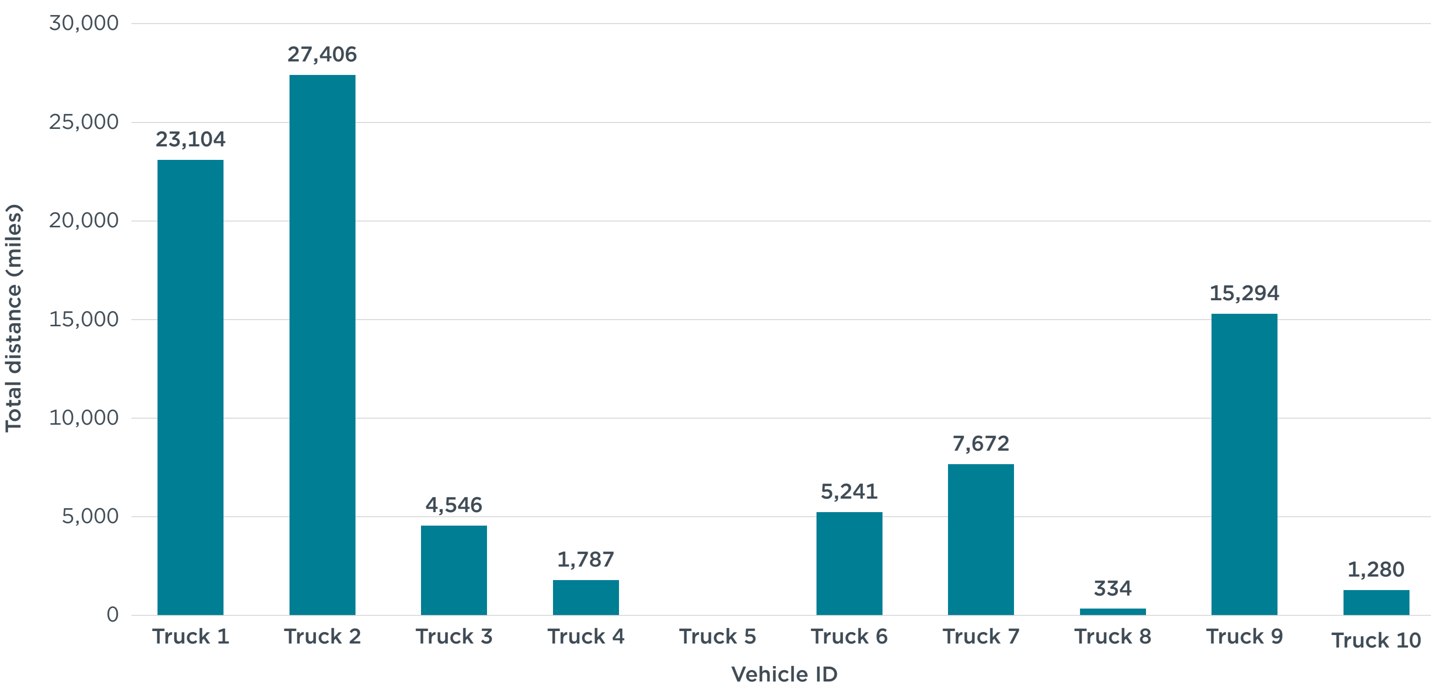
Figure 12

Total distance per vehicle



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The following sections build on these insights to develop representative drive cycles that capture the operational requirements of drayage trucks in the Seattle port region, starting with data preprocessing and cleaning.

DATA PREPROCESSING AND CLEANING

To support the analysis and drive cycle creation for drayage truck electrification, ICCT conducted systematic preprocessing and cleaning of raw telematics data collected from 10 drayage trucks. The data processing framework was structured in three distinct levels to ensure data quality and usability.

The raw telematics data was collected asynchronously through the MyGeotab API and comprised six parameters: engine speed, gear number, GPS coordinates, ignition status, odometer readings, and vehicle speed from the engine control unit. This asynchronous data required processing to create usable time series for analysis. Without proper preprocessing, parameters like road speed could show unrealistic behavior, such as gradual speed increases during known idle periods, which would inaccurately represent the actual vehicle operation.

To generate continuous time series data, the raw data was interpolated to create 1 Hz data. Different interpolation methods were applied based on the nature of each parameter:

» Road speed data was processed using a three-step approach: setting values to 0 when ignition was off, filling idle periods with 0 values to avoid unrealistic speed creep, and applying linear interpolation for remaining gaps.

» GPS coordinates were linearly interpolated.

» Discrete parameters like ignition status and gear number were filled using a downward fill method, where missing values took on the last known non-missing value.

The final step involved aggregating the 1 Hz data into trip-level statistics for broader operational analysis. Throughout this process, ICCT maintained documentation of data transformations and quality checks to ensure the resulting dataset accurately represented vehicle operations.

This systematically cleaned and harmonized dataset served as the foundation for subsequent drive cycle development and analysis, which is discussed in the following sections.

OPERATIONAL PATTERN ANALYSIS

Following the data cleaning process, operational patterns were analyzed through examination of daily distances and route characteristics. While total distance and days of operation provided an overview of data coverage, the distribution of daily distances reveals deeper insights into typical vehicle operations.

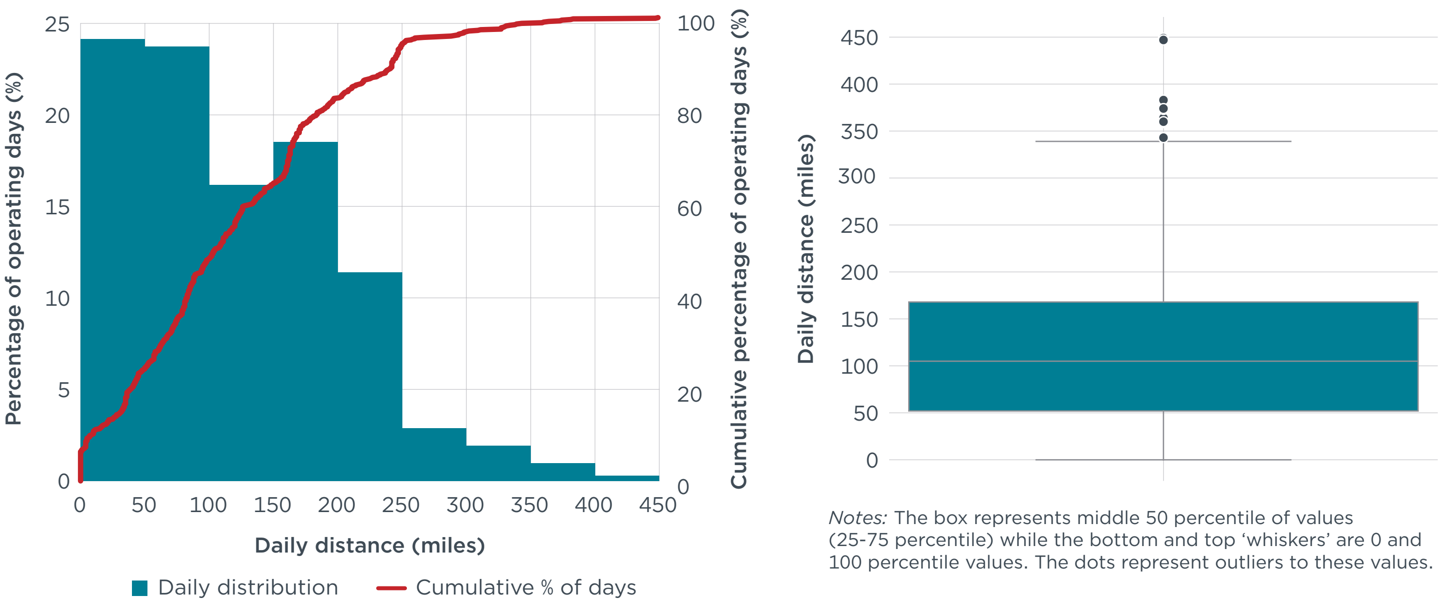
TEMPORAL DISTRIBUTION OF OPERATIONS

Analysis of combined daily travel distances reveals a log-normal distribution pattern (Figure 13), with vehicles operating across a range from 0–450 miles per day. The box plot shows that 50% of daily operations fall between approximately 50 miles

(25th percentile) and 175 miles (75th percentile), with a median around 100 miles. While most operations are concentrated in these shorter distances, the long right tail of the distribution indicates occasional long-haul trips extending to 400–450 miles. The cumulative distribution shows that approximately 80% of operating days involve distances under 200 miles, suggesting most daily activities focus on local and regional routes.

Figure 13

Daily distance distribution for all vehicles combined



Notes: The box represents middle 50 percentile of values (25-75 percentile) while the bottom and top 'whiskers' are 0 and 100 percentile values. The dots represent outliers to these values.

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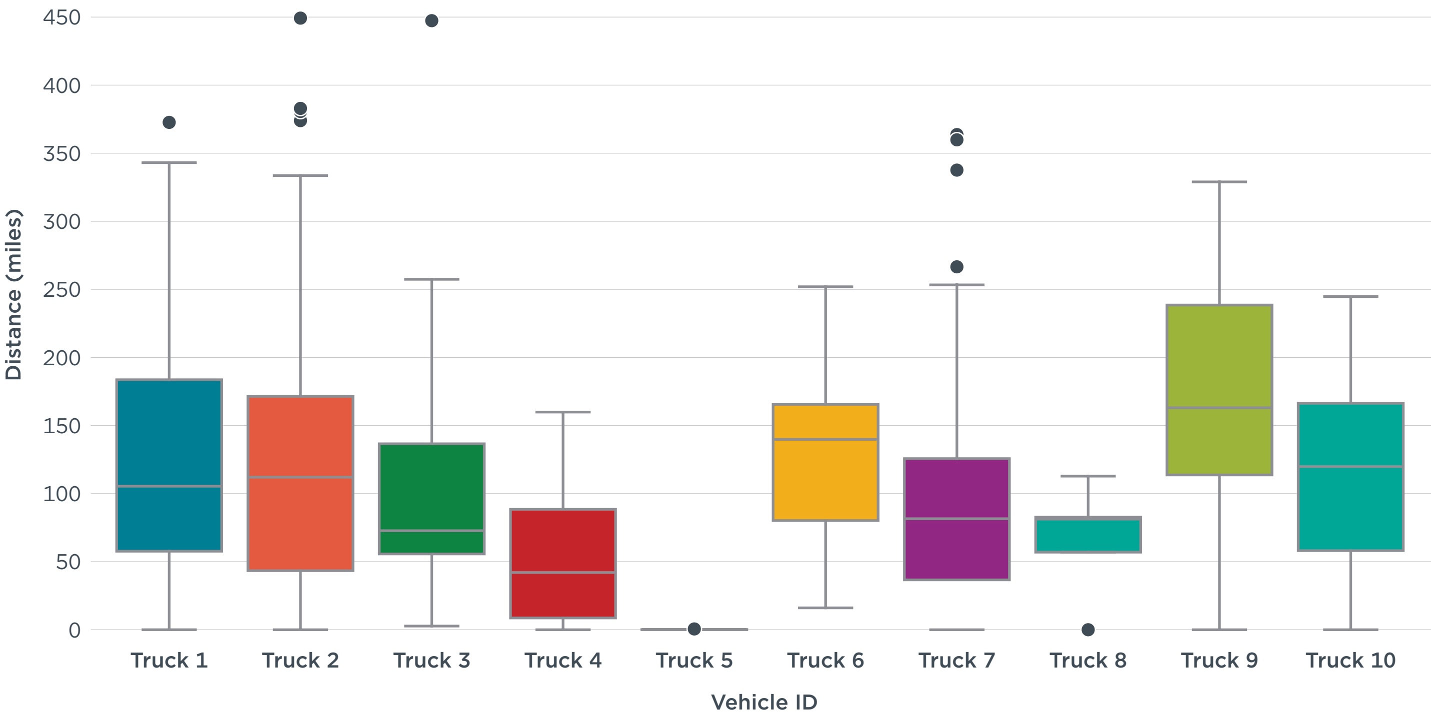
Individual vehicle analysis reveals distinct operational patterns across the 10 trucks (Figure 14). Trucks 1 and 2 show similar distributions with median daily distances of around 100 miles and upper quartiles extending to about 180 miles, with occasional trips reaching 400 miles. Truck 3 demonstrates a more moderate operational pattern with a median daily distance of approximately 75–100 miles, a focused operational range primarily between 50–135 miles, and maximum trips extending to around 250 miles. Truck 4 operates predominantly in shorter ranges, with 75% of its trips under 90 miles, suggesting a focus on local operations. Trucks 6, 9, and 10 demonstrate higher median distances (around 140–160 miles) and wider interquartile ranges, indicating consistent regional operations. Trucks 7 and 8 show more compact distributions mainly between 50–100 miles, while limited data from Truck 5 makes it unsuitable for further analysis. However, daily distance alone provides insufficient insight into operational patterns, as similar total distances could represent vastly different duty cycles; for instance, a 150-mile day could comprise two regional trips or multiple short local trips. A more granular analysis of individual trips and route patterns is needed to accurately characterize operations, which is addressed in the route selection methodology section.

Figure 14

Daily distance distribution by vehicle



Notes: The box represents middle 50 percentile of values (25-75 percentile) while the bottom and top 'whiskers' are 0 and 100 percentile values. The dots represent outliers to these values.

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SPATIAL DISTRIBUTION AND ROUTE FREQUENCY

Analysis of GPS data from the 10 vehicles reveals distinct patterns in route coverage and utilization across the Seattle metropolitan area. The categorization of drayage operations into local (under 40 miles), short haul (40–100 miles), and regional (over 100 miles) was based on the maximum trip distance rather than total daily distance. This approach was chosen because total daily distance could misrepresent the operational characteristics of drayage trucks. For example, a truck performing multiple short trips of 20–30 miles each could accumulate a total daily distance of 200–300 miles, making it appear similar to a truck making a single long-distance regional trip. However, these two scenarios represent fundamentally different operational patterns with distinct infrastructure needs, particularly for electrification planning. The maximum trip distance better reflects the actual range requirements and operational constraints of drayage trucks, as it captures the longest continuous distance a truck must travel without opportunity for charging or other services. The distribution of routes based on this categorization is shown in Table 3.

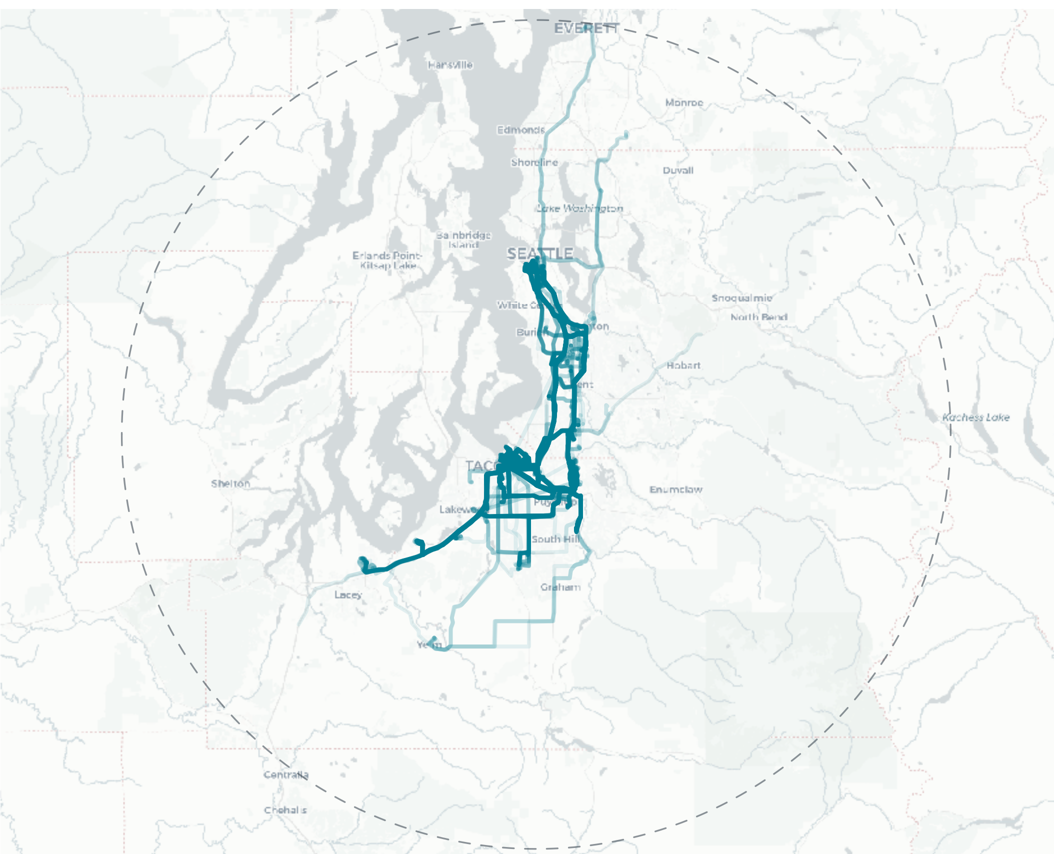
Table 3
Route category distribution for all vehicles combined

Route type	Total trips	Percentage
Local	500	63.1
Short haul	276	34.8
Regional	16	2.0

The maps below show the trips for each route type. The visualization demonstrates clear spatial patterns for each category. The darker segments in each map indicate frequently traveled corridors, suggesting established delivery patterns and regular service routes. This spatial and frequency analysis shows clear distinctions between urban delivery patterns and longer-distance transportation services, which could inform strategic placement of charging infrastructure based on actual route utilization.

Local routes of under 40 miles (Figure 15) are concentrated around Seattle and Tacoma port regions, with an operating radius of approximately 48.4 miles from port centers. These routes show the highest frequency, indicated by darker shades, on corridors connecting terminals within ports, with intense utilization between port terminals and nearby warehouse facilities.

Figure 15
Local routes for all vehicles combined

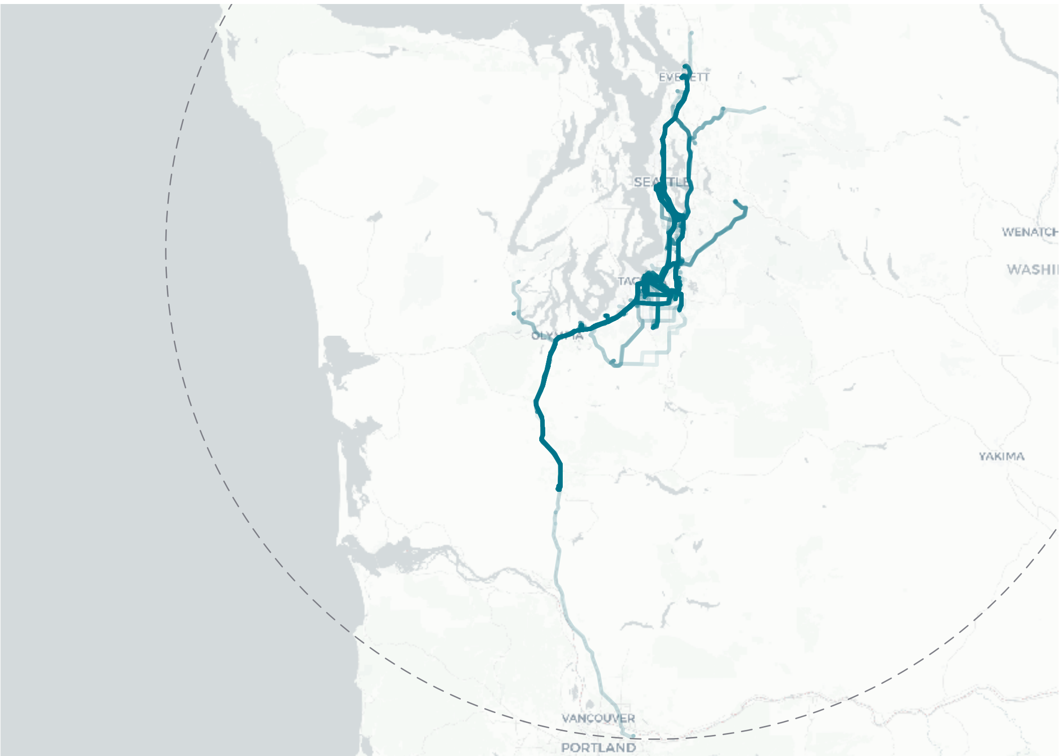


Local routes
Coverage radius: 48.4 mi
Darker blue indicates more frequent routes

Short-haul routes of 40–100 miles (Figure 16) primarily extend north to Everett and south towards Portland along the I-5 corridor, with an operating radius of 123.2 miles. The darkest blue segments indicate high-frequency usage between Seattle and Tacoma ports, with strong patterns of regular service to Kent Valley industrial areas.

Figure 16

Short-haul routes for all devices combined



Shorthaul routes

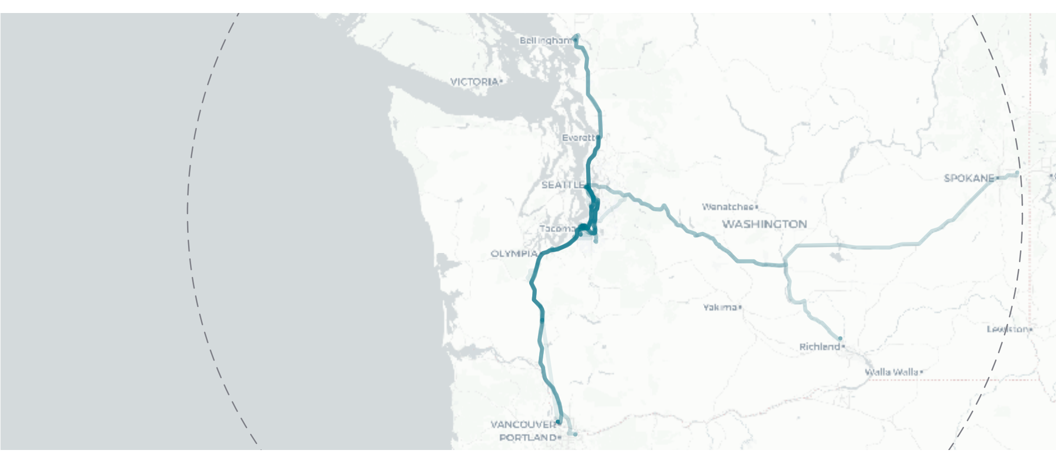
Coverage radius: 123.2 mi

Darker blue indicates more frequent routes

Regional routes of more than 100 miles (Figure 17) extend up to 234 miles from the port region, reaching Bellingham in the north, Spokane in the east, and Vancouver in the south. These routes follow major highways with regular but lower-frequency usage, showing consistent patterns along initial portions of I-5 and I-90.

Figure 17

Regional routes for all devices combined



Regional routes

Coverage radius: 234.0 mi

Darker blue indicates more frequent routes

REPRESENTATIVE DRIVE CYCLE DEVELOPMENT

ROUTE SELECTION METHODOLOGY

The selection of representative routes was intended to capture typical drayage operations while accounting for data quality and operational diversity. Initial analysis of operational data from the 10 drayage trucks revealed varying levels of data availability and distinct operational patterns across the fleet.

To ensure data quality and representativeness, a minimum threshold of more than 16.5 days of operational data was established based on the first quartile of operational days across all vehicles (Table 4). This threshold excluded three vehicles (Trucks 5, 8, and 10) with limited data (7, 5, and 11 days respectively), leaving seven vehicles for further analysis.

Table 4
Operational days statistics

Mean	72.9 days
Median	41.5 days
Standard deviation	78.0 days
25th percentile	16.5 days
75th percentile	90.8 days
Minimum	5.0 days
Maximum	232.0 days

The remaining vehicles demonstrated two distinct operational patterns: some regularly performed all three route types (local, short-haul, and regional), while others focused exclusively on local and short-haul operations. This operational division reflects fundamentally different vehicle electrification and infrastructure needs. Based on this observation, the vehicles were categorized into two groups:

» Full-range vehicles (Trucks 1, 2, 3, and 7): Vehicles demonstrating consistent operation across all three route types

» Local and short-haul vehicles (Trucks 4, 6, and 9): Vehicles focusing on shorter-distance operations

To identify representative drive cycles for each operational category, we calculated the root mean square error (RMSE) scores for each at multiple levels of analysis, considering both overall fleet patterns and group-specific operational characteristics.

Operational metrics selection

Three key operational metrics were selected based on their importance to drayage operations and vehicle electrification planning:

1. Number of trips per day: Indicates operational intensity and potential charging opportunities between trips
2. Total daily distance: Used for determining battery range requirements and energy consumption
3. Longest trip distance: Factor for route planning and charging infrastructure placement

These metrics together capture both the overall daily demand on the vehicle (total distance) and the operational pattern (trip frequency and length), which directly inform battery sizing and charging strategy development.

Statistical framework

To compare these trip and distance metrics on an equal basis, we first convert each value to a standardized score (z-score). A z-score indicates how many standard deviations a value is from the mean (Equation 1), to determine if a value is typical or unusual. A z-score of 0 means the value is exactly average, while a z-score of 1 means it's one standard deviation above average.

$$z = (x - \mu)/\sigma \qquad \text{(Equation 1)}$$

Where:

x is the value being standardized

μ is the mean

σ is the standard deviation

Root mean square error is then used to combine these standardized scores into a single measure of a representative route to measure the typical size of deviations from expected values. The basic RMSE formula for a single metric is shown in Equation 2.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} z_i^2} \qquad \text{(Equation 2)}$$

Where:

n is the count of values being considered

For our analysis, we calculate a combined RMSE that considers all three operational metrics, shown in Equation 3.

$$RMSE_{combined} = \frac{z_{trips}^2 + z_{distance}^2 + z_{longest}^2}{3} \qquad \text{(Equation 3)}$$

This score was calculated at three levels:

- Overall RMSE: Comparison with fleet-wide averages
- Group RMSE: Comparison with group-specific averages (full-range or local/short haul)
- Vehicle RMSE: Comparison with vehicle-specific averages

Selection process

Routes were first categorized based on their longest trip distance: local (under 40 miles), short haul (40–100 miles), and regional (more than 100 miles). Within each category, days were ranked by their combined RMSE score. While the lowest RMSE score typically indicated the most statistically representative day, additional validation criteria were applied to ensure data quality and operational relevance.

For data quality verification, we examined routes for complete GPS traces without significant gaps in position data, accurately recorded stops at known port locations, and the absence of artificial trip splits where continuous trips might be incorrectly divided due to GPS or data logging issues. Operational validation included confirming the presence of expected port stops, ensuring realistic route patterns following known road networks with logical progression between stops, and verifying complete single-day operations with all trips completed within one calendar day to ensure accurate daily statistics. Overnight trips were excluded because they artificially lower daily distance calculations—for example, a 300-mile trip starting at 10 PM and ending at 4 AM would show as two partial days rather than one complete operation.

For edge cases, particularly trips near category thresholds, such as longest trips close to 40 or 100 miles, we reviewed operational patterns to ensure appropriate categorization. When multiple days showed similar RMSE scores, preference was given to routes with more complete operational data that better represented typical drayage operations.

SELECTED ROUTES

The route selection methodology yielded representative routes for each operational group, capturing typical patterns while ensuring data quality. Table 5 presents the characteristics of the selected routes.

For the full-range vehicles group, the selected routes demonstrate characteristic progression from local to regional operations. Local routes show concentrated activity with 6–8 trips per day and total daily distances ranging from 62–80 miles. Short-haul routes show 7–10 daily trips and total daily distances between 169 and 232 miles. Regional routes show the greatest variation, with 3–11 trips and total daily distances from 161–449 miles.

For the local and short-haul vehicles group, selected routes reflect more concentrated operations. Local routes average 6–7 trips daily with total daily distances between 72 –97 miles, while short-haul routes show 7–8 trips per day with total daily distances ranging from 158–167 miles.

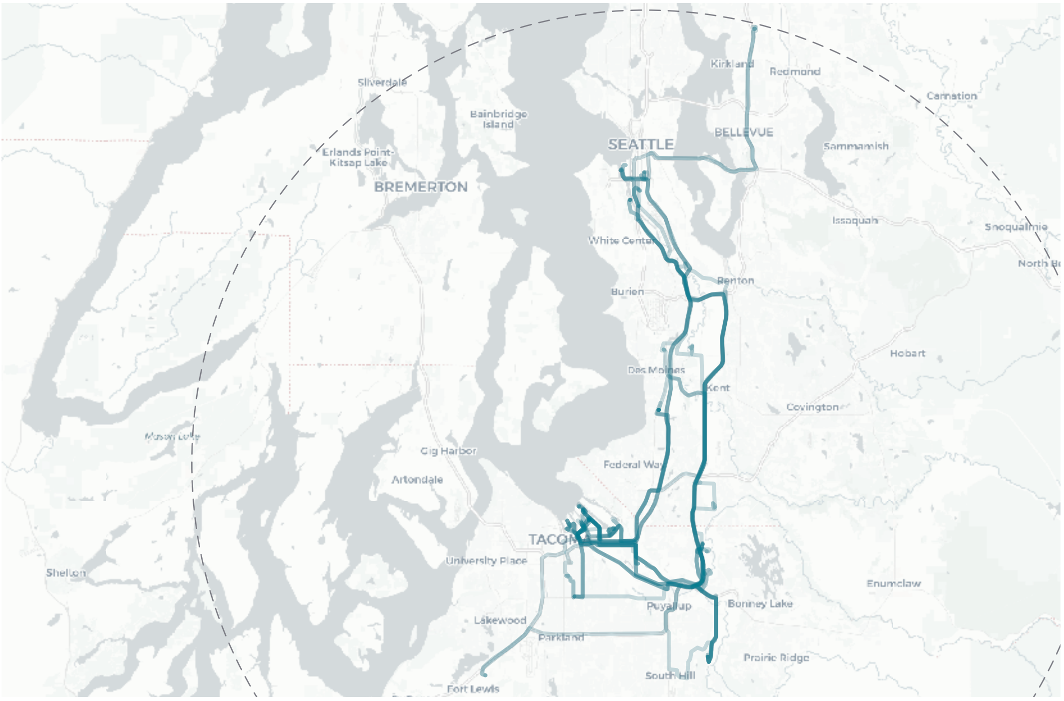
Table 5

Representative routes selected for each operational group

Device	Route type	Trips	Daily distance (mi)	Longest trip (mi)	RMSE overall	RMSE rank
Full range vehicles						
Truck 1	**Local**	7	77.69	20.77	0.512	1
Truck 1	**Short-haul**	9	188.1	61.78	0.633	1
Truck 1	**Regional**	3	160.43	149.08	2.165	3
Truck 2	**Local**	8	75.28	20.55	0.519	1
Truck 2	**Short-haul**	10	181.97	66.62	0.743	1
Truck 2	**Regional**	11	448.45	121.95	2.786	5
Truck 3	**Local**	7	61.75	14.71	0.668	1
Truck 3	**Short-haul**	9	231.39	55.13	0.821	2
Truck 3	**Regional**	8	446.04	226.6	4.128	1
Truck 7	**Local**	6	80.18	21.75	0.551	1
Truck 7	**Short-haul**	8	169.74	52.14	0.38	1
Truck 7	**Regional**	9	336.6	133.85	2.293	1
Local and short-haul vehicles						
Truck 4	**Local**	6	72.45	28.66	0.519	1
Truck 6	**Local**	7	96.96	37.39	0.242	1
Truck 6	**Short-haul**	7	158.34	40.83	0.249	1
Truck 9	**Local**	7	87.08	24.52	0.418	3
Truck 9	**Short-haul**	8	166.48	41.37	0.288	1

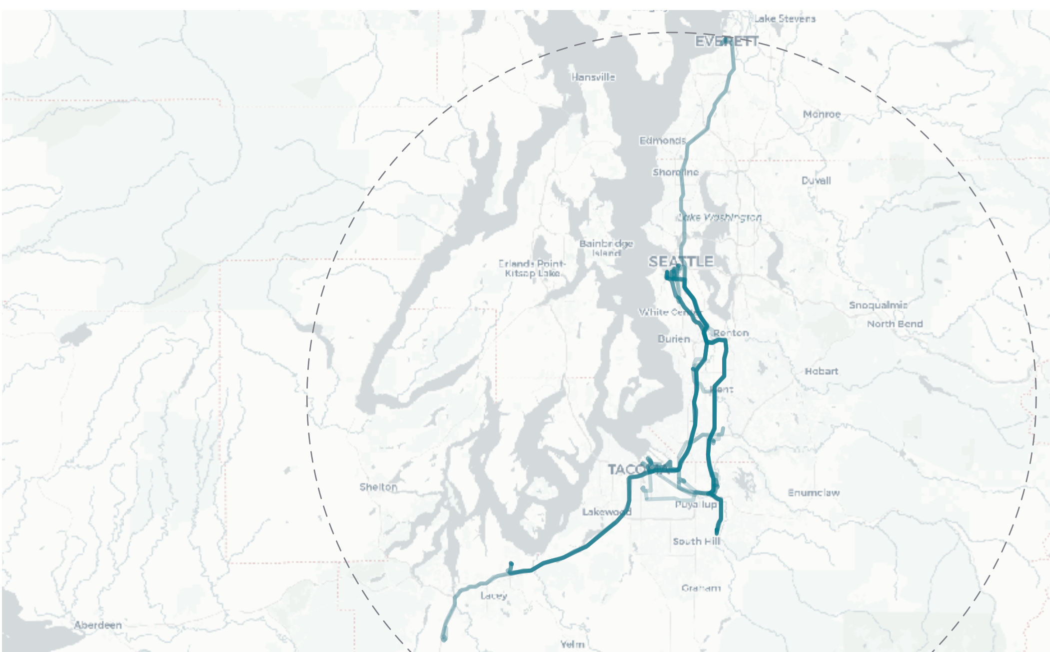
The spatial distribution of selected routes illustrates their representativeness. Local routes (Figure 18) show typical port-centric operations, with frequent trips between port terminals and nearby warehouses. Short-haul routes (Figure 19) demonstrate characteristic patterns connecting ports to distribution centers in neighboring cities. Regional routes (Figure 20) capture extended operations to distant destinations while maintaining typical port connections.

Figure 18
Selected representative local routes



Selected local routes
Coverage radius: 28.4 mi
Darker blue indicates more frequent routes

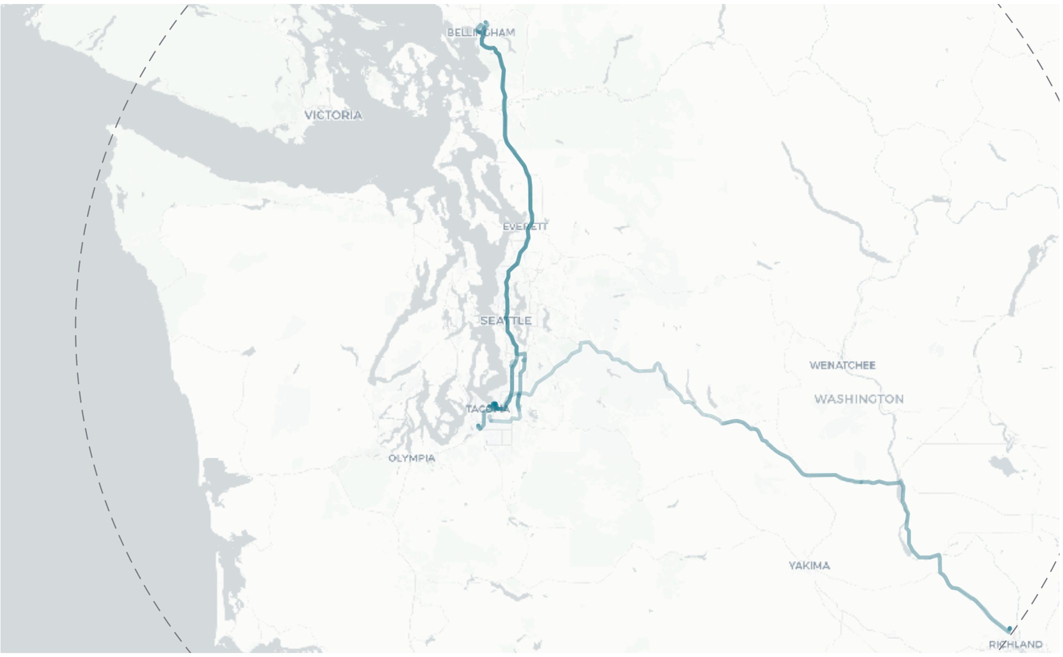
Figure 19
Selected representative short-haul routes



Selected shorthaul routes
Coverage radius: 43.5 mi
Darker blue indicates more frequent routes

Figure 20

Selected representative regional routes



Selected regional routes

Coverage radius: 144.7 mi

Darker blue indicates more frequent routes

DRIVE CYCLE CREATION PROCESS

The selected routes were processed through a multi-step procedure to create drive cycles suitable for vehicle simulation based on a framework developed by ICCT (Jin, Delgado, Gadepalli, & Minjares, 2020), the only difference being instead of generating several microtrips, a single trip was generated for a selected route date based on the RMSE selection procedure described in the previous section.

The representative drive cycles developed from the selected routes capture the diverse operational patterns of drayage trucks in the Seattle-Tacoma region. The example drive cycles shown below were selected randomly from the seven trucks analyzed, which consists of a total of 17 drive cycles.

Figure 21 shows a representative speed profile for a local drive cycle, characterized by frequent stops and low-speed operation. This specific example involves travel between the Tacoma port, the BNSF Intermodal facility in Tukwila, and The Outlet Collection in Auburn, with minor stops near the port. The maximum speed reaches around 60 mph, and the total cycle duration is approximately 8 hours with long stops throughout the day, aligning with the typical daily operation of local drayage routes.

Figure 21

Example of local drive cycle created using the selected routes

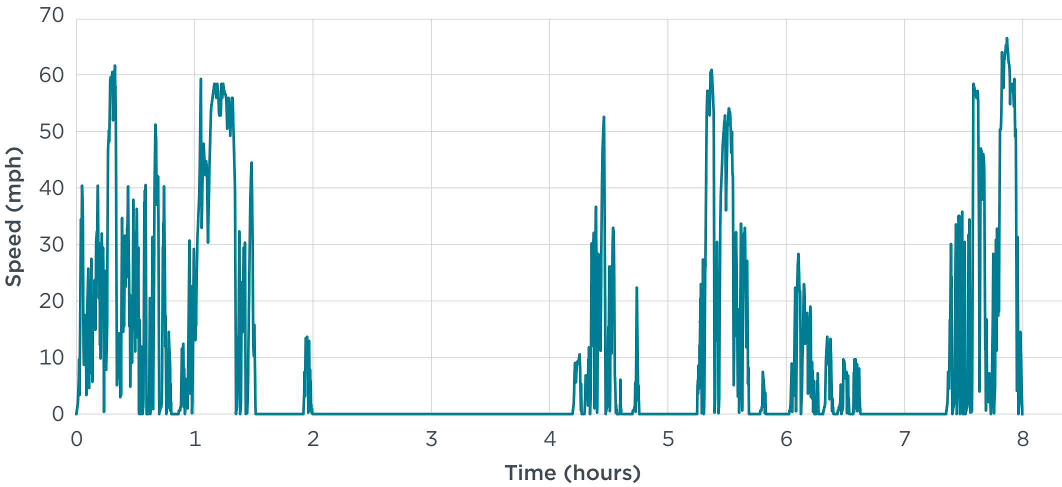


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Figure 22 presents a representative short-haul drive cycle, displaying a mix of low-speed operation and higher-speed segments. This route includes trips between the Tacoma port, nearby stops such as Milgard Windows and Doors in Fife, the BNSF Intermodal facility in Tukwila, and the Everett port, along with minor stops close to the ports. The maximum speed reaches around 60 mph, and the total cycle duration extends to about 10 hours with a couple of long stops, reflecting the increased daily range and operational time of short-haul routes compared with local operations.

Figure 22

Example of a short-haul drive cycle created using selected routes

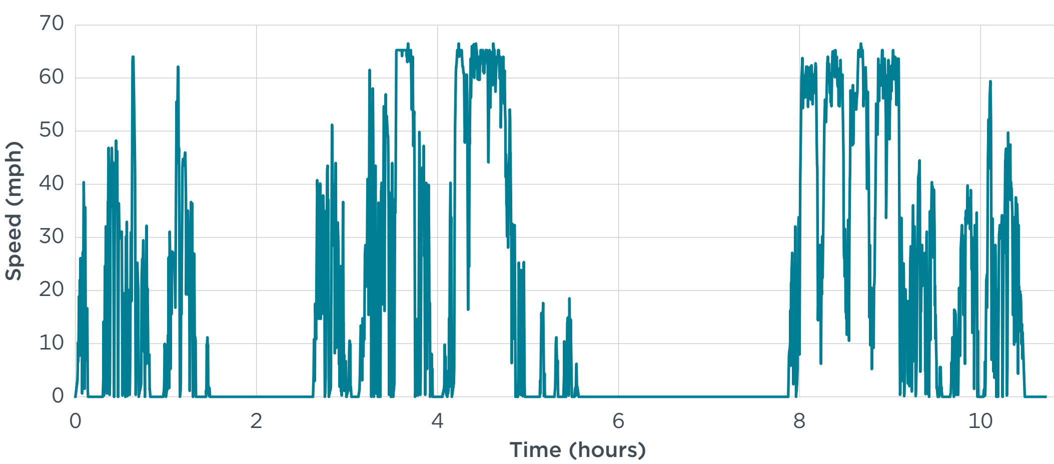

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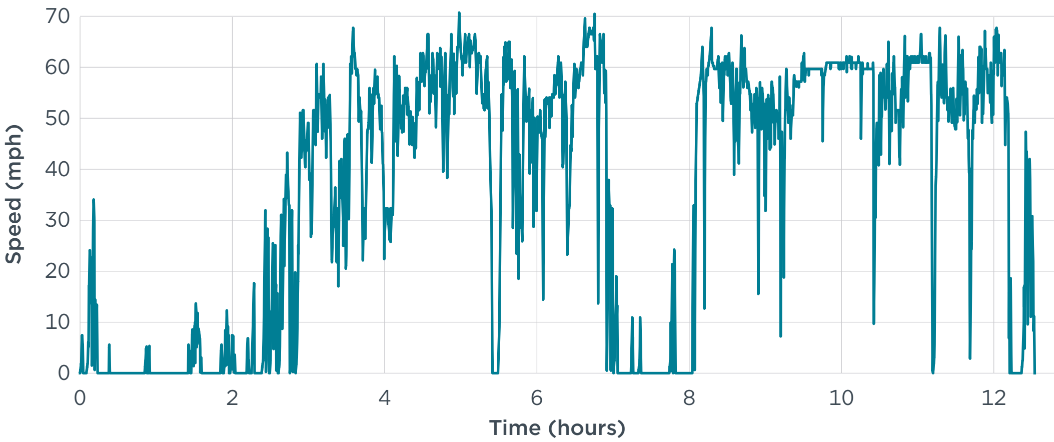
Figure 23 illustrates a representative regional drive cycle, showcasing extended periods of high-speed operation interspersed with low-speed segments and stops. This specific example features a drayage truck driving between the Tacoma port and the Ferguson Plumbing Distribution Center in Richland, with potential minor stops near the port. The maximum speed approaches 70 mph, and the total cycle duration stretches to nearly 12 hours with no long stops, capturing the extended range and operational requirements of regional drayage services.

Figure 23

Example of a regional drive cycle created using selected routes



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COMPARISON WITH OTHER DRAYAGE DRIVE CYCLES

To validate the developed drive cycles, we compared them with established cycles: the NREL Port Drayage Composite Cycle (Figure 24) and Fleet DNA Drayage Representative Cycle (Figure 25). Table 6 presents key metrics for both our Seattle-Tacoma cycles (Figure 21, Figure 22, and Figure 23) and these reference cycles. The metrics in the table are averages of all the cycles in the respective operational profile from Table 5.

The comparison reveals distinct characteristics of Seattle-Tacoma drayage operations. While all cycles share similar maximum speeds (around 65 mph), their operational patterns differ. Our cycles and the Fleet DNA cycle capture extended operations (496–668 minutes and 516 minutes, respectively), while the NREL cycle represents a shorter operational period (120 minutes).

Figure 24

NREL port drayage drive cycle

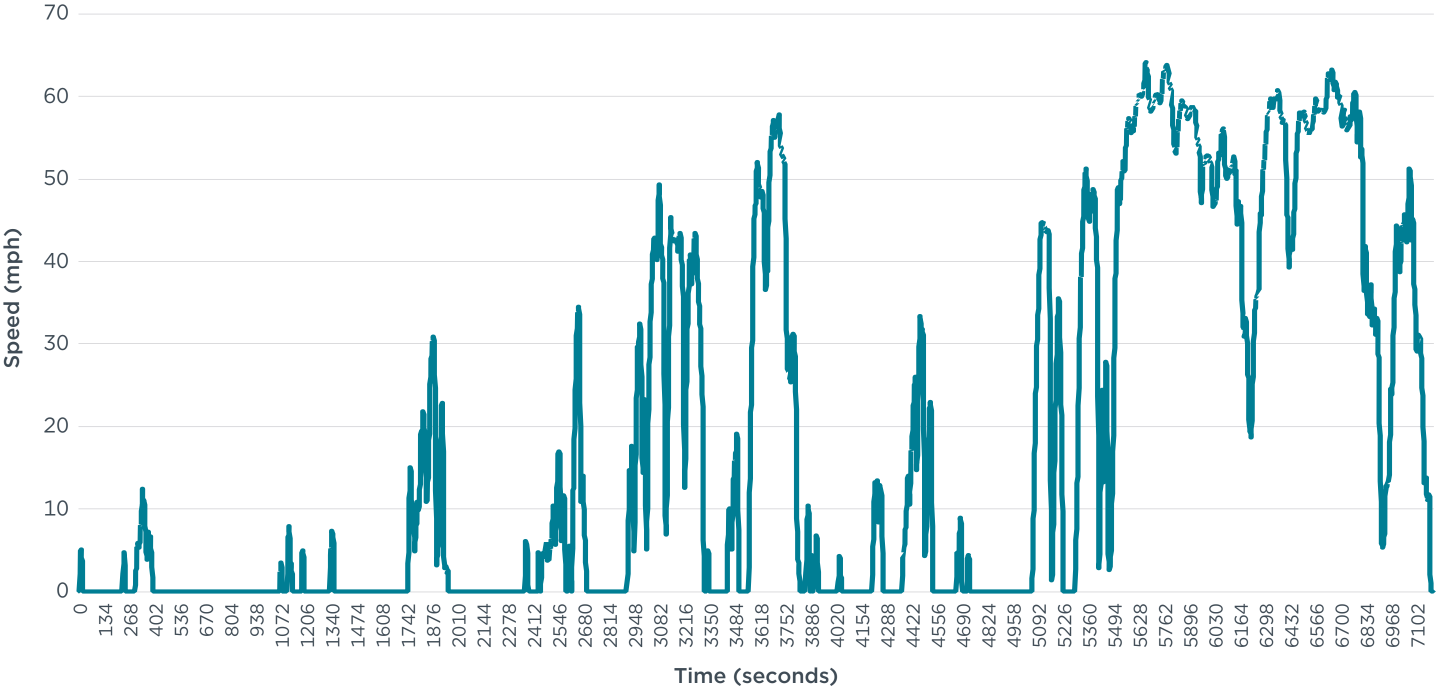

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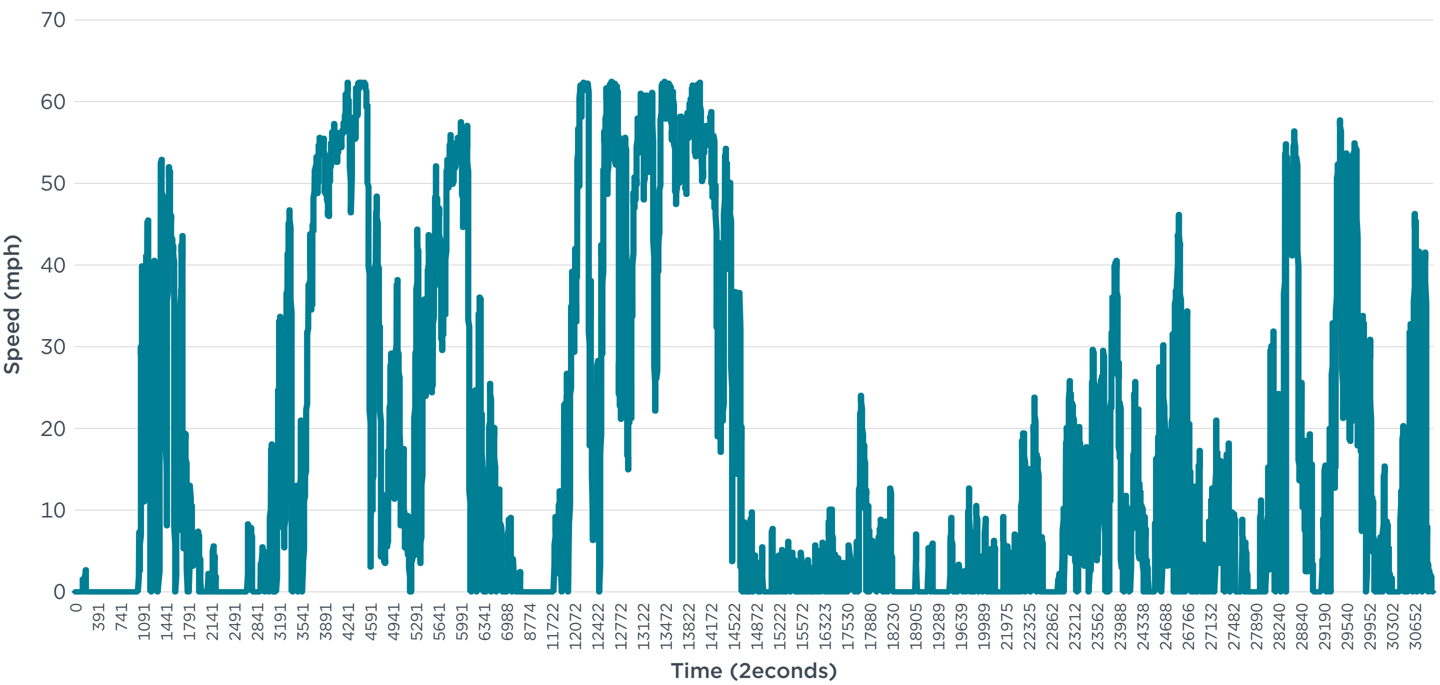
Figure 25

Fleet DNA drayage drive cycle



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In the progression from local to regional operations, daily distances increase substantially (53.8–178.3 miles), stopping frequency decreases (0.99–0.23 stops/mile), average speeds increase (7.5–19.8 mph), and kinetic intensity decreases (0.37– 0.11/mile). These metrics reflect the transition from terminal-focused operations to highway travel. Notably, while maximum speeds are similar across all categories (about 66 mph), average driving speeds show significant variation (16.8– 25.5 mph), indicating different proportions of highway versus terminal operation.

Compared with the reference cycles, Seattle-Tacoma operations show less aggressive acceleration patterns, as indicated by lower Positive Kinetic Energy values (0.07–0.18 ft/s^2 vs 0.60–0.89 ft/s^2). This difference might reflect regional variations in infrastructure, operational practices, or traffic patterns. The more distinct separation between operational types in Seattle-Tacoma cycles suggests potentially different infrastructure needs for each category of drayage service.

Table 6

Metrics comparing various drive cycles

Metric	Seattle-Tacoma local	Seattle-Tacoma short haul	Seattle-Tacoma regional	Fleet DNA representative	NREL CA composite
Duration (minutes)	496	650	668	516	120
Distance (mi)	53.8	98.6	178.3	96.9	35.2
Maximum speed (mph)[a]	66.5	66.5	66.2	62.6	64.2
Average speed (mph)[b]	7.5	9.2	19.8	16.7	17.6
Average driving speed (mph)[b]	16.8	17.0	25.5	27.3	33.3
Positive kinetic energy (ft/s^2)[b]	0.18	0.12	0.07	0.89	0.60
Stops per mile[b]	0.99	0.54	0.23	1.82	0.77
Kinetic intensity (1/mile)[b]	0.37	0.24	0.11	0.54	0.32

[a] Maximum speeds represent absolute maximum values within each category
[b] Metrics represent category averages for Seattle-Tacoma cycles

DISCUSSION

Analysis of drayage operations in the Seattle-Tacoma region reveals several key insights relevant for fleet electrification planning. The operational patterns identified through the fleet analysis and detailed route examination highlight both opportunities and challenges for electric vehicle adoption.

OPERATIONAL PATTERNS AND IMPLICATIONS

The analysis revealed three distinct operational patterns that raise specific questions about electrification strategies. Local operations, characterized by multiple short trips (averaging 7–8 trips daily) within 40 miles of the ports, raise the question of whether current battery technology combined with depot charging alone could meet these operational needs. The predictable patterns and frequent returns to base facilities suggest this might be feasible, but detailed energy consumption and stop location analysis would be needed to confirm.

Short-haul operations, extending 40–100 miles from ports, demonstrate more varied patterns with daily total distances ranging from 158–232 miles and typically involve 8–10 trips per day. For these operations, it is unclear if the same battery technology could suffice if supplemented by strategic opportunity charging, particularly given the concentration of routes along major corridors in the Kent Valley area and routes to Everett. This pattern of activity suggests potential locations for public charging infrastructure, but the viability depends on both technical feasibility and operational integration.

Regional operations present the most complex technical questions. These routes, extending beyond 100 miles and reaching destinations like Portland and Spokane, raise the question of whether a combination of en route charging and higher voltage batteries (800V) to accommodate megawatt charging could make electrification viable. Even on regional days, vehicles typically perform multiple trips (4–9 trips/day), suggesting that charging solutions would need to integrate with these complex duty cycles. Understanding the feasibility of this approach requires analysis of both the technical capabilities of high-voltage systems and the practical implementation of megawatt charging infrastructure along major corridors.

CONCLUSION

This study analyzed a population of drayage truck operations in the Seattle-Tacoma region to provide insights for fleet electrification planning. Through detailed analysis of telematics data from 10 vehicles, combined with driver surveys and terminal gate data from ports, the study established operational patterns and developed representative drive cycles for vehicle simulation.

Of the drivers surveyed for this study, a predominant percentage were independent owner-operators (65%), with unique financial and operational considerations compared with company fleets. The drivers also cited uncertainty in turn times, including occasionally excessive turn times, which can impact operational patterns.

The telematics data collected from the 10 drayage trucks revealed high variability in daily operations, with vehicles often serving multiple route types. Three distinct operational patterns—local, short haul, and regional—also emerged, which will likely require different electrification requirements such as charging infrastructure. The data also showed clear spatial patterns in route frequency, which could be used to identify potential charging infrastructure locations.

The drive cycles and route analysis performed for this paper will serve as the basis for two upcoming papers examining drayage truck electrification. Together, these studies will provide a comprehensive framework for evaluating and planning the transition to electric drayage trucks in the Seattle-Tacoma region and potentially other similar port areas.

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APPENDIX: SEATTLE-TACOMA PORTS ZERO-EMISSION DRAYAGE TRUCKING SERIES

This study serves as the first part of a planned three-part series examining drayage truck electrification in the Seattle-Tacoma port region. The insights from this operational analysis will directly inform the technical feasibility assessment in the second analysis and the economic analysis in the third analysis of this series.

The technical feasibility analysis will involve:

» Vehicle simulation using the developed drive cycles to determine energy consumption patterns

» Battery size optimization based on operational requirements

» Charging power requirements for different operational patterns

» Optimal placement of charging infrastructure based on identified route patterns

» Required charging power levels

The economic analysis will explore:

» Total cost of ownership of electric and diesel drayage trucks

» Impact of different operational patterns on vehicle economics

» Infrastructure cost allocation and business models

» Financial incentives needed for independent owner-operators

Together, these studies will provide a comprehensive framework for evaluating and planning the transition to electric drayage trucks in the Seattle-Tacoma region and potentially other similar port areas.

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