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Authors
Bae, Youngeun, PhD
Ritchie, Stephen G., PhD
Rindt, Craig Ross, PhD

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Youngeun Bae, Ph.D., Corresponding Author Assistant Project Scientist
Stephen G. Ritchie, Ph.D., Professor, Civil and Environmental Engineering Director
Craig Ross Rindt, Ph.D., Project Scientist

UC Institute of Transportation Studies, Irvine

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Charging Infrastructure Decisions by Heavy-duty Vehicle Fleet Operators: An Exploratory Analysis

Youngeun Bae, Ph.D., Corresponding Author
Assistant Project Scientist
Institute of Transportation Studies
4000 AIRB
University of California, Irvine
Irvine, CA 92697-3600
youngeub@uci.edu
ORCiD: 0000-0003-0798-6418

Craig Ross Rindt, Ph.D.
Project Scientist
Institute of Transportation Studies
4000 AIRB
University of California, Irvine
Irvine, CA 92697-3600
crindt@uci.edu
ORCiD: 0000-0002-3278-6488

Stephen G. Ritchie, Ph.D.
Professor, Civil and Environmental Engineering
Director, Institute of Transportation Studies
4000 AIRB
University of California, Irvine
Irvine, CA 92697-3600
sritchie@uci.edu
ORCiD: 0000-0001-7881-0415

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ABSTRACT

Insufficient charging/fueling infrastructure poses a major challenge to achieving U.S. policy goals for transitioning the heavy-duty vehicle (HDV) sector to zero-emission vehicles. Addressing the infrastructure needs of HDV fleet operators, who are key demand-side stakeholders, is crucial for developing effective solutions and strategies. This study investigates these needs through a fleet survey of California's drayage sector, focusing on battery electric trucks. Key aspects examined include preferences for charging locations, access types, charging duration, time-of-day for charging, and innovative solutions like Truck-as-a-Service. Analyzing responses from 53 companies with varying fleet sizes, annual revenues, and operational characteristics, the study employed a comprehensive exploratory approach, utilizing descriptive analysis, thematic analysis, and hypothesis testing. Findings reveal that while most fleets preferred on-site charging, about a quarter, primarily smaller fleets with five or fewer trucks, preferred both on-site and off-site options. Private access was often favored for on-site facilities, though some respondents recognized the benefits of shared access for expanding operational coverage. The study also identified a need for faster charging solutions at both off-site and on-site locations, particularly for long-haul or mixed operations. Time-of-day preferences varied widely, driven by the need for efficient operations. Furthermore, a small proportion of participating fleets preferred Truck-as-a-Service over traditional procurement, predominantly among smaller fleets or those with lower revenues. The comprehensive research findings contribute to a deeper understanding of charging infrastructure needs and offer practical insights for policy practitioners and industry stakeholders committed to advancing zero-emission infrastructure.

Keywords: heavy-duty vehicle, battery electric truck, charging infrastructure, fleet operator decision, drayage industry, fleet survey

BACKGROUND

In response to the pressing need to mitigate environmental and public health impacts from greenhouse gas emissions and air pollutants emitted from medium and heavy-duty vehicles (HDVs, defined by the U.S. FHWA as vehicles with a gross vehicle weight rating (GVWR) exceeding 10,000 lbs), many U.S. states are supporting the transition of the HDV sector towards zero-emission vehicles (ZEVs), such as battery electric or fuel cell electric vehicles (*1*). Among these states, California is leading with initiatives outlined in Executive Order N-79-20 (*2*), supported by the Advanced Clean Trucks (*3*) and the Advanced Clean Fleets (ACF) regulations (*4*). These initiatives aim for a 100% transition of the HDV sector to ZEVs by 2045, wherever feasible, and even sooner for drayage trucks, which are targeted to be fully zero-emission by 2035 (*2*). However, the penetration rate of ZEVs remains marginal, accounting for only 0.2% of HDVs registered in California (*5*). Accelerating ZEV adoption rates requires not only supply-side efforts, but also demand-side measures developed based upon a deep understanding of the decision-makers procuring ZEVs (*6*). Since about 90% of HDVs serve as fleet vehicles rather than personal transportation (*7*), fleet operators, who lead the decision-making process of fleet procurement in organizations (*8*), are key demand-side players to be understood.

Fleet operators have been encountering numerous barriers to ZEV adoption (*9*). One of the significant challenges is the lack of charging/refueling infrastructure for heavy-duty ZEVs (*9*, *10*). This complicates procurement decisions and operational practices for these innovative technologies (*10*). This issue has been referred to as a 'chicken-and-egg' dilemma, where each seems to cause the other to arise (*11*). Fleet operators are reluctant to adopt ZEVs due to limited charging/refueling opportunities, and infrastructure developers struggle with construction plans due to uncertain needs by fleet operators (*10*). Even if ZEV policies motivate fleet operators to consider these vehicles, a lack of understanding of their preferences and decisions regarding charging/refueling facilities could hinder the development of effective infrastructure plans, which would, in turn, impede ZEV demand and delay policy goals.

Despite the importance of understanding fleet operator perspectives on charging/fueling infrastructure, this topic remains underexplored in the literature. Our study thus addresses this critical knowledge gap and provide practical insights for policy and industry stakeholders, with a focus on battery electric trucks (BETs), which have gained greater attention among zero-emission technologies (*12*).

Several previous studies have explored charging infrastructure issues for HDVs from different angles, such as charging station locations (e.g., *13*), charging demand or profiles (e.g., *14–18*), charging management strategies (e.g., *19*), and charging scheduling problems (e.g., *20*). Key input parameters for modeling in these studies include the range of decisions made by fleet operators, such as the types of facilities they would use, when and where to charge, and the duration of charging. However, these studies tended to rely simplified assumptions, such as depot-only charging (*13*, *20*) or stations located only at highway intersections (*17*), or used input derived from travel data of existing diesel trucks (e.g., *13*, *15*, *16*, *18*, *19*), which may not necessarily reflect BET operations. Such assumptions, partly due to the lack of data from fleet operators, may not fully align with actual charging practices. As noted by Kchaou-boujelben (2021), who reviewed 179 research articles on charging station location problems, inaccurate assumptions that deviate from real-world charging behavior, such as regarding charging amount, time and location, could result in less practical and potentially misleading modeling outcomes (*21*).

Limited research has focused on fleet operator perspectives regarding charging infrastructure issues, with a few exceptions (e.g., (*10*, *22*)). The report by TRC Companies, Inc. (*22*) provided market insights into the HDV sector regarding various fuel technologies, including zero-emission fuels, and discussed infrastructure challenges. Their findings were partially based on a survey of 200 fleets operating in diverse HDV applications in the U.S. (*22*). A study by Bae et al. (*10*) investigated infrastructure decisions made by fleet operators who adopted compressed natural gas (CNG) HDVs, a commercially mature technology used in various fleet applications (*23*). Bae et al. (*10*) examined how HDV fleets utilized CNG fueling infrastructure, their satisfaction with the facilities, and the reasons behind their decisions to construct on-site fueling facilities or use off-site stations, based on 17 in-depth qualitative interviews. Nevertheless, detailed infrastructure issues were not comprehensively addressed (*22*), and the findings related to CNG fueling infrastructure (*10*) may have limited applicability to BET charging infrastructure, given differing technological properties, readiness levels, and subsequent fleet operator perceptions and decisions.

Therefore, our research aims to explore BET charging infrastructure needs from the viewpoint of HDV fleet operators, covering key areas such as charging locations, access types, charging duration, times of day for charging, and preferences for innovative solutions like Truck-as-a-Service (TaaS). TaaS offers a pay-per-use service, including both truck usage and charging facilities (*24*).

The specific research questions are below:

1) Assuming fleet operators procure BETs, which charging locations do they favor (e.g., on-site at depot vs. off-site stations) and what are the reasons for their preferences?
2) Which access types (e.g., private vs. shared access) do fleet operators prefer and for what reasons?
3) What are the longest charging times that fleet operators consider acceptable?
4) What times of day are favored by fleet operators for charging BETs, and why?
5) Is there interest among fleet operators in innovative charging solutions, like Truck-as-a-Service?

For each research question, we investigated how charging preferences vary across different fleet segments (e.g., in terms of fleet size, annual revenue, and short/long-haul operations), based on a case study on drayage fleets in California. Drayage trucks, defined by the U.S. EPA as heavy-duty Class 8 trucks with a GVWR over 33,000 lbs that transport containers and bulk freight between ports and near-port facilities, play a crucial role in port operations, the economy, and air quality (*25*). These trucks are subject to the most stringent targets under California's ACF regulations, which require that only zero-emission drayage trucks be registered starting January 1, 2024 (*4*). We conducted a fleet survey, developed based on prior qualitative research involving fleet interviews (*9*, *10*). The survey questionnaire, incorporating a range of question types and open-ended questions, was distributed to drayage fleet operators in California through the Drayage Truck Registry for the Ports of Los Angeles and Long Beach. By April 2024, a total of 71 drayage companies with diverse fleet characteristics participated. For our analysis, we focused on responses from 53 companies that aligned with the study's scope, excluding those who indicated intentions to discontinue their drayage business, relocate to another state, or operate only non-ZEVs. We employed a comprehensive exploratory approach, encompassing descriptive analysis, thematic analysis, and hypothesis testing.

The research findings advance our understanding of charging infrastructure needs for heavy-duty BETs from the perspective of HDV fleet operators. This contribution not only expands the existing body of knowledge but also provides practical insights for researchers in this field, ZEV policy practitioners, and industry stakeholders.

This paper is organized as follows. The next section outlines the methodology used in this study. The subsequent section discusses the study results. We then summarize the conclusions and suggest directions for future research.

METHODOLOGY

Survey Questionnaire Design

We developed a comprehensive survey questionnaire with the following key sections: 1) Basic Fleet Information, 2) Truck Choices, 3) Fleet Management Practices and Strategies, 4) Potential Charging Behavior, and 5) Perceptions. Each section included 4 to 12 main survey items and relevant follow-up questions when necessary. The initial draft questionnaire was formulated based upon prior qualitative research findings from HDV fleet operator interviews (*6*, *8–10*, *12*). We employed a multi-phase approach for survey implementation, comprising pretesting, a pilot survey, and a main survey. The survey questionnaire was uploaded to the online survey platform, SurveyEngine (*26*), and underwent internal pretesting. A pilot survey was then conducted with a small group of fleet operators to test the questionnaire from fleet operator viewpoints, and based on the feedback, the main survey questionnaire was refined. To accommodate comprehensive respondents, we prepared both English and Spanish versions of the questionnaire.

For this study, we selected survey items from the Potential Charging Behavior section, along with a few additional items from other sections, to address the research questions. These items included basic fleet information, such as fleet size, annual revenue, and operation types, and specific charging infrastructure preferences, including charging locations, access, acceptable charging duration, time-of-day for charging, and procurement preferences for TaaS. Given the context of the Potential Charging Behavior section, which assumes respondents might consider BET adoption, this section was directed at those planning to continue drayage operations in California. Respondents intending to discontinue their business, relocate to another state, or operate non-ZEVs only, especially under the ACF regulations, were filtered out from this section. The survey items were presented in single-option, multiple-option, or open-ended format. Table 1 provides the list of the selected survey items, their answer options, and types.

Table 1. List of Selected Survey Items and Response Options

Category	**Item**	**Answer Options**	**Type** [(a)]
Basic fleet information	Fleet size (trucks)	1, 2-5, 6-10, 11-20, 21-49, 50-99, 100+	S
	Approximate annual revenue	Less than $10M, Between $10M and $15M, Between $15M and $30M, More than $30M, Decline to state	S
	Operation type	Short haul (trucks that travel less than 200 miles each day), Long haul (all trucks that are not short haul), Both	S
Charging locations	Preferred location [(b)]	Mostly on-site, Mostly off-site, Both about equally	S
	Reason for the preferred location	*A text box provided for free answer*	(O)
Access to charging facilities	Preferred access for on-site charging	Our own private access, Shared private access by multiple fleets, No preference	S
	Preferred access for off-site charging	Public access, Access offered by a private provider, No preference	S
	Reason for the preferred access	*A text box provided for free answer*	(O)
Charging time	Acceptable longest duration for on-site charging	30 minutes or less, 1 to 1.5 hours, 2 to 3 hours, 5 to 7 hours, 10 to 16 hours	S
	Acceptable longest duration for off-site charging	30 minutes or less, 1 to 1.5 hours, 2 to 3 hours, 5 to 7 hours, 10 to 16 hours	S
Time of day for charging	Preferred time of day for on-site charging	Overnight, Right before starting daily operation, Between-shift daytime hours (in case of multiple shifts per day), Other (please specify)	M

Category	**Item**	**Answer Options**	**Type** [(a)]
	Preferred time of day for off-site charging	Overnight, Right before starting daily operation, En route to destination (at off-site stations), Between-shift daytime hours (in case of multiple shifts per day), Other (please specify)	M
	Reasons for the preferred time of day for on-site charging	Better fit with our daily schedule, Lower electricity rate, Less wait time, Other (Please specify)	(M)
	Reasons for the preferred time of day for off-site charging	Better fit with our daily schedule, Lower electricity rate, Less wait time, Other (Please specify)	(M)
Procurement types for ZEVs	Preference for procurement types for ZEVs: traditional buying, leasing vs truck-as-a-service	Buy, Lease, Truck-as-a-Service	S

Note: (a) S = single-option selection question. M = multiple-option selection question. O = open-ended question. ( ) = optional question. (b) The following descriptions on on-site and off-site charging were provided to respondents: On-site charging refers to charging that takes place at a location where trucks are parked (e.g., depot, fleet’s home base) or used (e.g., warehouse or distribution center). Off-site charging refers to charging trucks at a location separate from where they are parked or used, such as a public charging station or a dedicated facility (rather than fleet’s home base or final destinations).

Sampling and Recruitment

The target population for this study comprised drayage fleet operators at the Port of Los Angeles (POLA) and Port of Long Beach (POLB) in California. In 2019, approximately 22,500 drayage trucks were operating in California (*27*), with about 75% at POLA and POLB and the remaining 25% at other ports (*27*). Although full registration data were inaccessible, POLA’s analysis in June 2023 (*28*) indicated that 72.5% (810 out of 1,117) of drayage companies accessing the port were small fleets with 20 or fewer trucks, while 27.5% (307) were large fleets with over 20 trucks. Most of the drayage trucks at POLA (94.3%) operated on diesel, with 5.2% using natural gas and 0.5% using electricity.

We aimed to collect a minimum of 60 to 100 valid responses, by referring to previous studies (*29*, *30*), with approximately 10% of this sample targeted for the pilot survey. Stratified random sampling was used for the pilot survey to ensure a balance between subpopulations based on fleet size and alternative fuel adoption status. For the main survey, the census method was employed, which involves contacting all potential participants within the target population, to ensure a sufficient sample size. Participants were recruited via email invitations using the POLA/POLB drayage truck registries, which contained about 3,200 fleet operator contacts (*31*, *32*). In appreciation for participation effort, a $100 Amazon eGift card was offered to valid respondents, unless declined. All study materials and survey protocols were processed by the Institutional Review Board of the University of California, Irvine.

Participants completed the pilot survey in July 2023 and the main survey from December 2023 to April 2024. For both the pilot and main surveys, a total of 108 companies responded positively (3.4%) and 71 completed the survey (2.2%). The survey completion allowed for single or multiple sittings to accommodate flexibility, which resulted in an average completion time of 41 minutes for one sitting (59 respondents) and 4.4 days for multiple sittings (12 respondents). The response rates varied across sections, with filtering applied as needed, yielding 53 completed responses for the Potential Charging Behavior section. The characteristics of the participating fleets are summarized in Table 2.

Table 2. Basic Characteristics of Participating Fleets

Category	Number of Fleets	%	Category	Number of Fleets	%
Fleet size (a)			**Fuel adoption status** (b, c)		
Small fleet (≤ 20 trucks)	**35**	**66.0%**	Non-NGV-ZEV fleets	**37**	**69.8%**
1	2	3.8%	Diesel trucks only	31	58.5%
2 - 5	12	22.6%	Biodiesel adopters	5	9.4%
6 - 10	12	22.6%	Renewable diesel adopters	3	5.7%
11 - 20	9	17.0%	NGV adopters	**12**	**22.6%**
Large fleet (> 20 trucks)	**18**	**34.0%**	CNG adopters	9	17.0%
21 - 49	10	18.9%	LNG adopters	4	7.5%
50 - 99	2	3.8%	ZEV adopters	**10**	**18.9%**
≥ 100	6	11.3%	BET adopters	10	18.9%
Approximate annual revenue			HFCET adopters	4	7.5%
< $10M	29	54.7%	**BET charging infrastructure** (n = 10 adopters)		
$10M - $15M	6	11.3%	On-site / Off-site facilities		
$15M - $30M	4	7.5%	On-site (built, or plan to build)	9	90.0%
> $30M	7	13.2%	Off-site	1	10.0%
Decline to state	7	13.2%	Charging rate (currently used, or plan to use)		
Operational type			50 kW	1	10.0%
Short-haul (traveling less than 200 miles each day)	30	56.6%	150 kW	6	60.0%
Long-haul (traveling more than 200 miles each day)	3	5.7%	180 kW	2	20.0%
Both short- and long-haul	20	37.7%	350 kW	3	30.0%
			Not sure	1	10.0%
			Total	**53**	**100.0%**

Note: (a) The criterion defining a small fleet was informed by CARB's Innovative Small E-Fleet program (*33*). (b) ZEV = zero-emission vehicle, BET = battery electric truck, HFCET = hydrogen fuel cell electric truck, NGV = natural gas vehicle, CNG = compressed natural gas, LNG = liquefied natural gas. (c) The sum of each adopter category may exceed 100% as some fleets adopted multiple fuel types.

Data Analysis

We employed a comprehensive exploratory analysis using various methods. For the survey items with single or multiple-choice questions, we performed a descriptive analysis to understand an overview of the responses and detect any pattern or trends. Basic summary statistics were generated, accompanied by various charts and graphs. In addition, the analysis was further examined to identify potential differences among fleet segments, such as fleet sizes, annual revenues, and operation types. To verify these differences statistically, hypothesis tests were conducted, including the Chi-Square test and Fisher's Exact Test (*34*).

For the text responses in open-ended questions, we utilized thematic analysis (*35*) as a qualitative research approach, adhering to Braun and Clarke (*36*)'s six-phase approach: familiarizing with the data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the report. Through this process, we coded the qualitative data, extracted patterns, and identified themes to address the research questions.

RESULTS AND DISCUSSION

Characteristics of Participating Fleets

We analyzed several survey items from the Basic Fleet Information section to explore the key characteristics of the participating drayage fleets, including fleet size, annual revenue, operation type, and fuel technologies used (see Table 2). Fleet sizes spanned seven categories, from a single truck to over 100 trucks. To facilitate subsequent analyses, we categorized these fleet sizes into two groups, following the definitions in (*33*): small fleets with 20 trucks or fewer, comprising 66.0% of the respondents, and large fleets with over 20 trucks, representing 34.0%. Companies with annual revenue below $15 million constituted about two-thirds of participants (66.0%), while those above $15 million accounted for 20.7%, with 13.2% not disclosing their revenue.

Short-haul fleets (traveling less than 200 miles per truck each day (*37*)) comprised 56.6% of the total. Only three companies (5.7%) identified themselves as long-haul operators, while the remaining 37.7% reported mixed short-haul and long-haul operations. Figure 1 illustrates the distribution of the survey participants by fleet size and operation type. As expected for drayage industry participants, short-haul operations dominated most fleet size categories. However, for larger fleets, specifically those with 50-99 and over 100 trucks, the predominant operation type was a combination of short-haul and long-haul.

Of the 53 participating companies, 31 (58.5%) operated solely diesel trucks, while the remaining 22 (41.5%) used alternative fuels (including gaseous and/or zero-emission fuels). Specifically, 12 companies (22.6%) operated natural gas trucks, 10 (18.9%) operated BETs, and 4 (7.5%) operated hydrogen fuel cell electric trucks. Most of the BET adopters (9 out of 10) reported having, or planning to construct, on-site charging facilities. Charging rates for BETs ranged from 50kW to 350kW, with 150kW being the most common. Reported charging times for BETs varied from 1.5 to 12 hours, depending on the charging rate.

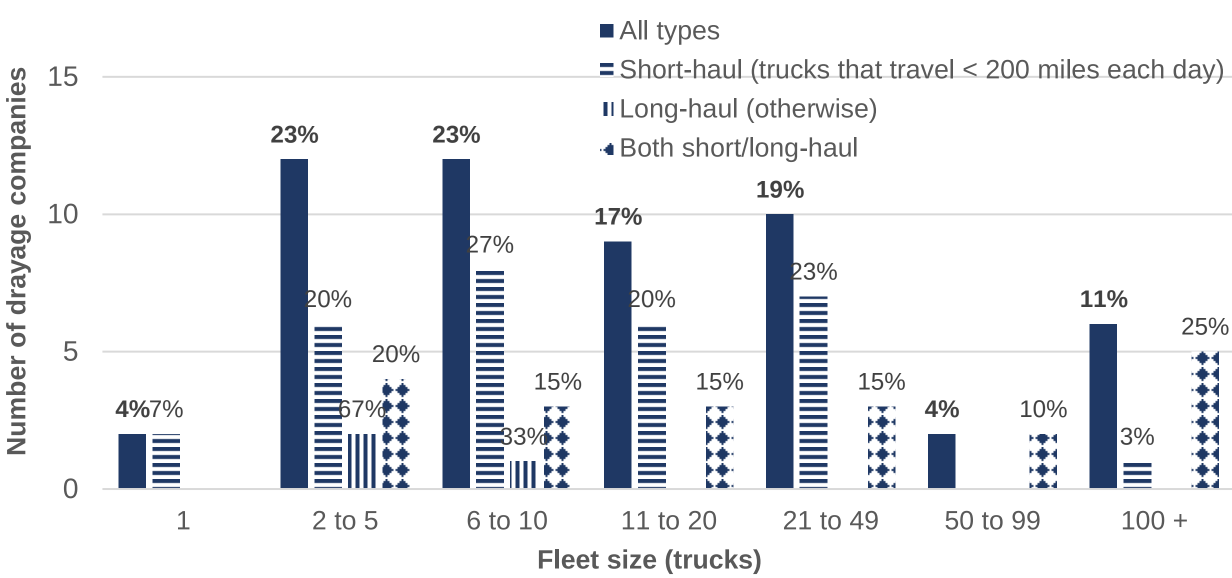


Figure 1. Distribution of Survey Participants by Fleet Size and Operational Characteristics

Charging Location Preferences

To address the first research question ("Which charging locations do fleet operators favor and what are the reasons for their preferences?"), we analyzed relevant survey data on charging location preferences in relation to various fleet characteristics. Figure 2 provides an overview of location preferences by short/long-haul operations, Figure 3 illustrates these preferences by fleet size, and Figure 4 depicts the preferences by annual revenue. Among the 53 participating drayage fleets, a majority (68%) preferred charging mostly on-site, while a notable proportion (26%) favored both on-site and off-site charging equally. Only a small fraction (6%) preferred charging mostly off-site. Analyzing these preferences by operation type (Figure 2) revealed that, as expected, short-haul operations predominantly preferred on-site charging (73%). For fleets with mixed short- and long-haul operations, over a third (35%) preferred both on-site and off-site charging.

The preference distribution by fleet size (Figure 3) indicates an interesting trend. A tipping point occurs where the preference shifts from 'both about equally' to 'mostly on-site,' observed in fleets with more than 5 trucks. This trend aligns with previous research on fleet operator decisions on CNG HDV refueling infrastructure (*10*), which found that fleets with more than 5 trucks had already built or planned to build on-site infrastructure, while smaller fleets relied on off-site stations. The preference distribution by annual revenue is depicted in Figure 4. As highlighted in the graph, only companies with annual revenues below $15M showed a preference for 'mostly off-site' charging. Responses indicating any reliance on off-site stations (i.e., 'mostly off-site' and 'both about equally') averaged 31% among these companies with annual revenues under $15M.

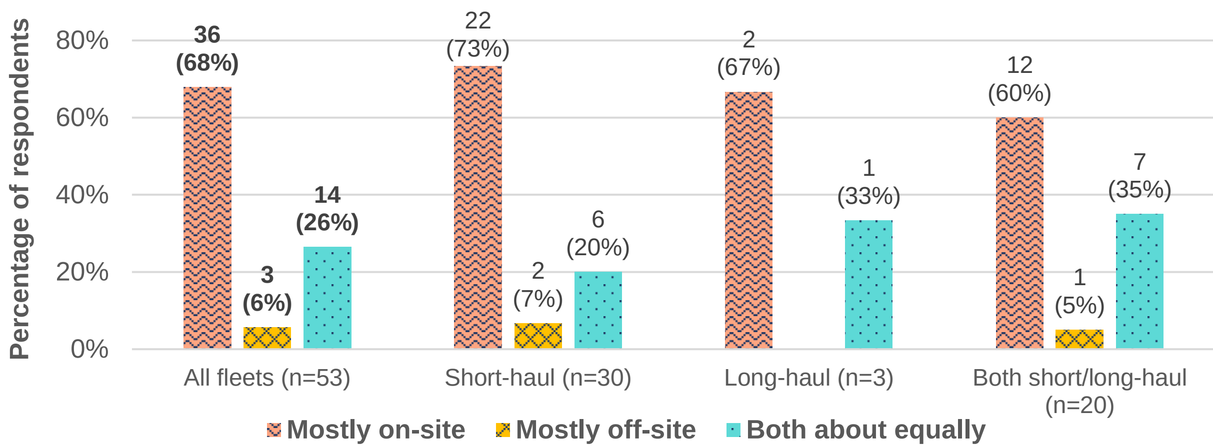


Figure 2. Charging Location Preferences by Operational Characteristics

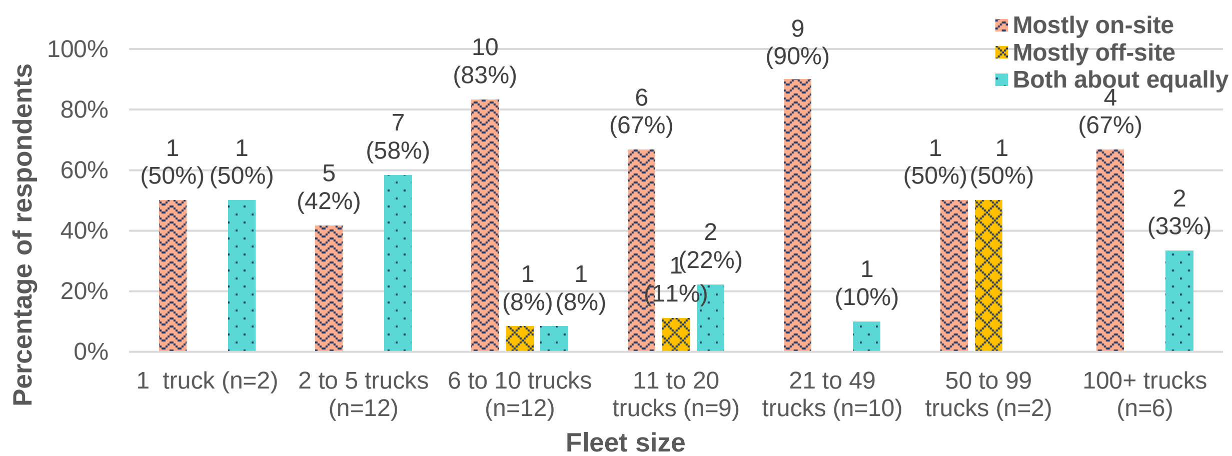


Figure 3. Charging Location Preferences by Fleet Size

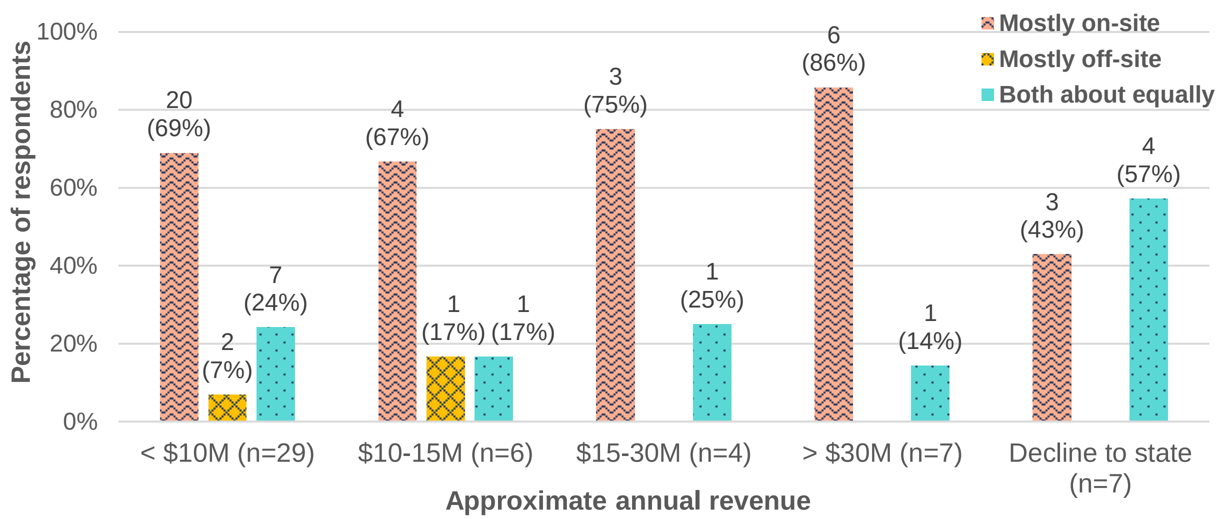


Figure 4. Charging Location Preferences by Annual Revenue

To statistically assess the relationships between reliance on off-site stations and fleet characteristics, hypothesis tests were performed. All hypothesis test results for this study are summarized in Table 3, including this case. Among various fleet variables, only the fleet size (5 or fewer trucks) showed a statistically significant relationship with reliance on off-site stations. Under the null hypothesis of no association between smaller fleet size ($\leq$ 5 trucks) and reliance on off-site charging stations, Fisher's exact test yielded a p-value of 0.042, rejecting the null hypothesis. In addition, the test produced an odds ratio of 4.3, indicating that smaller fleets with 5 or fewer trucks are approximately 4.3 times more likely to rely on off-site charging stations compared to larger fleets.

To further explore the reasons behind preferences for specific charging locations, we analyzed responses to an open-ended question: "Please provide any additional thoughts regarding the location for charging your BETs. For example, why would you prefer on-site or off-site facilities?" The themes derived from the thematic analysis are summarized in Figure 5. Fleet operators reported various advantages of on-site charging. The most frequently mentioned benefit, by 26% of the participating fleets, was the convenience, efficiency, and flexibility of charging trucks using on-site facilities. In addition, many operators highlighted the advantages of having greater control over facility operations and saving on driver costs, as drivers would need to be paid hourly if they were off-site. One operator noted the potential to reduce fueling costs by installing solar panels on-site. Another operator viewed constructing on-site facilities as a good investment for their company. However, several also expressed concerns about building on-site infrastructure, including expensive construction costs, restrictions posed by landlords, and the requirement of a 10-year operation agreement if financially supported (*38*).

Regarding off-site charging stations, most comments highlighted concerns. Several fleet operators cited driver costs for traveling to off-site stations and long charging times as significant issues. One operator remarked, "*Even if public charging stations are available, charging takes many hours, and I cannot have drivers on duty, being paid hourly wage, waiting for the vehicle to charge*." Others were concerned about the possibility of off-site stations being crowded, leading to substantial time loss for drivers. Also, several operators pointed out the uncertainty of the off-site station availability, and emphasized the need for improvements in fast charging technology in the near future.

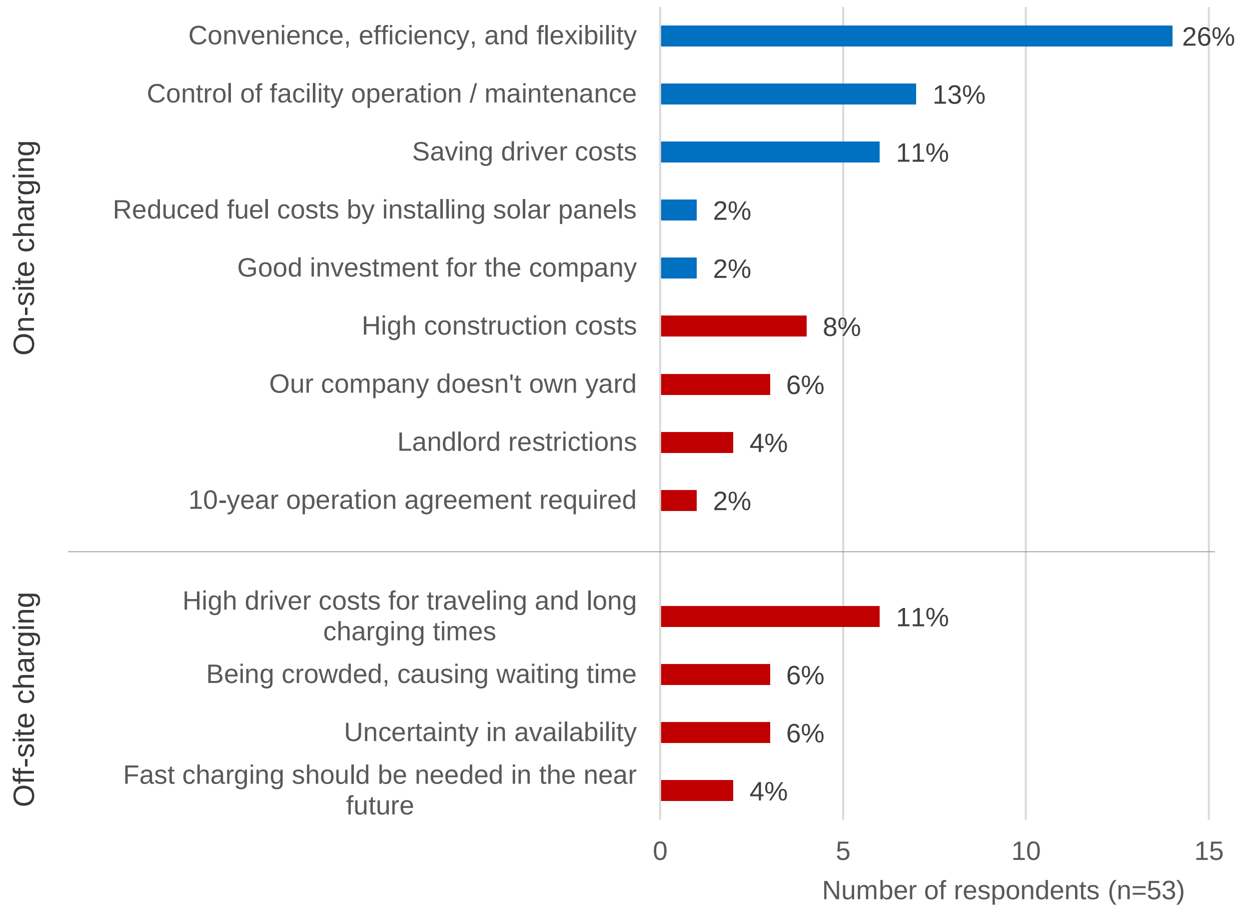


Figure 5. Additional Qualitative Responses on Preferred Charging Locations

Charging Access Preferences

To explore the second research question ("Which access types do fleet operators prefer and for what reasons?"), we analyzed relevant survey data, summarized in Figures 6 and 7. Figure 6 illustrates the distribution of preferred access types for on-site and off-site charging among small and large fleets, while Figure 7 summarizes the reasons behind these preferences.

For on-site charging, a substantial majority of large fleets (88%) preferred private access. Among small fleets, two-thirds (64%) preferred private access, with about a third (30%) showing no preference. Only a minor fraction of both small and large fleets (6%) preferred shared access. The most frequently mentioned reason for preferring private access was efficient operation, cited by 25% of the participating fleets. This was followed by the desire for direct control over facility operations and ensuring security and safety. Moreover, some fleet operators cited drawbacks of shared access, which led them to prefer private access. One such drawback was the potential for complex processes and conflict: "*Sharing the same charging assets would lead to conflict from multiple fleets*." Concerns about overcrowding and wait times when sharing access were also noted. Despite these concerns, a few (6%) preferred shared access and noted advantages such as benefits for many fleets and reduced construction costs.

For off-site charging, approximately half of both small and large fleets preferred public access, while the remaining half had no specific preference. In response to the open-ended question about their reasons for these preferences, several fleet operators emphasized the importance of availability, efficiency, and cost. One operator commented, "*They just need to be available like diesel stations. A heavy load […] not on a straight, flat route […] could really drain a battery*." Another remarked, "*We do* *not operate consistent routes and require refueling availability virtually everywhere*." Meanwhile, a small fraction of small fleets (8%) preferred access provided by a private provider, citing a similar reason of "*maximizing availability*."

Hypothesis tests were conducted to identify any differences in access preferences between small and large fleets. As visually inferred from the graphs, the test results indicated no significant statistical difference, with the p-value exceeding 0.05 (see Table 3).

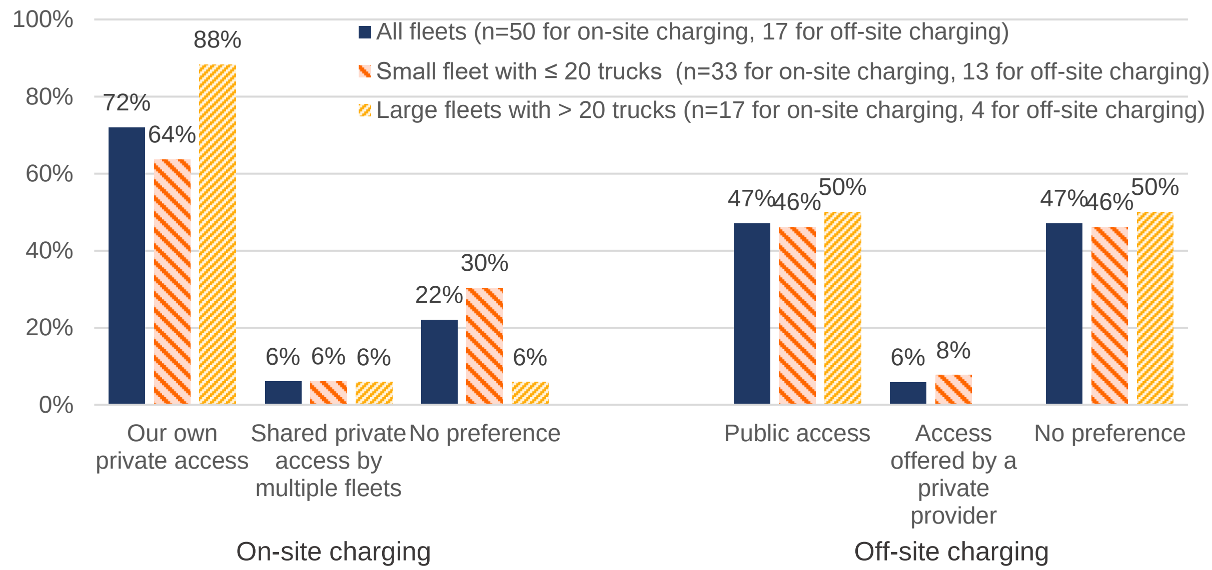


Figure 6. Charging Access Preferences by Fleet Size

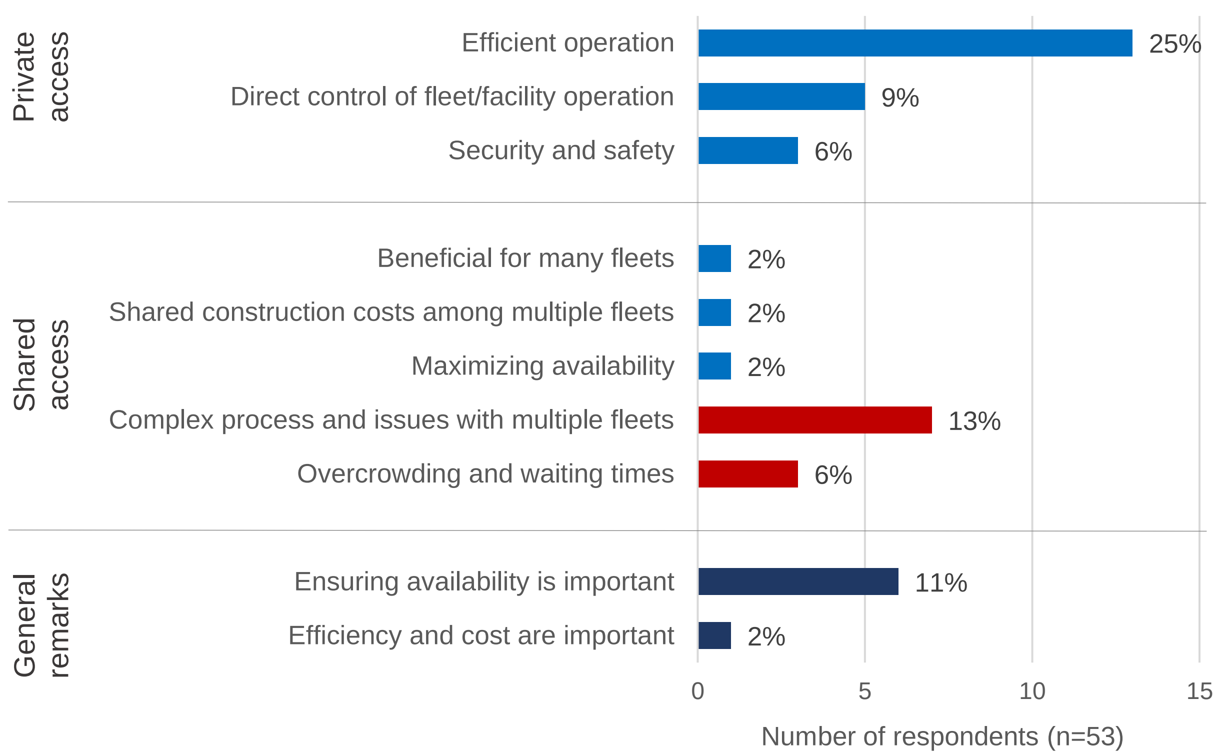


Figure 7. Additional Qualitative Responses on Preferred Charging Access

Acceptable Charging Time

To address the third research question ("What are the longest charging times that fleet operators consider acceptable?"), we analyzed the survey data, focusing on any differences between on-site and off-stie facilities and operation types. Figure 8 illustrates the distribution of acceptable charging times for on-site versus off-site facilities. For on-site charging, acceptable times ranged from less than 30 min to up to 16 hrs, with the most preferred time being 1 to 1.5 hrs (30%). Other acceptable times included 30 min or less and 2 to 3 hrs (each 22%), followed by 5 to 7 hrs (18%), with 10 to 16 hrs being the least preferred (8%). In contrast, for off-site facilities, the most frequently acceptable charging time was less than 30 min (71%), with the maximum being up to 3 hrs. To examine the association between reliance on off-site stations and a preference for faster charging (less than 1.5 hrs or even 30 min), both Chi-square and Fisher's exact tests were conducted. The results consistently yielded p-values close to or below 0.05 (see Table 3). These results led to the rejection of the null hypothesis, which indicates an association between off-site charging reliance and preference for faster charging.

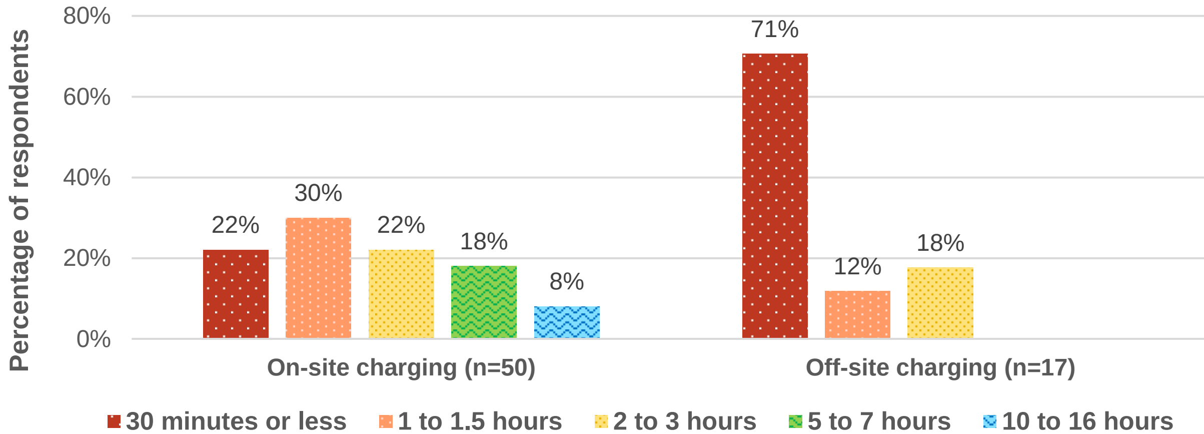


Figure 8. Acceptable Longest Charging Times at On-Site vs. Off-Site Facilities

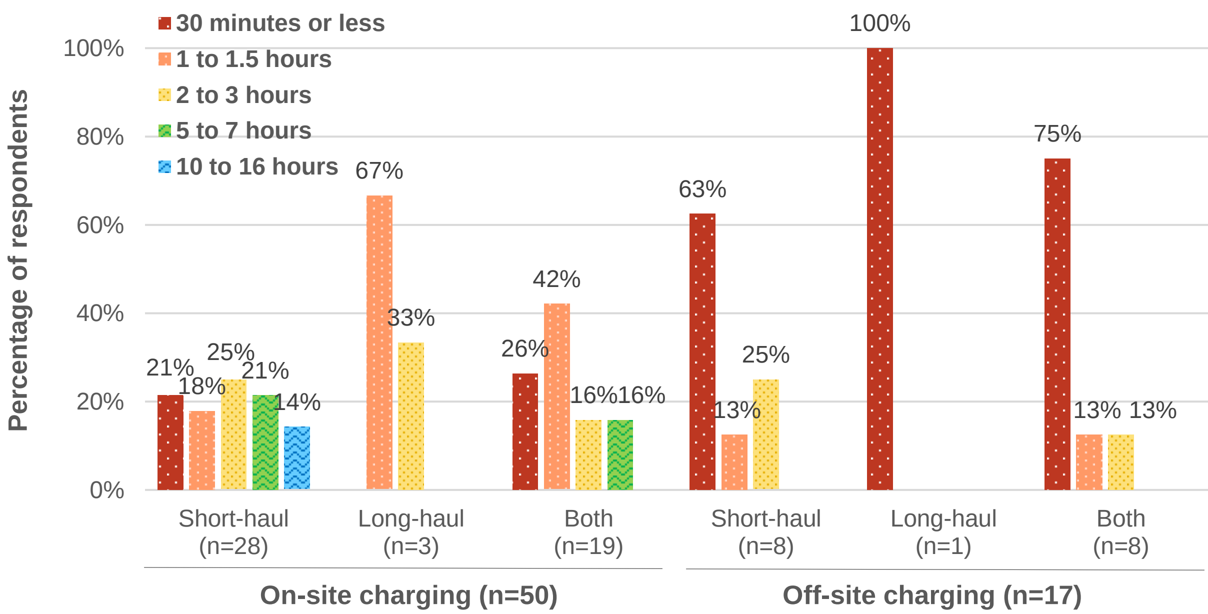
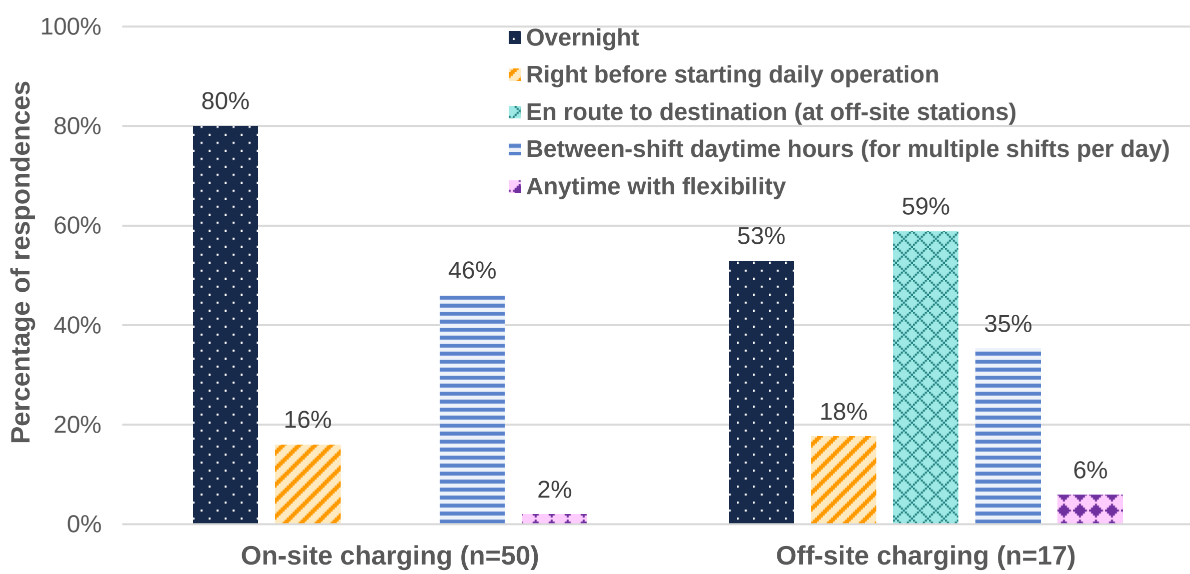


Figure 9. Acceptable Longest Charging Times at On-Site vs. Off-Site Facilities by Operation Types

The distribution of acceptable charging times for different operation types is detailed in Figure 9. For on-site charging, distinct preferences were observed across short-haul, long-haul, and mixed operations, while off-site charging consistently showed a preference for faster charging across all operation types. For short-haul operations, a range of charging times, from less than 30 min to up to 16 hrs, was reported as acceptable by 14% to 25% of the responses. For long-haul operations, charging times up to 3 hrs were acceptable at on-site facilities, likely due to the need for longer travel distances and limited downtime. In mixed short/long-haul operations, acceptable charging times were spread across a wide range. Compared to short-haul-only operations, there was a higher preference for 1 to 1.5 hrs (42%), and none accepted 10 to 16 hrs for charging time. A hypothesis test was conducted under the null hypothesis that there is no association between operation types and the need for faster charging (less than 90 min) at on-site facilities. The Fisher's exact test yielded a p-value of 0.099, rejecting the null hypothesis at the 10% significance level.

Preferred Time of Day for Charging

To investigate the fourth research question ("What times of day are favored by fleet operators for charging BETs, and why?"), we examined the survey responses about the preferred times of day for charging and the reasons behind these preferences. Figure 10 presents the distribution of preferred times of day for on-site versus off-site charging. For on-site charging, the dominant preference was overnight (80%), with nearly half also preferring between-shift daytime hours (46%). This was followed by 16% preferring the time right before starting daily operations. In contrast, off-site charging preferences were more varied, with the most favored choice being en route to the destination (59%), followed by overnight (53%) and between-shift daytime hours (35%). A few respondents preferred the time right before starting daily operations (18%), or opted for the free-answer option, noting 'anytime with flexibility' (6%). These variations in time-of-day preferences between on-site and off-site charging were confirmed by Fisher's exact test (see Table 3). However, no significant differences in time-of-day preferences were detected between fleet sizes or operation types.

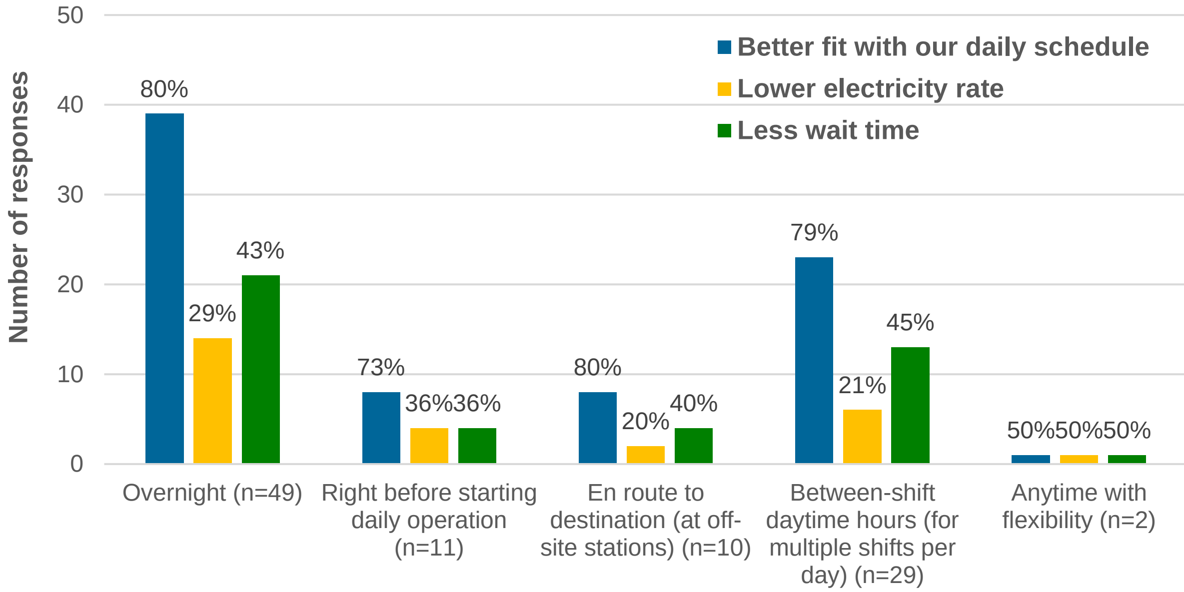


Note: The total percentage exceeds 100% as respondents could select multiple options.

Figure 10. Time-of-Day Preferences for On-Site vs. Off-Site Charging

Figure 11 outlines the reasons for the preferred times of day. The distributions of these reasons did not show significant statistical differences across different times of day (see Table 3). The most common reason for preference across most categories was a better fit with their daily schedule (73% to

80%). The second most cited reason was less wait time (36% to 45%), followed by lower electricity rates (20% to 36%). Overall, these responses indicate the importance for fleet operators to maintain efficient operations and minimize downtime. One fleet operator commented, "*Trucks sitting still do not generate income. If the trucks are being utilized, they're moving day and night.*"



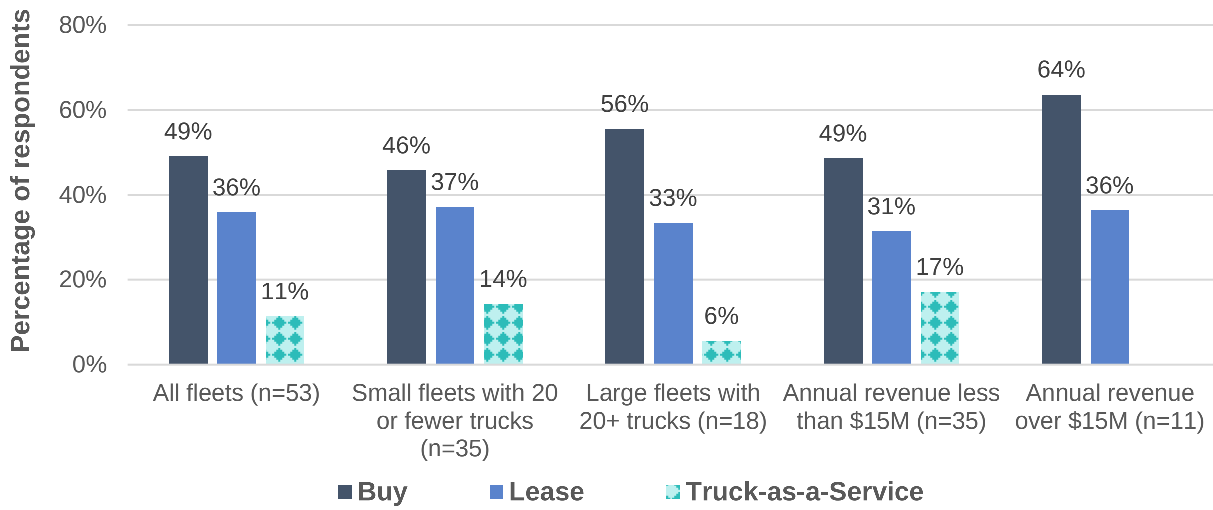
Note: The total percentage exceeds 100% as respondents could select multiple options.

Figure 11. Reasons for Preferred Times of Day for Charing BETs

Preference for Truck-as-a-Service

Regarding the fifth research question ("Is there interest among fleet operators in innovative charging solutions, like Truck-as-a-Service?"), we analyzed the survey data on preferred procurement options for ZEVs. The survey question asked, "Assume that zero-emission vehicles (ZEVs) are available in the market, including battery electric and hydrogen fuel cell electric trucks. If you were to procure a ZEV for your next truck, which type of procurement would you prefer?" Respondents could choose from buy, lease, and truck-as-a-service. In our survey, TaaS was explained to participants as a service where the provider is responsible for purchasing and installing charging/fueling equipment, and users pay on a per-mile or per-use basis.

Figure 12 presents an overview of responses across different fleet segments. Of the 53 companies surveyed, 11% (6 companies) expressed a preference for TaaS. All these companies reported annual revenues of less than $15M, and most (5 out of 6) were small fleets with fewer than 20 trucks. These findings suggest a potential interest in innovative charging solutions among smaller organizations. However, hypothesis tests indicated no statistically significant differences in TaaS preference between small and large organizations (see Table 3). Since this analysis was based on a single survey item, further research, employing more rigorous methods such as stated preference choice experiments, may be required to thoroughly assess the demand for TaaS.



Note: The following explanation of TaaS was provided to respondents: "Truck-as-a-service allows you to lease ZEVs as needed. The TaaS provider is responsible for purchasing and installing charging/fueling equipment, which means that you will have access to charging/fueling facilities. This service also includes maintenance and repairs of the vehicle and the infrastructure. You will need to pay for the use of this service on a per-mile or per-use basis.

Figure 12. Preference for Truck-as-a-Service vs. Buying and Leasing Options across Various Fleet Segments

Table 3. Summary of Hypothesis Test Results for Associations between Charging Preferences and Fleet Characteristics

Null hypothesis (H_0)	**Chi-squared test** (N = 53)		**Fisher's exact test**		**Rejection of H_0** [(b)]
	χ^2 statistic (df)	**p-value** [(a)]	**p-value**	**Odds ratio**	
Charging location					
There is no association between fleet size (whether it is 5 or fewer trucks or more) and reliance on off-site charging stations.	4.04 (1)	.045 [(!)]	.042	4.30	*Rejected* ***
There is no association between annual revenue (less than $15M vs over $15M) and reliance on off-site charging stations.	<0.01 (1)	>.9	>.9	0.92	Not rejected
There is no association between operation types (whether they include long-haul operations or not) and reliance on off-site charging stations.	0.44 (1)	.505	.384	1.75	Not rejected
Charging access					
There is no association between fleet size (small vs large fleets) and access preferences at on-site facilities.	3.99 (2)	.136 [(!)]	.117	n/a	Not rejected
There is no association between fleet size (small vs large fleets) and access preferences at off-site facilities.	0.33 (2)	.849 [(!)]	>.9	n/a	Not rejected
Charging duration					
There is no association between reliance on off-site charging stations and the preference for faster charging times of less than 1.5 hours.	3.79 (1)	.052	.035	4.54	*Rejected* ***
There is no association between reliance on off-site charging stations and the preference for faster charging times of less than 30 minutes.	11.00 (1)	.001	.001	9.40	*Rejected* ***
There is no association between operation types and the preference for faster on-site charging times of less than 1.5 hours.	4.13 (2)	.127 [(!)]	.097	n/a	*Rejected* *
Time of day for charging					
There is no association between preferred times of day for charging and the type of charging location (on-site vs off-site).	28.76 (4)	< 0.001 [(!)]	< .001	n/a	*Rejected* ***
There is no association between preferred times of day for charging and the reasons for those preferences.	1.77 (8)	>.9 [(!)]	>.9	n/a	Not rejected
Preference for Truck-as-a-Service					
There is no association between fleet size (small vs large fleets) and preferences for TaaS.	0.21 (1)	.645 [(!)]	.650	0.37	Not rejected
There is no association between annual revenue (less than $15M vs over $15M) and preferences for TaaS.	0.97 (1)	.324 [(!)]	.311	0.00	Not rejected

Note: (a) Chi-squared approximation may be inaccurate for any cell with an expected value of 5 or fewer in the contingency table. These instances are marked with (!). (b) Rejection of the null hypothesis at the 1%, 5%, and 10% significance levels is denoted by ***, **, and *, respectively.

CONCLUSIONS

Inadequate infrastructure presents a major challenge to achieving heavy-duty ZEV policy goals. Understanding the infrastructure needs of fleet operators, who are key demand-side stakeholders, is vital for developing effective infrastructure solutions and strategies. This study explored these needs through a fleet survey of California's drayage sector, examining key aspects such as charging locations, access types, charging duration, time-of-day preferences, and innovative solutions like TaaS. By analyzing recent data from fleet operators with diverse fleet sizes, annual revenues, and operational characteristics, our study offers comprehensive insights that can support more realistic modeling of related research problems, including charging demand projection and station location optimization. Insights drawn from fleet operators, key players in the ZEV transition, offer valuable evidence for policymakers involved in charging infrastructure planning and implementation. In addition, industry stakeholders, from drayage companies to infrastructure developers, can leverage these insights to guide the development and deployment of ZEV infrastructure solutions.

While most drayage companies surveyed preferred on-site charging, approximately a quarter favored both on-site and off-site options equally. Notably, these companies were typically smaller fleets with 5 or fewer trucks, indicating the need for off-site infrastructure support for them. Meanwhile, those preferring on-site charging cited concerns such as construction costs and procedural barriers. Policy and industry stakeholders should continue to develop support mechanisms to alleviate these obstacles. Regarding charging access, most respondents preferred private access for on-site facilities to ensure efficient operations and control, whereas only a small fraction preferred shared access. Although shared access could benefit other fleets by expanding operational coverage with additional charging opportunities, issues such as complex processes and potential conflicts among multiple fleets were noted. Addressing these drawbacks with practical solutions should be essential, informed by input from various stakeholders.

Regarding charging time, the survey findings indicate a need for faster charging options, such as under 1.5 hours or even 30 minutes, not only at off-site stations but also at on-site facilities, particularly for long-haul or mixed operations. Support for the development of fast charging technologies should be directed toward technology providers and research entities. In addition, time-of-day preferences varied widely, including overnight, daytime between shifts, and en route, depending on the charging location, primarily driven by the need for efficient fleet operations. These findings should be integrated into related research areas such as electricity demand forecasting in temporal and geographical dimensions. Furthermore, a small percentage of respondents showed a preference for TaaS, which includes charging solutions, over traditional truck procurement methods. Most of these fleets had small fleet size or lower annual revenues, indicating the necessity for innovative charging solutions tailored to smaller organizations and greater awareness of such options if their benefits are demonstrated.

This research has several limitations that suggest directions for future research. First, the methodology employed a fleet survey with single-option, multiple-option, and open-ended questions. Although the findings were comprehensive in addressing the research questions, future research could benefit from alternative approaches, such as stated preference choice experiments with larger sample sizes, to assess the demand for various charging solutions. Second, the study's scope was limited to the drayage industry. Examining other HDV applications, particularly those with differing operational characteristics such as long-haul or residential area operations, would help broaden our understanding of infrastructure needs. Third, while this study centered on California, many other U.S. states are also pursuing zero-emission HDVs. Research in these states would offer valuable insights into this area. Collectively, these research findings will be instrumental in developing effective solutions to HDV charging infrastructure challenges.

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AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: YB, CRR, and SGR; data collection: YB; analysis and interpretation of results: YB; draft manuscript preparation: YB. All authors reviewed the results and approved the final version of the manuscript.

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